Impact of urban form on Land Surface Temperature (LST) based seasonal characteristics: Empirical study from Nanjing

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Abstract. A good urban thermal environment is of great importance to the quality of human settlements and the sustainable development of cities. However, with the development of urbanization, the change of urban form such as the increase of impermeable area caused the increase of LST. This study will take the 11 districts of Nanjing as study area to evaluate the influence of urban form on LST from three dimensions: land use, landscape index and traffic accessibility. The study found that there was a significant positive correlation between road network density (RND) and LST7 (land surface temperature in July) (1% significance level). Following that, there were patch density (PD) (5%), patch cohesion index (COHESION) (5%) and PVA (10%), all of which were negatively correlated with LST7. However, the regression fitting degree of LST1 (land surface temperature in January) and urban form index was only about 2%. Besides, different regions are affected by urban form indexes in varying degree. The study provides scientific implications for relieving surface temperature and improving thermal environment in Nanjing city.

1. Introduction

With the development of urbanization, the composition and area of land use type are changing, especially the increase of impermeable area, which leads to the continuous increase of urban total heat emission[1]. At the same time, human activities affect the urban spatial forms, such as the degree of fragmentation of green landscape. These changes further affect urban climate and lead to the urban heat island effect (UHI)[5]. This will harm the urban thermal environment and the quality of human living environment. Therefore, exploring the influence mechanism of land use change and urban form on the UHI is significant. At present, many articles focused on using the urban form elements related to architectural form such as building density, building height and floor area ratio[1]. However, as a crucial part of urban morphology, landscape features have not received much attention. At the same time, there are different conclusions about the influence of landscape indexes on surface temperature. Some study have been pointed out that landscape index has a strong correlation with urban surface temperature[2]. However, some studies concluded the impact of landscape index on LST is not significant[3]. That may because the degree of influence of landscape features may be influenced by the study area and the study period[2-4]. Therefore, exploring the impact of urban morphology in different regions on LST based seasonal characteristics will supplement the existing literatures about the relationship between landscape indicators and LST. Thus, this article will define urban form from three dimensions: land use, landscape characteristics, traffic accessibility and evaluate the influence mechanism of these index on LST in different seasons, then qualitatively discuss the influence in regions and put forward some suggestions.
2. Data and method

2.1. Study area
Nanjing City is located in the east of China, the lower reaches of the Yangtze River. The city’s areas include Xuanwu, Qinhua, Jianye, Gulou, Pukou, Qixia, Yuhuata, Jiangning, Liuhe, Lishui and Gaochun District. The community unit is the basic unit for rational planning of land use and the allocation of public facilities. Thus, at the community level, this study analyzed the spatiotemporal patterns of LSTs and their driving mechanisms at the 11 districts of Nanjing.

2.2. Data

2.2.1. Data sources.
The land use data were provided by the geographical information monitoring cloud platform (http://www.dsac.cn/). The land use types were divided into six categories: arable land; forest land; grassland; water area; urban, rural, residential, industrial, and mining land; and unused land. In addition, vegetation area is the sum of forest land and grassland area. And total land area is the sum of the six kinds land area. PD and COHESION in Nanjing in 1995-2018 are based on land use data obtained by FRAGSTATS 4.3 software. RND is the ratio of road network length to administrative area in each community. The road network length in 1995-2000 is the road identification of Nanjing traffic map and that in 2005-2018 is from Open Street Map (https://www.openstreetmap.org/). About the data of LST1 and LST7, the satellite images selected in this study were the MODIS data from 2000 to 2018. And the data in 1990-1995 were retrieved using Landsat imagery. The selected months were January (representing winter) and July (summer) of each study year, without clouds. Notably, the image from July 1995 in summer was affected by clouds, and the actual data obtained were inconsistent. Thus, the LST of that year was acquired using interpolation.

