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Urban heat island effects derived from dense Landsat thermal observations in Nanjing, China

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Abstract. An urban heat island (UHI) is an urban area where temperatures are higher than they are in the surrounding suburban areas. UHIs are of great scientific concern in the context of global environmental change. As a result of rapid economic development over the past three decades, the urban area in China has increased significantly. In the present study, to objectively determine the spatiotemporal patterns of UHI effects in Nanjing, surface brightness temperatures of the urban areas of Nanjing, which originated from remote sensing imagery of Landsat TM/ETM+ from 1988 to 2011, were inversed, and then the UHIs were extracted and graded by choosing a stable forest area as the suburban reference. When the results were combined with the surface meteorological data, a good relationship was found between the brightness temperatures and the ground-truth temperatures. The results of contrast analysis indicated that, over time, most of the heat islands of Nanjing remained over the central portions. The area and the intensity of the heat islands have both increased remarkably over the past 20 years.

1. Introduction

Global warming has received great attention. The IPCC Forth Assessment Report concluded that average global surface temperature increased by 0.74°C in the past century and that the warming in the latest 50 years was mostly due to the increase of greenhouse gases [1]. However, many studies have found that the warming observed in China is related not only to the effects of greenhouse gases but also to the effects of urban heat islands (UHIs), which exist mainly in the Yangtze River Delta region of eastern China [2]. UHI refers to the higher surface air temperatures occurring in urban areas relative to the surrounding suburban and rural areas [3]. UHI effects, which result from urbanization and industrialization, can exacerbate pollution, affect the quality of life of city dwellers, and worsen regional climate [4]. Thus, objectively monitoring urban thermal fields and related studies are essential.

Ground-based meteorological observations and remote-sensing technologies are two commonly used approaches in UHI research; each has pros and cons. The former has the advantage of analyzing directly the differences in temperatures between urban and suburban areas, but because of the discrete

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distribution and limited numbers of observation stations, it has shortcomings in large-scale studies. Remote sensing, on the other hand, is useful for analysis of regional-scale characteristic because of the continuity of observations, and it is widely used in larger-scale research. When remote sensing is used, land-surface temperature is usually retrieved through a mono-window algorithm, a thermal radiance transfer equation, and an image-based inversion algorithm based on thermal infrared data. The latter algorithm is relatively simple, and it can be used to study the dynamic changes of the thermal fields. However, the best method for delimiting UHIs is still uncertain. At present, the equal interval method and the mean-standard deviation method are those most commonly used [5, 6]. However, neither of these methods makes clear physical sense or reveals the difference between urban and suburban areas. Hence, better methodologies to map UHIs accurately need to be developed. In addition, many studies that have found UHI effects to be related to the weather conditions have been based on meteorological observations alone, without the use of remote sensing analysis [7].

Nanjing, a historical metropolitan area and the capital of Jiangsu province, is located in the Yangtze River Delta. Nanjing has had a fast-growing economy and accelerating urbanization over the past three decades, and it is referred to as one of the three so-called giant heating stoves in mainland China. Thus, its UHI effects exemplify eastern China. In the present study, we retrieved surface brightness temperatures from Landsat TM/ETM+ images from 1988 to 2011 and then extracted the UHIs in urban areas of Nanjing by choosing a stable forest area as the suburban reference. This method made clear physical sense. Combined with the corresponding daily surface meteorological observations, the correlation between brightness temperatures and the ground-truth temperatures was confirmed and the impacts of weather elements on the UHI results were analyzed further. Through contrast analysis, the spatiotemporal characteristics of the UHIs were evaluated quantitatively.

2. Materials and methods

2.1. Materials

The dense Landsat TM/ETM+ images from 1988 to 2011 were utilized to extract the UHIs over the urban area of Nanjing. Some of the images were purchased from the Centre for Earth Observation and Digital Earth, Chinese Academy of Sciences, and the others were downloaded from the global land cover facilities of the University of Maryland at http://glcf.umiacs.umd.edu/data/. In addition, a topographic map with a scale of 1:50,000, covering Nanjing, and daily ground-based meteorological records from the meteorological bureau of Jiangsu province were used.

