J2.3 ASSESSING CAUSES IN SPATIAL VARIABILITY IN URBAN HEAT ISLAND MAGNITUDE

Melissa Hart* and David J. Sailor
Portland State University, Portland OR

1. INTRODUCTION

Urban areas are not homogenous in their land-use and surface characteristics and the urban thermal environment not only varies from its rural surrounds but also varies within the urban area. Understanding the causes of this intra-urban variability in urban climate is a first step in improving urban planning and development. Toward this end a method for quantifying causes of spatial variability in the urban heat island (UHI) has been developed. Vehicle based temperature traverses were used to determine spatial differences in summertime ~2m air temperature across the Portland, Oregon and Houston, Texas metropolitan areas. Summer 2006 traverses concentrated on hot days in Portland. During the current 2007 summer we have expanded the analysis to include different weather conditions in Portland, thereby including days representative of the more typical mild conditions experienced during the Portland summer in addition to the rare hot days. Summer 2007 traverses also included a series of early morning and afternoon traverses during two days in Houston, Texas.

Urban characteristics most important to spatial variability of UHI intensity differ depending upon city morphology, location and climatic zone. Whilst the general causes of the urban heat island are well known, it is not well understood how much influence different urbanization characteristics (e.g. land-use, road density, vegetation coverage) have on the intensity of the UHI. This paper investigates the influence of urbanization on the urban climate, and in turn assesses the causes of spatial variability in the summertime urban heat island by using a combination of mobile vehicle temperature traverses and GIS resources. A tree structured regression model is used to quantify the land-use and surface characteristics that have the greatest influence on UHI intensity and this model is used to produce maps of summertime nocturnal and daytime (both weekday and weekend) UHI intensity. Portland Oregon is used as the test case for the application of this method. While Portland is not widely viewed as a city with significant heat issues, it presents an opportunity to study a potentially vulnerable city where future population growth, expansion of the air-conditioning market, and global climate change may combine to increase the importance of the summertime UHI. Ongoing investigations will utilize the method to investigate the spatial variability of the UHI in subtropical Houston.

2. METHODS AND DATA

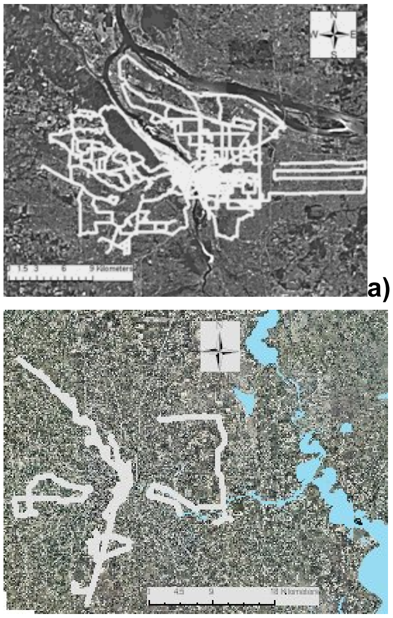
2.1 Vehicle Temperature Traverses

Each traverse platform consisted of a class A ceramic wound Resistance Temperature Detector (RTD) mounted within a 12 cm long, 2.5 cm diameter white plastic shade tube. The shade tube was supported on a passenger-side window-mounted mast approximately 25 cm above the vehicle roof and 30 cm away from the edge of the vehicle. The RTD sensors were connected to data logging temperature recorders with an estimated system accuracy of +/- 0.15 ^{o}C and a (90%) response time of less than 9 seconds in 1 m/s airflow; the response time for speeds the vehicles were traveling during traverses was calculated to be less than 4 seconds. The movement of the vehicle aspirated the sensors and measurements recorded when the car was stationary (e.g. at traffic lights) were not used in the analysis. Temperature was recorded every five seconds. A time synchronous GPS system (BlueGPS units from RoyalTek) was also attached to each car so that each temperature measurement could be paired with a GPS location, velocity, and altitude.

Each day's traverse involved between one and six cars, and lasted less than one hour. Over the two summers traverses have been undertaken on 11 days in Portland, with a total of 54 separate vehicle traverses and 2 days in Houston, with a total of 12 separate vehicle traverses. Traverses were undertaken just prior to sunrise to capture the nocturnal UHI and close to the hottest part of the day to capture daytime UHI. The difference between the measured urban temperature and a representative fixed rural site was calculated in order to determine instantaneous UHI intensity.

