Urban thermal landscape characterization and analysis

Y Xue\textsuperscript{1,2}, T Fung\textsuperscript{2} and J Tsou\textsuperscript{3}

\textsuperscript{1} Satellite Surveying and Mapping Application Center, National Administration of Surveying, Mapping and Geoinformation, Beijing, China
\textsuperscript{2} Department of Geography and Resource Management, the Chinese University of Hong Kong, Shatin, Hong Kong SAR, China
\textsuperscript{3} School of Architecture, the Chinese University of Hong Kong, Shatin, Hong Kong SAR, China

E-mail: xueyc@sasmac.cn

Abstract. Urban warming is sensitive to the nature (thermal properties, including albedo, water content, heat capacity and thermal conductivity) and the placement (surface geometry or urban topography) of urban surface. In this research, the pattern and variation of urban surface temperature is regarded as one kind of landscape, urban thermal landscape, which is assumed as the presentation of local surface heating process upon urban landscape. The goal of this research is to develop a research framework incorporating geospatial statistics, thermal infrared remote sensing and landscape ecology to study the urban effect on local surface thermal landscape regarding both the pattern and process. This research chose Hong Kong as the case study. Within the study area, urban and rural area coexists upon a hilly topography. In order to probe the possibility of local surface warming mechanism discrepancy between urban and rural area, the sample points are grouped into urban and rural categories in accordance with the land use map taken into a linear regression model separately to examine the possible difference in local warming mechanism. Global regression analysis confirmed the relationship between environmental factors and surface temperature and the urban-rural distinctive mechanism of dominating diurnal surface warming is uncovered.

1. Introduction

Urbanization favours the development of urban warming which has been observed through long term climatic records [1] and thermal infrared remote sensing [2][3]. Since urban buildings play a dominant role on urban warming in direct and indirect way and account for a large single fraction of energy use[4][5]. Regarding the mitigation strategies from building sector through urban planning and design, in the literature many researches have been carried out by Passive and Low Energy Architecture (PLEA) from architecture community to study how to effectively mitigate the effect of urban warming. However, urban building thermal performance is confined with local climate and the impacts of urban warming is magnified with high rise high density urban buildings as well [6]. This complicated interactive correlation between urban building and local climate limits and obscures the effect of these thermal efficiency and mitigation strategies. Currently only scant knowledge on environmental performance of the different land uses is available [7]. An assessment of the local thermal response to the urban surface and geometry impact has not been fully addressed with the estimates based on urban

\textsuperscript{1} Corresponding author. Present address: No.28 Lianhuachi west road, Beijing, China.
rural comparison (e.g. UHI) [8]. Urban surface warming is conceived as a big contribution to urban warming, the study of urban surface warming possesses significant meaning for probing into the problem of urban warming. Moreover the importance of urban thermal performance can be acknowledged in a wider context of urban landscape as one component towards sustainable development.

With the remote sensing technology development, high spatial and temporal resolution imagery available provides the potential to monitor and analyze the urban surface thermal landscape with more detail. “In spite of these progresses and achievements over the past 15 years, however, thermal remote sensing of land surface temperatures and urban heat islands has largely been limited to qualitative description of thermal patterns and simple correlations with land covers”, and “this is due partly to the tendency to use thematic land use and land cover data, not quantitative surface descriptors, to describe urban landscapes” [9]. Moreover quantitative evaluation regarding the influences of these local environment indicators on local surface temperature variation is scarce or partially given for a few isolated factors, such as vegetation NDVI or biomass, urban street canyon represented by Sky View Factor. This prevents the clear delineation regarding the process of local surface warming, which made a systematic investigation of urban thermal landscape valuable for a comprehensive review about the integrated effects of local environmental setting on urban surface thermal anomalies.

The knowledge regarding the urban effects on local warming is limited in the literature and is fundamental for bridging the application gap of transferring urban thermal environment knowledge into urban planning and design application through passive cooling urban planning and design application. Endeavours are quite scarce to characterize and analyze the spatial heterogeneity and dependence of urban thermal landscape in depth. In this research, the pattern and variation of urban surface temperature is regarded as one kind of landscape, urban thermal landscape, which is assumed as the presentation of local surface heating process upon urban landscape. The goal of this research is to develop a research framework incorporating geospatial statistics, thermal infrared remote sensing and landscape ecology to study the urban effect on local surface thermal landscape regarding both the pattern and process.

2. Methodology
In this research, the focus would be put on local surface warming based on the elevated land surface temperature derived from thermal infrared remote sensing. Urban surface thermal landscape can be characterized through the landscape metrics evaluation and spatial-temporal comparison of urban surface temperature pattern. In order to further improve our understanding of urban effects on local surface warming the correlation analysis would be carried out utilizing regression analysis to examine the potential mechanism of urban surface heating.

