Dynamical Monitoring and Evaluation Methods to Urban Heat Island Effects Based on RS&GIS

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Abstract
At present, research about Urban Heat Island Effects (UHI) is a hot issue in urban climate and ecological environment. Because remote sensing technology has many advantages, it becomes an important means of UHI research. How to use multi-temporal thermal infrared remote sensing data and dynamically monitor and evaluate UHI is a very interesting research topic. This article took Luzhou City in Sichuan Province, China as an example and explored methods to monitoring and evaluating UHI based on Landsat-5 TM data, which obtained on September 15, 1988, and Landsat-7 ETM+ data which obtained on August 29, 2002. Technical methods and research route established by this article can provide references for other similar research, and have application and popularizing value.

1. Introduction

Urban Heat Island Effects (UHI) is a phenomenon that the city temperature is higher than the natural environment temperature in suburb (ZHOU Shuzhen, 1994). The city part protrudes and looks like a warm island, in the chart of temperature spatial distribution (see Figure 1). In 1818, Lake Howard, who was a climatologist, discovered that air temperature in urban region was higher than that in suburban area, and he put forward the concept of “urban heat island”(Howard L., 1833). At present, research about UHI is a hot issue in urban climate and urban ecological environment. Many scholars have researched UHI using thermal infrared remote sensing data, and made great progress. Using multi-temporal thermal infrared remote sensing data can dynamically monitor and evaluate UHI. This article take Luzhou City in Sichuan Province, China, as an example, and explores methods to monitoring and evaluating UHI using multi-temporal thermal infrared remote sensing data to provide references for other similar research.

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2. Research region and data source

Luzhou City lies in the southeastern of Sichuan Province, China. It is located in the junction of the Yangtze River and the Tuojiang River (see Figure 2). The geographic scope is from 27º38´N to 29º20´N, and from 105º09´E to 106 º 28´E. The distance is 113km from the east to the west, and that is 185km from the south to the north. It is 267km from Chengdu City, which is the capital of Sichuan province. Luzhou is a famous national historical and cultural city in China, and it is called “Liquor City”. In 2010, the area of the built-up region was 82.66km², and the population was 0.84 million in the downtown.

This paper used Landsat-5 TM data, which obtained on September 15, 1988, and Landsat-7 ETM+ data which obtained on August 29, 2002. The satellite channel number is 128/040. The spatial resolution of this image is 30m. Image quality is very good.

![Figure 1. Urban heat island model](image1)

![Figure 2. General situation of research region](image2)
3. Data process and information extraction

3.1 Extracting urban boundary

Extracting built-up region information by using remote sensing data has become an important aspect of remote sensing applications. Extracting built-up region information by adopting NDBI (Normalized Difference Building Index) and adjusting threshold values, based on remote sensing data. For Landsat data, NDBI is defined as following (YANG Shan, 2000):

\[
NDBI = \frac{(TM_5 - B_4)}{(TM_5 + TM_4)}
\]

(1)

In theory, if NDBI>0, the pixel of remote sensing image is regard as built-up region, otherwise, it is not built-up region. However, error occurs in factual operation. Correct built-up region information can be obtained by adjusting threshold values of NDBI. Lastly, urban boundary was obtained by converting extracted results into vector data.

Figure 3 reflected urban built-up region in 1988 and 2002. The area of built-up region in 1988 was 811.9 hm², and that in 2002 was 2062.3 hm².

3.2 Retrieving brightness temperature

What infrared remote sensing detects is the radiation temperature of urban underlying surface, that is, brightness temperature (TB). Retrieves brightness temperature according to the following methods. Firstly, accomplish radiation calibration. Radiation calibration is a process of converting the digital value (DN) of remote sensing data into spectral radiance value of sensor. For Landsat7 ETM+6 data, the calculation formula for radiation calibration is as following (T. Arvidson, 2002):

\[
L_h = \text{gain} \times \text{DN} + \text{bias}
\]

(2)

Where, \(L_h\) is the spectral radiation value of pixels in sensor (W·m⁻²·sr⁻¹·μm⁻¹), DN is the gray value...
of image. The parameter of “gain” and “bias” can be obtained from image header.

For Landsat5 TM6 data, the calculation formula for radiation calibration is as following (G. M. Chander, 2005; J. F. Mustard et al., 1999; QIN Zhihao et al., 2001):

\[ L = DN \times 0.005632156 + 0.1238 \]

Where, \( L \) is the spectral radiation value of pixels in sensor (mW cm\(^{-2}\) ster\(^{-1}\) μm\(^{-1}\)), \( DN \) is the gray value of image.

