

# The role of urban parameters in the development of urban heat island: analysis and statistical modelling

Joon Ho LEE<sup>1</sup>, M. Shahgedanova<sup>2</sup> and K. White<sup>2</sup>

Laboratoire de Mécanique des Fluides UMR-CNRS 6598  
Research Institute on Urban Sciences and Technics, IRSTV FR CNRS 2488  
Ecole Centrale de Nantes, BP 9210, 44321 Nantes cedex 3, France  
E-mail: Joon-Ho.Lee@ec-nantes.fr

<sup>2</sup> Department of Geography, The University of Reading,  
Whiteknights PO Box 227, Reading, RG1 6AH, UK

## Abstract

Structures of urban canopies and urban parameters (e.g. building density, proportion of vegetation cover, materials) control the development of urban heat islands (UHI) and understanding these controls is important for prediction of the future evolution of UHI. Although the significance of this influence has long been recognised, few detailed studies of such links encompassing entire urban area exist. In this study, an extensive data base of urban parameters, land use and urban canopy characteristics (LUC) has been compiled for Reading, UK for different time periods through the use of contemporary and historical aerial photography, Ordnance Survey (OS) maps and ground surveys. The data have been converted into gridded data sets with a spatial resolution of 500 m. Multiple regression modelling has been used to quantitatively link these data sets with observations of air temperature which have been conducted across Reading (representing different LUC types) in 2005-2006. The proportional extent of vegetation cover, built up ratio, and distance from town centre have been identified as the main controls over UHI intensity and spatial difference between air temperatures in Reading. These parameters explain between 38% and 77% of total variance in the structure and formation of UHI. The developed statistical models enable construction of spatial models of air temperature in urban areas for different time periods, both in the past (using historical urban parameter data) and in the future (using urban development plans).

Key words: urban heat island (UHI), land use classification, urban parameters, regression model

## 1. Introduction

The composition and structure of urban area together with the urban parameters (e.g. construction materials, vegetation cover) have a significant effect on local climate: the urban areas are 2-6°C warmer than the surrounding countryside known as urban heat island (UHI). Statistical modelling provides useful quantitative information about the contribution of urban factors to UHI development, and helps better understanding of the causal relationships that enable to assess and predict the formation and evolution of UHI phenomena. The aim of this paper is to examine spatial structure and diurnal variations of surface and air temperatures in a medium-size urban area in south-eastern England and to link these temperatures with characteristics of urban canopy which are changing over time (i.e. between the 1960s and 2000s).

## 2. Data and methods

As a study area, the city of Reading is located in south-eastern England with population over 235,000. Reading has experienced substantial expansion in the past 50 years, and is going through a series of major developments. The centre of Reading is on a low ridge between the Rivers Thames and Kennet close to their confluence. Reading belongs to the Mid-latitude Wet Climate zone (Cf) with moderate temperature in Köppen climate classification.

In order to perform this study, the air temperature ( $t_a$ ) measurements are carried out at *in situ* 16 sites from Aug 2005 to Oct 2006 and one Meteorological observatory measurement is employed as a reference. With help of historical airborne images, OS maps and other urban characteristics data, the land use and urban canopy (LUC) classifications (Table 2.1) are identified and designated to gridded cells (500\*500m) in Figure 2.1. Each grid cell with LUC type is quantitatively associated with several urban parameters; built-up ratio, the number of buildings, H/W ratio, the used materials (for physical properties, e.g. emissivity), NDVI, water surface ratio, the distance from the city centre and population. In addition, the grid-cell LUC types are assigned to the urban development of Reading in time series from 1960 to 2005.

Thanks to the statistical models, the contribution of urban parameters to the formation of UHI intensity is quantitatively analysed for the different time scales such as daily, seasonal and yearly. The linear regression models with identified parameters are applied to the geospatial models in order to infer spatio-temporal changes in UHI intensities. The interpolated results of  $t_a$  are tested to validate through the comparison with *in situ* measurements. The development of UHI intensity is also identified from 1960 with a 15 year interval.