2.1. Landscape metrics
Derived from landscape ecology which the quantification of environmental heterogeneity has long been an objective [10], landscape metrics is often used to quantify spatial-temporal dynamics of landscape pattern. This spatial technique has been widely employed to derive quantitative measures of spatial patterns present in maps or remote sensing imagery [11]. In this research the urban surface temperature distribution is regarded as one representation of urban surface thermal landscape, landscape metrics was introduced to characterize the pattern and measure the dynamics of urban thermal landscape across space and time. In this research, the landscape metrics evaluation would be carried out at the landscape scale for overall structure measurement in order to achieve a general overview about the heterogeneity of urban thermal landscape, the structural descriptive indices would be the main focus. The metrics are selected from each category including [12][13][14]: patch area metrics which measure the number and size of patches; edge and shape metrics which quantify the occurrence of ecotones; diversity metrics and landscape configuration metrics. The chosen set of
metrics includ: Number of Patches (NP); mean patch area (AREA_MN); Largest Patch Index (LPI); Landscape Shape Index (LSI); Modified Simpson's Diversity Index (MSIDI); area-weighted mean Fractal Dimension Index (FRAC_AM) and Interspersion & Juxtaposition Index (IJI).

2.2. Regression analysis
From the urban landscape point of view, “each component surface in urban landscapes (e.g., lawn, parking lot, road, building, cemetery, and garden) exhibits a unique radiative, thermal, moisture, and aerodynamic properties, and relates to their surrounding site environment” [15]. The surface composition and configuration of urban fabrics which is fragmented and intensively variable in the spatial distribution made the heterogeneity and complexity of urban surface thermal landscape in spatial-temporal dimension. From this perspective landscape composition and configuration are hypothesized to influence urban surface thermal landscape represented by urban surface temperature distribution.

In this study, multiple linear regression analysis would be employed to probe the relationship between urban environment and thermal landscape diversity. Besides urban surface temperature map derived from remote sensing data, a host of biophysical indicators listed below can be generated from satellite images as well. In conjunction with geographic information systems (GIS) geospatial analysis, other measures of urban form, such as location and elevation, site openness to the sky, etc., can be calculated to quantify site specific physical and spatial characteristics. Table 1 cites all variables employed in the regression models. Under the research assumptions aforementioned, the important factors that have correlation with the urban surface temperature are listed.

Table 1. Variables list for regression analysis.

| Variables | Label | Description | Note |
|-----------|-------|-------------|------|
| Y         | ST    | surface temperature at image time of day/month/year | Dependent variable |
| X₁        | NDVI  | vegetation NDVI at image time of day/month/year |  |
| X₂        | Hshad | solar radiation at image time of day/month/year |  |
| X₃        | Footsq | building square footage measurement with area ratio |  |
| X₄        | Elevation | elevation |  |
| X₅        | SD    | road network density in year**** | Independent variables |
| X₆        | Disttocoast | distance from coast |  |
| X₇        | Diffuse | diffuse radiation at image time of day/month/year |  |
| X₈        | TPU   | population density in year**** |  |

3. Study area
Hong Kong is a maturely developed city with a subtropical climate and an extremely high population density. Lack of lands for development leads to the high rise and high density urban development, which caused lots of urban environmental issues, such as bad urban ventilation in winter, transportation congestion, urban public health etc. This high density and high rise development would inevitably accelerate the climate change impact on Hong Kong. According to the HKO, long term meteorological trends of urban warming have been detected in Hong Kong [6]. The study area mainly covers the overlapped area of all of the remote sensing images collected in Hong Kong illustrated in figure 1, with all the weather stations located within the study area. The related meteorological data of these stations was purchased from Hong Kong Observatory (HKO) to provide simultaneous field
measurements. Within the study area, the elevation ranges from 0 rising to 957 meter of Tai Mo Shan in the New Territories. Most of the extensive urban development with high density housing located sparsely. Besides housing estates, the study area includes a few industrial development areas; the diverse land use in the study area provides practical meaning for the study of local effect on surface thermal anomalies under the subtropical climate. The study period ranges from 2003 to 2006 when the ASTER data used for this site study is available.

4. Results and discussions
In this research ASTER LST(Land Surface Temperature) images used for urban thermal landscape study have a resolution of 90m grid, all the calculations of landscape metrics indices is based on this resolution at the landscape scale. The landscape metrics calculation is imposed on the classes represented by the integer deg C of surface temperature, i.e. the classification of surface temperature image with 1 deg C spacing. This made the study focus on the overall pattern of urban surface temperature as whole within study area. At the same time it avoids the possible bias introduced by various scale of patches along with diverse classification schemes. The measures listed above were calculated using FRAGSTATS, with the result shown in table 2. The rows with deeper colors are corresponding to the evaluation of nighttime surface temperature patterns, and the others are the daytime measurements.

