THE RELATIONSHIP BETWEEN LAND SURFACE TEMPERATURE AND LAND USE: A REMOTE SENSING ANALYSIS OF COLOMBO, SRI LANKA

Laranjeira, M.M*

Rekha Nianthi K.W.G**

Almeida Pinheiro C. de***

Abstract

Land Surface Temperature (LST) is an important factor in urban climate studies because it modulates both the energy balance and air temperatures of the urban canopy layer. It is now a well established fact that LST is closely related to spatial distribution of land use, and surface radiative and thermal properties. Therefore, urban areas with mixed land use types comprise a mosaic of warm, heat releasing surfaces, and cool, evaporative surfaces. The purpose of our research is to investigate the relationship between LST and land use/land cover (LULC) types in the urban area of Colombo, Sri Lanka. LST values were derived from a Landsat 7 ETM+ multispectral image acquired on March 14, 2001. Several indices were derived namely NDVI (Normalized Difference Vegetation Index), NDBI (Normalized Difference Built-up Index), NDWI (Normalized Difference Water Index), and NDBaI (Normalized Difference Bareness Index). These indices were used to classify distinct LULC types (vegetation, built-up areas, densely built-up areas, and moist surfaces). The correlations between LST, NDVI, NDBI, NDWI, and NDBaI indices were analysed, and the thermal signature of each LULC type was statistically established. The results show positive correlations between NDBI, NDBaI and LST, and negative correlations between NDVI, NDWI and LST. Densely built-up areas (NDBI>0.25)

* Geographical Studies Center, University of Lisbon, Portugal, and Department of Geography, University of Minho, Portugal

** Department of Geography, University of Peradeniya, Sri Lanka

*** Department of Geography, University of Minho, Portugal

were found to have significantly higher LST values than vegetation areas (with a mean of 30.7^oC and of 26.1^oC, respectively). In fact, the spatial pattern of LST reveals major gradients between cooler green spaces and their warmer built-up surroundings. As a conclusion, this study stresses the importance of the presence of urban green parks (with large water surfaces) in the urban environment of Colombo, due to their cooling effect.

Key words: urban climate; thermal infrared remote sensing; spectral indices; spatial analysis

Introduction

Urbanization entails the conversion of land surfaces, from natural to impervious ones (Deng & Wu, 2013), drastically altering their radiative and thermal properties. For a large city experiencing rapid expansion and population growth, there could be major changes in the urban thermal environment (Xiong *et al.*, 2012). The increase of impervious cover may significantly modify heat storage, sensible and latent heat fluxes within the urban canopy layer. As a result, higher surface and air temperatures can be experienced in urban areas. This leads to a changed thermal climate that is warmer than the surrounding non-urbanized areas (Voogt & Oke, 2003). Owing to these (and other) impacts, impervious surface coverage is no longer considered just as an indicator of the degree of urbanization, but has become a key indicator of environmental quality (Arnold & Gibbons, 1996).

Land Surface Temperature (LST) is an important variable in urban thermal environment studies (Weng, 2009). It varies in response to the surface energy balance and modulates the air temperature of the urban canopy layer (Voogt & Oke, 2003). It is now a well established fact that LST is closely related to the spatial distribution of land use/land cover (LULC) types (Weng, 2009). The partitioning of sensible and latent heat fluxes – and thus LST response – is a function of varying surface water content and vegetation cover (Chen *et al.*, 2006). Therefore, urban areas with mixed LULC comprise a mosaic of warm, heat releasing surfaces, and cool, evaporative surfaces.

Remotely sensed thermal infrared data has been extensively used to retrieve LST (Weng, 2009), with the advantage of making available a time-synchronized, spatially continuous series of records over whole urban areas. Additionally, several indices have been proposed based on the analysis of the spectral signatures of different land surfaces. These biophysical descriptors that can be directly derived from multispectral imagery data are more suitable to characterize urban surface properties than traditional LULC classifications (Ridd, 1995). Nevertheless, Deng & Wu (2013) pointed out that although an individual index is able to quantify certain characteristics of land surfaces, a comprehensive analysis is still necessary so as to consider the variety of thermal properties related with different urban biophysical compositions.The main purpose of our research is to investigate the influence of LULC types on LST patterns in the urban area of Colombo, Sri Lanka. Specific objectives of this study are: (i) to examine the spatial relations between LST and urban surface biophysical descriptors (spectral indices); (ii) to quantitatively characterize LULC types using the biophysical descriptors; (iii) to statistically establish the relationships between LST and the biophysical descriptors, as well as the relationships among these indices; and (iv) to quantitatively determine LST variations (and thus the thermal signature) for different LULC types.