Table 2.1. Land use and urban canopy (LUC) classifications compared with ‘urban climate zone’ (UCZ; Oke, 2006)

	UCZ	Code	Land use and urban canopy (LUC)	%
RA	5	1	Detached houses and newly developed detached houses area	2.4
	7	2	Large detached houses area	4.8
	5	3	Semi-detached townhouses area and terraced-look houses area	4.8
	5	4	Semi-detached houses area, school area and green area	3.6
	2	5	Terraced houses area	3.6
	3	6	Mixed area of semi-detached houses with terraced houses including green and open space	8.3
	5	7a	Mixed area of detached houses with semi-detached houses with the patch of green area	3.6
	5	7b	Mixed area of detached houses with semi-detached houses with dense vegetation	1.2
	5	7c	Mixed area of detached houses with semi-detached houses with sparse vegetation	8.3
	3	8	Mixed area of detached with semi-detached and terraced-look houses (newly developed)	8.3
NRA	2	9	Modern town houses area including flats and halls	4.8
	4	10	Industry area	2.4
	1	11	Commercial area	6.0
	4	12	Retail park areas with large car park	1.2
	1	13	Business area	4.8
	6	14a	Public service areas with large building and parking lots	11.9
	6	14b	Public service areas with large green area and waters	4.8

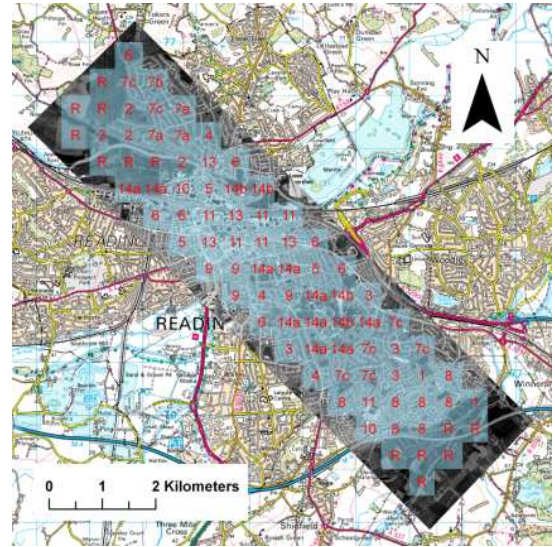


Figure 2.1. Grid-cell based map with LUC classification

### 3. Results and discussion

Various statistical methods are used to build models, such as multiple regression, principal component and factor analysis. In this study, a stepwise regression approach has been used to (i) identify parameters defining UHI intensity, (ii) model spatial structure and temporal variations of UHI in the study area, and (iii) model UHI intensity in the study area from the identified predictors for different stages of urban development.

Table 3.1. Urban parameters exhibiting a statistically significant correlation coefficient (at 0.05 confidence level) with  $\Delta t_a$  in the study area at different time scales

$\Delta t_a$ with time scale	Urban parameters
Annual mean	Building%, Built-up%, NDVI, Distance, Population
Summer mean	NDVI, Population
Winter mean	Building%, Road%, Built-up%, NDVI, H/W, Distance, Population
Winter max	Distance, Population

The Table 3.1 summarises that urban parameters have been correlated with the  $\Delta t_a$  measured at each LUC type. Out of all these characteristics of the urban surface, NDVI and distance from the town centre explain 70% of variance in the annual mean  $\Delta t_a$  dataset (Eq-1). In Summer, when the  $\Delta t_a$  values were the highest, a single parameter (NDVI) explains 38% of variance in  $\Delta t_a$  dataset (Eq-2). Vegetation has been found to play a major role in controlling urban temperature patterns in a number of studies, e.g. Spronken-Smith and Oke (1998), Upmanis *et al.* (1998) and Balázs *et al.* (2007). The built-up% and the distance from the town centre explained most of the variance in the Winter  $\Delta t_a$  dataset, while distance from the town centre was the main parameter explaining variance in the Winter  $\Delta t_{a \text{ max}}$  values, explaining 77% and 42% of the variance respectively (Eq-3 and Eq-4). The impact of built-up ratio on urban temperature patterns is well documented in many studies, including Unger *et al.* (2001), Botlyán and Unger (2003) and Balázs *et al.* (2007).

