STUDY ON THE INFLUENCE OF URBAN FORM ON THERMAL ENVIRONMENT FROM THE VIEW OF INTEGRATED ALBEDO

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ABSTRACT

Most of the scholars were working on applying high albedo materials to mitigate heat island. However, some emerging researches have shown that high albedo materials are not suitable for mass use in cities because of many negative side effects. In urban area, there is a special phenomenon in solar exchange characterized by multiple reflection of solar radiation. It induces special solar trapping effect which contributes to urban heat island. Therefore, the integrated albedo in urban area is more worthy of attention for urban heat island mitigation.

Therefore, this paper focuses on the integrated albedo in urban area. Based on the local climate zones (LCZ) theory, this paper selects typical LCZ samples at block scale in the central area of Chengdu, China and explores the mutual influence rules of urban form, integrated albedo and thermal environment.

The results show that pervious surface fraction, building density and sky view factor have significant influences on integrated albedo, while the influence of height of roughness elements on integrated albedo is obviously weak. The land cover indicators have stronger influences on integrated albedo than that of geometric structure indicators on integrated albedo. Integrated albedo has significant influence on surface heat island.

Key words: urban form, integrated albedo, urban heat island, remote sensing inversion, statistical analysis

INTRODUCTION

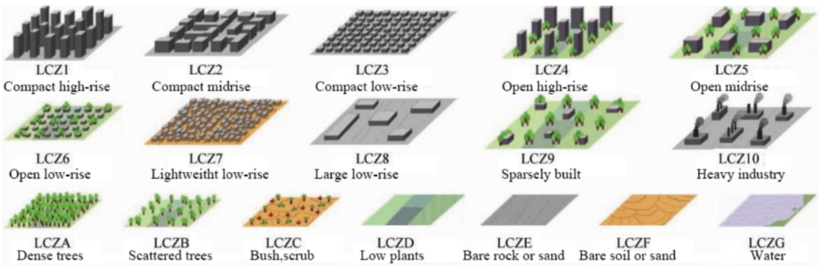
With the development of urbanization, urban heat island problem becomes more and more serious. Albedo represents the ratio of reflected radiations to incident radiations on surface (Xin Zhao, et.al.2013), which can characterize the solar radiation exchange. In the previous studies about albedo, many scholars pay more attention to high albedo surface materials, they were working on applying high albedo materials to mitigate heat island. However, some scholars have raised doubt: Is high albedo materials widely applied in city "Silver Bullet" for mitigating urban heat island? Some emerging researches have shown that high albedo materials are not suitable for mass use in cities because it will bring many negative side effects, such as influencing human thermal health, reducing precipitation and causing thermal discomfort, etc (Yang, J, et.al.2015).

Compared to the simple solar radiation exchange in flat rural area, there is a complicated and special solar radiation exchange phenomenon in rugged urban area. Urban fabrics are characterized by the solar trapping effect due to multiple reflections of radiation within the geometry, in turn generating more energy absorption and contributing to the urban heat island (Anne Bernabé, et.al.2015). Therefore, the integrated albedo affected by urban fabrics is more worthy of attention for heat island mitigation in city. The integrated albedo in urban area is closely related to urban form characteristics in the aspects of land cover, geometry arrangement and surface material, etc (Anne Bernabé, et.al.2015). So it can be seen that the integrated albedo reflects the dual information of urban form and thermal environment, which is regarded as an important medium for the mutual connection between them in terms of radiative heat transfer.

Therefore, this paper focuses on the study of the integrated albedo in urban area, aims at exploring the influence of urban form on thermal environment from the view of integrated albedo. Based on the local climate zones (LCZ) theory, this paper selects typical LCZ samples at block scale in the central area of Chengdu, China to explores the mutual influence rules of urban form, integrated albedo and thermal environment.