Methodology

Colombo city located in the Western province of Sri Lanka, and its main commercial and administrative centre, was selected as the study area. Besides Colombo Municipal Council (MC), several wards from both Kolonnawa Urban Council (UC) and Sri Jayawardenapura Kotte Municipal Council (MC) were included in this study, as part of Colombo suburban areas (Figure 1).

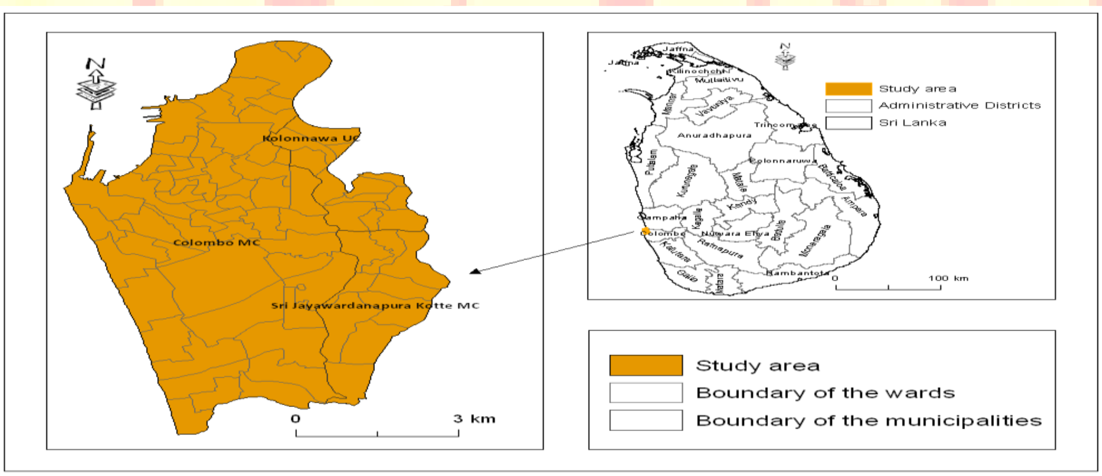


Figure 1: Location and administrative boundaries of the study area

A Landsat 7 ETM+ multispectral image acquired on March 14, 2001 (day time) under relatively clear atmospheric conditions was used in this research. LST values were retrieved from the thermal infrared band 6.1 following the procedures described in Landsat Project Science Office (2001), under the assumption of a uniform emissivity.

Using the ETM+ image reflective bands, several spectral indices were derived in order to discriminate among the fundamental biophysical components of the urban environment, namely impervious surfaces, vegetation, exposed soil (Ridd, 1995), and water. These indices are, as follows: NDBI (Normalized Difference Built-Up Index; Zha *et al.*, 2003); NDVI (Normalized Difference Vegetation Index; Rouse *et al.*, 1973); NDBaI (Normalized Difference Bareness Index; Zhao & Chen, 2005); NDWI (Normalized Difference Water Index; Gao, 1996); MNDWI (Modified Normalized Difference Water Index; Sharma *et al.*, 2013). NDBI efficiently distinguishes built-up areas, despite the fact that it is incapable to differentiate among industrial, commercial and residential areas (Zha *et al.*, 2003). NDVI is the most frequently used vegetation index and gives a good estimate of vegetation cover for a wide range of grass densities (Purevdorj *et al.*, 1998). NDBaI is used to extract bare, dry soil and concrete surfaces. NDWI is sensible to the water content of surfaces, may they be water bodies or vegetation. Therefore, NDWI can help estimate overall moisture content of land cover but it cannot be used to effectively extract water bodies (Sharma *et al.*, 2013). MNDWI was then derived to map out water, though it was not used for further analysis.

