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Abstract. An abnormal heat island, in which genesis is totally different from that of a normal heat island, exists in typical karst city Guiyang in southwestern China and dominates its regional thermal environment. Based on Landsat enhanced thematic mapper plus images and moderate-resolution imaging spectroradiometer land surface temperature products, the abnormal heat island in this area is accordingly extracted. Through overlaying and statistic analysis in geographic information system, this paper studied the relationship among the abnormal heat island and karst distribution, vegetation coverage, and temperature difference at day and night with the following results: nearly 70% of the abnormal heat island distributes in karst and semi-karst areas, 95.7% of abnormal heat islands mainly distribute in region of low-vegetation coverage (percentage of vegetation lower than 45%); 82.28% of abnormal heat islands are in regions where the temperature difference between day and night is over 14°C. The results show that the formation of an abnormal heat island largely depends on rock types and the area of bare rock. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JRS.8.083637](https://doi.org/10.1117/1.JRS.8.083637)]

Keywords: abnormal heat island effect; karst city; enhanced thematic mapper plus; moderate-resolution imaging spectroradiometer land surface temperature; bare rock.

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1 Introduction

The urban heat island (UHI), a feature for which the temperature in urban areas is higher than that in rural areas,¹ is mainly caused by the following aspects: high thermal conductivity of the underlying surface, which is made of cement, asphalt, etc. in urban areas; accumulated solar energy absorbed by air pollutants; a large number of artificial heat sources in urban areas; and heat diffusion difficulty caused by dense buildings. The urban heat island forms with the generation of a high temperature center descending to its periphery. Scholars have done a lot of research on the formation of urban heat islands and have achieved a lot. Kim² studied the phenomenon of the urban heat island in metropolitan Washington, DC. Oke³ gave a comprehensive review of the energy balance approach and its development as applied to urban areas. Larson and Carnahan⁴ used Landsat thematic mapper (TM) thermal infrared data to observe mesoscale temperature differences between urban and rural areas in Indianapolis. Weng⁵ used three TM images to study the UHI phenomenon in Guangzhou, China. Rizwan et al.⁶ presented a review of the available literature on the generation, determination, and mitigation of UHI. These researchers generally agree that the main cause of UHI is the large amount of heat generated from the urban structures and the anthropogenic heat sources.

Massive high-temperature plaques are found in rural areas in typical karst city Guiyang.⁷ However, the underlying surfaces corresponding to these plaques are not built-up areas but

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natural surfaces. This paper calls them on the whole abnormal heat islands, compared with normal heat islands, which have large coverage, wide distribution, and great impact on the regional thermal environment. Currently, few studies have been conducted on abnormal heat islands in karst areas except Chen,⁸ who used four TM images from four different seasons to demonstrate the existence of an abnormal heat island in Huaxi district of Guiyang, China. In order to explore the formation and distribution of abnormal heat islands in the typical karst city, this paper retrieved the land surface temperature at day and night from Landsat enhanced thematic mapper plus (ETM⁺) and moderate-resolution imaging spectroradiometer land surface temperature (MODIS LST) images, and separately analyzed the relationships among abnormal heat island and karst distribution, vegetation coverage, and temperature differences of day and night. The results should lay the basis for making decisions on relative policies.

2 Methods

2.1 Study Area and Data

Guiyang is located in the east of Yunnan-Guizhou plateau in southwestern China (Fig. 1). The general geographical position of the central city is 106°27'E and 26°44'N. The city, with karst areas accounting for 82% of the land area and an average elevation of 1100 m asl, is located in one of the largest karst geomorphology distributing areas in the world.⁹ Guiyang has a mild, moist subtropical climate because of diversity in geographical and topographical features, high elevation, and low latitude. The yearly mean temperature is 15.3°C, and the yearly rainfall is 1197 mm.¹⁰ Though Guiyang is a famous tourism city, it is facing rapid urban expansion, industrial development, climate warming, and environmental deterioration in recent years, which caught people's attention and made them focus on the regional thermal environment.