* *Corresponding author address:* Melissa Hart, Portland State Univ., MME Dept., Portland OR, 97207; e-mail: mhart@pdx.edu

Figure 1 shows the coverage of Portland (a) and Houston (b) traverses. These figures show that the vehicle traverses covered a large amount of the metropolitan area, particularly for Portland, providing spatially dispersed temperature measurements.



a)

b)

Figure 1: Coverage of summer 2006 and 2007 vehicle temperature traverses for a) Portland and b) Houston.

2.2 GIS Resources

GIS resources were used to investigate the influence of surrounding surface and land-use characteristics on the spatial variability of the UHI. Land-use parameters used included the proportion of land-use that was residential (single family or multi-family), commercial or industrial, the total floor space of surrounding buildings and the total length of surrounding roads (RLIS, 2006). Surface characteristics included the proportion of the surface that was tree canopy, ground vegetation, impervious or loose surface cover and were acquired from the City of Portland, Bureau of Planning (City of Portland, 2006). GIS analyses are confined to Portland for this paper; future investigations will expand these analyses to include Houston.

The Portland metropolitan area was divided into an 80 by 55 grid, with grid cells of 300 m. This grid was then used to aggregate land-use and surface characteristics from the GIS resources.

2.3 Regression Tree Analysis

To determine the importance of the various land-use and surface parameters on the spatial distribution of the urban heat island across Portland the statistical program CUBIST (Rulequest, 2006) was used to construct a tree structured regression model. The independent variable in the analysis was mean UHI intensity for each grid cell covered by temperature traverse. The independent variables in the model were the surface and land-use characteristics mentioned above. A case (in this instance a grid cell) moves down a specific branch of the regression tree depending on if it satisfies the conditions of a rule, e.g. if one of the independent variables for that case is greater than or less than a particular value (Breiman et al., 1984). Once a case reaches a terminating node of the regression tree a multiple linear regression model for that node is used to predict the intensity of the UHI within that grid cell. This method allows for the determination of the most important land-use or surface variables affecting UHI intensity for different regions within the metropolitan area.

2.3 Production of UHI Intensity Maps

Using the tree structured regression models it is possible to produce maps showing the spatial variability of UHI intensity across all areas of the city where GIS information on land-use and surface cover are available.

3. RESULTS

3.1 Vehicle Temperature Traverses- Portland

The spatial variability in temperatures measured across the urban area on the Portland traverse day June 26th, 2006 is presented in Figure 2a). During the June 26th traverse temperatures varied by 5.5 ºC across the area measured. Figure 2b) shows the spatial variability in the UHI intensity. The UHI is shown to be positive in the downtown and the majority of the suburban areas, whilst there is a strong negative UHI (a cool island) in the area within and surrounding Forest Park, a large forested park within the Portland metropolitan area. This June day broke temperature records in Portland with temperatures of over 40 ºC experienced. These hot Portland days are usually associated with a dry tropical air mass and only occur approximately 5% of the time during the summer (Sheridan, 2002). Traverses during more typical Portland summertime conditions (dry maritime air mass, occurring ~48% of the time (Sheridan, 2002) show a not as pronounced UHI with downtown temperatures up to 2 ºC higher than rural surrounds but suburban temperatures similar to rural surrounds. Nocturnal traverses show a pronounced UHI surrounding the downtown and industrial and commercial land-use intense areas.

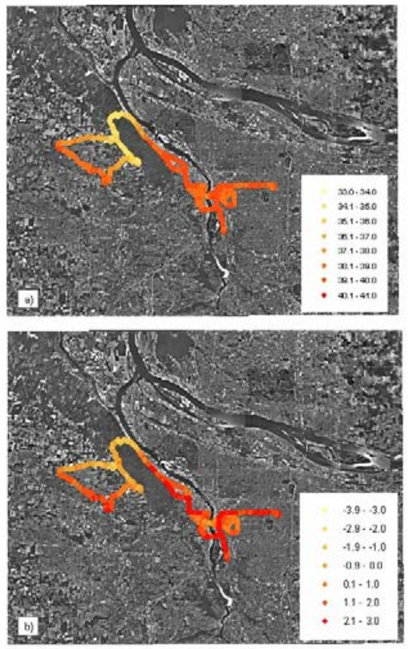


Figure 2: a) Temperatures measured (the legend shows temperatures in degrees Celsius) and b). UHI magnitude (the legend shows temperatures in degrees Celsius), during an afternoon vehicle traverse, June 26th 2006.

3.2 Vehicle Temperature Traverses- Houston

Houston traverses were undertaken on two days during the 2007 summer associated with a moist tropical air mass. Temperatures peaked at 36 ºC with the warmest parts of the city close to the downtown region and just north of the highly industrialized region surrounding the ship channel (Figure 3a). UHI magnitude was highest in these areas with temperatures up to 2.8 ºC higher than the rural surrounds.