To quantitatively examine relationships among LST and the spectral indices, a sample of 5000 points was generated using a random without replacement sampling method. These points were employed to extract values of LST, NDBI, NDVI, NDBaI, and NDWI. Each of the five data series was submitted to the Shapiro-Wilk normality test, which showed that none have a normal distribution. Consequently, a non-parametric hypothesis test, alternative to Pearson's correlation – the Spearman's rank correlation –, was used to assess associations between variables.

To better understand the relationship between LST and land surfaces, the thermal signature of each LULC type must be determined (Weng *et al.*, 2004). Visual analysis of the 'natural colour' composite of bands 5, 4, 3 (RGB) from the ETM+ image helped in identifying four major LULC types in the study area of Colombo; these are built-up, densely built-up, vegetation and moist surfaces. Hence, the formerly sampled data series of NDBI, NDVI and NDWI were used to quantitatively classify these LULC types by setting the appropriate threshold values, as suggested by Chen *et al.* (2006). Using a propositional logic (conditional) system, the four LULC classes were identified, as follows: (1) vegetation, if NDBI <0.1 and NDVI >0.2; (2) moist surfaces, if NDBI<0 and NDWI >0 and NDVI≤0.2; (3) built-up, if 0.1≤NDBI≤0.25; (4) densely built-up, if NDBI>0.25.

Results

Colombo MC has a very low vegetation cover as a result of its high rate of urbanization and concentration of secondary and tertiary economic activities (Manawadu & Liyanage, 2008). In the 'natural colour' image of the study area (Figure 2), impervious surfaces (mainly built-up areas) of Colombo MC are coloured purple. The bright green colour in the eastern part of the image represents wetlands (along the main water canals) and the green patches throughout the area correspond to urban vegetation. The dark purple linear features are streets and roads. Dark blue and black depict water bodies (except for the patches in the lower right portion of the image which are clouds).

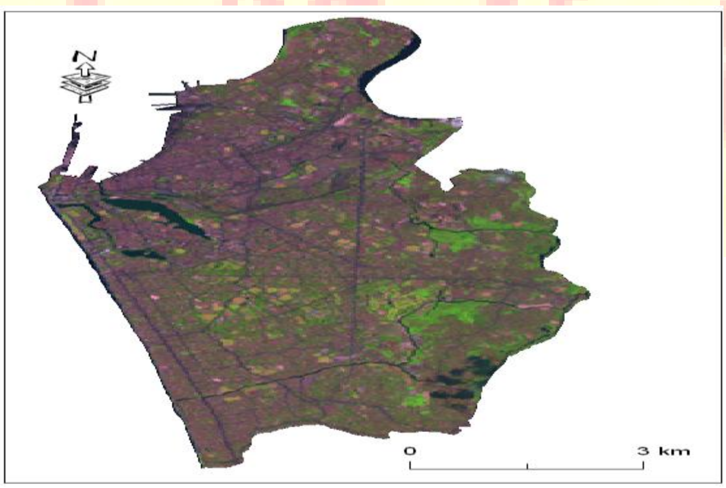


Figure 2: 'Natural colour' composite of bands 5, 4, 3 (RGB) from March 14, 2001 Landsat ETM+ image for the study area of Colombo

Results show that LST range from 18°C to 36°C, with a mean value of 29.7°C in Colombo study area (Figure 3). It is evident from Figure 3 that there is a thermal gradient as one progress from the central part of the city (harbour area), where LST>31°C, out into its Northern and Southern sectors. In fact, LST<28°C occur mainly in the suburban areas of Kolonnawa UC and Sri Jayawardenapura Kotte Municipal MC.

