A study on the changes of urban heat island in Beijing based on satellite remote sensing

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Abstract: Beijing city, capital of China, has experienced a rapid urban expansion over the past two decades due to accelerated economic growth. Remote sensing techniques were used to detect urban changes based on multi-temporal Landsat data. The impact of urban growth on urban heat island (UHI) and its change was examined. The results revealed a notable increase in built-up area and UHI area during the two periods and the UHI change pattern was much similar to the built-up area change pattern, both affected by the ring road system of Beijing.
Keywords: Urban heat island, Change, TM, Beijing.

1. Introduction

Urbanization, the conversion of other types of land to uses associated with growth of populations and economy, is a main type of land use and land cover change in human history. Urban development usually gives rise to a dramatic change of the earth's surface, as natural vegetation is removed and replaced by non-evaporating and non-transpiring surfaces such as metal, asphalt, and concrete. This alteration will inevitably result in the redistribution of incoming solar radiation, and induce the urban-rural contrast in surface radiance and air temperature. The difference in ambient air temperature between an urban area and its surrounding rural area is known as the effect of urban heat island (UHI). Generally speaking, two types of UHI can be distinguished pertinent to the methods of temperature measurement:(1)the canopy layer heat island and (2)the boundary layer heat island[1].Satellite-derived surface temperatures are believed to correspond more closely with the canopy layer heat islands, although a precise transfer function between the ground surface temperature and the near ground air temperature is not yet available[2].With the development of world-wide urbanization, urban heat island effects are becoming more and more distinct in many major cities due to the artificial heating emission, simultaneous removal of natural land cover and introduction of urban materials[3]. The goal of this paper is to detect the urban growth pattern and the urban heat island changes of Beijing city using multi-temporal Landsat images.

2. Study area and methodology

2.1 Study area and data description

Beijing is the capital and one of the largest cities situated in north of China(39° 56′ N,116° 20′ E), with an area of 16808 km^2 and a population of about 13 million. The road network of Beijing city is briefly constructed with ring roads and radial as its arteries. The road around the Forbidden City is named as the first ring, and the ring roads beyond are the second, third, fourth and fifth ones in terms of the radial distance from the center of the city. The heat island effect on Beijing was evident from 1961 to 2000, and the mean daily temperature in the city was 4.6℃ higher than that in the suburb, being reinforced from 1978 to 2000[4].

The satellite remotely sensed data sets used in this study were three Landsat Thematic Mapper(TM) images, acquired on 26 September 1987, 28 August 1994, and 31 August 2001. Each Landsat image was registered to common projection (Albers Conical Equal Area) based on 1:10,000-scale digital map with precise of less than 0.5 pixel size in root-mean-squared error.

2.2 Radiometric normalization of multi-temporal images

The radiometric normalization of multi-temporal satellite optical images of the same terrain is often necessary for land cover change detection. Previously, ground reference data or pseudo-invariant features(PIFs) were used in the radiometric rectification of multi-temporal images. But ground reference data are costly and difficult to acquire for most satellite remotely sensed images and the selection of PIFs is generally subjective. In addition, these methods were mainly used on radiometric normalization of two images acquired on different dates. Conservation of radiometric resolution in the case of radiometric normalization between more than two images was also a problem. Yong Du et al.[5]proposed a new procedure for radiometric normalization between multi-temporal images of the same area based on principal component analysis(PCA). In this procedure, the selection of PIFs is done statistically. The satellite images are normalized radiometrically to a common scale tied to the reference radiometric levels and this procedure ensures the conservation of radiometric resolution for the multi-temporal images involved. In this paper, this procedure was used to do the radiometric normalization of the three Landsat TM images. Considering the need of built up area extraction, we only chose band3, band4, and band5 to do the radiometric normalization.

2.3 urban expansion detection and analysis

Land covers in urban areas tend to change more drastically over a short period of time than elsewhere because of incessant urbanization. Urbanization has led land covers to change especially frequently in peri-urban areas in Beijing as a result of rapid economic development. These changes can be ideally monitored and detected from remotely sensed images.