Table 2. Landscape metrics indices during the study period.

| Date       | NP    | AREA_MN | LPI | LSI   | FRAC_AM | MSIDI  | IJI  |
|------------|-------|---------|-----|-------|---------|--------|------|
| st04172006 | 59890 | 0.96    | 0.027 | 128.51 | 1.013  | 4.65   | 75.68|
| st10232005 | 60574 | 0.95    | 0.030 | 128.10 | 1.011  | 4.71   | 79.33|
| st10012005 | 54486 | 1.06    | 0.017 | 125.51 | 1.021  | 3.87   | 73.14|
| st11212004 | 63260 | 0.91    | 0.011 | 130.53 | 1.009  | 4.77   | 77.08|
| st10052004 | 60617 | 0.95    | 0.013 | 128.99 | 1.012  | 4.48   | 79.37|
| st11032003 | 63157 | 0.91    | 0.024 | 130.41 | 1.009  | 4.79   | 77.77|
| st10282003 | 53985 | 1.07    | 0.018 | 124.85 | 1.022  | 4.16   | 76.35|

As can be seen the daytime urban thermal landscape has more diversity than the nighttime with comparison of diversity index, Modified Simpson's Diversity Index (MSIDI). By comparison within
each year day-night observation pair, it can be easily found that daytime surface temperature patterns presents much more diversity than the nighttime with higher MSIDI, the surface temperature variation during nighttime tends to be relatively smoother than that during daytime. This may be due to the intensive change of solar radiation situation during daytime which introduces more variation through shading by buildings or other man-made objects under a complex urban canopy with high rise high density settlements. In temporal dimension from 2003 to 2006, it is interesting to find that the diversity indexes MSIDI are decreasing in daytime observation. The diversity and fragmentation metrics had revealed the influence of urban development on overall urban landscape pattern. Along with urban development, daytime pattern of urban thermal landscape presents more fragmentation, less diversity and uneven texture distribution than before through daytime observations comparison made in temporal dimension.

For the analysis of the relationship between local surface temperature and urban environmental measures by linear regression analysis, there are 276 sample points selected correspondingly for urban and rural area in according with the land use map and taken into a linear regression model separately in order to probe the discrepancy of local surface warming mechanism between urban and rural area. The statistical result of the regression analysis is summarized in table 3. Within each set of rows of the table, the upper row shows the urban regression model, and the lower row shows the rural regression model. The rows in deep color are related to nighttime models, others are daytime evaluations. As can be concluded that the models have confirmed the correlations between local surface temperature and those urban environmental factors, at the same time most of the rural models have a better fit than urban models during daytime when comparing the R-square of the models. This may be due to the relatively simple local environment affecting local warming in rural area than in urban areas, where the air pollution, anthropogenic heat, etc, have not cause obvious problems. However the influences of such factors are obvious in urban area and not taken into consideration within current statistical model. While during the urban warming process these factors may play a noticeable role which should not be overlooked. On the other hand there is no obvious trend which can be identified for nighttime models between urban and rural.

All the models demonstrate consistency regarding the negative effect of vegetation on local surface temperature variation both during day and night, in urban and rural area. By comparing the value of vegetation coefficients between urban and rural, it can be seen that the coefficient value of vegetation is bigger in urban models than rural models within most of the image time. This indicates that vegetation plays a more obvious role on urban surface cooling than rural area. At the same time solar radiation shows significant correlation with daytime surface temperature. Comparatively, the parameter coefficient of solar radiation in rural model is mostly bigger than the corresponding urban model within each daytime observation. This indicates that solar radiation plays an obvious role of surface heating in rural area. Moreover, distance from coast plays a distinct role on local surface warming during daytime and nighttime by comparing corresponding regression model coefficients varying from positive to negative. Distance from water body has a positive correlation with daytime surface temperature and indicates possible warming effect during daytime, which means increasing the distance from water may lead to the location-specific surface temperature heightening and implies a cooling effect when approaching large water body like coast (decreasing the distance from coast) during daytime when the surface temperature of coast is relatively lower than land surface temperature which is identified in most daytime observations. While it is negatively related with the nighttime surface temperature which indicates that the increase in distance from coast may have an effect causing local surface temperature decrease (i.e., surface cooling) and implies warming effect when being closer to coast during nighttime when the coast surface temperature is relatively higher than land surface temperature observed in nighttime LST images.
Table 3. Discrepancy of global linear regression model between urban and rural.

