Application of Urban Thermal Environment Monitoring Based on Remote Sensing in Beijing

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Abstract

Remote sensing has become an important method for monitoring urban thermal environment, but, it is still difficult to analyse the spatio-temporal change of urban thermal environment quantitatively only by ground surface temperature (or brightness temperature). Three indexes on urban thermal environment monitoring are proposed in this paper: heat island intensity, heat field intensity index and heat island proportion index. Based on MODIS surface temperature products and FY3A/MERSI data of two years, urban thermal environment is monitored by remote sensing method in Beijing. The empirical results verify that three indexes proposed in this paper are meaningful in monitoring of urban heat island. It can not only monitor the intensity and changes of the urban heat island in Beijing effectively, but also, it is positive to carrying out meteorological operations in city thermal environment monitoring.

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Keywords: Ground surface thermal environment; heat island intensity; heat field intensity index; heat island proportion index; Beijing

1. Introduction

Under the background of global warming and rapid urbanization, urban thermal environment is considered to be one of the important factors in leading urban ecological environment. The most obvious feature of urban thermal environment is urban heat island effect (UHI). UHI is a kind of heat gathering phenomenon in the city caused by city building and human activities. It is also one of the most striking features of urban climate[11]. Urban heat island has become the attention focus in scientific community, managers and even the public. Using the meteorological data, remote sensing, simulation models and stationing observation methods, scholars have researched on the formation mechanism of urban heat island, intensity characteristics of heat island, harm and mitigation of urban heat island widely[2-4]. Conventional monitoring method of urban heat island is to observe at a fixed-point or by a mobile car.
This method can measure the temperature accurately, so it is suitable for researching the urban thermal environment quantitatively[5]. However, it is poor in synchronization and spatial representation, also it cost highly. By the means of remote sensing, the observational data have several advantages, such as: good time synchronization, covering a wide range, intuitive, quantitative and so on. It can reduce the local environmental human interference and the cost[6]. Therefore, using thermal infrared remote sensing data has become the primary means of urban thermal environmental research in cities such as Beijing, Shanghai and Shenzhen[7-9]. In the studies of city space thermal environment monitoring, the surface temperature is the most basic indicator of the thermal environment. Multi-temporal remote sensing data are needed in the study of dynamic changes on thermal environment. Due to different imaging conditions of multi-temporal remote sensing data, the surface temperature is different obviously under different weather conditions and time even if in the same area. Therefore, it can not reflect the dynamic changes of urban heat island to set the absolute value of surface temperature as the indexes in monitoring surface thermal environment. In order to reflect the spatial pattern and dynamic change of urban thermal environment, a series of indexes systems on monitoring of urban thermal environment are needed to develop basing on the remote sensing characteristics.

In this paper, on the basis of remote sensing data with middle or coarse resolution, the monitoring indexes on urban thermal environment are established preliminarily: heat island intensity, heat field intensity index and heat island proportion index. These indexes were used to monitor the urban thermal environmental in Beijing and achieved good results. It is positive to the implementation of remote sensing to monitor urban thermal environment in the future.

2. Establishment of the monitoring indexes on urban thermal environment

Generally speaking, urban heat island refers to the phenomenon that the city atmospheric is warmer than the surrounding suburbs. The urban heat island observed by thermal infrared remote sensing can be called surface urban heat island (SUHI), or more professionally, what they "saw" is the spatial patterns of uplink thermal infrared radiation received by the remote sensing sensors[7,10]. The surface seen in SUHI effective radiated area depends on the geometry view of the sensor and the land surface structure. Due to the three-dimensional structure of the city, the important part in city surface may not been seen completely. Compared to the direct measurement of the temperature heat island, the surface urban heat island observed by thermal infrared remote sensing is indirect measurement. The influence of atmospheric should be considered, also, the surface radiation characteristics that effect the radiation emission and reflective included in the sensor range of wavelengths should be taken into consideration.