BACKGROUND

This paper takes local climate zones (Hereinafter referred to as LCZ) theory (Stewart ID, Oke TR, 2012) as research basis. This theory breaks the "urban-rural dichotomy" used in traditional heat island research, it subdivides the heterogeneous structure inside the city based on the thermal environment attributes, and aims at studying the relative gap of the heat island inside city (i.e., the local heat island magnitude) (Stewart ID, 2011). LCZ theory divides the urban form/surface landscape into 17 types, including 10 built landscape types (LCZ1~10) and 7 natural cover types (LCZA~G) , and it uses four levels of indicator thresholds including land cover, geometry, material properties and human activities to classify and define these types (Figure 1). This theory studies the characteristics of the thermal climate profile on the local climate scale, which generally corresponds to the blocks and districts from several hundred meters to several kilometers on the spatial scale. Each LCZ is an area with similar land cover, structure, materials and human activities.



Local climate zone (LCZ)	Sky view factor[a]	Aspect ratio[b]	Building surface fraction[c]	Impervious surface fraction[d]	Pervious surface fraction[e]	Height of roughness elements[f]	Terrain roughness class[g]
LCZ 1 *Compact high-rise*	0.2–0.4	> 2	40–60	40–60	< 10	> 25	8
LCZ 2 *Compact midrise*	0.3–0.6	0.75–2	40–70	30–50	< 20	10–25	6–7
LCZ 3 *Compact low-rise*	0.2–0.6	0.75–1.5	40–70	20–50	< 30	3–10	6
LCZ 4 *Open high-rise*	0.5–0.7	0.75–1.25	20–40	30–40	30–40	>25	7–8
LCZ 5 *Open midrise*	0.5–0.8	0.3–0.75	20–40	30–50	20–40	10–25	5–6
LCZ 6 *Open low-rise*	0.6–0.9	0.3–0.75	20–40	20–50	30–60	3–10	5–6
LCZ 7 *Lightweight low-rise*	0.2–0.5	1–2	60–90	< 20	<30	2–4	4–5
LCZ 8 *Large low-rise*	>0.7	0.1–0.3	30–50	40–50	<20	3–10	5
LCZ 9 *Sparsely built*	> 0.8	0.1–0.25	10–20	< 20	60–80	3–10	5–6
LCZ 10 *Heavy industry*	0.6–0.9	0.2–0.5	20–30	20–40	40–50	5–15	5–6
LCZ A *Dense trees*	<0.4	>1	<10	<10	>90	3–30	8
LCZ B *Scattered trees*	0.5–0.8	0.25–0.75	<10	<10	>90	3–15	5–6
LCZ C *Bush, scrub*	0.7–0.9	0.25–1.0	<10	<10	>90	<2	4–5
LCZ D *Low plants*	>0.9	<0.1	<10	<10	>90	<1	3–4
LCZ E *Bare rock or paved*	>0.9	<0.1	<10	>90	<10	<0.25	1–2
LCZ F *Bare soil or sand*	>0.9	<0.1	<10	<10	>90	< 0.25	1–2
LCZ G *Water*	>0.9	<0.1	<10	<10	>90	–	1

[a] Ratio of the amount of sky hemisphere visible from ground level to that of an unobstructed hemisphere
[b] Mean height-to-width ratio of street canyons (LCZs 1–7), building spacing (LCZs 8–10), and tree spacing (LCZs A–G)
[c] Ratio of building plan area to total plan area (%)
[d] Ratio of impervious plan area (paved, rock) to total plan area (%)
[e] Ratio of pervious plan area (bare soil, vegetation, water) to total plan area (%)
[f] Geometric average of building heights (LCZs 1–10) and tree/plant heights (LCZs A–F) (m)
[g] Davenport et al.'s (2000) classification of effective terrain roughness (z_0) for city and country landscapes. See Table 5 for class descriptions

(Values of geometric and surface cover properties for local climate zones. All properties are unitless except height of roughness elements (m).)

Figure 1. Types classification and indicators definition of LCZ theory (Redrawing according to reference (Stewart ID, Oke TR, 2012)).

