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A GIS APPROACH TO URBAN HEAT ISLAND RESEARCH: THE CASE OF  
HUNTSVILLE, AL.

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## INTRODUCTION

GIS (Geographic Information System) is a system of hardware, software, and procedures designed to support the capture, management, manipulation, analysis, modeling and display of spatially-referenced data for solving complex planning and management problems.<sup>1</sup> In essence, GIS performs three major functions: (1) to process and display maps, (2) to create a database, and (3) to carry out spatial analysis.<sup>2</sup> With the advent of personal computer technology in recent years, the capability of GIS has been greatly enhanced particularly in the area of mapping and spatial data manipulation. A typical application of GIS involves overlaying different layers of spatial data together to produce a new map of some desired characteristics, normally involving the concept of union and intersection in Boolean algebra. GIS has been used extensively in ecology and environmental research,<sup>3</sup> but not much in the atmospheric science. This paper advocates its use in an urban heat island study.

The urban heat island represents a case of inadvertent human modification of climate in an urban environment. Changnon<sup>4</sup> suggested that the magnitude and extremes of the changes in urban precipitation and temperature were similar to those predicted to develop over the next 100 years by the global climate models. Urbanization changes the nature of the surface and atmospheric properties of a region. As a result, radiation balance in the urban areas is altered and sensible heat is added to the point that urban areas are warmer than surrounding rural areas. Oke<sup>5</sup> observed that at the boundary between the rural area and the urban area, a sharp rise in temperature occurs, culminating to a peak temperature at the Central Business District (CBD) of the city, hence the name "urban heat island". The extent and intensity of the urban heat island are a function of population size, land use, and topography.<sup>6,7</sup> Because the urban heat island exhibits spatial variations of temperatures, the use of GIS is appropriate.

The research on the urban heat island focuses on the acquisition of 15 bands of visible and thermal infrared data (ranging from 0.45 to 12.2  $\mu\text{m}$ ) from an aerial platform using NASA's ATLAS (Airborne Thermal/Visible Land Application Sensor) sensor over Huntsville, Alabama. These data will be acquired in early September. The research reported in this paper is an analysis of the impact of population, land use, and topography on the shape of the urban heat island that could be developed in Huntsville using the GIS approach. The outcome of this analysis can then be verified using the acquired remotely sensed data.

## THEORETICAL CONSIDERATIONS

All surfaces on earth receive short-wave radiation during the day and exchange long-wave radiation continuously with the atmosphere. The net amount of radiation received by a surface depends on the temperature, emissivity and reflectivity of the surface exposed to radiative exchange. The general form of the equation describing the radiation budget is:

$$R_n = (1-\rho)S_t + L_d - L_u \quad (1)$$

where  $R_n$  is net radiation,  $\rho$  is reflection coefficient,  $S_t$  is the total flux (short-wave atmospheric radiation, being made up of a direct flux on the horizontal surface ( $S_b$ ) and a diffuse flux ( $S_d$ )),  $L_d$  is the downward flux (long-wave atmospheric radiation received at the surface) and  $L_u$  is the upward flux (long-wave emission from the surface).<sup>8</sup> The amount of total flux depends on the cosine of the zenith angle  $\psi$ , or the amount of sky visible to the surface. In the urban area, man-made land surfaces have changed the reflectivity and hence the amount of reflected solar radiation. Because of the heterogeneous nature of the land use pattern in the urban area, reflection coefficients vary across the urban area. According to the Stefan-Boltzmann law, the flux of radiation emitted by the surface, i.e.,  $L_u$  in Equation (1), depends on the surface temperature as:

$$L_u = \sigma T^4 \quad (2)$$

where  $\sigma$  is the Stefan-Boltzmann constant ( $= 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ ), and  $T$  is the surface temperature in absolute (K) units. However, reflectivity of the surface refers to short-wave radiation (0.15-3  $\mu\text{m}$ ), while the overall emissivity ( $\epsilon$ ) of the surface refers primarily to the long-wave radiation (3-100  $\mu\text{m}$ ) as in this case. Equation (2) has to be modified to become:

$$L_u = \epsilon \sigma T^4 \quad (3)$$

By the principle of conservation of energy that

$$\text{absorptance} + \text{reflectance} + \text{transmittance} = 1,$$

and by assuming that the surfaces are opaque to thermal radiation (as in most remote sensing applications), we can establish the relationship that absorptance + reflectance = 1. According to Kirchhoff radiation law that spectral emissivity of a surface equals its spectral absorptance, we can establish the relationship that the higher the surface's reflectance, the lower its emissivity and absorptance, and vice versa.<sup>9</sup>

In applying all the above considerations to urban heat island research, one should note a two-layer classification of urban modification put forth by Oke (1976). There is a distinction between the Urban Boundary Layer (UBL) and the Urban Canopy Layer (UCL) because the processes responsible for its creation may be different. UBL refers to the layer above the roofs of buildings in the urban area, which is an advective phenomenon involving internal radiative effects and the entrainment of warm air from the inter-building spaces beneath and the inversion of the mixed layer above. UCL is near the street level where the magnitude and dynamics of the heat island are largely a response to microscale site factors such as building geometry and surface materials. The amount of sky visible at the street level will affect the amount of atmospheric radiation received. The analysis presented in this paper focuses on the UCL rather than the UBL.

## METHODOLOGY

The analysis requires a number of data input: (1) reflectance of the land use surfaces in the city of Huntsville, (2) population distribution, and (3) topography of the site.