Figure 4a shows the UHI magnitude of a traverse undertaken just prior to sunrise the following day. The UHI reached a maximum of 3.2 ºC with warmest regions associated with regions of high density commercial and industrial land use (Figure 4b). The UHI magnitude is less as you travel away from the downtown core and in park regions. In future investigations the tax-lot scale GIS resources of land use in Houston will be used to qualitatively assess the causes of this spatial variability's in Houston UHI intensity.

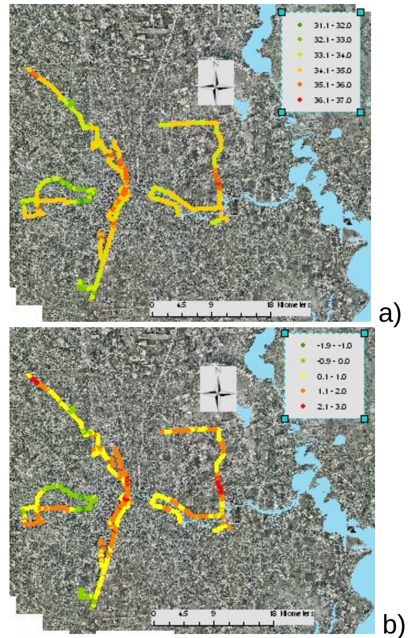


Figure 3: a) Temperatures measured (the legend shows temperatures in degrees Celsius) and b). UHI magnitude (the legend shows temperatures in degrees Celsius), during an afternoon vehicle traverse, July 31st 2007.

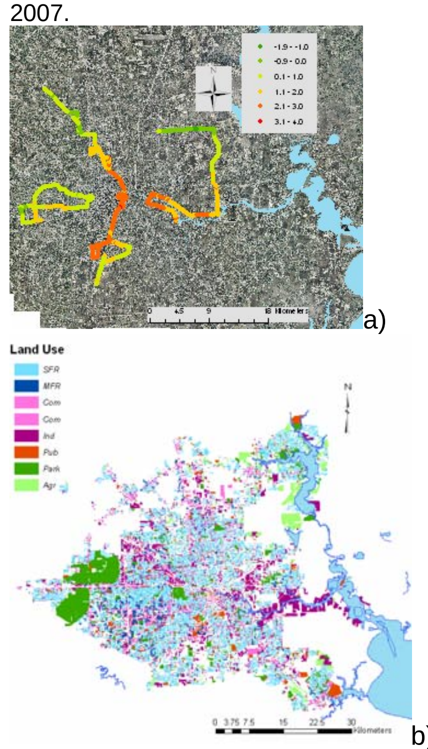


Figure 4: a) UHI magnitude (the legend shows temperatures in degrees Celsius), during an early morning vehicle traverse, Aug 1, 2007, and b) Houston land-use characteristics.

3.2 Tree Structured Regression- Portland

Current TSR analyses are confined to hot dry tropical air mass Portland traverse days, future investigations will expand these analyses to include traverse days associated with other weather types. To examine any temporal differences in causality of UHI intensity, tree structured regression models were produced separately for nocturnal UHI and both weekend and weekday daytime UHI. Tolerance values for all variables in terminal node multiple regression models were greater than 0.2, so there was no problem with multicollinearity between the independent variables (Rawlings, 1988).

The first rule for daytime UHI regression trees differentiated between grid cells based on canopy cover (an example of a TSR model is given in Figure 5). The first terminating node produced a predictive model for UHI intensity for areas where canopy cover is greater than 64% for the weekend traverses. This model predicted a negative UHI for those areas on the order of -2.6 ºC. Building floor space is the last rule, for grid cells not satisfying Rule 1 and occupying the first terminal node (therefore less canopy cover), highest temperatures were experienced when building floor space within the grid cell is less than 19113 m^2.

