A satellite remote sensing based assessment of urban heat island in Lanzhou city , northwest China

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ABSTRACT: As a promising application, quantitative remote sensing of urban heat island (UHI) could facilitate our understanding of urban/suburban environment and its relationship with urbanization. This paper investigates the urban heat island effect of Lanzhou, China, a densely built up city in a valley, based on Landsat ETM+ image acquired on April 22, 2000, whose spatial resolution is sufficient for measurement of some important environmental parameters. For better quantification, Land surface temperature (LST) was retrieved using the mono-window algorithm, vegetation fraction was derived using vegetation–impervious surface–soil spectral mixture model, and Normalized Difference Vegetation Index (NDVI) was also derived from the corrected image. Then the relationship between LST and NDVI as well as vegetation fraction was estimated. Results show that Lanzhou city's urban heat island effect is significant, which could be visually characterised by the spatial pattern, extent, heterogeneity and intensity of retrieved thermal properties, and the maximum urban/suburban temperature difference reaches 6.9℃. Moreover, by analyzing urban composition, it is revealed that LST possessed a strong negative correlation with the vegetation abundance and suggested that vegetation is a key factor controlling the spatial distribution of land surface heat flux. Particularly, due to the scarcity of vegetation, some hotspots are bare soil distributing on suburban surrounding hill, the surface temperature of which is even slightly higher than downtown. These results can help us develop countermeasures to thermal environmental problems in urban areas. Besides the fundamental surface biophysical characteristics, further study will introduce another two factors, one is impervious surface fraction, the other is principal demographic descriptor---population density, to describe the relationship among them for urban heat island studies.

Ⅰ. Introduction

Urban heat island (UHI) effect is one of the most typical phenomena of urban climate, for which the temperature of the central urban locations are several degrees higher than those of nearby rural areas of similar elevation (Chou, 1985). The main contributing factors of it are urbanization and anthropogenic activity, since they induce changes in the physical characteristics of the surface (albedo, thermal capacity, heat conductivity, moisture) and changes in radiative fluxes and the near surface flow. Especially, the simultaneous removal of natural land cover and the introduction of urban materials (e.g., concrete, asphalt, metal) alter the surface energy balance, with a consequent increase in land surface temperature, then the increase in sensible heat flux at the expense of latent heat flux, finally air temperature. As a result, UHI effect would forces the development of meteorological events such as increased precipitation, boosts energy demands, poses threats to environmental quality and long-term sustainability of localities, and potentially contributes to global warming and vegetation greener.

Traditionally, UHI studies are conducted for isolated locations and with in situ measurements of air temperatures or ground meteorological data (Streutker, 2002; Weng, 2004). Though in situ measured data takes precedence in temporal resolution, its spatial resolution is poor. Moreover, it is limited to describe the response rather than the physical processes and the forcing of repartitioned surface energy fluxes over urbanized surfaces (Owen, 1998). By contraries, in virtue of high spatial resolution, satellite remote sensing can monitor urban heat island on all scales, predominantly on regional or continental scales, and provide quantitative physical data, present heterogeneous distributed land surface characteristics, all of which could greatly facilitate our understanding of urban/suburban environment and its relationship with urbanization.

In past several decades, numerous UHI studies utilizing remote sensing technique have been done all over the world. Originally, the leading approach of urban heat island analysis is to establish certain models by regression analysis using some observational samples, then transform digital number (DN) recorded by sensor (later instead by remote sensing retrieved brightness temperature) into air temperature. Along with the stepwise advancement of land surface temperature's retrieval method, people recently prefer to use the actual temperature of land surface to describe UHI, which is believed to correspond more closely with near-ground air temperature (e.g.,Streutker,2002;Liu,2003;Weng,2004;Nichol,2004), achieving more accurate results. However, many people still keep on using radiation temperature or radiant flux density to analyze urban thermal environment in respect of its simplicity (e.g., Lo, 1997;Chen, 2002). Another key point is that more and more research are focusing on the relationship between LST and normalized difference vegetation index(NDVI) as well as vegetation abundance(eg.,Owen,1998;Xiao,2002;Weng, 2004), making a great deal contributions to estimate UHI magnitude and urban sprawl.

However, quantitative remote sensing studies of urban heat island (UHI), a promising application, currently are still rather limited. By utilizing a Landsat ETM+ imagery this study aims to introduce much more simple and handy combinatorial method to retrieve some biophysical parameters in point so as to examine the surface temperature UHI in Lanzhou city, northwest China and to investigate the relationship between LST and NDVI plus vegetation fraction.