In the research of the urban thermal environment monitoring, the main method is to analyze with the surface temperature data obtained by remote sensing retrieval. The record of thermal infrared remote sensing is the sum of emission radiation of the object surface, environment and atmospheric radiation. This radiation value can be replaced radiation brightness temperature easily, and it is not the real temperature of the land surface. Because the city underlying surface is abnormal complexity and it is difficult to acquire real-time data at the satellite transit time, there are several difficulties in accurate retrieval of the surface temperature. The urban heat island mainly reflects heat differences within the space, so, when the city limited area and the lunt condition are assumed to be approximate consistent, the surface urban heat island can be studied according to the radiation brightness temperature. Therefore, the urban thermal environment monitoring indexes can be established usually by the surface temperature. When the surface temperature is difficult to achieve, the radiation brightness temperature can be used to monitor the urban heat island.

2.1. Heat Island Intensity

According to the research methods of urban heat island in most literatures, urban heat island intensity (UHII) is defined as the temperature difference between urban and suburbs. In the filed of surface urban heat island, it can be defined as the surface temperature difference between urban and suburbs. It can be
used to reflect the degree that urban surface temperature is higher than the suburbs. In some cases, the surface temperature of city is lower than the suburban countryside, this can be called urban cold island. Urban heat island intensity can be expressed as:

\[ UHII_i = T_i - \frac{1}{n} \sum_{1}^{n} T_{\text{crop}} \quad (1) \]

Where, \( UHII_i \) is the heat island intensity of the \( i \)th pixel in the image; \( T_i \) is the surface temperature; \( n \) is the effective pixel number in suburban farmland; \( T_{\text{crop}} \) is the surface temperature of suburban farmland.

To ensure the selection of remote sensing images in suburban farmlands is representative, 2 ~ 3 suburbs around the city are selected generally, and the area of each suburbs is more than 5 x 5 pixels. The suburban farmlands selected generally have the following characteristics: (1) flat open fields with large area coverage whose the elevation difference is small to city center; (2) stable structure, where the cropping system and soil properties change rarely in quite a long time; (3) far from the city center relatively, where it will not easily affected by environmental pollution of urbanization.

The essence of heat island intensity is the size of temperature anomalies. The size of temperature anomalies is relevant to the size of time scale. The temperature anomalies difference in one day is larger obviously than that in ten-day, one month or one season. According to the test analysis of a large number of remote sensing image and the reference literature\(^{[11]}\), set one day and ten-day, one month or one season as two time scale, the heat island intensity can be divided into 7 level: strong cold island, sub-strong cold island, weak cold island, no heat island, weak heat island, sub-strong heat island and strong heat island. This is different to the research of temperature heat island intensity\(^{[12]}\), the specific division is shown in table 1.

### TABLE I. THE DIVISION AND DEFINITION OF URBAN HEAT ISLAND INTENSITY

<table>
<thead>
<tr>
<th>Level ( \text{(daily)} )</th>
<th>( UHII ) ( \text{(average of ten-day, monthly or quarterly)} )</th>
<th>Level definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \leq -7.0 )</td>
<td>( \leq -5.0 )</td>
</tr>
<tr>
<td>2</td>
<td>(-7.0 \sim -5.0)</td>
<td>(-5.0 \sim -3.0)</td>
</tr>
<tr>
<td>3</td>
<td>(-5.0 \sim -3.0)</td>
<td>(-3.0 \sim -1.0)</td>
</tr>
<tr>
<td>4</td>
<td>(-3.0 \sim 3.0)</td>
<td>(-1.0 \sim 1.0)</td>
</tr>
<tr>
<td>5</td>
<td>(3.0 \sim 5.0)</td>
<td>(1.0 \sim 3.0)</td>
</tr>
<tr>
<td>6</td>
<td>(5.0 \sim 7.0)</td>
<td>(3.0 \sim 5.0)</td>
</tr>
<tr>
<td>7</td>
<td>(&gt;7.0)</td>
<td>(&gt;5.0)</td>
</tr>
</tbody>
</table>

#### 2.2. Heat Field Intensity Index

In view that the urban heat island research focuses on the spatial distribution characteristics of the underlying surface temperature, in order to eliminate the absolute temperature difference between different seasons, the heat field intensity index (HFII) is proposed here. HFII is defined as the normalization of remote sensing surface heat field. It can judge the heat distribution range and position of
relatively high temperature or low temperature in one image clearly, with an indicating significance of heat field. It can be expressed as:

\[ H_i = \frac{T_i - T_{\text{min}}}{T_{\text{max}} - T_{\text{min}}} \]  

(2)

Where, \( H_i \) is the heat field intensity index of the \( i \)th pixel; \( T_i \) is the surface temperature; \( T_{\text{min}} \) is the effective lowest temperature in image field; \( T_{\text{max}} \) is the effective highest temperature in image field. The larger the heat field intensity index is, the greater the possibility locating in a heat island is.