2.2.2. Explanatory variables.
This paper divided urban form from three dimensions. Based on this, four influential variables were selected (Table 1)[6-7]. The reasons for studying urban form through three dimensions are as follows.

About the landscape index, landscape measurement can effectively quantify the structural composition and spatial morphological of patches. Specifically, the composition refers to the composition proportion of each landscape type, while the spatial configuration mainly refers to the area, shape, agglomeration, heterogeneity, etc. of the landscape elements. They affect the solar radiation absorption, evaporation transpiration and other ecological processes directly and then determine the heat transfer relationship on the earth's surface[8]. In this paper, PD and COHESION are selected as the two indicators of landscape index. PD reflects the degree of fragmentation of the landscape. The greater is the value, the more severe is the fragmentation. COHESION represents the physical connectivity of the patches. The higher is the value, the better is the physical connectivity between the patches. About land use, land types have different capacities to absorb heat and dissipate heat and green space and vegetation area have great effects on mitigating heat island effect[5]. In this study, PVA is regarded as the land use index affecting LST. About road network density, it is an important indicator of economic development and embodiment of regional traffic accessibility. It reflects anthropogenic heat release from the perspective of transportation.

In conclusion, the land use and landscape index represent the ability of offsetting or aggravating the LST of the region itself. Road network density can be regarded as the reflection of human activity from the view of transportation. These three dimensions of urban form can fully explain the influence of region itself and human activities on surface temperature.
2.3. Methods

To quantify the impacts of urban form on LST, the ordinary least squares (OLS) method is the most commonly used method for analyzing the relationships between two or more variables. In this paper, the OLS regressions between LST and urban form index are shown below:

\[
LST1 = a_0 + a_1PVA + a_2PD + a_3COHESION + a_4RND + \varepsilon_1
\]

\[
LST7 = c_0 + c_1PVA + c_2PD + c_3COHESION + c_4RND + \varepsilon_2
\]

Besides, the study explored the effect of urban form on LST using panel data. In order to study the correlation characteristics of different research objects at different time period, using appropriate method is significant. Among many statistical methods, panel analysis is suitable. Hsiao [9] points out that the analysis in panel data provides a greater capacity to capture complex behaviors in the series with respect to purely time series analysis or cross-sectional analysis.

Before the panel analysis, the study summarized the statistical information of variables and carried out multicollinearity analysis (Table 2). The results show that there is no multicollinearity in variables. The panel regression forms are comprised of the pooled regression (PA), the random effects estimation (RE) and the fixed effects estimation (FE). After F-test, Least Square Dummy Variable Model (LSDV) and Lagrange multiplier test (LM), FE is the most appropriate method to study the influence of urban form on LST1 and LST7.

### Table 1. Explanatory variable description.

| Type            | Variables (abbreviated) | Formula | Description                                                                 |
|-----------------|-------------------------|---------|-----------------------------------------------------------------------------|
| Land use        | Percentage of vegetation area (PVA) | \(A_{va}/A_i\) | Percentage of vegetation area in each community (Unit: %)                   |
| Landscape index | Patch density (PD)     | \(m/A\) | Land use patch density per community (Unit: n/100ha)                        |
|                 | Patch Cohesion Index (COHESION) | \[
1 - \frac{\sum_{j=1}^{n} p_{ij}^*}{\sum_{j=1}^{n} a_{ij}^*} \sqrt{\frac{\sum_{j=1}^{n} a_{ij}^*}{\sum_{j=1}^{n} p_{ij}^*}} \times \left[ 1 - \frac{1}{\sqrt{Z}} \right] \times 100
\] | Patch Cohesion Index of land use in each community (Unit: %) |
| Traffic accessibility | Road network density (RND) | \(L/A_i\) | The ratio of road network length to administrative area in each community (Unit: km/km²) |

Note: \(A_{va}\) is the vegetation area in each community; \(A_i\) is the area of each community; \(m\) is number of patches; \(A\) is total landscape area; \(p_{ij}\) is the perimeter (in terms of cell numbers) of patch \(j\) of land-use class \(i\); \(a_{ij}\) is the area (in terms of cell numbers) of patch \(j\) of land-use class \(i\); \(Z\) is the total number of cells in a given area; \(n\) is the number of patches for land-use class \(i\); \(L\) is the road network length in each community.