MODIS LST and Landsat ETM⁺ satellite images are the data source of this study. MODIS is an important sensor carried on satellites Terra and Aqua, which cooperate with each other to

Fig. 1 Location of study area.

make repeated observation of surface of the whole earth in 1 or 2 days. The transit time of Aqua satellite is 13:30 pm and 1:30 am. The MODIS sensor has 36 discrete spectral bands (0.4–14.4 μm), which contain 16 thermal infrared bands with the maximum spatial resolution of 1000 m.¹¹ Compared with TM, the ETM⁺ sensor not only raises the thermal infrared band's spatial resolution from 120 to 60 m but also adds a new panchromatic band of 15 m.

This paper retrieved information of an abnormal heat island in the study area from ETM⁺ (August 28, 2009), with data of ETM⁺ (September 21, 2001) in the same area for ancillary research to reflect the longitudinal variation regularity. The processing level of images was systematic correction (Level 1G); the original instrumental resolution was 60 m. MODIS MOD11 product LST images (1 km resolution; 8-day composites; Level 2G) in the corresponding date were used to generate temperature maps at night. In order to do raster calculation with a map of LST in daytime, the MODIS LST image with spatial resolution of 1 km was resampled to 60 m.

2.2 Land Surface Temperature Retrieval

A monowindow algorithm is expressed as Eq. (1).^{12,13} Emissivity, transmittance, and effective mean atmospheric temperature are required

$$T_S = \{a(1 - C_6 - D_6) + [b(1 - C_6 - D_6) + C_6 + D_6] \times T_{\text{sensor}} - D_6 T_a\} / C_6, C_6 = \varepsilon_6 \tau_6, \\ D_6 = (1 - \tau_6)(1) + (1 - \varepsilon_6)\tau_6, \quad (1)$$

where T_S is the LST in band 6, two constants a and b are 67.355351 and 0.458606; ε_6 is the emissivity, which can be classified and computed by normalized difference vegetation index (NDVI); T_{sensor} is the at-sensor brightness temperature in K; τ_6 is the atmospheric transmittance, $\tau_6 = 0.975290 - 0.08007 \omega$ (if $0.4 < \omega < 1.6$), where ω is the water vapor content in the atmosphere, the unit is g/cm^2 ; T_a represents the effective mean atmospheric temperature, for mid-latitude summer $T_a = 17.9769 + 0.91715 \times T_0$, where T_0 is the near-surface atmospheric temperature, the unit is K; and ω and T_0 were obtained from local weather stations.

With the support of spatial modeling tool of ERDAS IMAGINE (a remote sensing image processing system developed by the United States), the process of LST retrieval includes three steps. First, brightness temperature was calculated by Eqs. (2) and (3).¹⁴ Second, the NDVI was calculated by ETM3⁺ and ETM4⁺, and surface emissivity was gained by various methods.¹⁵ Last, the land surface temperature was calculated by Eq. (1), and is shown in Fig. 2. The land surface temperature was classified into five grades by average segmentation as high temperature ($>33^\circ\text{C}$), subhigh temperature (27°C – 33°C), intermediate temperature (21°C – 27°C), sublow temperature (15°C – 21°C), and low temperature ($<15^\circ\text{C}$). The first two grades were regarded as the heat island

$$L = (L_{\text{max}} - L_{\text{min}}) \cdot \frac{\text{DN}}{Q_{\text{max}}} + L_{\text{min}}, \quad (2)$$

where L is at-sensor radiance; L_{max} is the biggest radiance, $L_{\text{max}} = 12.65 \text{ W}/(\text{m}^2 \cdot \text{sr} \cdot \mu\text{m})$, L_{min} is the smallest radiance, $L_{\text{min}} = 3.20 \text{ W}/(\text{m}^2 \cdot \text{sr} \cdot \mu\text{m})$, and they were obtained from the meta file; DN is the brightness value of ETM6⁺; Q_{max} is the maximum brightness value

$$T_{\text{sensor}} = \frac{K_2}{\ln(K_1/L + 1)}, \quad (3)$$

where T_{sensor} is at-sensor brightness temperature in K; $K_1 = 666.09 \text{ W}/(\text{m}^2 \cdot \text{sr} \cdot \mu\text{m})$, $K_2 = 1282.71 \text{ K}$.