TB can be calculated according to the following formula (G. M. Chander, 2005; J. F. Mustard et al., 1999):

\[ T = K_2 / \ln (1 + K_1/L) - 273.15 \]

Where, \( T \) is TB of pixels and its unit is °C; \( K_1 \) and \( K_2 \) are the constants, as for ETM+ band6, \( K_1 \) is 666.093 W m\(^{-2}\) ster\(^{-1}\) μm\(^{-1}\), and \( K_2 \) is 1282.708 k; as for TM band6, \( K_1 \) is 60.766 mW cm\(^{-2}\) ster\(^{-1}\) μm\(^{-1}\), and \( K_2 \) is 1260.56 k.

Using Eq.(2),(3) and (4), and using the software of ENVI, the TB chart of Luzhou City can be obtained as shown in Figure 4 and Figure 5, which represents on September 15, 1988 and on August 29, 2002 respectively.

3.3 Normalizing brightness temperature

There is need in normalizing TB in order to eliminate impact on research for time difference. According to Eq. (5), normalize TB in different phase into from 0 to 1 (XU Hanqiu, and CHEN Benqing, 2003).

\[ N_i = \frac{T_{S_i} - T_{S_{min}}}{T_{S_{max}} - T_{S_{min}}} \]

Where, \( N_i \) is the result value after normalizing, \( T_{S_i} \) is the original TB value, \( T_{S_{min}} \) is the minimum value of TB, and \( T_{S_{max}} \) is maximum value of TB.

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**Figure 4.** TB chart on September 15, 1988

**Figure 5.** TB chart on August 29, 2002
3.4 Classification of brightness temperature

Mean-Standard Deviation Method is an ideal method to temperature grade classification (CHEN Songlin, and WANG Tianxin, 2009). Standard Deviation reflects the deviation value for average temperature. Classify urban brightness temperature into low temperature area, secondary low temperature area, medium temperature, secondary high temperature area, and high temperature area. The basic principle of using Mean-Standard Deviation Method for temperature classification is shown in Table 1. $\mu$ is the average temperature, std represents standard deviation of TB and $T_s$ represents TB value of image pixel. Classify TB chart in the research region based on map algebra of GIS and according to Table 1. Subset classification chart of TB using urban boundary on September 15, 1988, and obtain classification chart of TB in urban built-up region in 1988 (see Figure 6). Subset classification chart of TB using urban boundary on August 29, 2002, and obtain classification chart of TB in urban built-up region in 2002 (see Figure 7).

<table>
<thead>
<tr>
<th>Temperature Classification</th>
<th>Interval of Temperature Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>high temperature area</td>
<td>$T_s &gt; \mu + \text{std}$</td>
</tr>
<tr>
<td>secondary high temperature area</td>
<td>$\mu + 0.5\text{std} &lt; T_s \leq \mu + \text{std}$</td>
</tr>
<tr>
<td>medium temperature area</td>
<td>$\mu - 0.5\text{std} \leq T_s &lt; \mu - 0.5\text{std}$</td>
</tr>
<tr>
<td>secondary low temperature area</td>
<td>$\mu - \text{std} &lt; T_s &lt; \mu - 0.5\text{std}$</td>
</tr>
<tr>
<td>low temperature area</td>
<td>$T_s &lt; \mu - \text{std}$</td>
</tr>
</tbody>
</table>

Table 1. Heat island temperature classification using mean-standard deviation method

![Figure 6. Classification chart of TB in built-up region on September 15, 1988](image)

![Figure 7. Classification chart of TB in built-up region on August 29, 2002](image)

After counting Figure 6 and Figure 7, the area and percentage of different temperature classification in urban built-up region in 1988 and 2002 was obtained (see Table 2).
Table 2. Area-proportion statistics of different TB grade in 1988 and 2002

<table>
<thead>
<tr>
<th>Temperature Classification</th>
<th>1988-9-15</th>
<th></th>
<th>2002-8-29</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>area (hm²)</td>
<td>proportion (%)</td>
<td>area (hm²)</td>
<td>proportion (%)</td>
</tr>
<tr>
<td>high temperature area</td>
<td>714.3</td>
<td>87.98</td>
<td>1722.2</td>
<td>83.51</td>
</tr>
<tr>
<td>secondary high temperature area</td>
<td>67.2</td>
<td>8.28</td>
<td>202.8</td>
<td>9.83</td>
</tr>
<tr>
<td>medium temperature area</td>
<td>27.1</td>
<td>3.34</td>
<td>132.8</td>
<td>6.44</td>
</tr>
<tr>
<td>secondary low temperature area</td>
<td>2.5</td>
<td>0.31</td>
<td>3.1</td>
<td>0.15</td>
</tr>
<tr>
<td>low temperature area</td>
<td>0.7</td>
<td>0.09</td>
<td>1.4</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>811.9</strong></td>
<td><strong>100.00</strong></td>
<td><strong>2062.3</strong></td>
<td><strong>100.00</strong></td>
</tr>
</tbody>
</table>

4. Evaluation methods to UHI

4.1 Evaluation methods to single-temporal UHI

Evaluate single-temporal UHI adopting Weighted-Average-Heat-Island-Intensity (WAI) and Urban-Heat-Island-Ratio-Index (URI).