2.2. Methods

To map the UHIs of Nanjing, it was necessary to co-register multitemporal images. All the original images were geo-referenced to a common UTM coordinate system based on the topographic map and then resampled using the nearest-neighbour algorithm with a 60-meter spatial resolution for thermal bands. The geometric RMS of the rectification was within the sub-pixel level.

Satellite TIR sensors measure radiances at the top of the atmosphere, and the at-satellite brightness temperatures can be used to reflect the distribution of the surface thermal fields. To eliminate the intrinsic errors of the sensors and retrieve the brightness temperatures, radiometric calibration was performed to convert the original images into a physically meaningful radiometric scale by means of the following equation in concert with the latest coefficients and constants outlined in Chander et al. [8]:

$$L_\lambda = \left(\frac{LMAX_\lambda - LMIN_\lambda}{Q_{cal\max} - Q_{cal\min}}\right)(Q_{cal} - Q_{cal\min}) + LMIN_\lambda \tag{1}$$

where L_λ is the spectral radiance at the sensor's aperture, $Q_{calmax} = 255$, $Q_{calmin} = 0$, Q_{cal} is the DN, and $LMIN_\lambda$ and $LMAX_\lambda$ are the spectral radiances for band 6 at digital numbers 1 and 255, respectively. Atmospheric effects were not reduced in this study, as discussed in another section below.

When the radiometric calibration was done, radiance images could be obtained by the following equation:

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} - 273.15 \tag{2}$$

where T is the effective at-sensor brightness temperature in Kelvin (K), L_λ is the spectral radiance at the sensor's aperture, ln is the natural logarithm, K_1=666.09 Wm^{-2}sr^{-1}μm^{-1} (ETM+), K_2=1282.71 K (ETM+), and K_1=607.76 Wm^{-2}sr^{-1}μm^{-1} (TM), K_2=1260.56 K (TM). Brightness temperature images could then be derived.

After brightness temperatures images are derived, the UHIs should be extracted in a way that is consistent with its physical meaning. However, the delimitation methods that have been applied in the past for UHIs vary. Most studies use the equal-interval method and the mean-standard-deviation method to assign land-surface temperatures to different classes [5, 6]. These methods seem rational, but they are limited because neither of them expresses a clear physical meaning or is able to reveal the temperature difference between the urban and suburban areas. Moreover, it is not easy to recognize the boundary between the urban and the suburban area directly accompanying the accelerated urbanization over time. Wang et al. found that different rural baselines influenced not only the intensity of UHI but also its seasonal variation [9]. In the present study, we chose a stable forest area (Purple Mountain) as the suburban reference, and the UHIs were then extracted through subtraction:

$$T_{UHI} = T - T_R \tag{3}$$

where T_{UHI} represents the intensity of the UHIs, T is the brightness temperature of each pixel, and T_R is the corresponding average temperature of the suburban reference area. The Purple Mountain area was chosen as the suburban reference because for a long time it has experienced little human impact.

3. Results and discussion

3.1. Correlation between brightness temperatures and the ground- truth temperatures

The brightness temperatures retrieved from the thermal infrared images are not the real temperatures of the ground surface because there are atmospheric effects that were not eliminated in the present study. Liu et al. found that the correlation between mean brightness temperature of pixels in a region and the surface temperature is more obvious for a single pixel because the atmospheric and environmental effect is more obvious for a single pixel [10]. In the present study, we combined the mean brightness temperatures with average daily surface temperatures and found a significant correlation. Figure 1 shows that there is a good linear relationship (r^2=0.46, p<0.01), indicating that the ground-truth temperature could be well estimated by the retrieved brightness temperature.