2.3 Extraction of Abnormal Heat Island

UHI is an urban area with high temperature of air or surface compared to the temperature of air or surface in surrounding rural areas. The urban high temperature is mainly caused by anthropogenic heat released from vehicles, power plants, air conditioners, and other heat sources. The heat is stored and reradiated by massive and complex urban structures. This paper calls UHI

Fig. 2 Land surface temperature map during the daytime in 2009.

caused by reasons discussed above a normal heat island. However, massive high-temperature plaques are found in rural areas, and the underlying surfaces corresponding to these plaques are not built-up areas but natural surfaces in the karst city, which, in this paper, are called abnormal heat islands. The difference between normal and abnormal heat islands lies in the formation of the heat island. Thus, this paper defines the high-temperature plaques that are corresponding to built-up areas as normal heat islands and the rest as abnormal heat islands.

According to the definition, the abnormal heat island was extracted with following steps. First, a land usage classification map was produced by extraction of land use information from ETM⁺. Second, the land surface temperature grade map was masked with built-up land in the land use classification map according to the definition of normal heat island. The normal heat island corresponding to built-up land was, then, removed, and the rest of the heat island plaques in the temperature grade map were abnormal heat island plaques. The distribution of abnormal heat island is shown in Fig. 4.

The distribution map shows that the abnormal heat islands are mainly located in northwest of Qingzhen, southwest of Huaxi district, and Baiyun district. Area statistics are available after masking. The results are shown in Table 1.

From statistical results shown in the table, it can be found that the area of abnormal heat island is much larger than the area of normal heat island. However, the area of normal heat island is increasing with the development of the city, which conforms to reality. The stability of the abnormal heat island partly reflects that the formation of the abnormal heat island is different from that of a normal heat island.

Table 1 The area statistics of normal and abnormal heat islands in study area.

Time phase	Total area of heat island (km ²)	Area of abnormal heat island (km ²)	Area of normal heat island (km ²)	The percentage of abnormal heat island (%)
September 21, 2001	555.51	426.29	129.22	76.74
August 28, 2009	722.51	476.47	246.04	65.95

3 Analysis of Formation of Abnormal Heat Island

3.1 Relationship between Abnormal Heat Island and Karst Distribution

The superposition analysis between the distribution map of the abnormal heat island and that of karst in Guiyang leads to the conclusion that the karst distribution in Guiyang directly influences the abnormal heat island in this area (Fig. 3).

In the superimposed image, the red plaques are the abnormal heat islands in karst area, the blue plaques are the abnormal heat islands in semikarst area, and the green plaques are the abnormal heat islands in nonkarst area. The area of each part is calculated by attribute computing, and the result is shown in Table 2.

The above table demonstrates that nearly 70% of area of the abnormal heat islands in Guiyang distribute in karst and semikarst areas.

3.2 Correlation between Abnormal Heat Island and Vegetation Coverage

Vegetation coverage is the ratio between vertical projection area of vegetation canopy and the total soil area. With the NDVI, which has been gained previously, vegetation coverage can be calculated quickly by Eq. (4)¹⁶

$$f = \frac{\text{NDVI} - \text{NDVI}_{\min}}{\text{NDVI}_{\max} - \text{NDVI}_{\min}}, \quad (4)$$

where f is the vegetation coverage of a single pixel, $\text{NDVI}_{\max}$ is the maximum of normalized difference vegetation index in research area, while the $\text{NDVI}_{\min}$ is the minimum. In this study, the $\text{NDVI}_{\max}$ and $\text{NDVI}_{\min}$ are 0.79 and 0.05, respectively.

Correlation analysis is done for analyzing the relationship between abnormal heat island and vegetative coverage. First, 50 spots were randomly selected from the map of abnormal heat island distribution. The temperature and vegetation coverage of each spot in vegetation coverage grayscale image were recorded. Then, the correlative coefficients between temperature and vegetation coverage were calculated with “Correl” function in Excel. Finally, the correlation

Fig. 3 Relations map of abnormal heat island and karst distribution.