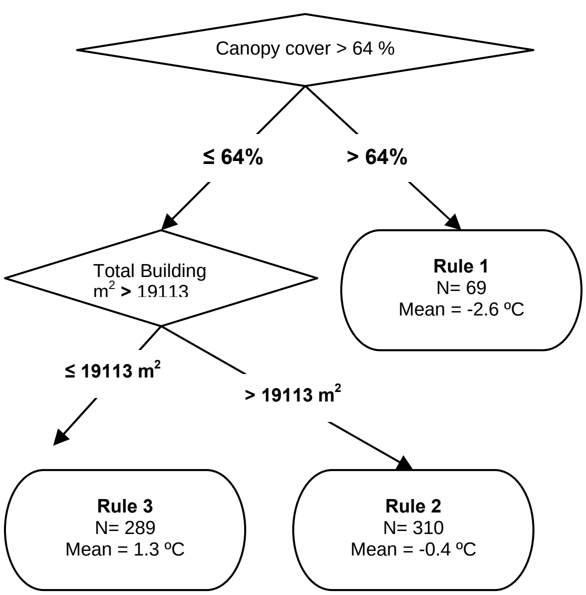


Figure 5: Tree structured regression model for weekend daytime UHI intensity, where N = the number of grid cells within each terminating node and Mean = the mean UHI intensity for that terminating node.

As with the afternoon model, the morning regression tree was split initially by canopy cover with the minimum UHI intensity occurring in grid cells where canopy coverage is greater than 42%. However, unlike the afternoon analyses, there is no negative UHI experienced in areas of high canopy coverage, rather temperatures in the high canopy regions of the city in the early morning are on average 0.7 ºC warmer than the surrounding rural temperatures. Road length is the next variable of importance is quantifying the influence of land-use and surface characteristics on spatial differences in the morning UHI. UHI intensity is higher for gird cells with more road coverage (greater than 1912 m), however this difference is small (1.9 ºC for grid cells with more road coverage, compared to 1.8 ºC for grid cells with less).

3.2 Predictive UHI Maps- Portland

Figure 6 presents the spatial variability of both nocturnal and daytime UHI intensity across the Portland metropolitan area, produced by applying the tree structured regression models to the gridded land-use and surface characteristics. Accuracy of the predicted UHI intensity maps was determined by calculating the Root Mean Square Error (RMSE) between the grid average UHI intensity traverse observations and the grid UHI intensity calculated using the tree structured regression models, this RSME ranged from 0.97 ºC for the weekday nocturnal UHI map to 1.30 ºC for the weekend daytime map.

Figure 6 illustrates that some regions within the Portland metropolitan area can experience a negative UHI during summertime afternoons. The regions that experience a negative UHI are those with greatest canopy coverage as determined by the first rule of daytime tree structured regression models, this is generally the area encompassing Forest Park. Forest Park is the coolest region of the city and is generally 2-4 ºC cooler than the rural surrounds and can be up to 10º C cooler than surrounding urban regions. During the afternoon (Figure 6a), the warmest areas of the city are just across the Willamette River (to the east) from the downtown area, an area characterized by commercial land-use and an industrial area just to the north of the downtown between Forest Park and the Willamette, these regions experience a predicted UHI intensity of up to 5 ºC.

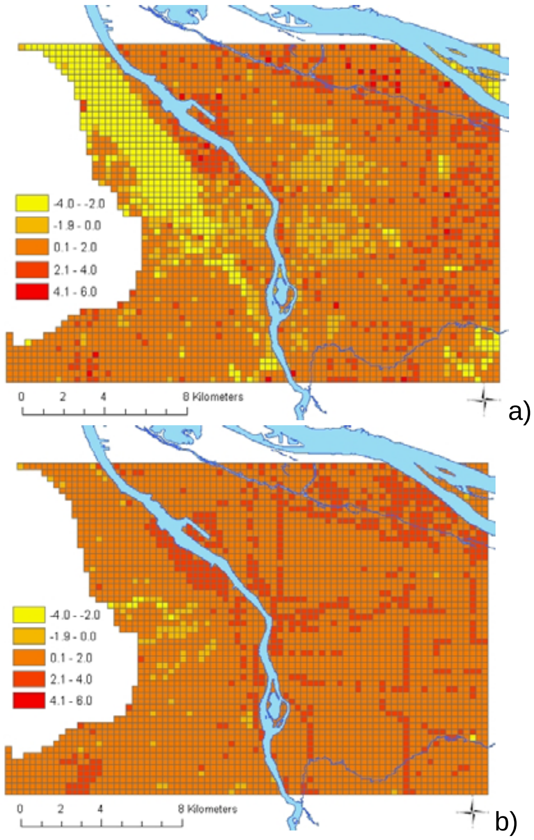


Figure 6: Grid values of UHI intensity produced using tree structured regression models (UHI magnitude is in º C) for a) weekend daytime, and c) weekday nocturnal.

During the early morning hours (Figure 6b) the majority of the Portland metropolitan area experienced a positive UHI, including Forest Park. This UHI is on average up to 2 ºC warmer than the rural surrounds. The warmest areas of the city during the morning hours are the industrial region to the north of the downtown, commercial areas in the northwest region of the metropolitan area (just below the Columbia River), and along some of the major arterial roads. Downtown temperatures are similar to those experienced in the suburbs.