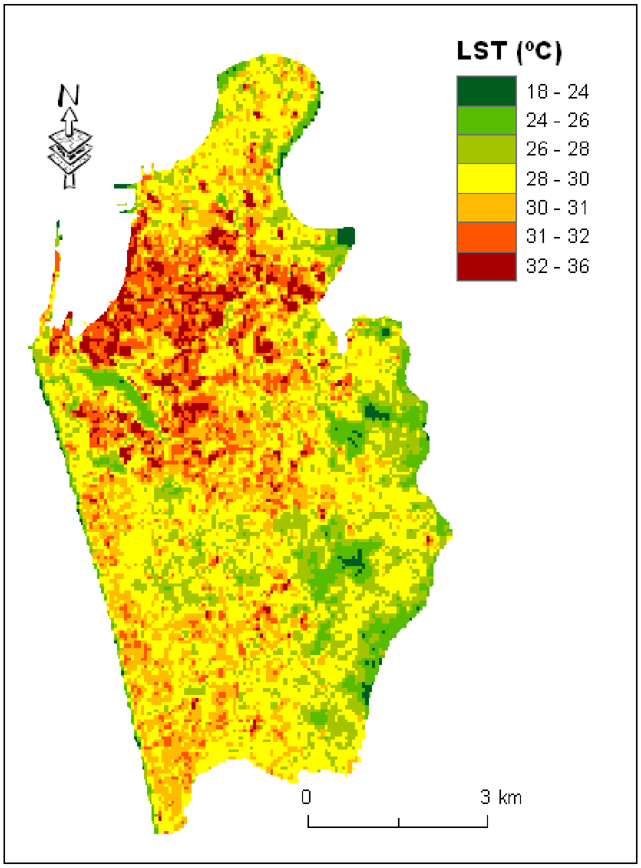


Figure 3: Land surface temperature in Colombo retrieved from March 14, 2001 Landsat ETM+ image

As expected, the highest values of NDBI are found in the harbour area and along the coastal wards, while NDBaI presents a much more scatter pattern (Figure 4). Where built-up and other impervious surfaces predominate, NDVI presents the lowest values and vegetation cover (NDVI>0.2) is reduced to small, disperse patches. The only noteworthy vegetation areas correspond to wetlands, distributed between Kolonnawa UC and Sri Jayawardenapura Kotte MC (Figure 4). While NDWI>0 depicts every evapotranspirating surface, which include urban green spaces, wetlands and water bodies, MNDWI clearly distinguishes this last ones from all others[1].

[1] Note that patches in the lower right part of the NDWI and MNDWI maps are clouds.