Ⅱ. Study Area

Lanzhou, consisted of eight municipal entities, is located on the northeastern edge of Tibet Plateau. Coming through a rapid development and urbanization during the last three decades, this region has been the commercial, financial and cultural centre of Gansu province, northwest China, with a population of over 3.095 million.

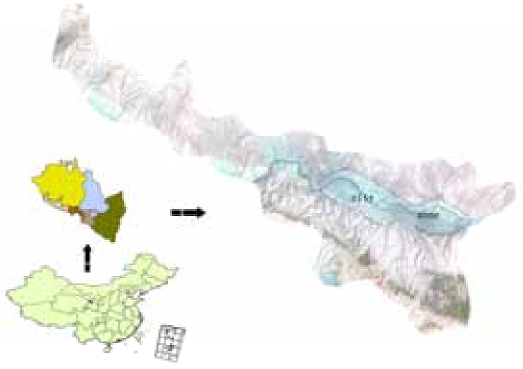


Figure1. The location of study area

As limited by its special topography, Lanzhou city(35°59′–36°12′N;103°23′–103°58′E)is densely built up in a yellow river valley, which is long and narrow in east-west direction. Known as a typical valley-basin city, the urban-suburban city zone covers an area of about 133 km^2 with an average population density of 1147 people even high to 3667 people in the metropolitan area. The actual study extension in this research is defined as an erose polygon to cover the urban-suburban zone as much as possible, inevitably including some bare hills around. Moreover, some studies about Lanzhou city using conventional means have shown that basing on the general region climate and landform background, the influences of urbanization on this city's urban climate mainly exhibit three significant effects, namely, urban heat island, urban dry island and air pollution(Yang, 1994; Zhao&Wang, 2002). Validating and lucubrating UHI effect and the relationship to vegetation abundance by remote sensing can amply aid us to catch on its inner mechanism, thereby propose countermeasures for the city's environment protection and future development.

Ⅲ. Methodology

A. Retrieval of LST

The surface temperature that is central to surface energy balance is of prime importance to the study of urban climatology (Voogt, 2003). Conventional methods of LST retrieval using thermal remote sensing are mainly through split-window or radiative transfer equation (RTE), both of which can do atmospheric correction. Limited by Landsat's sole thermal band, only RTE method using such atmospheric simulation programs as 6S, LOWTRAN or MODTRAN can be used. However, it needs in situ atmospheric profile data simultaneously with the satellite passes which is usually unavailable in daily life (Qin, 2001; Sobrino, 2004).

Based on thermal radiance transfer equation, Qin et al. (2001) developed a mono-window algorithm for obtaining LST, avoiding the dependence on radiosounding in the RTE method but also doing atmospheric correction. This algorithm merely needs three parameters: emissivity, transmittance and effective mean atmospheric temperature. Qin et al. (2003, 2004) also proposed some means for determination of these parameters, all the Correlative equations are given following:

$$T_s = \frac{1}{C}[a(1-C-D)+(b(1-C-D)+C+D)T_{sensor}-DT_a] \quad (1)$$

$$C = \tau\varepsilon \quad (2)$$

$$D = (1-\tau)[1+\tau(1-\varepsilon)] \quad (3)$$

$$a = -67.355351, b = 0.458606 \quad (4)$$

Where T_{sensor} is the at-sensor brightness temperature derived from Plank function, T_a is the mean atmospheric temperature which can be represented by a simple relationship with near surface temperature T_0 , τ is the total atmospheric transmissivity which can be estimated from the atmospheric water vapor content w, and ε is the land surface emissivity, estimating it from NDVI is reasonable and operative (Qin,2004;Sobrino, 2004).

$$T_{sensor} = K_2 / \ln(1+K_1 / L_{(\lambda)}) \quad (5)$$

$$L_{(\lambda)} = Gain \cdot DN + Offset \quad (6)$$

$$K_1 = 666.09 mWcm^{-2} sr^{-1} \mu m^{-1} \quad (7)$$

$$K_2 = 1287.71K \quad (8)$$

$$T_a = 16.0110 + 0.92621T_0 \quad (9)$$

$$\tau = 0.974290 - 0.08007w \text{ (high } T_0\text{)} \quad (10)$$

$$\tau = 0.982007 - 0.09611w \text{ (low } T_0\text{)} \quad (11)$$

$$\varepsilon = 0.004P_v + 0.986 \quad (12)$$

$$P_v = [\frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}}]^2 \quad (13)$$

$$NDVI_{\max} = 0.5 \text{ ; } NDVI_{\min} = 0.05 \quad (14)$$

It is possible to obtain NDVI values from at-sensor or TOA reflectance. However, it is more accurate to atmospherically correct the TOA values in order to obtain at-surface reflectance and, in this way, estimate NDVI values more representative of the natural surfaces (Sobrino, 2004). So, the Landsat ETM+ image was first corrected to subtract impacts of the atmosphere using 5S program (Qi, Michigan State University), except the thermal band6.Then integrating the basic measured meteorological data obtained from weather station with the above-listed formulae, LST was retrieved. Besides, it was resampled to 30m resolution to match with Vegetation Fraction and NDVI image.