According to a lot of experiments with remote sensing images, the heat field intensity index can be divided into five levels: low temperature area, sub-low temperature area, normal temperature area, sub-high temperature area and high temperature area. They can reflect the size of urban heat island effectively. The specific division is shown in table 2.

<table>
<thead>
<tr>
<th>level</th>
<th>Heat field intensity index</th>
<th>level definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0~0.1</td>
<td>low temperature area</td>
</tr>
<tr>
<td>2</td>
<td>0.1~0.3</td>
<td>sub-low temperature area</td>
</tr>
<tr>
<td>3</td>
<td>0.3~0.7</td>
<td>normal temperature area</td>
</tr>
<tr>
<td>4</td>
<td>0.7~0.9</td>
<td>sub-high temperature area</td>
</tr>
<tr>
<td>5</td>
<td>0.9~1.0</td>
<td>high temperature area</td>
</tr>
</tbody>
</table>

2.3. Heat Island Proportion Index

In view Referring to the urban heat island proportion index (UHPI) proposed in related literature\(^{(13)}\), the "brightness temperature level" option is revised instead of "heat island intensity level". It can be expressed specifically as:

\[ UHPI = \frac{1}{100m} \sum_{i}^{n} w_i p_i \]  

(3)

Where, \( UHPI \) is the urban heat island proportion index; \( m \) is the level number of the heat island intensity; \( i \) is the level serial number of urban temperature higher than the suburban temperature; \( n \) is the level number of urban temperature higher than the suburban temperature; \( w_i \) is the weight of the \( i \)th level, taking the level number; \( p_i \) is the percentage of the \( i \)th level. Generally, the larger \( UHPI \) is, the more serious the heat island phenomenon. The value is between 0~1.0, the larger the value, the more serious the heat island phenomenon. When the value is 0, it shows there is no heat island phenomenon; and when the value is 1, it shows the field locates in heat island area. According to the definition of heat island strength level, we can know that \( m = 7 \) and \( n = 3 \).

Urban heat island proportion index is the ratio of heat island area with region area calculated basing on the urban spatial units, and the weight is given to represent the development degree of heat island in this spatial unit. Therefore, the UHPI not only can compare the heat island intensity of different spatial units, but also can compare the heat island intensity of the same area at different times.
3. Typical applications of thermal environment monitoring indexes in Beijing area

3.1. Application of Heat Island Intensity

(1) Choices of Suburban Farmland

Figure 1 is the land use type figure for Beijing area. There are mainly mountain forest in the north and northwest areas; and the eastern and southern areas are plains farmland. In addition to that, there is a flat dam farmland in Yanqing in northwest area, but its altitude is higher obviously than the plains in eastern and southern areas. According to the front choosing principle of the suburban farmland, two farmlands areas are selected. One of them locates at southeast of Beijing, and the other locates at the junction of Beijing east and Hebei Province (seen in Figure 1). They are all far from the city center, locate at the same altitude and the planting structure are stability. The range of each area is 5×5 pixels. They can represent the condition of suburban farmlands in Beijing.

(2) Daily Monitoring

The fifth channel of FY-3A/MERSI thermal infrared remote sensing data is adopted to monitor the urban heat island in Beijing area. The center wavelength of the fifth channel is 11.25μm. And, the spatial resolution of it is 250m. Comparing to the satellites like MODIS and NOAA, monitoring with thermal infrared remote sensing has the advantage of spatial resolution \(^{[14-15]}\). According to the daily monitoring index of heat island intensity shown in table 1 and land surface temperature retrieved by the fifth channel data of FY-3A/MERSI satellite at 10:45, June 25th, 2009, the heat island intensity monitoring figure of eight districts in Beijing (Figure 2) is produced. Figure 2 shows: at nearly 11 am, weak heat island phenomenon appeared in eight districts of the Beijing, sub-strong heat island appeared in some areas such as Qianmen and Shougang, weak cold island and sub-strong cold island appeared in the water areas such as Zhongnanhai and Kunming Lake. This is according with the actual situation. So, the daily monitoring index of heat island intensity is according with the reality.