4.1.1 Calculation of heat island intensity

WAI is a better index for describing heat island intensity (Shangming Dan et al., 2010). WAI is using average temperature in outskirt area as basis, classify the temperature in built-up regions, and then calculate by the percentage of areas with different temperatures. The classification of the temperature in urban built-up region in this paper is using the five grades classified by “Mean-Standard Deviation Method”, get the average temperature of the five grades, and eventually calculate the heat island intensity by using the percentage of areas with different grades.

$$ WAI = \sum_{i=1}^{5} (T_{i_{avg}} - T_{O_{avg}}) \times A_i $$

Where, $T_{i_{avg}}$ represents average temperature of different temperature grade from high to low respectively. $T_{O_{avg}}$ is the average temperature in outskirt area. And $A_i$ represents the percentage of different temperature grade from high to low.

4.1.2 Calculation of Urban-Heat-Island Ratio Index

URI is used to depict development degree of heat island (XU Hanqiu, and CHEN Benqing, 2003). The greater URI is, the more severe the heat island phenomenon is.

$$ URI = \frac{1}{100m} \sum_{i=1}^{n} w_i p_i $$

Where, $m$ is the number of brightness temperature grade, $i$ represents temperature grade that in urban region is higher than in suburbs, $n$ is the number of temperature grade that in urban region is higher than in suburbs, $w$ is weighted value, it take the value of temperature grade as result, $p$ is area percentage.

4.1.3 Results analysis

According to Eq. (6), WAI in 1988 was 2.95°C, and that in 2002 was 3.29°C. According to Eq. (7), URI in 1988 was 0.946, and that in 2002 was 0.914.

Above research results demonstrate that WAI in Luzhou City increased 0.34 °C, the increase rate was
not large. The proportion of URI declined, which demonstrate that the development degree of heat island has reduced. The reason is that the area of built-up region in 1988 is 811.9 hm$^2$, and that in 2002 is 2062.3 hm$^2$, which was not in contradiction with increase of heat island intensity.

4.2 Dynamic evaluation methods to UHI

Analyze dynamic characteristics of UHI in different time adopting the following methods.

4.2.1 Quantitative Analysis of UHI in different urban regions

(1) Analysis of brightness temperature grade change in old urban region

The old urban region was the regions which occurred in 1988 and 2002 at the same time, that is, the urban boundary in 1988. Subset classification chart of TB in 2002 using urban boundary in 1988, and obtain the TB grade of the old urban boundary in 2002, and then subtract classification chart of TB in 1988, and obtain the grade change chart of TB in 1988-2002(see Figure 8). Conversion results of various grades of TB are displayed in Table 3.

![Figure 8. the grade change chart of TB in old urban region in 1988-2002](image)

**Table 3. Transition matrix of different TB grade in old urban region in 1988-2002**

<table>
<thead>
<tr>
<th></th>
<th>2002-8-29 high temperature</th>
<th>secondary high temperature</th>
<th>medium temperature</th>
<th>secondary low temperature</th>
<th>low temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988-9-15 high temperature</td>
<td>686.16</td>
<td>20.16</td>
<td>7.29</td>
<td>0.63</td>
<td>0.09</td>
</tr>
<tr>
<td>secondary high temperature</td>
<td>45.45</td>
<td>14.85</td>
<td>6.75</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>medium temperature</td>
<td>10.80</td>
<td>7.02</td>
<td>8.82</td>
<td>0.45</td>
<td>0.09</td>
</tr>
<tr>
<td>secondary low temperature</td>
<td>0.63</td>
<td>0.27</td>
<td>1.08</td>
<td>0.45</td>
<td>0.09</td>
</tr>
<tr>
<td>low temperature</td>
<td>0.36</td>
<td>0.09</td>
<td>0.18</td>
<td>0.09</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Comprehensive analysis according to Figure 8 and Table 3 showed that, from 1988 to 2002, The area of the region that TB grade do not change was 710.37 hm$^2$, and accounted for 87.50% of old urban region.
The area of the region that TB grade increased was 65.88 hm$^2$, and accounted for 8.11% of old urban region. The area of the region that TB grade reduced was 35.64 hm$^2$, and accounted for 4.39% of old urban region.