METHODOLOGY

1. LCZ classification map construction and samples selection

LCZ map of the central area of Chengdu is constructed by the WUDAPT method which is based on remote sensing image classification (Bechtel B, et.al. 2015). The LCZ samples are selected according to the spatial distribution characteristics of LCZ types characterized by the area proportion statistics of different LCZ types. In the LCZ samples selection process, the type combination and quantity scale of LCZ samples are allocated according to the actual area proportion statistics of LCZ types.

At the same time, in addition to based on the actual proportion, in order to maintain the relative balance of quantity scale of various LCZ types samples, oversampling and undersampling method are appropriately combined for sampling. Oversampling is to increase the samples quantity for some types with smaller proportion, undersampling is the opposite.

2. Urban form indicators acquisition and analysis

The urban form indicators of the LCZ samples are mainly acquired by online investigation method. The quantitative indicators including building density (BD), pervious surface fraction (PSF), height of roughness elements (Z_H) and sky view factor (SVF) are selected to analyze urban form characteristics. These indicators are derived from LCZ theory. Building density and pervious surface fraction belong to land cover indicators, height of roughness and sky view factor belong to geometric structure indicators.

Since the various urban form indicators of LCZ samples may be interrelated, it is necessary to use the Pearson correlation coefficient (Rogers G S, 1969) to analyze the correlation among various urban form indicators, so as to judge whether the urban form indicators have linkages effect in influencing the integrated albedo and surface heat island.

3. Albedo acquisition and analysis

(1) Albedo acquisition

In this paper, remote sensing inversion method is used to acquire the albedo data. The key steps of inverting the surface albedo using Landsat standard remote sensing data products include: Firstly, the surface reflectance is obtained after quantitative processing (radiation calibration, atmospheric correction, etc.), so as to eliminate the influence of the atmosphere on remote sensing data; Secondly, realize the conversion of narrow-band albedo to wide-band albedo (Liang S, et.al. 2003).

This paper downloads the advanced product data of Landsat 8 surface reflectance of Chengdu from the United States Geological Survey (USGS) official website at 11:33 am on August 11, 2019 (Beijing time). This data has been quantified processing by radiation calibration and atmospheric correction. Therefore, the second calculation step is carried out directly. The surface is assumed to be lambertian in the albedo calculation process, and the anisotropy is not considered. The calculation formula (G. Baldinelli,et.al.2017) is:

$$A = 0.043+0.082*b1+0.064*b2+0.173*b3+0.114*b4+0.237*b5+0.252*b6+0.034*b7$$

Among them, b1to b7 represent the 1to 7 band of the advanced surface reflectance products respectively.

(2) Integrated albedo extraction

After acquiring the albedo, it is necessary to calculate the integrated albedo of the LCZ samples, that is, the average albedo value. So it is necessary to create a vector boundary map of each samples in ArcGis software, and then use statistics function in ENVI software to calculate the average values according to their vector boundary maps.

(3) Integrated albedo increment calculation

Integrated albedo increment is characterized by the difference of integrated albedo ($A_{LCZ\,X} - A_{LCZ\,Y}$) between different LCZ types. The calculation of the integrated albedo increment ($\Delta A_{LCZ\,X}$) of the LCZ samples can refer to the surface heat island calculation (see below). It uses LCZD as basic reference type for calculation. The calculation formula is:

$$\Delta A_{LCZ\,X} = A_{LCZD} - A_{LCZX}$$

Among them, $\Delta A_{LCZ\,X}$ represents the integrated albedo increment of LCZX. $A_{LCZ\,X}$ represents the integrated albedo of LCZ X, and A_{LCZD} represents the average integrated albedo of all LCZD samples.

4. Thermal environment indicators acquisition and analysis

(1) surface temperature acquisition

In this paper, the remote sensing inversion method is used to acquire the thermal environment indicators. The Landsat 8 standard satellite image data required for the surface temperature inversion and the image data required for the albedo inversion are consistent in date and time.