Figure 1. Land use type figure of Beijing area and the choices of suburban farmland.
(3) Quarterly Monitoring

Surface temperature data adopted the average LST products of MODIS/Terra at near 10 pm in continuous 8 days. This products is one of the important business products of MODIS satellite\(^{[16]}\). Its monitoring accuracy to the land surface temperature can up to 1K \((1\sigma)\). It can monitor the urban heat island strength and seasonal changes in Beijing area effectively\(^{[17]}\).

According to the average LST products of MODIS/Terra in continuous 8 days in 2001 and 2006, the average quarterly heat island intensity of Beijing in 2001 and 2006 were monitored using the head island quarterly monitoring index. The monitoring result of 2006 is shown in figure 3. From the figure 3, we can see: heat island effect appeared at night in four seasons in Beijing and most areas located at no heat island areas. Obvious heat island areas were concentrated in eight districts of Beijing (four urban areas, Chaoyang, Haidian, Shijingshan and Fengtai). But, the heat island intensity level and area distributed differently in each season, there were no obvious strong heat island areas in spring, summer and autumn, mainly sub-strong heat island areas. However, there were obvious strong heat island areas in winter. The heat island area in winter was largest, followed by spring and autumn; the heat island area in summer was smallest. This result is similar to the research result by temperature data in related literatures\(^{[18-19]}\) : the heat island in winter was strongest, followed by spring, and the heat island area in summer was weakest. The monitoring result in 2001 was similar to that in 2006.

In addition, the average heat island intensity at night of January, April, July and October in 2001 and 2006 were monitored by the above data. The result indicated: heat island of January in winter was the strongest, followed by that of April in spring and October in autumn, that of July in winter was the weakest, it was consistent with the front season monitoring results. The above monitoring results showed that heat island intensity index had an indicating significance to monthly and quarterly heat island monitoring. It was according with the reality.

3.2. Application and Comparison of Heat Field Intensity Index

Using the average LST products of MODIS/Terra in continuous 8 days all over 2001 and 2006, the urban heat field intensity index of Beijing area was calculated according to the Eq. (2). The results were listed in table 3. Setting the heat field intensity index of 2006 as an example, heat field intensity index can reflect the spatio-temporal distribution of urban thermal envionment effectively. In spatial, most of the area belonged to normal temperature area, high temperature area concentrated inside the eighth ring of
Beijing. There was obvious heat island effect. In time, if taking high temperature range as heat island area, the heat island area statistics to the eighth ring of Beijing in figure 4 showed that: the high temperature ranges in Beijing were 234 km in spring, 210 km in summer, 230 km in autumn and 249 km in winter. In other words, the high temperature ranges in winter was the largest, followed by spring and autumn, and summer was the smallest. The results were according with seasonal variation of heat island in Beijing. Therefore, the heat field intensity index had indicating significance to the spatio-temporal strength of heat island. The monitoring result in 2001 was similar to that in 2006.

In spatial distribution, the heat island strength and heat field intensity index in each season had a similar distribution trend. The values of them in spring, summer, autumn and winter were 0.965, 0.984, 0.974 and 0.981 respectively. If setting the sub-strong heat island and strong heat island as heat island areas, the statistics of heat island areas in eight districts of Beijing showed that the heat island areas in spring, summer, autumn and winter were 272, 206, 404 and 763 square kilometers. In terms of heat island area, the seasonal change on heat island intensity was much larger than that on heat island intensity index. The difference on heat island intensity between winter and summer was 557 square kilometers, while, the difference on heat field intensity index between winter and summer was 39 square kilometers. This result showed that the heat island intensity may be more indicating significance in heat island scope than heat field intensity index.

Figure 3. Quarterly distribution of heat island intensity in Beijing area in 2006
3.3. Application of Heat Island Proportion Index

By the average surface temperature products of MODIS/Terra in continuous 8 days in 2001 and 2006, the urban heat island proportion index (UIPI) at different time, in different season within urban central area of Beijing were calculated according to the Eq. (3). The results were listed in table 3.