4. DISCUSSION AND CONCLUSIONS

The most important urban characteristic separating warmer from cooler regions of the Portland metropolitan area was canopy cover, regardless of day of week or time of day. This illustrates the importance of parks and green spaces on the spatial variability of summertime urban air temperatures. The influence of Portland's Forest Park is greatest during the warmest part of the day when factors such as shading from the dense canopy and evapotranspiration are most important.

Areas with dense canopy cover during the early morning were slightly cooler than surrounding urban areas; however this temperature difference was smaller than the intra-urban temperature difference experienced during the day. In addition, densely canopied urban areas were warmer than the rural surroundings, experiencing a slight heat island rather than the cool island experienced during the day. While the dense canopy cover shades the surface from solar radiation keeping it cooler during the day, the low sky view factor can also serve to reduce the amount of long-wave radiation emitted at night thereby slowing the cooling of the park (Spronken-Smith and Oke, 1999).

The warmest area of the city regardless of time of day or week is a region associated with industrial land-use; the elevated temperatures experienced in this industrial region are probably due to a combination of lack of vegetation or canopy cover and continuous anthropogenic heat emissions.

This paper has introduced a method for investigating the spatial variability in UHI intensity using vehicle temperature traverses and GIS resources. Tree structured regression models have allowed the determination of the most important land-use or surface variables affecting summertime UHI intensity for different regions of a metropolitan area. The construction of separate models for nocturnal and daytime (weekday and weekend) UHI has allowed for investigation of temporal differences in spatial variability in UHI, and the influence of anthropogenic activity on UHI intensity on weekdays compared to weekends. Ongoing investigations include: investigating the spatial variability of the UHI under different weather conditions, further investigation of temporal differences in UHI by undertaking vehicle temperature traverses during additional times of the day, and expanding the analyses to an additional city- Houston, Texas.

ACKNOWLEDGEMENTS

The authors wish to thank the various participants in the traverse measurements. We also thank Kevin Martin, GIS specialist with the City of Portland Bureau of Planning for providing the Portland GIS data and the Houston Advanced Research Center (HARC) for support during the Houston traverses and providing Houston GIS resources. This research was supported by the National Science Foundation under Grant No. 0410103. Any opinions, findings, and conclusions or recommendations expressed in this material are

those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

Breiman, L., J. H. Freidman, C. J. Stone, and R. A. Olshen, 1984: *Classification and Regression Trees*. *Wadsworth statistics/probability series*, CRC Press, 391 pp.

Chow, W. T. L. and M. Roth, 2006: Temporal dynamics of the urban heat island in Singapore. *International Journal of Climatology*, **26,** 2243-2260.

City of Portland, 2006: Natural Resource Inventory Update - vegetation mapping project, 18 pp.

ODOT, cited 2007: Daily vehicle miles traveled. [Available online from http://www.oregon.gov/ODOT/.]

Rawlings, J. O., 1988: *Applied regression analysis : a research tool*. Wadsworth & Brooks/Cole Advanced Books & Software, 553 pp.

RLIS, cited 2006: Regional Land Information System. [Available online from http://www.metro-region.org/article.cfm?ArticleID=1024.]

Rulequest, cited 2007: Rulequest research data mining tools. [Available online from http://www.rulequest.com/.]

Sailor, D. J. and L. Lu, 2004: A top-down methodology for developing diurnal and seasonal anthropogenic heating profiles for urban areas. *Atmospheric Environment*, **38,** 2737-2748.

Sheridan, S. C., 2002: The redevelopment of a weather-type classification scheme for North America. *International Journal of Climatology*, **22,** 51-68.

Shutters, S. T. and J. Balling, Robert C., 2006: Weekly periodicity of environmental variables in Phoenix, Arizona. *Atmospheric Environment*, **40,** 304-310.

Simmonds, I. and K. Keay, 1997: Weekly cycle of meteorological variations in Melbourne and the role of pollution and anthropogenic heat release. *Atmospheric Environment*, **31,** 1589-1603.

Spronken-Smith, R. A. and T. R. Oke, 1998: The thermal regime of urban parks in two cities with different summer climates. *International Journal of Remote Sensing*, **19,** 2085-2104.

——, 1999: Scale modeling of nocturnal cooling in urban parks. *Boundary-Layer Meteorology*, **93,** 287-312.

Voogt, J. A., 2002: Urban heat island. *Causes and consequences of global environmental change*, I. Douglas, Ed., John Wiley & Sons, Ltd, 660-666.