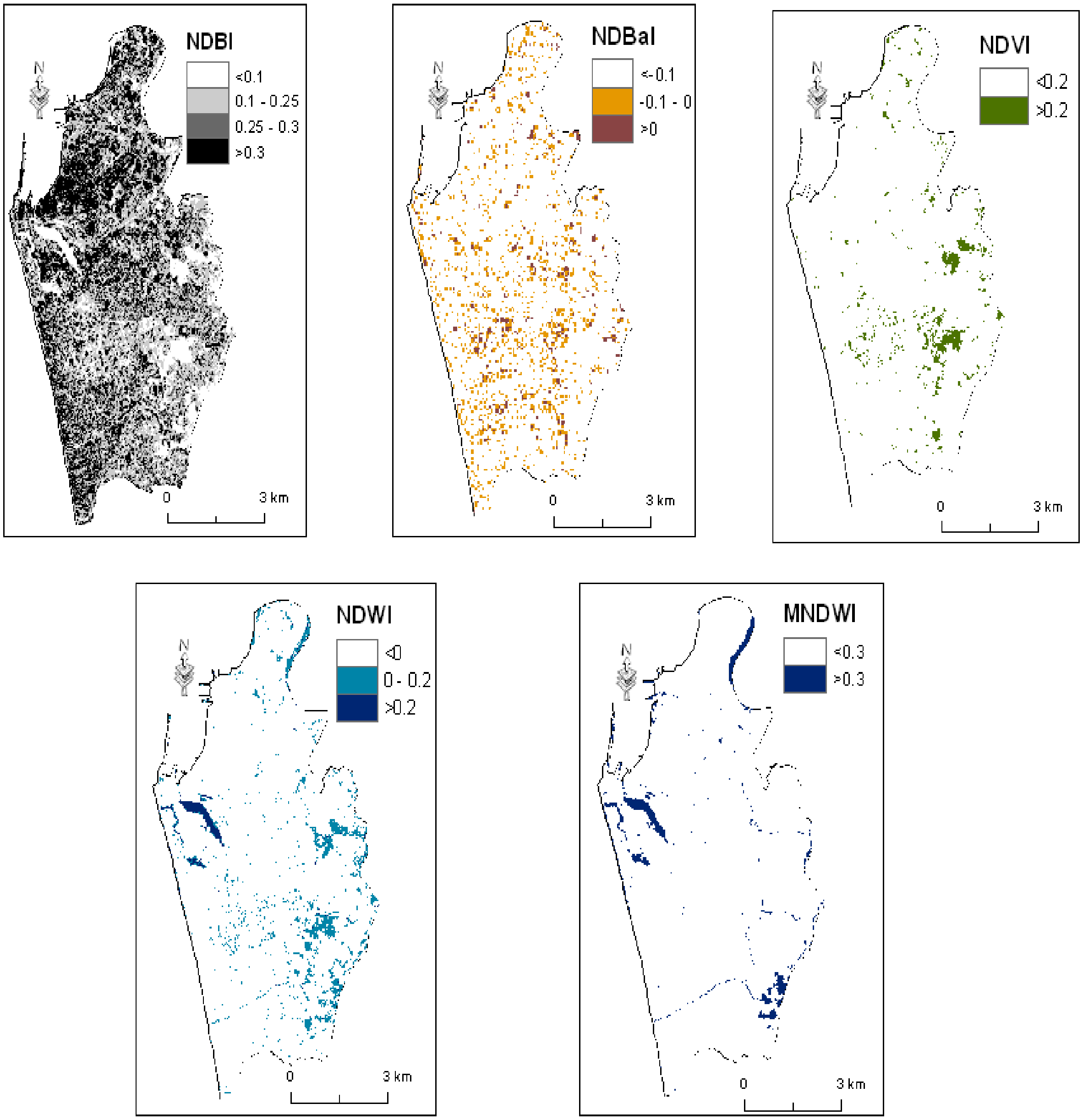


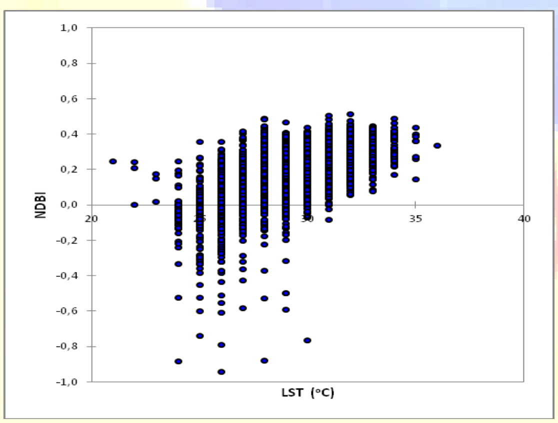
Figure 4: NDBI, NDBaI, NDVI, NDWI and MNDWI indices in Colombo derived from March 14, 2001Landsat ETM+ image

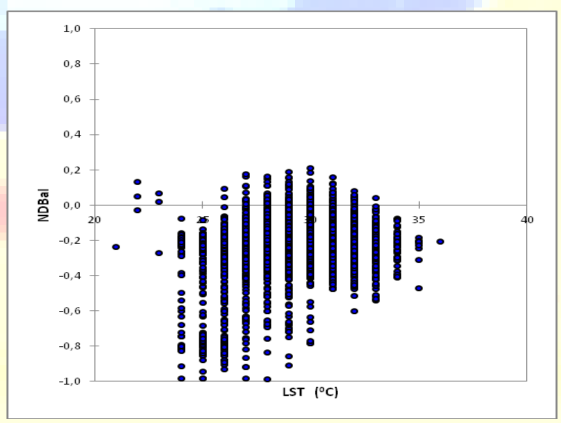
Results of the correlation analyses (Table 1 and Figure 5) demonstrate that LST presents a positive correlation with NDBI and NDBaI. In contrast, LST correlates negatively with NDVI and NDWI. These results are consistent with Sharma *et al.* (2013). Though statistically significant, LST-NDBaI and LST-NDWI are fairly weak correlations (Figure 5). LST and NDBI present the strongest correlation (ρ^2=35%).