B. Derivation of vegetation fraction

Vegetation fraction depicts the amount and nature of vegetation cover, and for urban areas which are commonly characterized by partial vegetation cover, surface thermal properties can largely influence the measurement of LST through the thermal processes of conduction, convection, and radiation. Correspondingly, for remote sensing images, especially for low to medium resolution images such as Landsat ETM+ images, the spectrum of a pixel may represent a combination of several land use types, not only one land use and land cover class. For better understanding UHI effect in Lanzhou city, it is necessary to unmix the pixel to sub-pixel scale at a certain extent.

Ridd (1995) conceptually proposed the vegetation-imperious surface-soil model(V-I-S) for parameterizing biophysical composition of urban-suburban environments, and this model conducted in subsequent researches and applications has proven valuable in describing urban composition and dynamics. This study still utilizes the expedient V-I-S three endmember model implemented with the normalized spectral mixture analysis (NSMA) method (Wu, 2004) to quantify Lanzhou city's urban vegetation abundance, ignoring the water.

Significant brightness variation exists in the spectra of each pure land cover type. After normalization, much brightness variation can be removed or reduced despite some loss of information come into being (Wu, 2004):

$$\overline{R_b} = \frac{R_b}{{}^{1}\!/_{N}\sum_{b=1}^{N} R_b} \times 100 \qquad (15)$$

Where $\overline{R_b}$ is the normalized reflectance for band b in a pixel; R_b is the original reflectance for band b; and N is the total number of bands (6 for ETM+ image).

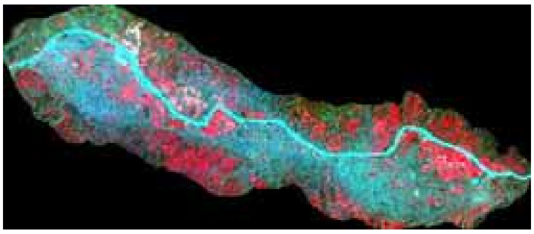


Figure2. Normalized reflectance image for the study area

With the normalized spectra, three endmembers, vegetation, impervious surface and soil are selected through visualizing spectral scatter plots of image band combinations, to model heterogeneous urban environments. Using an inverse least square devolution method and endmember spectra, a fully constrained linear SMA method was applied to quantify urban composition:

$$\overline{R_b} = \sum_{i=1}^{N} \overline{f_i}\,\overline{R_{i,b}} + e_b \qquad (16)$$

$$\sum_{i=1}^{N} \overline{f_i} = 1 \text{ and } \overline{f_i} \ge 0 \qquad (17)$$

$\overline{f_i}$ is just the fraction of endmember i; $\overline{R_{i,b}}$ is the normalized reflectance of endmember i in band b; e_b is the residual. And the model fitness can be assessed by the residual term e_b or the RMS over all image bands (Wu & Murray, 2003):

$$RMS = \sqrt{\sum_{b=1}^{N} e_b^2 \Big/ N} \qquad (18)$$

Ⅳ. Results and Discussions

Lanzhou city's LST image whose values range from 285.0k to 314.6k shows that this city's UHI effect is significant, which could be visually characterised by the spatial pattern, extent, heterogeneity and intensity (see Fig 3), and the maximum urban/suburban temperature difference approximately reaches 6.9℃.