<table>
<thead>
<tr>
<th>TABLE III</th>
<th>THE DIVISION AND DEFINITION OF HEAT FIELD INTENSITY INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different Season</td>
<td>UIPI</td>
</tr>
<tr>
<td>2006 spring</td>
<td>0.69</td>
</tr>
<tr>
<td>2006 summer</td>
<td>0.53</td>
</tr>
<tr>
<td>2006 autumn</td>
<td>0.76</td>
</tr>
<tr>
<td>2006 winter</td>
<td>0.88</td>
</tr>
<tr>
<td>2001 spring</td>
<td>0.78</td>
</tr>
<tr>
<td>2001 summer</td>
<td>0.65</td>
</tr>
<tr>
<td>2001 autumn</td>
<td>0.72</td>
</tr>
<tr>
<td>2001 winter</td>
<td>0.87</td>
</tr>
</tbody>
</table>

From the UIPI in different seasons, the UIPI in winter was highest and that in summer was lowest in both 2001 and 2006. This was consistent with the current rule that heat island effect in Beijing is strongest in winter and weakest in summer. So, the UIPI index has practical significance.
However, the strengths in spring and autumn were not stable; the heat island intensity in autumn in 2006 was higher than that in spring, on the contrary, the heat island intensity in autumn in 2001 was lower than that in spring.

From the UIPI at different times, the UIPI in winter was still the highest and heat island was strongest. But, other seasons were different at different times. For example, between 8.22 ~ 8.29 in summer of 2006, the UIPI was higher than that between 10.16 ~ 10.23 in autumn and 5.1-5.8 in spring, which may be related to atmospheric circulation and weather situation.

The statistics to heat island proportion index of all districts and counties in Beijing in 2006(Figure 5) showed that: for each season, the heat island proportion index of all districts and counties were highest in winter and lowest in summer, that in spring and autumn were between them.

![Figure 5. Heat island proportion index distribution in different season of all districts and counties in Beijing in 2006](image)

For each districts and counties, the heat island proportion index of city (city center of Beijing, including four districts as Dongcheng, Xicheng, Xuanwu and Chongwen) was significantly higher than other districts and counties. The heat island proportion indexes of city were 0.86 in spring, 0.75 in summer, 0.91 in autumn and 1.00 in winter respectively, this indicated that city located in strong heat island level. Followed by Shijingshan and Chaoyang districts, Yanqing was lowest. The heat island proportion indexes of Yanqing were 0.0 in spring, 0.0 in summer, 0.02 in autumn and 0.12 in winter respectively, this indicated that there was almost no heat island effect in Yanqing in spring summer and autumn, just a faint heat island effect in winter. The heat island proportion index of Shunyi, Pinggu, Mentougou, Minyun, Huairou, Daxing and Changping were lower than 0.10, there were almost no heat island effect. Setting the heat island conditions in fifth ring area of Beijing representing the whole region of Beijing, the heat island proportion index in Beijing area were 0.69 in spring, 0.53 in summer, 0.76 in autumn and 0.88 in winter respectively, this showed that the heat island effect in Beijing was quite obvious.

4. Conclusions and discussions

Three indexes of surface urban heat island effect are proposed in this paper, based on the characteristics of surface urban heat environment. Moreover, they are applied to the urban heat island monitoring, using the MODIS 1-km resolution surface temperature data and FY-3A/MERSI satellite data of Beijing area in 2001 and 2006. The application results show that:

Heat island intensity can monitor the strength of urban heat island at different time scale(daily, ten-day, monthly and quarterly) effectively. Heat island intensity index can monitor the temperature of urban heat island at different spatio-temporal scale effectively. Heat island proportion index can compare the strength of urban heat island at different spatio-temporal scale quantitatively. They all have positive
meaning in urban thermal environment monitoring. It is not only positive to research the surface urban heat island quantitatively, but also it is positive to carrying out meteorological operations in city thermal environment monitoring.

However, three indexes of thermal environmental remote sensing monitoring are applied in Beijing area only. Because the climate differences between north and south are significant, also, the background types of urban underlying and climate circulation background are both significantly different. Moreover, affecting reasons to the formation of urban heat island are complex. Whether the thermal environmental monitoring indexes proposed in this paper are applicable to other areas or not still requires further researches and experiments.

References