Table 2 The area statistics of abnormal heat island in different karst regions.

Phase	The area of abnormal heat island in karst (km ²)	The area of abnormal heat island in semikarst (km ²)	The area of abnormal heat island in nonkarst (km ²)	The percentage of the first two items (%)
September 9, 2001	282.63	21.66	121.83	71.4
August 28, 2009	304.37	14.80	157.18	67.0

coefficients were gained, with -0.56 on September 21, 2001, and -0.57 on August 28, 2009, respectively.

The results show that the absolute value of the correlation coefficient is between 0.5 and 0.8, which means that there is a conspicuous negative correlation between the land surface temperature and vegetation coverage in the area of abnormal heat island. Compared to areas with high level of vegetation coverage, areas with low level of vegetation coverage evaporate smaller amounts of water. Thus, the heat taken away by water is relatively low. Moreover, sufficient photosynthesis consumes much more energy in areas with a high level of vegetation coverage. All these causes lead to heat accumulation in low level of vegetation coverage areas, which come as one important genesis of heat island formation.

The area of abnormal heat island corresponding to low-vegetation coverage was also calculated. First, the map of abnormal heat island distribution in low-level vegetation coverage areas was generated by expert classifier ERDAS. Two variables—map of vegetation coverage and map of abnormal heat island distribution—were in the decision tree. Second, the decision rule that low vegetation coverage rate was under 45% was defined according to standards for classification and gradation of soil erosion (SL190-2007) promulgated by the Ministry of Water Resources of China.

The statistics show that the area of abnormal heat island in low vegetation coverage area is 456.23 km², which takes 95.7% of the total area of the abnormal heat island, which is 476.74 km², on August 28, 2009. The conclusion is that the abnormal heat island is mainly found in areas of low vegetation coverage (Fig. 4).

3.3 Relationship between Abnormal Heat Island and Temperature Difference at Day and Night

The intrinsic attribute of an object is thermal inertia, which consists of unchangeable elements such as thermal conductivity, density, and specific heat capacity. By absorbing and emitting solar energy, the temperature of details increases in the daytime and decreases in the night. Details of high thermal inertia, such as water, show small temperature difference between day and night. On the contrary, details with low thermal inertia, warming fast in daytime and cooling fast at night, show substantial temperature discrepancy between day and night, such as bare rock. Therefore, details of different thermal inertia in the temperature difference map between day and night can be distinguished.^{17,18} The typical details in karst area, besides built-up land, water, and road (mainly refers to cement and asphalt roads which can easily be mixed up with bare rock road), can be divided into three categories: vegetation, soil, and rock,^{19,20} among which built-up land and roads have been removed by masking. The vegetation is with large thermal inertia because vegetation contains a larger quantity of water, which has the largest thermal inertia; the thermal inertia of soil is different because of the different soil moisture content; and the thermal inertia of bare rock and bare soil with little moisture is the smallest. This paper studies the genesis of abnormal heat island formation with temperature difference maps between day and night generated by MODIS LST of the corresponding phase.

3.3.1 Generation of temperature map at night with moderate-resolution imaging spectroradiometer land surface temperature

MODIS LST image (1-km resolution; 8-day composites; and Level 2G) was preprocessed by MODIS reprojection tool. Then, data of surface temperature in night (LST_Nighr_1 km) were

Fig. 4 Relations map of abnormal heat island and vegetation coverage.

separated and added with the projection named WGS_84_UTM_Zone_48 N, and output as HDFEOS format (hierarchy data format was designated as the standard format for storage and release Earth observation system data by NASA, in 1993). The digital number of dataset of night surface temperature, which had been preprocessed with the support of ERDAS IMAGINE modeling tools, multiplied with corresponding calibration coefficient and then subtracted 273.15 to gain data of land surface temperature during the night (Fig. 5), where the unit was °C.^{21,22}

3.3.2 *Overlay analysis of karst abnormal heat island map and the temperature difference map of day and night*

With the support of raster calculator and spatial analyst of ARCGIS 9 (an integrated collection of GIS software products for building a complete GIS), the temperature map of study areas in the daytime was retrieved by ETM⁺ and then subtracted from the temperature map of night processed by MODIS LST. Density slicing was the next step, and the result was a temperature difference map between day and night in the study area, which then was divided into 10 temperature sections by every 2°C (Fig. 6). It was regarded as a small temperature difference when it is 6°C or lower, medium temperature difference between 6°C and 14°C, and big temperature difference over 14°C.