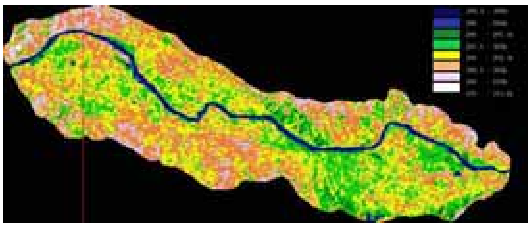
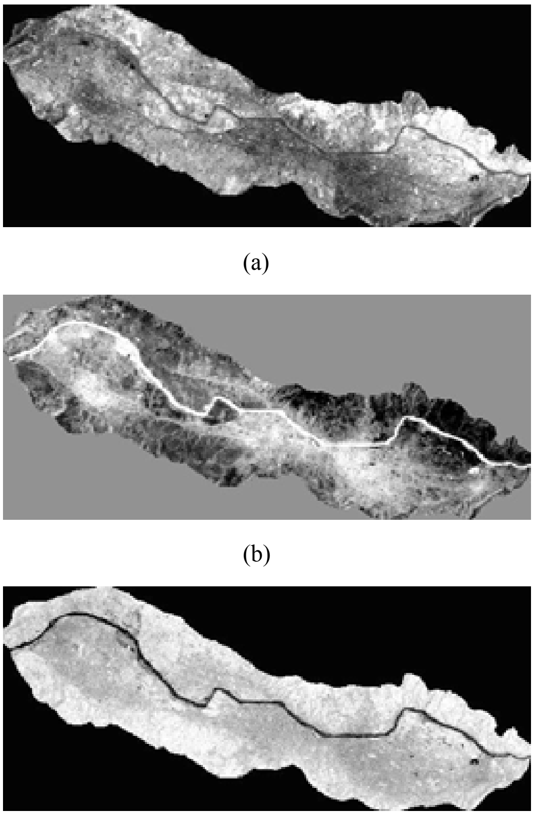


Figure3. Land surface temperature image

Detecting the magnified and detailed image, it puts up that there was an obvious gradual thermal change as progressed from the Central Business District (CBD) out into the countryside. And the most extensive of urban heat islands were distributed in the central part of the CBD. However, due to the scarcity of vegetation, some hotspots are bare soil distributing on suburban surrounding hill, the surface temperature of which is even higher than downtown.

Though NSMA model, Lanzhou city's image was unmixed to three fraction images (see Fig 4).These images describe that the proportion of green vegetation, impervious surface and soil in each pixel, not their actual distribution in the image.

The vegetation fraction image derived from NSMA model is the indicator of vegetation abundance. In this image, kowned vegetated areas such as forest and dense grass appear very bright, the fraction of them are near 70-85%, while partial vegetation-covered areas such as cropland and residential areas appear gray, the raction of them are near 20-40%, and CBD and water appear dark, they exhibited lowest vegetation fraction value, near to 3%.


(a)

(b)

(c)

Figure4. Fraction images generated from NSMA model (a—vegetation; b—impervious surface; c—soil)

The order of them are consistent with them in NDVI image (see Fig 5).Besides vegetation, impervious surface also shows a clear distribution pattern coherent with known LUCC information.

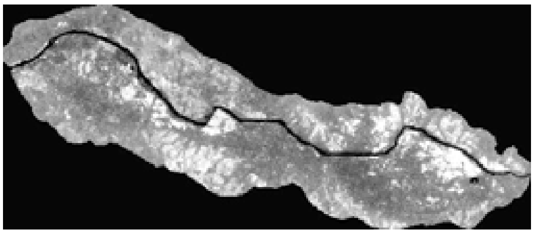


Figure5. NDVI derived from corrected image

To estimate the relationship between LST and vegetation abundance indicators, viz. NDVI and VF (vegetation fraction), many samples were interpretatively collected and made to do linear regression analysis:

$$LST = -43.912NDVI + 306.01 \qquad R^2 = 0.8164 \quad (19)$$

$$LST = -23.285VF + 310.97 \qquad R^2 = 0.9641 \quad (20)$$

The results revealed that LST possessed a strong negative correlation with the vegetation abundance in Lanzhou city, and the negative correlation existed between LST and vegetation fraction was even stronger. It is also suggested that vegetation is a key factor controlling the spatial distribution of land surface heat flux. Since both vegetation indicators show strong negative correlation with LST, it can be concluded that the higher biomass a land cover had, the lower the land surface temperature a land cover was.

V. Conclusions

Our study to assess urban heat island in Lanzhou city, northwest China by using mono-window algorithm and NSMA model with an object to derive even more accurate surface parameters from Landsat ETM+ data shows that this city has a significant UHI effect, and it possesses a strong negative correlation with vegetation abundance, especially the unmixed vegetation fraction. That is to say, vegetation is one of the main contributors to the variations of spatial pattern spectral radiance and texture in LST, thus to UHI. Due to data deficiency, the validation of these results has to be done in future. Besides the fundamental surface biophysical characteristics, further study will conduct another two factors, one is the impervious surface fraction, another is the principal demographic descriptor---population density in the UHI assessment.

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