Remote sensing materials in the form of aerial photographs and satellite images are usually converted into useful information such as land cover maps using two conventional methods: manual interpretation and computer-assisted digital processing. Remotely sensed data have become increasingly available in a digital form, allowing for their computer-assisted interpretation and processing. Irrespective of the specific form of the remote sensing materials, manual interpretation is tedious, time-consuming, and the interpreted results highly subjective to the image analyst. By comparison, supervised classification is much faster and requires far less human intervention. But, automatic classification of satellite images for urban areas is a difficult task to achieve at a high accuracy level due to the diverse range of covers. Considerable efforts have gone into simplifying the process of automatically mapping land cover, such as using indices. A new and simple method (Y.ZHA et al. 2003)[6] was proposed for the rapid and accurate mapping of built-up areas (including barren land) based on the combinational use of normalized difference built-up index (NDBI) and normalized difference vegetation index (NDVI). The mapping is accomplished through arithmetic manipulations and recoding of NDBI and NDVI images. Here, in this paper, such a method was used to extract built-up area. The results are as follows (Fig. 1). The red color indicates the built-up area (including barren land).

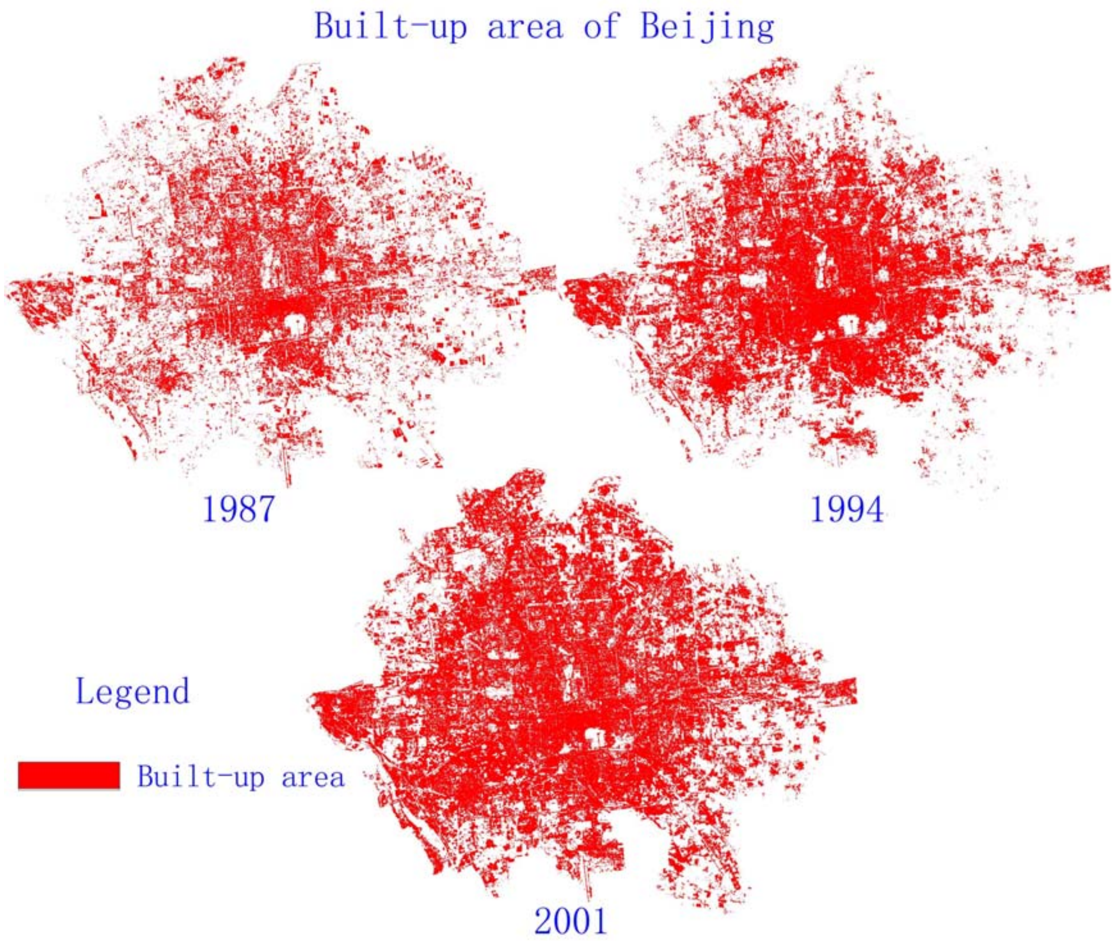

Fig.1 Built-up area of Beijing

Built-up area change images were also produced using image differencing (Fig. 2). In Fig.2, the black rings are the ring roads of Beijing.