Conclusions can be made from Fig. 6. Areas where temperature difference between day and night is lower than 6°C because of high thermal inertia of water are: Hongfeng lake, Baihua lake, and Dongfeng reservoir in the south, east, and northwest of Qingzhen respectively, Songbaishan reservoir in Huaxi district, Aha reservoir in Nanming district, and Qianling lake and Xiaoguan reservoir in Yunyan district. Areas where the temperature difference is also 6°C–8°C because of high-thermal inertia of water are: surrounding areas of Hongfeng lake, Baihua lake, and Aha reservoir. Areas where temperature difference between day and night is between 8°C and 12°C because of high-vegetation coverage are: east and west of Qingzhen and southwest and middle east of Huaxi. Areas where the temperature difference between day and night is higher than 14°C mainly are in the north central part of Qingzhen, midwest of Huaxi, and carbonatite outcropped areas in south of Baiyun and Wudang districts.

Fig. 5 Land surface temperature map during night in 2009.

The relationship between distribution of abnormal heat islands and the temperature difference of day and night was analyzed based on overlay of the map of abnormal heat islands and the map of temperature differences of day and night in ARCGIS. The statistics showed that 82.28% of the abnormal heat islands were in regions where temperature difference between day and night was over 14°C. It meant that 82.28% of the abnormal heat islands lay in areas covered by details with low thermal inertia, such as bare rock and bare soil with low moisture content.

According to the three relation maps (Figs. 3, 5, and 6), most parts of the abnormal heat island form due to bare karst rock existing in karst and semikarst topography where vegetation coverage is low, and temperature difference between day and night is bigger. These features, however, are the same to some part (about 30%) of the abnormal heat island in nonkarst

Fig. 6 Relations map between temperature differences of day and night and abnormal heat island distribution in Guiyang.

regions. It can be found through field survey that the underlying surfaces corresponding to these plaques are dry land for planting, which mainly concentrates in the rural areas. The date of the images used in this study was the end of August, when widely cultivated corn in these regions was harvested. Therefore, bare dry land is the root cause of the abnormal heat islands in nonkarst regions.

4 Conclusion

First, the area of the abnormal heat island is two to three times larger than the area of the normal heat island in Guiyang, which makes the abnormal heat island a main influential factor on heat environment study in the area. Second, nearly 70% of the abnormal heat islands in Guiyang distribute in karst and semi-karst areas. Third, 95.7% of the abnormal heat islands mainly distribute in regions of low vegetation coverage, which is under the rate of 45%, and last, 82.28% of the abnormal heat islands are in regions where temperature difference between day and night is over 14°C. All these results suggest that the abnormal heat island in the study area is mainly caused by bare karst rock and bare soil. Namely, the root cause of abnormal heat islands in this region is prominent and potential rock desertification.

The typical characteristic of karst city is that the karst vegetation, covering limestone peaks scattered in urban areas, plays an important role in climatic regulation in karst city. Once the karst vegetation is destroyed, it will be difficult to restore in the short term because of the thin soil layer of limestone. The decline of forest coverage results in infiltration of surface water. Loose soil layer surface eroded by surface runoff will result in further soil loss and mother rock outcrop, and the rock desertification will come into being. Moreover, bared limestone, with large calorific capacity, leads to surface temperature increase, and finally the abnormal heat island forms.

Thus, the UHI formation not only lies in activities of human beings in urban areas, but in rock types and the extent of bare rock. It makes comprehensive control of rocky desertification crucial to the improvement of regional thermal environment in karst areas.

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