Table 1: Spearman's rank correlation coefficients (*p*<0,0001)

Variables	LST	NDBI	NDWI	NDBaI	NDVI
LST	1				
NDBI	0.593	1			
NDWI	-0.093	-0.063	1		
NDBaI	0.140	0.257		1	
NDVI	-0.523	-0.680	0.083	0.063	1

NDBI and NDVI present a very strong negative correlation (ρ^2= 46%; Table 1). All the other correlations between the spectral indices are comparatively weak.





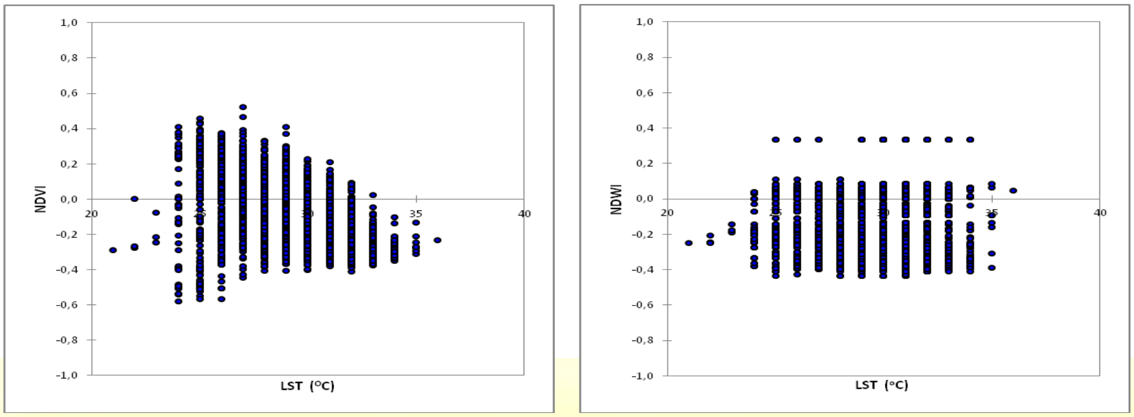
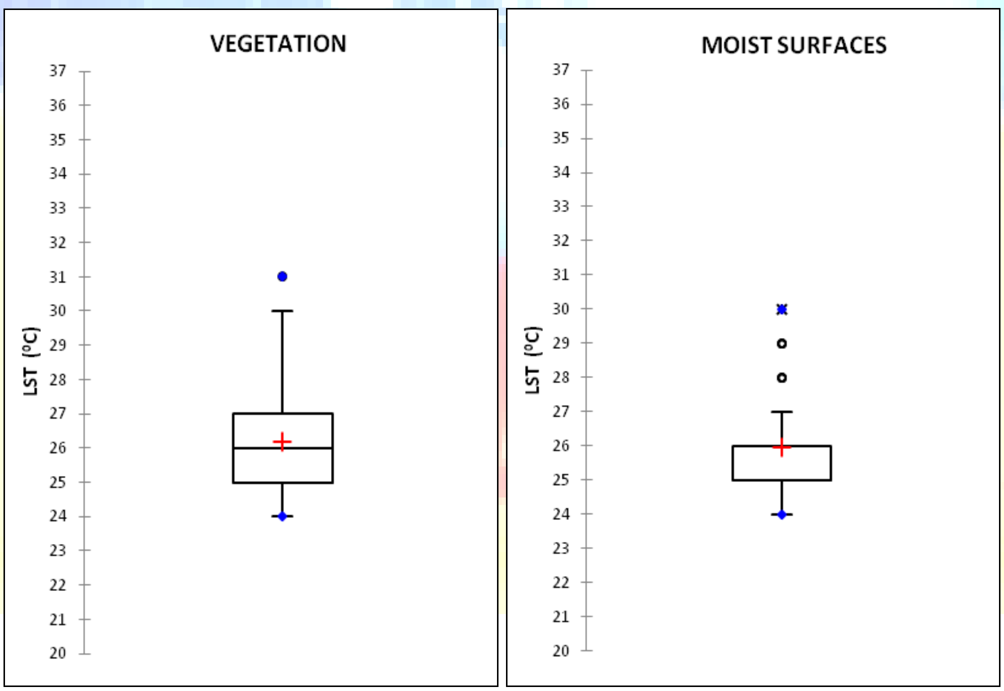


Figure 5: Scatterplot of the LST-NDBI, LST-NDBaI, LST-NDVI, LST-NDWI feature space

Figure 6 shows that vegetation and moist surfaces have notably different thermal signatures from built-up and densely built-up areas.