$$\Delta t_a = 0.994 - 1.272 * \text{NDVI} - 1.21 * 10^{-4} * \text{Dist} \quad (\text{Eq-1}, R^2 = 0.700)$$

$$\Delta t_a = 1.652 - 2.221 * \text{NDVI} \quad (\text{Eq-2}, R^2 = 0.376)$$

$$\Delta t_a = -0.667 + 1.719 * 10^{-2} * \text{Built}\% \quad (\text{Eq-3}, R^2 = 0.592)$$

$$\Delta t_{a \text{ max}} = 0.990 - 1.70 * 10^{-4} * \text{Dist} \quad (\text{Eq-4}, R^2 = 0.418)$$

With help of linear regression models, Figure 3.1 illustrates the spatio-temporal distribution of  $\Delta t_a$  are interpolated on the basis of LUC grid-cell map (Figure 2.1) for the different time scales. For the interpolation, inverse distance weighting (IDW) function is applied to assign the values.

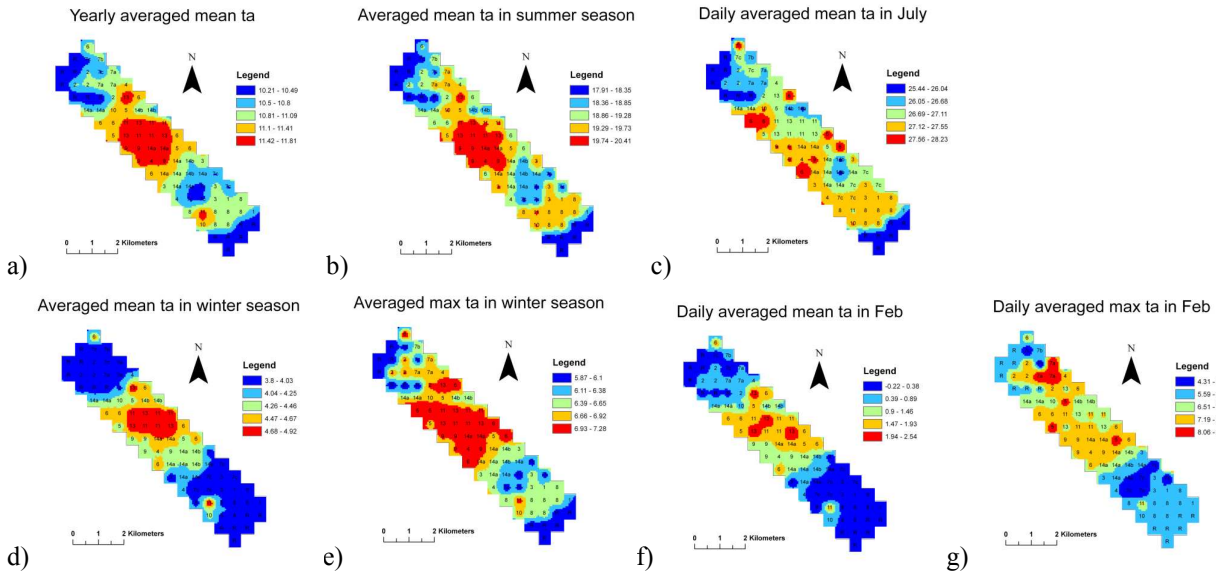


Figure 3.1. Geospatially interpolated air temperature distribution in Reading (a: yearly, b: summer, c: daily summer, d: winter, e: winter max, f: daily winter and g: daily max winter)

Through the use of *in situ* measurements at 16 sites and a reference (Met. Observatory), geospatial  $t_a$  models developed for Summer and Winter have been tested using linear regression analysis. The mean square error (MSE) of estimated values with measured values is 0.12 for Summer, 0.06 for Winter mean air temperatures and 0.28 for Winter maximum air temperatures. The coefficient of determination is 97% for Winter mean air temperatures (Figure 3.2).