### Table 2. Descriptive statistics.

| Type            | V | Min  | Max  | Mean | SD  | S  | K   | VIF |
|-----------------|---|------|------|------|-----|----|-----|-----|
| Land use        | V | 0.01 | 36.65| 10.88| 9.45| 1.46| 4.88| 1.26|
| Landscape index | Patch density | 0.24 | 2.12 | 1.24 | 0.59 | -0.33 | 1.77 | 1.77 |
|                 | Patch Cohesion Index | 98.73 | 99.77 | 99.35 | 0.30 | -0.38 | 2.12 | 1.46 |
| Traffic accessibility | Road network density | 0.07 | 5.64 | 1.02 | 1.29 | 2.04 | 6.12 | 1.49 |
| LST             | LST-1 | 2.52 | 10.01 | 6.34 | 1.84 | -0.44 | 2.43 | —— |
|                 | LST-7 | 24.67 | 35.33 | 31.79 | 1.99 | -0.81 | 4.27 | —— |

Note: \(V\) = variable, \(SD\) = standard deviation, \(S\) = skewness coefficient, \(K\) = kurtosis coefficient.
3. Result

3.1. Temporal and spatial analysis of LST and urban form in 11 districts

LST7 of 11 districts showed an overall trend of rise while LST1 fluctuated during 1995-2018. LST1 reached the maximum value in 2015 and the minimum value in 2018. Besides, the regions with high LST7 in 2015-2018 were concentrated in the central region of Nanjing while the spatial distribution of LST1 was relatively diverse, among which LST1 in Xuanwu and Gulou was always lower.

In 1995-2018, Xuanwu was heading the list in PVA with 36% (not shown in figure 2 (a)) while that in Qinhuai was the lowest with 0.1%. Besides, PVA in all regions except Xuanwu was decreasing. PD in Gulou was always the lowest. And except for Lishui, PD in other regions was decreasing. About landscape index, COHESION was highest in Liuhe and lowest in Yuhuatai. Besides, in Liuhe, Gaochun et al., the value of COHESION was decreasing while that in Gulou, Qinhuai et al. was increasing. RND in each district is on the rise and the growth of RND was quick in 2010-2018 instead of slow growth in 1995-2010.

Figure 1. LST1 and LST7 in 11 districts of Nanjing.

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3.2. OLS and panel data analysis

Under OLS, RND has a significant positive correlation with LST7. Following RND, the significant factors were PD, COHESION and PVA, which were negatively correlated with LST7. The three panel models all show the same correlation as OLS. In FE, the order of significance effect from large to small is: COHESION, RND, PVA and PD.

OLS is not suitable for the exploration of LST1 and urban form index. In FE, only RDP presented negative correlation significance, while other indexes had no significant influence.

Table 3. Comparative results of LST-7 and explanatory variables among the OLS, PA, RE and FE regression analyses.

| Type             | Variables                  | OLS     | PA       | FE       | RE       |
|------------------|----------------------------|---------|----------|----------|----------|
| Land use         | Percentage of vegetation area | -0.047*  | -0.047** | -0.527** | -0.465** |
|                  |                            | (-1.980)| (-2.460) | (-2.290) | (-2.460) |
| Landscape index  | Patch density              | -1.155**| -1.155** | -0.695   | -1.155** |
|                  |                            | (-2.570)| (-2.260) | (-0.570) | (-2.260) |
|                  | Patch Cohesion Index       | -1.959**| -1.959***| -2.135   | -1.959***|
|                  |                            | (-2.420)| (-4.280) | (-1.110) | (-4.280) |
| Traffic accessibility | Road network density     | 0.563***| 0.563*** | 0.504*** | 0.563*** |
|                  |                            | (3.010) | (2.920)  | (3.170)  | (2.920)  |
| Test coefficient  | Prob>F                     | 0.0000  | 0.0000   | 0.0154   | 0.0000   |
|                  | R²                          | 0.3915  | 0.3915   | 0.2253   | 0.1912   |

Statistically significant * at the 10%, ** at the 5% and *** at the 1% confidence level.
Note: (The data in parentheses is the statistical value of t).