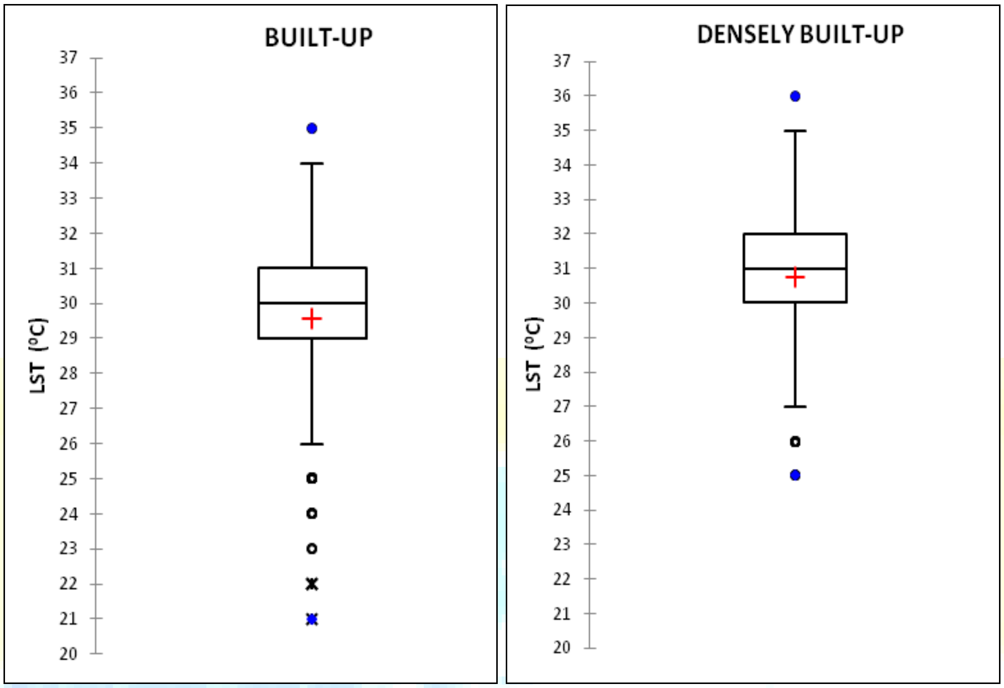


Figure 6: Boxplot of LST by land cover types

LST values are slightly higher in densely built-up areas than in built-up areas. The former presents a mean LST of 30.7ºC, while built-up mean is of 29.6ºC. LST lower than 29.0ºC and 30ºC only occur in 25% of observations for built-up areas and densely built-up areas, respectively. Furthermore, in 25% of the densely-built observations LST values are higher than 32.0ºC, while the 3rd quartile corresponds to 31ºC for the built-up data series. On the other hand, vegetation cover and moist surfaces have a mean LST of 26.2ºC and 26.0ºC, respectively. These two LULC types are characterized by a very similar thermal signature. LST values higher than 27.0ºC only occur in 25% of observations for vegetation. The 3rd quartile is a bit lower (26.0ºC) for moisture surface data series. In both cases, LST<25.0ºC occur in 25% of observations.

Discussion and Conclusions

In this study a mosaic of warm and cool areas is easily identified for Colombo urban area. Warm surfaces in the harbour area and surrounding wards, which produce, store and release heat to the urban canopy layer (by long-wave radiation emission and sensible heat turbulent fluxes) constitute marked surface urban heat islands (SUHI; Voogt & Oke, 2003). Cool areas relate to evapotranspirating surfaces (water bodies, vegetation, wetlands), and their cooling effect due to the release of latent heat. In fact, LST increases whenever NDVI and NDWI decline in favour of higher NDBI (and NDBaI) values, where built-up areas predominate over vegetation cover, moist soil, wetlands or water bodies. Hence, densely built-up have radically higher LST than vegetation and moist surfaces (with mean values of 30.7ºC, 26.1ºC e 26.0ºC, respectively).