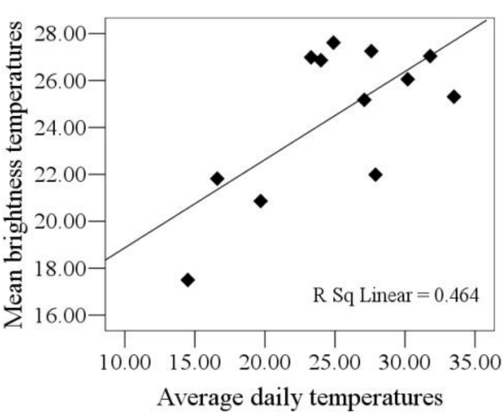

Figure 1. The relationship between mean brightness temperatures of each map and corresponding average daily surface temperatures.

3.2. Impacts of the meteorological elements

Complex weather factors affect imaging by remote sensing, especially the effects of cloud noise when the satellite passes. Hence, the UHIs retrieved show not only the pattern of the urbanization but also the impacts of meteorological elements. Many studies have analyzed the effects on UHI under different weather conditions and have found by meteorological observations that wind speed, precipitation, cloud cover and so forth were the main factors [7, 11]. Figure 2 is the UHIs mapped in the present study. It has been graded into 7 different magnitudes. We have masked the cloud noise on the map particularly because it is not the real underlying surface feature. According to Figure 2, we can recognize that some UHIs are not very obvious (e.g. 1992, 2003, 2005, and 2007). We referred to the corresponding ground meteorological records and found that there was a higher humidity in 1992, a higher wind speed and cloudiness in 2003 and 2005, and a higher magnitude of low clouds and rainfall in 2007, all of which are in good agreement with the obvious degree of the corresponding UHIs. The distribution of the UHI in 2011 is much wider than it is in other years, probably because of the high temperature and wind speed. In addition, the rapid expansion of urban land use in 2011 also contributed to the UHI. It is worth mentioning that the complex influences of the subtropical monsoon climate of Nanjing have a considerable effect on the UHIs, but there is still uncertainty in the results.