It uses the atmospheric correction method to acquire the surface temperature. The fundamental principle is to estimate the effect of the atmosphere on the surface heat radiation at first, and then subtract this atmospheric effect part from the total amount of heat radiation observed by the satellite sensor, so as to acquire the surface heat radiation intensity, and then convert this heat radiation intensity into the corresponding surface temperature (Shubin Deng, et.al. 2014).

(2) Spatial resolution adjustment

After the surface temperature inversion is completed, it's necessary to adjust spatial resolution. Research on the samples at block scale is a relative precise research in thermal infrared remote sensing. It requires relatively high spatial resolution. However, the Landsat 8 TIRS data resolution for inducing thermal radiation in Landsat8 standard images is 100m, and the surface reflectance product resolution is 30m. They are not consistent in spatial resolution. Therefore, in order to ensure the same resolution of different data and make the resolution as high as possible, the surface temperature data with lower resolution after Landsat8 TIRS inversion need to be downscaled to meet the demand.

The main method is to use random forest regression model combined with spectral indexes including normalized vegetation index (NDVI), normalized water index (NDWI), normalized multi-band drought index (NMDI), normalized building index (NDBI), soil adjusted vegetation index (SAVI), normalized drought index (NDDI) and 7-band surface reflectance as regression kernels for downscaling, so as to downscale the surface temperature data from 100 meter resolution to 30 meter resolution.

(3) Surface heat island calculation

In this paper, the calculation of the surface heat island mainly depends on the definition of "local heat island magnitude" in the LCZ theory. It's characterized by the temperature difference($T_{LCZ\,X}-T_{LCZ\,Y}$) between different LCZ types. According to Stewart's suggestion(Stewart ID, Oke T R, 2012), this paper uses LCZD as the basic reference type for calculation. The calculation formula is:

$$UHI_{LCZ\,X} = T_{LCZX}\text{-}T_{LCZD}$$

Among them, $UHI_{LCZ\,X}$ represents the local surface heat island magnitude of LCZX, T_{LCZX} represents the surface temperature of LCZX, and T_{LCZD} represents the average temperature of all LCZD samples.

5. Result data processing

The Pearson correlation coefficient analysis method(Rogers G S, 1969) is used to deeply explore the correlation between urban form and integrated albedo and the correlation between integrated albedo and surface heat island.

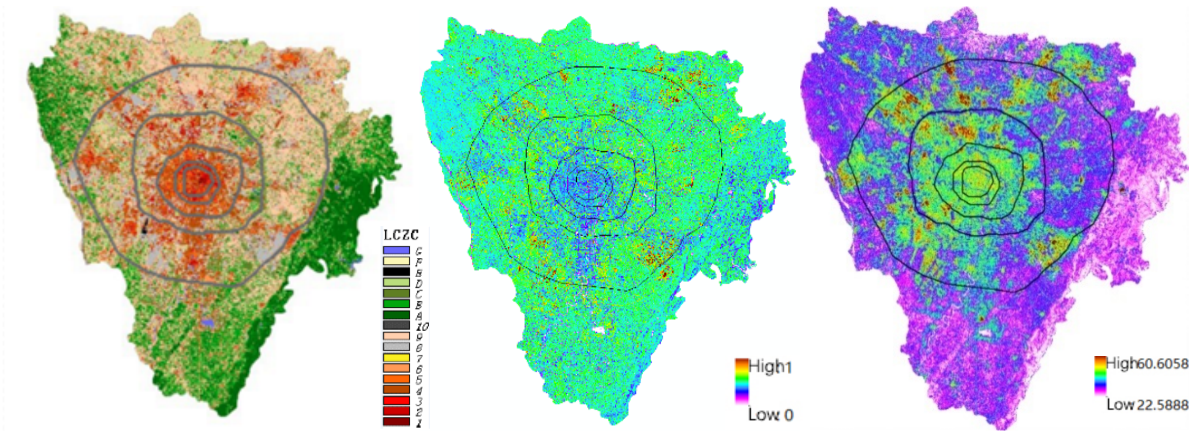
It's worth particular noting that although LCZA/B belong to the natural cover types, their vegetation type belong to arbor, the height of roughness are higher, the sky view factor are smaller, and the terrain roughness class are larger, so they are different from other natural cover types (LCZC/D). Therefore, compared with other natural cover types (LCZC/D), their integrated albedo are relatively smaller, and they are more similar to the built landscape types in terms of the integrated albedo values, which will interfere with the judgment of the overall rules of natural cover types. Therefore, LCZA/B are excluded from the correlation calculation because of their particularity.