(2) Analysis of brightness temperature grade change in urban expansion region

Urban expansion region is still rural in 1988, while in 2002, it has become urban boundary. According to Figure 3, urban expansion region in 1988-2002 can be obtained, and subset classification chart of TB in 1988-2002 using it, and obtain classification chart of TB of urban expansion region in 1988-2002. Then the classification chart of TB in urban expansion region in 1988 subtract that in 2002, and obtain the grade change chart of TB in urban expansion region from 1988 to 2002 (see Figure 9). Conversion results of various grades of TB are displayed in Table 4.

![Figure 9. the grade change chart of TB in urban expansion region from 1988 to 2002](image)

Table 4. Transition matrix of different TB grade in urban expansion region in 1988-2002

<table>
<thead>
<tr>
<th>Units:hm$^2$</th>
<th>high temperature</th>
<th>secondary high temperature</th>
<th>medium temperature</th>
<th>secondary low temperature</th>
<th>low temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002-8-29</td>
<td>263.16</td>
<td>28.53</td>
<td>5.31</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1988-9-15</td>
<td>302.94</td>
<td>50.04</td>
<td>22.41</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>high temperature secondary high temperature</td>
<td>416.16</td>
<td>79.02</td>
<td>72.09</td>
<td>0.54</td>
<td>0.27</td>
</tr>
<tr>
<td>medium temperature secondary low temperature</td>
<td>4.68</td>
<td>2.07</td>
<td>5.31</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>low temperature</td>
<td>0</td>
<td>0</td>
<td>0.09</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Comprehensive analysis according to Figure 9 and Table 4 showed that, from 1988 to 2002, the area of the region that TB grade increased was 810.27 hm$^2$, and accounted for 64.68% of urban expansion region.
The area of the region that TB grade did not change was 385.38 hm², and accounted for 30.76% of urban expansion region. The area of the region that TB grade reduced was 57.15 hm², and accounted for 4.56% of urban expansion region. The reason causing these results is that urban expansion region was suburb, while in 2002, gradually evolved into urban region. The type and nature of the underlying surface has undergone fundamental change, which resulted in temperature exaltation.

4.2.2 Overall analysis of UHI change

According to Table 3 and Table 4, whether in old urban region or urban expansion region, the TB grades in most regions convert each other, and some higher, some lower. In order to reflect the overall change in temperature is increased or decreased, this article constructs the Brightness-Temperature-Grade-Change-Index (TGCI).

\[
TGCI = \sum_{i=1}^{n} w_i \cdot GB_i
\]

Where, \(n\) is the number of TB grade change types, and it has twenty-five types in theory. \(GB\) is grade change series of TB. If grade change become decreasing, \(GB\) is negative. If grade change become increasing, \(GB\) is positive. \(w\) is the area percentage.

If \(TGCI > 0\), it shows that increasing trend is greater than decreasing trend, and change trend performances overall increasing. If \(TGCI < 0\), it shows that increasing trend is weaker than decreasing trend, and change trend performances overall decreasing.

After calculation, \(TGCI\) in urban expansion region was 0.938, which demonstrated that UHI enhanced in 1988-2002. This was because this part region evolved from suburbs into urban region. \(TGCI\) in old urban region was 0.043 which demonstrated that UHI slightly increased in 1988-2002, which was consistent with calculation results of Weighted-Average-Heat-Island-Intensity.

5. Conclusion

This article explored methods to monitoring and evaluating UHI using multi-temporal thermal infrared remote sensing data. The main conclusions are the following. (1) It is feasible to dynamically monitor and evaluate Urban Heat Island Effects using thermal infrared remote sensing data. (2) In Luzhou City, \(WAI\) in 1988 was 2.95 °C, and that in 2002 was 3.29 °C, \(URI\) in 1988 was 0.946, and that in 2002 was 0.914. \(WAI\) increased 0.34 °C, the increase rate was not large. The proportion of \(URI\) declined, which demonstrate that the development degree of heat island has reduced. (3) In old urban region, from 1988 to 2002, the area of the region that TB grade do not change was 710.37 hm², and accounted for 87.50% of old urban region. (4) In urban expansion region, the area of the region that brightness temperature grade increased was 810.27 hm², and accounted for 64.68% of urban expansion region. (5) \(TGCI\) in urban expansion region was 0.938, which demonstrated that UHI enhanced in 1988-2002. This was because this part region evolved from suburbs into urban region. \(TGCI\) in old urban region was 0.043 which demonstrated that UHI slightly increased in 1988-2002, which was consistent with calculation results of \(WAI\).

Acknowledgment

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References