From Fig.1, a statistic table (table 1) was made.

Table 1. The total areas and percentages of built-up and barren land in 1987, 1994 and 2001.

year	The total area of built up and barren land（KM^2）	Percentage(％)
1987	241.4	26.9
1994	338.2	37.8
2001	487.9	54.5

Table 1 shows that, in 1987, the total area of built-up and barren land in Beijing was only 241.4 KM^2, accounting for 26.9％ of the study area. However, in 1994 and 2001, the total areas of built-up and barren land were 338.2 KM^2 and 487.9 KM^2, the percentages were 37.8％ and 54.5％, respectively. From this table, it is clear that there has been a considerable increase in built-up area during the two periods. From 1987-1994, the total area of built-up and barren land increased from 241.4 KM^2 to 338.2 KM^2, about 96.8 KM^2 and 10.9％of the study area. And from 1994-2001, it increased from 338.2 KM^2 to 487.9 KM^2 , about 148.7 KM^2 and 16.7％of the study area. Obviously, the built-up area increased more drastically in the second period than that of the first period.

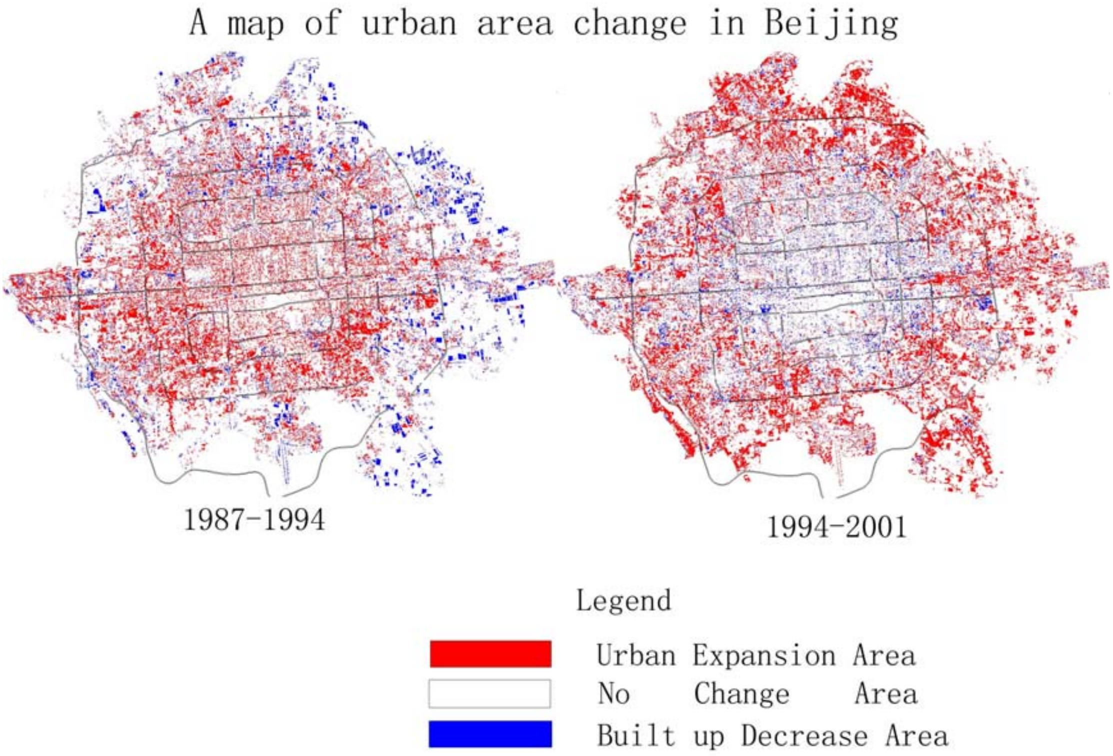

Fig.2. A map of urban area change in Beijing, 1987-2001.