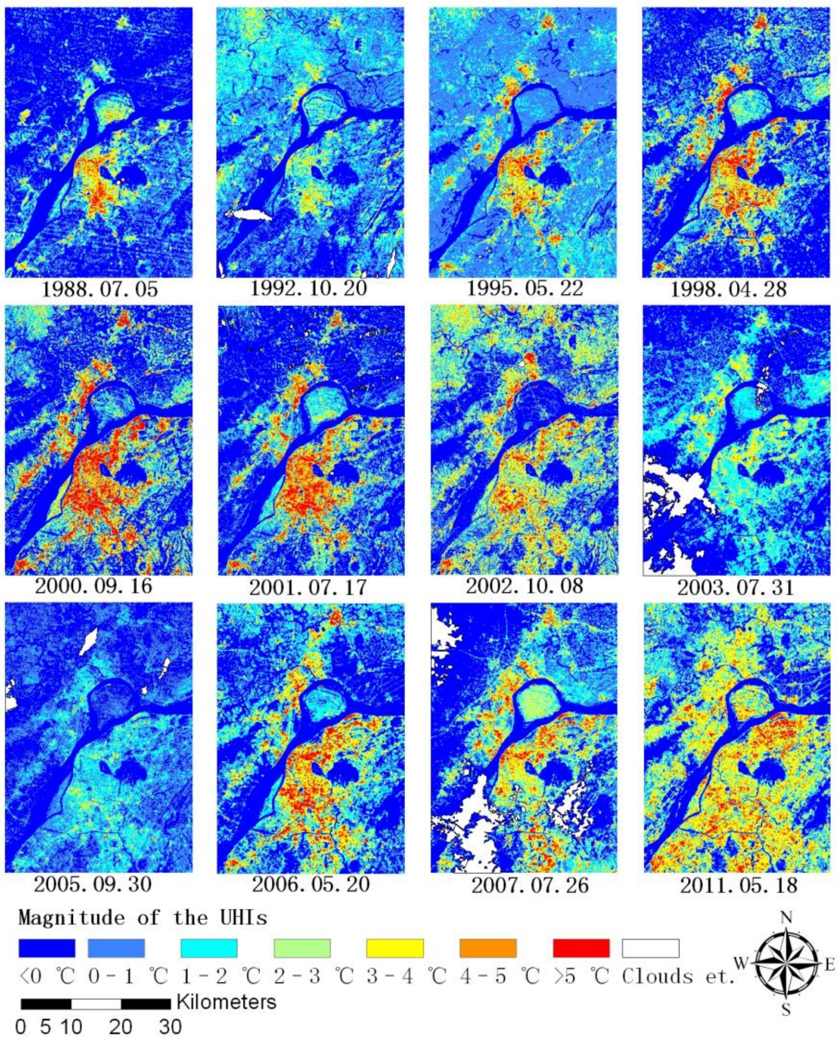

Figure 2. UHIs of Nanjing derived from dense Landsat images (1988–2011). The UHIs were graded into 7 magnitudes according to the deviation from the mean value of the suburban reference temperature (0°C). The cloud noise is displayed as white polygons on the map.

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3.3. Spatiotemporal characteristic of UHIs

To compare the spatiotemporal differences of the UHIs at different times using remote sensing, first the date differences and the weather conditions should be considered. We chose the data for May 22 (1995) and May 20 (2006) for contrast analysis of the UHIs because of their similar dates and clear and calm weather conditions. The clear and calm weather conditions meant that the cloud covers were both less than a fifth, there were no low clouds, and the wind speed was less than or equal to 2 m/s [12].

Examination of the grading maps for 1995 and 2006 indicated that the predominant status of the heat islands remains stable over the central portions of the city, such as Xuanwu Lake-Qin huai River belt. Obviously increasing areas of the UHIs identified from the maps are Dachang district, Jiangning district and Qixia district. The statistics in Table 1 show the dynamics of the heat island percentages of different UHI magnitude between 1995 and 2006. There is an increasing trend in the heat island area when the magnitude exceeds 2°C.

Table 1. Dynamics of the heat island percentages between 1995 and 2006.

Time	Percentage					
(year)	0–1°C	1–2°C	2–3°C	3–4°C	4–5°C	>5°C
1995	51.8	19.4	7.2	3.6	2.7	1.1
2006	17.9	19.0	8.2	8.7	4.0	3.8

In addition to analysis of the heat island intensity of the two years, we chose a stable commercial district located in the Xinjiekou-Confucious Temple area as an urban area of Nanjing that is as large as the suburban reference area (Figure 3). The intensity was calculated as the difference in the average temperatures of the suburban and the urban areas. The intensity of the UHI was 3.2°C in 1995 and 4.1°C in 2006, a clear increase over the past 20 years.

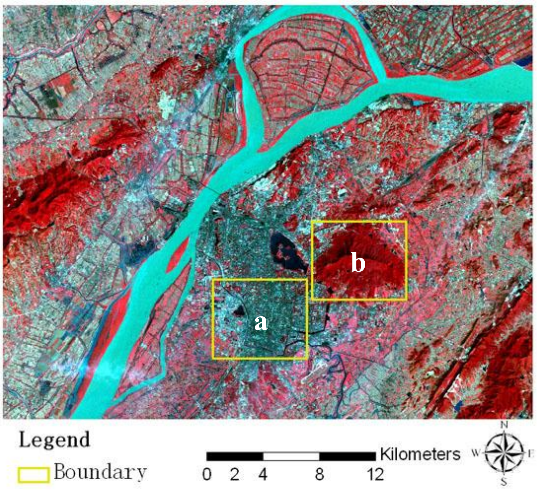

Figure 3. Ranges of the urban and suburban areas selected in this study. The region **a** stands for the urban area, and **b** stands for the suburban reference area.

4. Conclusions

This study has successfully described the UHIs of Nanjing in different years from 1988 to 2011 by choosing a stable forest area as the suburban reference area. This choice makes clear physical sense, and it characterized the UHIs objectively. Brightness temperatures showed a good correlation with ground-truth temperatures, especially under suitable weather conditions. The results indicated that the major part of the heat islands of Nanjing has remained mainly in the central portions of Nanjing over time. The intensity of the UHI was 3.2°C in 1995 and 4.1°C in 2006, a clear increase over the past 20 years. However, some uncertainties in UHI detection still exist due to the complicated influences of the subtropical monsoon climate and seasonal temperature variations.

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