FINDINGS

1. The acquisition results of relevant indicators in the research scope.

This paper selects the urban central area in Chengdu, China as research scope. This scope refers to the urban planning area in the latest Master Plan of Chengdu (2016-2035).

The acquisition results of relevant indicators and the calculation results of the area proportion of LCZ types are shown in Figure 2. It can be seen that LCZ types in central area of Chengdu are comprehensive, covering both built landscape and natural cover types. The threshold ranges of albedo and surface temperature are 0-1and 22.59-60.61℃ respectively. From downtown to suburb, LCZ type changes from built landscape to natural cover type and albedo changes from low to high. The change of surface temperature is opposite to the change of albedo. Surface temperature changes from high to low.



Local climate zones (LCZ)map   Surface albedo(A)map   Surface temperature (LST) (℃) map

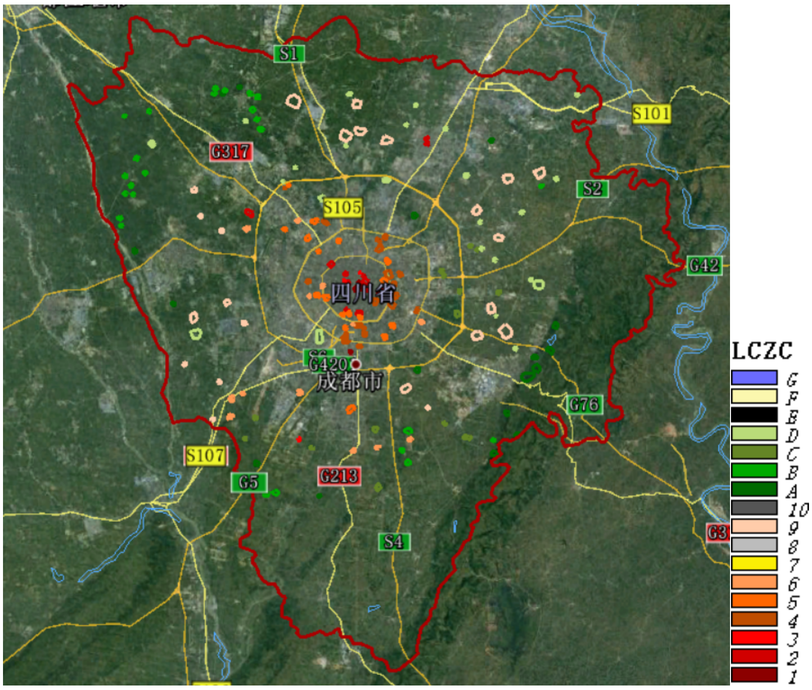
LCZ Type	LCZ1	LCZ2	LCZ3	LCZ4	LCZ5	LCZ6	LCZ8	LCZ9	Built types total
Area proportion	0.11%	2.04%	0.03%	10.68%	3.93%	1.19%	12.10%	31.65%	61.73%
LCZ Type	LCZA	LCZB	LCZC	LCZD	LCZE	LCZG			Natural types total
Area proportion	11.73%	11.58%	6.65%	7.37%	0.15%	0.80%			38.27%

Area proportion of LCZ types

Figure 2. The acquisition result maps of relevant indicators and the area proportion occupied by each LCZ type.

2. The selection results of LCZ samples

Typical LCZ samples selection results have been shown in Figure 3. In terms of type combinations, there are 11 types including LCZ1~6/9/A/B/C/D. In terms of quantity scale, there are 150 samples.