Table 4. Comparative results of LST-1 and explanatory variables among the OLS, PA, RE and FE regression analyses.

| Type             | Variables                  | OLS     | PA       | FE       | RE       |
|------------------|----------------------------|---------|----------|----------|----------|
| Land use         | Percentage of vegetation area | -0.015  | -0.015***| -0.089   | -0.015***|
|                  |                            | (-0.550)| (-4.160) | (-0.330) | (-4.160) |
| Landscape index  | Patch density              | -0.427  | -0.428   | -3.349***| -0.428** |
|                  |                            | (-0.810)| (-1.680) | (-4.010) | (-1.680) |
|                  | Patch Cohesion Index       | -0.013  | -0.014   | -0.260   | -0.014   |
|                  |                            | (-0.010)| (-0.030) | (-0.230) | (-0.030) |
| Traffic accessibility | Road network density     | -0.145  | -0.145   | -0.429** | -0.145   |
|                  |                            | (-0.660)| (-1.560) | (-2.740) | (-1.560) |
3.3. Effects of urban form on LST in 11 districts and relevant advice

PVA in Qinhuai and Gulou are relatively low and gradually decreasing. Besides, Qinhuai, Gulou and Jianye have been in the backward position of PD. Thus, Jianye should effectively promote the landscape fragmentation. In Qinhuai and Gulou, the vegetation area should be enlarged and the landscape fragmentation should be improved. Although PVA of Xuanwu has been in the leading position, LST7 has been in a high state. This phenomenon can be explained by the small PD and COHESION and dense RND. Thus, it’s necessary to improve the fragmentation and connectivity of patches in Xuanwu. Yuhuatai has larger PD and smaller COHESION and the landscape connectivity should be enhanced to alleviate the rise of LST7. Different from the five districts mentioned above, the remaining six districts have lower LST7. In terms of vegetation area, Jiangning, Pukou, Lishui and Qixia are relatively large, averaging around 14%, which is the main reason for the low LST7. PD value in Liuhe and Gaochun is in the lead which is regarded as the main causes of low LST7. Therefore, these districts should maintain and promote the existing landscape features and vegetation area advantages to create a comfortable thermal environment.

Four urban form indicators can explain 40% of the LST7 while the FE regression result of LST1 has only 2% explanation degree. Related research reveals the causes of this phenomenon and this is because of the winter coverage range of green space area, the influence of the artificial surface and other complex factors[3-4]. Similar to most studies, this study proves the weak explanation of urban form to LST1[5].

4. Conclusions

From the perspective of urban form, this paper analyzes the spatial-temporal characteristics of LST7 and LST1 in 11 districts of Nanjing and then uses OLS and panel data to analyze the influence of urban form on LST. The conclusions are as follows: LST7 and LST1 have different spatiotemporal characteristics. The area with high LST7 was concentrated in central of Nanjing. LST1 reached the highest in 2015 and the lowest in 2018. Besides, there was a significant positive correlation between RND and LST7. Following that, there were PD, COHESION and PVA, all of which show negatively correlation. The regression fitting degree of LST1 and urban form was only about 2%. Last, different regions are affected by urban form in varying degrees: for example, PD is the main factor to explain lower LST7 in Pukou while LST7 in Xuanwu is in a high state due to the drop of COHESION. The results can provide appropriate suggestions for mitigating LST in 11 districts in Nanjing City.

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