Our results suggest urbanization can raise LST by replacing natural land cover with impervious surfaces, that have a higher heat storage capacity, reduced evaporation and are made of non-transpiring materials. This has serious consequences on additional cooling energy consumption. As a conclusion, this study stresses the importance of the presence of natural land and urban green parks (with large water surfaces) in the urban environment of Colombo, due to their cooling effect and air advection caused by differences in LST and air temperatures between the green, moist areas and its warmer built-up surroundings.

Acknowledgement

This paper was prepared while the second author was functioning as a post-doctoral scholar at the Department of Geography, University of Minho, Portugal under the EU Granted Erasmus Mundus Scholarship programme, 2012/13

References

1. Arnold, C.L., and Gibbons C.J, 1996, Impervious surface coverage: the emergence of a key environmental indicator, Journal of the American Planning Association, 62, pp 243-258.
2. Chen, X., Zhao, H., Li, P., and Yin, 2006, Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes, Remote Sensing of Environment, 104, pp 133-146.
3. Deng, C., and Wu, C, 2013, Examining the impacts of urban biophysical compositions on surface urban heat island: A spectral un-mixing thermal approach, Remote Sensing of Environment, 131, pp 262-274.
4. Gao, B, 1996, NDWI: a normalized difference water index for remote sensing of vegetation liquid water from space, Remote Sensing of Environment, 58, pp 257-266.
5. http://landsathandbook.gsfc.nasa.gov/pdfs/Landsat7Handbook.pdf.
6. Landsat Project Science Office, 2001, Landsat 7 Science Data Users Handbook, NASA. Retrieved October 15, 2012

7. Purevdorj, T.S., Tateishi, R., and Honda, Y, 1998, Relationships between percent vegetation cover and vegetation indices, International Journal of Remote Sensing, 19, pp 3519-3535.

8. Ridd, M. K, 1995, Exploring a V-I-S (vegetation-impervious surface-soil) model for urban ecosystem analysis through remote sensing: comparative anatomy for cities. International Journal of remote Sensing, 16, pp 2165-2185.

9. Rouse, J.W., Haas, R.H., Schell, J.A., and Deering, D.W, 1973, Monitoring vegetation systems in the Great Plains with ERTS. Third ERTS Symposium, NASA, pp 309-317.

10. Sharma, R., Ghosh, A., and Joshi, P.K, 2013, Analyzing spatio-temporal footprints of urbanization on environment of Surat city using satellite-derived bio-physical parameters. Geocarto International, 28, pp 420-438.

11. Voogt, J., and b Oke, T. 2003, Thermal remote sensing of urban climates. Remote Sensing of Environment, 86, pp 370-384.

12. Weng, Q, 2009, Thermal infrared remote sensing for urban climate and environmental studies: methods, applications, and trends, ISPRS Journal of Photogrammetry and Remote Sensing, 64, pp 335-344.

13. Weng, Q., Dengsheng, L., & Schubring, J, 2004, Estimation of surface temperature-vegetation abundance relationship for urban heat islands studies, Remote Sensing of Environment, 89, pp 467-483.

14. Xiong, Y., Huang, S., Chen, F., Ye, H., Wang, C., & Zhu, C, 2012, The impacts of rapid urbanization on the thermal environment: a remote sensing study of Guangzhou, South China. Remote Sensing, 4(7), pp 2033-2056.

15. Zha, Y., Gao, J., and Ni, S, 2003, Use of normalized difference built-up index in automatically mapping urban areas from TM imagery. International Journal of Remote Sensing, 24(3), pp 583-594.

16. Zhao, H., and Chen, X, 2005, Use of normalized difference bareness index in quickly mapping bare areas from TM/ETM+. Geoscience and Remote Sensing Symposium, 3(25-29), pp 1666-1668.