Fig.2 shows the areal extent and spatial occurrence of the urban area change. The red indicates the built-up increased area, while the blue represents the built-up decreased area, which means the land use (land cover) changes from built-up and barren land to other types (vegetation, water, etc). From Fig.2, we can see that, from 1987-1994, urban expansion mainly occurred within the fourth ring road and from 1994-2001 urban expansion mainly occurred outside the fourth ring road. Beijing city developed from its center to its outside, like the water waves. This development pattern is in accordance with its ring road system.

From stated above, with the fast development of Beijing city, the land use and land cover have undergone a dramatic change and the urban area has increased sharply. These changes would inevitably exert impact on its environment.

2.4 Urban heat island (UHI) study

Studies on urban heat island using satellite remote sensing data have been conducted primarily using NOAA AVHRR data, of which the spatial resolution is 1.1KM and found suitable only for small-scale urban temperature mapping. The much higher resolution (120m) Landsat TM thermal infrared data were seldom used to retrieve land surface temperature (LST) because it has only one thermal channel. The fact of possessing only one thermal channel is a critical limitation with respect to obtaining LST, for it does not allow to apply neither a split-window method nor a temperature/emissivity separation (TES) method and therefore to obtain information about the emissivity spectrum of natural surfaces. However, the proposal of a generalized single-channel algorithm(Jiménez-Muñoz and Sobrino,2003)[7] makes it practical to use Landsat TM data to retrieve land surface temperature. This algorithm only uses the total atmospheric water vapour content and the emissivity data. The main advantage of this algorithm compared with the other single-channel methods is that in-situ radiosoundings or effective mean atmospheric temperature values are not needed. This algorithm was used in this paper to retrieve land surface temperature. The total atmospheric water vapour content was obtained using the meteorological observation data. Emissivity data was got from the Qin's method[8]. Because the TM6 data were acquired in different year and under different weather conditions, the calculated temperature could not be compared directly and must be normalized. Normalization was done according to the following formula.

$$T = \frac{t - t_{min}}{t_{max} - t_{min}}$$

where t indicates the temperature before normalization, t_{max} and t_{min} are the maximum and minimum temperature before normalization, T represents the normalization result. T belongs to 0～1 after normalization. 0 and 1 represent the minimum and maximum temperature respectively. Then we can compare the relative value. The T values belonging to 0.6～1 were considered to be the urban heat island area. In this way, the distribution map (Fig.3) of urban heat island was obtained.