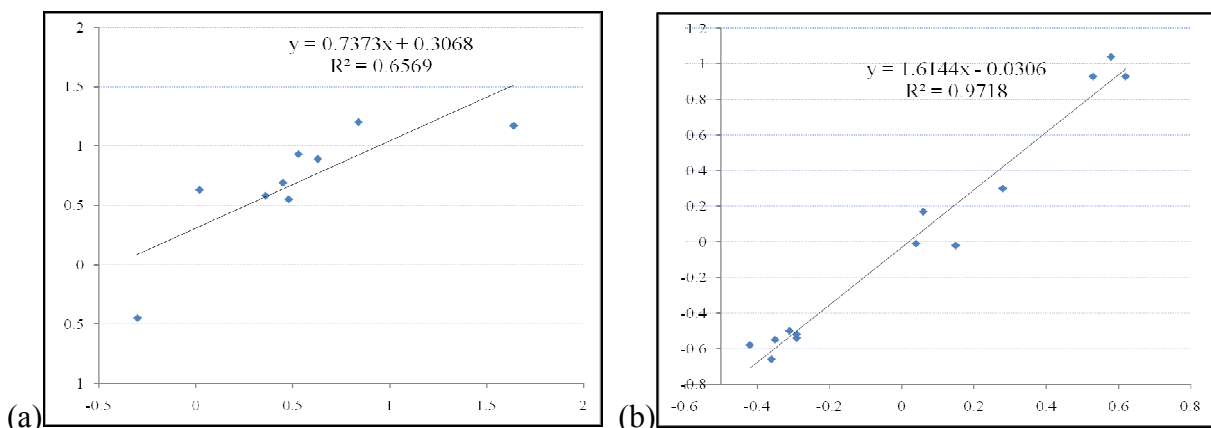


Figure 3.2. The statistical validation of modelled  $\Delta t_a$  with measured  $\Delta t_a$  for Summer (a) and Winter (b), 2005

On the basis of grid-cell LUC classifications (mentioned above), urban development in Reading has been identified in different years (Figure 3.3). This approach has allowed an assessment of the evolution of UHI as a result of urban development. Through the use of statistical equations, spatial patterns of  $\Delta t_a$  are illustrated for different years: 1960, 1975, 1990 and 2005 (e.g. Figure 3.4 for Winter mean  $\Delta t_a$ ).

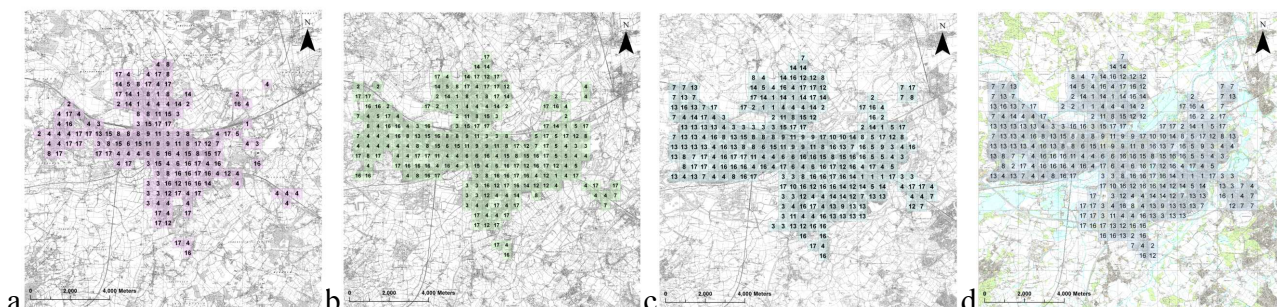


Figure 3.3. Urban development and its expansion in Reading in different year (a: 1960, b: 1975, c: 1990 and d: 2005): Each grid cell indicates LUC type