To obtain the reflectance data for the land use surfaces, color infrared aerial photography acquired on October 9, 1992 at the nominal scale of 1:48,000 was used. First, fifteen aerial photographs were manually interpreted with the aid of a mirror stereoscope supplemented by ground checking. Eleven classes of land use/cover were delineated: (1) forest, (2) commerce and services, (3) high-tech offices and factories, (4) residential, (5) agricultural, (6) military, (7) quarry, (8) educational, (9) golf courses and parks, (10) wetland, and (11) water bodies. The result is a land use/cover map at the scale of 1:48,000. Next, two aerial photographs (frame numbers 13 and 20) which covered the major part of the city and its adjacent rural area were scanned using a flat-top color scanner with a resolution of 600 bpi. This produced a digital image of the photograph in three bands (blue, green, and red) with digital values of the pixels ranging from 0 to 255 (i.e., 8-bit data). The green band was found to be the best to use to obtain the reflectance data of each land use/cover type. By calibrating the data using a lake (such as the lake at the University of Alabama at Huntsville) which should have a reflectance of 0 per cent and the quarry which exhibited the brightest reflectance (assumed to be 100 per cent), the digital number for each class of land use/cover was converted into reflectance data. All these were accomplished with the aid of a raster GIS software package known as IDRISI developed by Clark University. The land use/cover map was reduced to a scale of 1:75,000. It was then digitized and transformed into a raster-based map with a cell size of 571.5 m x 571.5 m. Because the land use/cover map was directly traced from the aerial photographs, distortions caused by tilts and relief displacements were present. The rasterized image of the map was rectified and transformed into the Universal Transverse Mercator (UTM) coordinates based on four GPS ground control points provided by the Planning Department of the City of Huntsville, with the aid of the IDRISI program. By assigning the reflectance value to the appropriate land use/cover class, a reflectance map in correct UTM coordinates was produced.

Population data for Madison County in 1990 by census tracts were obtained from the Planning Department of the City of Huntsville. The census tract boundary map for Huntsville was digitized and converted into raster format with the same resolution as that of the land use/cover map and rectified to the same UTM coordinate system. Population density was then assigned to each appropriate census tract using the IDRISI program, thus producing a map of population densities by census tracts.

Topography was represented in terms of terrain heights acquired by GPS for 363 points covering the city of Huntsville. A program called SURFER was used to carry out a spatial interpolation of the heights points by the method of kriging. The result was a rasterized

contour map, which was then imported to IDRISI where it was made to register with the land use/cover map.

Because these three layers of data were registered to the same UTM coordinate system, they could be overlaid by the IDRISI program to create a new map and to investigate the spatial relationships among these layers. This is the typical GIS approach. In this analysis, our objective is to determine the interaction between reflectance and population density, in particular, the locations where both high reflectance and high population density occur together. These would be areas of high temperatures in the city. Their locations were then related to the topography.

### RESULTS OF ANALYSIS

High reflectance was found to occur in the commerce/services uses which are found along the major highways and in the Central Business District (CBD). High population densities were found in the Mastin Lake Road area, Oakwood Avenue area, and Bob Wallace-Drake Street area --- located respectively to the northwest, east and southwest of the Memorial Parkway. A big contrast in population density between the city and the rural area was seen. The high reflectance and high population density produced a distinct urban heat island following the North-South aligned Memorial Parkway and the East-West running I-565 offshoot. This North-South alignment has been dictated by the North-South trending mountain ridge (Green Mountain) to its east. The land use/cover type on the mountain ridge is predominantly forest (low reflectance and hence high emissivity and high absorptance), thus presenting a contrast to the generally high reflectance land use surfaces of the city. The Tennessee River runs across the southern edge of the city. The Redstone Arsenal to the southwest of the city has low population density but some high reflectance. The combined effect of the two has not produced significantly high temperature in the region, and presented a contrast to the city area to its northeast. All these results suggest that the site of Huntsville is most favorable to the development of urban heat island.

### IMPLICATIONS TO THE THERMAL INFRARED IMAGING AND CLIMATE CHANGE

The analysis above presented some interesting observations to the use of thermal infrared imaging for urban heat island detection in Huntsville. The North-South running Memorial Parkway is an important corridor along which the reflectivity of the land use surfaces will have a significant impact on urban heat island development at the Urban Canopy Layer (UCL). By integrating the visible channels of the ATLAS sensor (channels 1 to 6: 0.45-0.90  $\mu\text{m}$ ), reflection coefficients of the different land use surfaces can be obtained. Emissivity of the land use surfaces can be obtained from the thermal infrared channels of 3.35  $\mu\text{m}$  to 12.2  $\mu\text{m}$  (channels 9 to 15). Based on the Stefan-Boltzmann Law, the radiant temperature ( $T_{\text{rad}}$ ) of

the land use surfaces can be calculated. With a knowledge of emissivity of each surface, the kinetic temperature ( $T_{kin}$ ) of the surface can be computed using the following relationship:

$$T_{rad} = \varepsilon^{1/4} T_{kin} \quad (4)$$

Finally, it has been observed by examining past records of temperature and precipitation data for Huntsville from 1959 to 1991 that Huntsville appeared to be in the cycle of temperature and precipitation increase in recent years, as revealed by the three-yearly moving averages. One can only speculate whether such increases in temperature and precipitation have been impacted by the possible intensification of urban heat island effect in recent years.

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