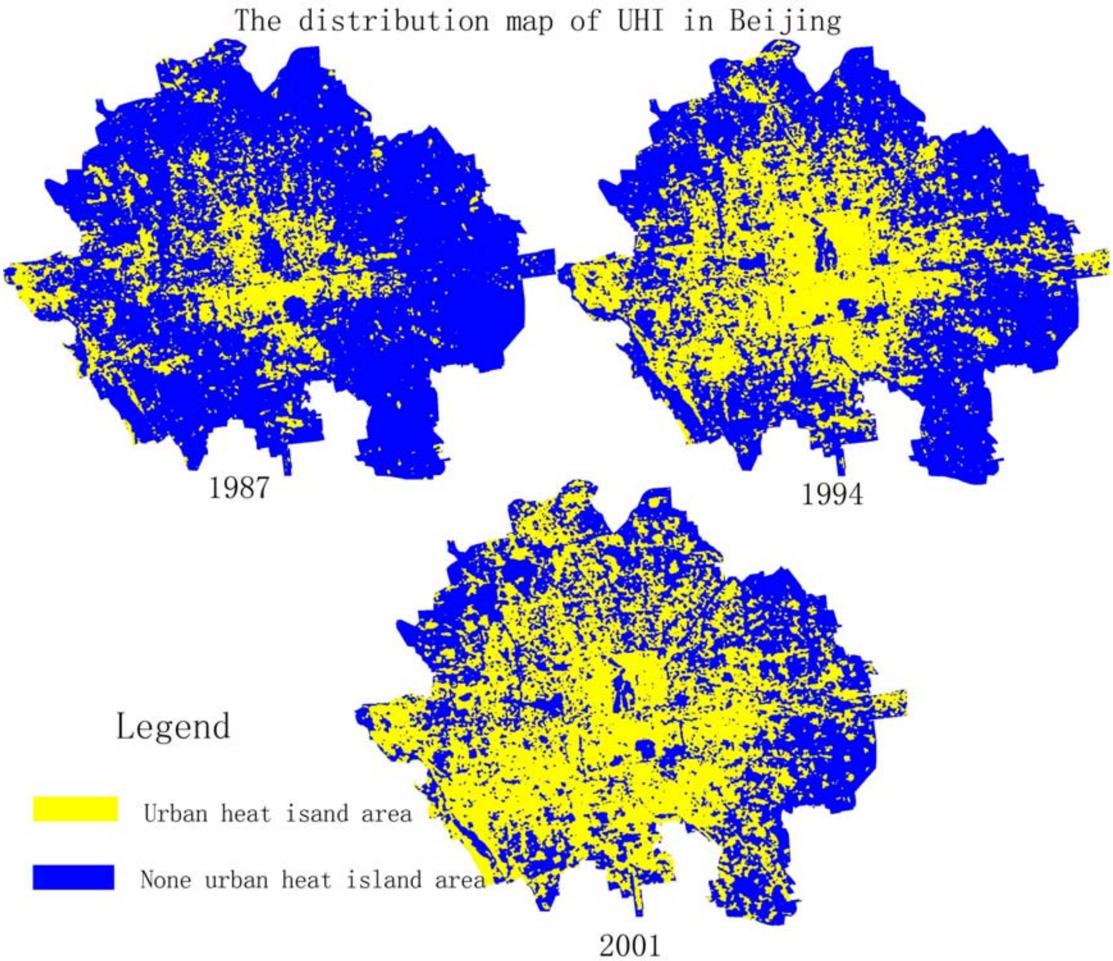

Fig.3. The distribution map of UHI in Beijing, 1987-2001.

According to Fig.3, Table 2 was obtained.

Table 2. The area and percentage of the Urban Heat Island,1987-2001.

year	The area of the Urban Heat Island（KM^2）	Percentage(%)
1987	164.9	18.5
1994	356.8	39.9
2001	482.4	54.0

From Table 2, we can see that from 1987-1994, the area of the urban heat island increased from 164.9 KM^2 to 356.8 KM^2, an increase of 191.9 KM^2 and 21.4 ％, while from 1994-2001, it increased from 356.8 KM^2 to 482.4 KM^2, an increase of 125.6 KM^2 and 14.1 ％. The urban heat island increased sharply during both periods. But the statistics reveals that during the first period, it increased faster than the second period. In order to show the areal extent and spatial occurrence of the urban heat island changes, image differencing was used to get the UHI change map (Fig.4).