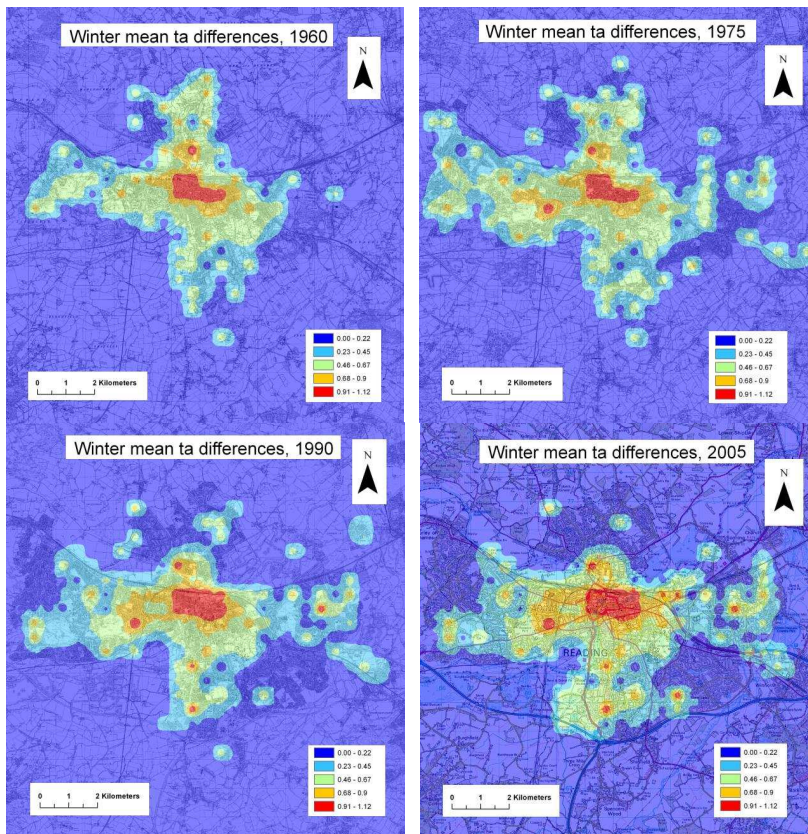


Figure 3.4. Assumed spatial distribution of Winter mean  $\Delta t_a$  ( $^{\circ}\text{C}$ ) in different years on the grid-cell based urban development (Figure 3.3)

#### 4. Conclusion

In this paper, an attempt has been made to model spatial distribution of  $\Delta t_a$  and  $\Delta t_{a \max}$  in different years and to compare the development of urban heat island (intensity and structure) over the 1960 - 2006 period. Model validation, using independent datasets, has shown that the spatial models perform well with regard to  $\Delta t_a$  for both Summer and Winter periods (the latter exhibits a particularly close agreement). The  $\Delta t_{a \max}$  patterns are reconstructed with lower reliability. It would be desirable to use a more extensive observational record for both modelling and model validation, and it is envisaged that this effort will be made in the future. However, at this stage it is concluded that the proposed methodology can be used for an assessment of the impact of urban development on the intra-urban climate patterns and climatic comfort with regard, not only to historical development, but also to future urban development plans. The modelled historical  $\Delta t_a$  values clearly demonstrate that urban expansion results in the development of secondary centres of urban heat island in Reading. This refers to both construction of large public buildings and commercial centres with large parking lots and to the development of new residential areas, especially those with high building density.

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