| Y           | $\beta_0$ | $+\beta_1X_1$ | $+\beta_2X_2$ | $+\beta_3X_3$ | $+\beta_4X_4$ | $+\beta_5X_5$ | $+\beta_6X_6$ | $+\beta_7X_7$ | $+\beta_8X_8$ | $R^2$ | $F$  |
|-------------|-----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-------|------|
| Surface Temperature | Constant | Vegetation NDVI | Solar Radiation | Building Square Footage | Elevation | Road Density | Distance from Coast | Openness to Sky | Population Density |       |      |
| ST04172006 | 24.064    | -13.137        | 0.23           | 2.219          | 0.318         | -1.28E-005    | 0.322           | 25.590         | ***             |      |      |
| ST04172006 | 21.649    | -13.994        | 0.15           | 17.580         | -0.05         | 0.419          | 0.363           | 38.569         | ***             |      |      |
| ST10232005 | 24.804    | -13.598        | 0.30           | 1.638          | 0.175         | -0.011        | 0.435           | 69.731         | ***             |      |      |
| ST10232005 | 20.626    | -3.467         | 0.30           | 15.197         | -0.05         | 0.26           | 0.486           | 51.131         | ***             |      |      |
| ST11212004 | 24.654    | -13.384        | 0.041          | 5.820          | 0.037         | -0.179        | 0.463           | 58.468         | ***             |      |      |
| ST11212004 | 23.560    | -5.079         | 0.45           | 10.201         | -0.03         | 0.251          | -0.125          | 2.215           | ***             |      |      |
| ST1032003  | 32.157    | -9.531         | 0.37           | 9.697          | 0.96          | -1.79          | 0.463           | 38.430         | ***             |      |      |
| ST1032003  | 33.605    | -9.313         | 0.51           | 12.224         | 0.294         | -0.049        | 0.388           | 34.271         | ***             |      |      |

$***$ = significant at .1% level
By comparing these overall regression models between urban and rural, urban local surface warming has a close relationship with vegetation, solar radiation, building square footage, and distance from coast. Besides these factors, while the surface temperature in rural area shows more sensitivity with the geographical situation of local environment including elevation. At the same time population density plays an important role on local surface warming during nighttime in both urban and rural area. Besides the variation in daytime and nighttime surface heating mechanism, the regression models between urban and rural area also shows obvious discrepancy when comparing the parameter coefficients of constant, vegetation NDVI, distance from coast, openness to sky and population density. Moreover the influence of geographical situation has been recognized in rural surface warming models but not identified in urban models.

5. Conclusions
In this study, through the landscape metrics analysis of urban thermal landscape, the pattern evolution of urban thermal landscape in temporal dimension is characterized. The regression analysis showed that the relationship of surface temperature variation and the referred location-specific environmental factors exhibits deviation between urban and rural in terms of the mechanism and coefficient inconsistency. The illustrated discrepancy of urban rural pattern within each daytime and nighttime regression models revealed the spatial association of the relationship between surface temperature variation and local environment setting.

6. References
[1] Karl T.R., Diaz H.F. and Kukla G. 1988 J. Clim. 1 1099-1123
[2] Rao P.K. 1972. B. of American Meteorological Society 53 647-8
[3] Roth M., Oke T.R. and Emery W.J. 1989 Int. J. Rem. Sens. 10(11) 1699-1720
[4] IPCC 2007 A Climate change 2007: The Physical Scientific Basis (Summary for Policymakers) p10
[5] IPCC 2007 B Climate Change 2007: Mitigation of Climate Change (Summary for Policymakers) 3-4
[6] Hong Kong Observatory 2004 Technical Note No.107
[7] Pauleit S. and Duhme F. 2000 Landscape and Urban Planning 52(1) 1-20
[8] Lim Y. K., Cai M., Kalnay E. and Zhou L. 2005 Geophys. Res. Lett. 32
[9] Voogt J. A. and Oke T. R. 2003 Remot. Sens. of Envi. 86 (3) 370-84
[10] O’Neill R. V., Krummel J. R. et al 1988 Landsc. Ecology 1(3) 153 – 62
[11] Carrão H. and Caetano M. 2002 The Effect of Scale on Landscape Metrics. http:www.igeo.pt/gdr/pdf/Carrao2002c.pdf (last accessed Dec 22.2007)
[12] Herzog F. and Lausch, A. 2001 Environ. Monit. and Asses. 72(1) 37–50
[13] Griffith J.A., Martinko E.A. and Price K.P. 2000 Landsc. Urban Plan. 52 (1) 45-61
[14] Riitters K. H., O’Neill R. V. et al. 1995 Landscape Ecology 10(1) 23–39
[15] Oke T.R. 1982 Quarterly Journal of Royal Meteorology Society 108 1-24