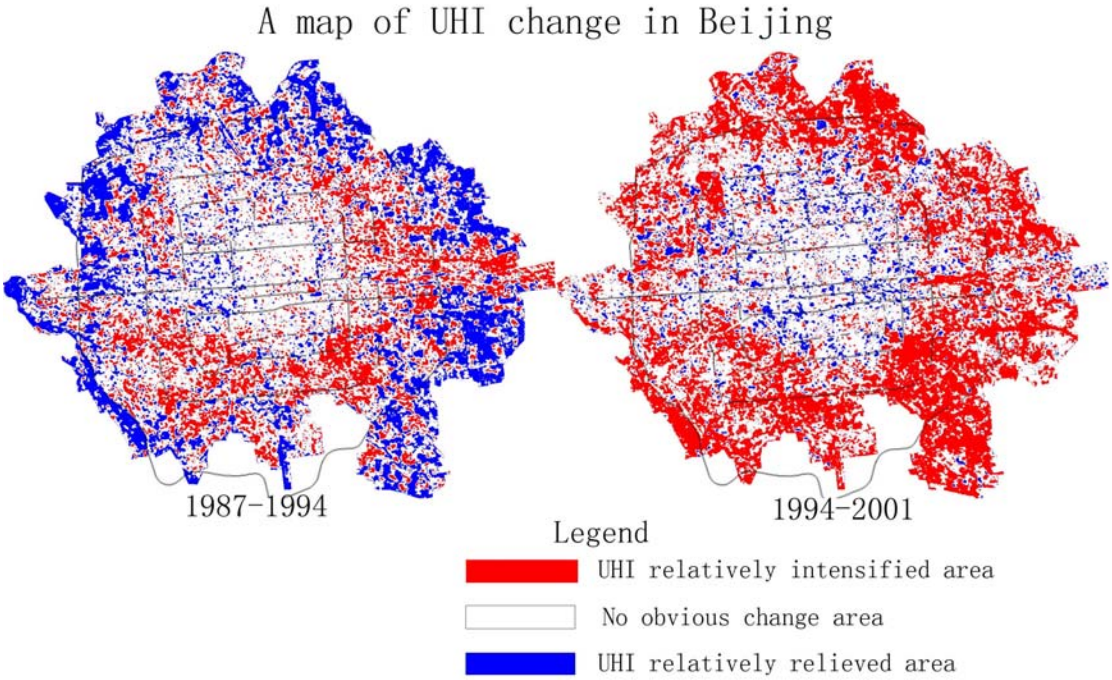

Fig.4. A map of UHI change in Beijing, 1987-2001.

From Fig.4, no obvious changes can be seen within the third ring road, because it is the intense urban heat island area during both periods. The UHI relatively intensified areas during the two periods are both like rings; the second period lies outside of the first period, which is also like water waves.

2.5 The relationship between built-up area change and UHI change

The interactions of urban surfaces with the atmosphere are governed by surface heat fluxes, the distribution of which is drastically modified by urbanization. The main contributing factors are changes in the physical characteristics of the surface (albedo, thermal capacity, heat conductivity), owing to the replacement of vegetation by asphalt and concrete; the decrease of surface moisture available for evapotranspiration; and the changes in the radiative fluxes and in the near surface flow, due to the complicated geometry of streets and tall buildings, and anthropogenic heat. As aforementioned, from 1987-1994, the built-up area (including barren land) increased from 241.4 KM^2 to 338.2 KM^2, an increase of 96.8 KM^2 and 10.9％of the study area. And from 1994-2001, it increased from 338.2 KM^2 to 487.9 KM^2 , about 148.7 KM^2 and 16.7％ of the study area. In the mean time, from 1987-1994, the area of the urban heat island increased from 164.9 KM^2 to 356.8 KM^2, an increase of 191.9 KM^2 and 21.4 ％. From 1994-2001, it increased from 356.8 KM^2 to 482.4 KM^2, an increase of 125.6 KM^2 and 14.1％. Comparing the built-up change map and the UHI change map, we can find that the UHI relatively intensified area coincides with the built-up expansion area. The no change built-up area corresponds to the no obvious UHI change area or the UHI relatively relieved area. Built-up decrease area, which means the land use and land cover changed from built up (including barren land) to other types (e.g. vegetation, water, etc.), lies in the UHI relatively relieved area. Furthermore, urban area change and UHI change during the two periods show the same characteristics, both changing from the center of Beijing to its outside like water waves, which is in accordance with its ring road system. Obviously, the built-up area increased more drastically in the second period (16.7％)than the first period(10.9％). But the UHI area increased faster in the first period(21.4％) than the second period (14.1％). The possible reasons are, during the second period, urban growth was under reasonable planning, green land of the city was improved, and the citizens paid more attention to the city environment, all of which helped to alleviate the deterioration of the thermal environment of Beijing.

3. Discussion and conclusion

In this study, three Landsat TM images acquired on 26 September 1987, 28 August 1994, and 31 August 2001 were used to detect urban expansion and UHI changes in Beijing. Band3, band4 and band5 of each data set were respectively normalized radiometrically with a radiometric normalization procedure based on principal component analysis (PCA). Built-up area was extracted and its change was analyzed. Land surface temperature retrieved from a generalized single-channel algorithm was normalized in order to do the UHI change analysis. Results revealed a notable increase in built-up area and UHI area during the two periods, being from 1987 to 1994 and from 1994 to 2001. The UHI change pattern was much similar to the built-up area change pattern, both affected by the ring road system of Beijing. It is worth noting that the UHI area increased faster in the first period(21.4％) than the second period (14.1％), although the built-up area increased more drastically in the second period (16.7％)than the first period(10.9％). The possible reasons are, during the second period, urban growth was under reasonable planning, green land of the city was improved, and the citizens paid more attention to the city environment. Although UHI and its change were affected by urban expansion obviously, it is a complicated phenomenon affected by many factors. Other factors affecting UHI and its change of Beijing will be discussed in further studies.

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