LCZ Type	LCZ1	LCZ2	LCZ3	LCZ4	LCZ5	LCZ6	LCZ9	Built types total
Number Proportion	5 3.33%	14 9.33%	4 2.67%	19 12.67%	17 11.33%	12 8.00%	19 12.67%	90 60%
LCZ Type	LCZA	LCZB	LCZC	LCZD	Natural types total			
Number Proportion	17 11.33%	16 10.67%	12 8.00%	15 10.00%	60 40%			
Total: Number:150; Proportion:100%								

Figure 3. Spatial distribution and quantity statistics of LCZ samples in the urban central area of Chengdu.

3. The mutual influence rules of various urban form indicators

The analysis results of Pearson correlation coefficient have been shown in Figure 4. There are clear correlations between two indicators among building density, pervious surface fraction and sky view factor. However, the correlation between height of roughness elements and the other three indicators are weak. It indicates that some of the urban form indicators have linkage effects on the integrated albedo and surface heat island.

	Building density(%)	Pervious surface fraction (%)	height of roughness elements(meter)	sky view factor
Building density(%)	1	-0.957**	0.418	-0.871**
Pervious surface fraction (%)		1	-0.546	0.914**
height of roughness elements(meter)			1	-0.630**
sky view factor				1
Note: ** indicates significant correlation at the 0.01 level (bilateral); * indicates significant correlation at the 0.05 level (bilateral).				

Figure 4. Pearson correlation analysis between two of urban form indicators.

4. The mutual influence rules of urban form, integrated albedo and thermal environment

(1) The influence rules of urban form on integrated albedo

The analysis results of Pearson correlation coefficient have been shown in Figure 5. It can be seen there is a significant negative correlation between building density and integrated albedo, a significant positive correlation between pervious surface fraction/sky view factor and integrated albedo. And a significant negative correlation between height of roughness elements and integrated albedo is only presented in low-rise types.

Through comparing the magnitude of Pearson correlation coefficient, it can be found that there are clear differences in the influence of various urban form indicators on integrated albedo. The indicators order of influential ability from strong to weak is that pervious surface fraction, sky view factor, building density and height of roughness elements. In general, the land cover indicators have stronger influence on integrated albedo than that of geometric structure indicators on integrated albedo.

Pearson correlation analysis		
	Pearson correlation coefficient	Significance
Building density(%)	-0.867**	0.00
Pervious surface fraction (%)	0.905**	0.00
Height of roughness elements (meter)	-0.601**	0.00
Sky view factor	0.880**	0.00
Note:LCZA/B is special and does not conform to the overall rules, so it is not included in statistics calculation **indicates significant correlation at the 0.01 level (bilateral); *indicates significant correlation at the 0.05 level (bilateral)		

Figure 5. Correlation analysis between urban form and integrated albedo.

(2) The influence rules of integrated albedo on thermal environment

Based on the analysis of Pearson correlation coefficient, there is a significant positive correlation (at the 0.01 level (bilateral)) between integrated albedo increment and thermal environment. The Pearson correlation coefficient is 0.761. It indicates that that surface heat island can be mitigated potentially through improving integrated albedo by urban form control to a certain extent.

CONCLUSIONS AND PROSPECTS

This paper adopts sampling survey method to study the influence rules related to integrated albedo of the LCZ samples in Chengdu. The research results show that the influence of various urban form indicators on integrated albedo are different. The integrated albedo has a certain influence on surface heat island.

It can be seen that the integrated albedo has the potential to be included in the urban planning to improve the thermal environment. The integrated albedo can be regulated by controlling the urban composite morphological elements, thereby improving the heat island.

The research in this paper also provides a reference paradigm for the research of thermal environment-sensitive indicators. The researches on thermal environment-sensitive indicators can promote the cooperation and connection of urban planning and climatology, and better serve for climate-sensitive planning and design. Especially in the context of diverse and systematic new territorial spatial planning in China, the research value is more prominent.

In the further research, there are a lot of work worth doing. We can add research in different scopes, for example in the downtown area (inside the third ring road), and make a comparison analysis of influence rules between different scopes.

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