Using Landsat TM thermal data to map micro-urban heat islands in Dallas, Texas

By

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Introduction

The urban heat island is a growing environmental concern that has interested scientists since 1833 (Oke, 1982). In simple terms, a heat island may be described as higher temperatures within cities than in surrounding rural areas (Goward 1981). The two major factors that lead to the formation of heat islands are the effects of street canyon geometry on radiation and the effects of thermal properties on heat storage release (Oke et al., 1991). Other factors may include rapid runoff of precipitation, reduction of evapotranspiration, and waste heat from residential and other buildings, (Matson et al., 1978). Weather conditions that facilitate the formation of heat islands are what Oke et al. (1991) and Johnson et al. (1991) describe as "ideal" conditions -- calm, cloudless conditions at night. The greatest intensity of heat islands in temperate areas occur in summer and autumn, when warmer weather conditions exist (Oke, 1982).

The most common methods for studying urban heat islands are urban-rural meteorological station comparisons, auto-traverse methods, remote sensing techniques (aircraft and satellite infrared) and computer modeling (Henry et al., 1989). Satellite studies are ideal for analysis of urban heat islands because they overcome the problems associated with the more common methods (Henry et al., 1989). Using satellite data for heat island studies is better than traditional methods that require on the ground analysis because it eliminates the problem of multiple user interpretation of the data, and it is a much faster process (Møller-Jensen, 1990). Satellite studies of urban heat islands may be most viable because they are more representative of the urban canopy as a whole and have the capability of repeated, synoptic coverage (Henry et al. 1989). Thermal studies of urban heat islands using satellite data have been performed by a number of researchers, including Price (1979), Balling and Brazel (1988),
These studies show that in commercial, residential and industrial areas, temperatures are approximately 10-15°F hotter than vegetated areas.

The presence of urban heat islands has led to alterations in the climate of some urban areas. In the last fifty years the average temperature of downtown Los Angeles has increased by 5°F, the August temperatures in San Francisco have increased by 0.2°F per decade, and the annual mean temperatures of Washington D.C. are increasing at a rate of 0.5°F per decade (Semrau, 1992). In fact, most urban areas around the world with populations greater than 100,000 have heat islands that are 2-8°F warmer than rural temperatures (Semrau, 1992). These elevated temperatures in urban areas increase national peak electricity demand by up to 2%, which translates into a cost of up to $1 million an hour (Semrau, 1992). As urban temperatures increase, additional environmental problems develop, including elevated concentrations of CO₂, trace gases, and atmospheric particulates which may contribute to global warming (Price, 1979). The negative effects of an urban heat island extend well beyond simple temperature increases.

The concentration of this study is not on the entire urban area as one large heat island, but on isolated sections of an urbanized environment that are significantly hotter than their surroundings. A study of these “micro-urban heat islands” follows the same parameters as any typical comparison of urban heat island temperatures to rural climates. This is because the natural areas within a city such as parks, lawns and forests behave thermally the same as rural landscapes (Goward, 1981).
Objectives

The purpose of this study was to determine the relationship between the absence of trees and the presence of micro-urban heat islands. The objectives were to determine the usefulness of Landsat TM bands 3 and 4 for tree cover mapping, and the usefulness of TM band 6 in identifying micro-urban heat islands. All 7 bands were utilized in this study to provide the full spectral curve for differentiating all cover types. When micro-urban heat islands were determined and mapped in relation to tree cover, the final objective of this study was to combine the information into a GIS to obtain a map or blueprint of the exact locations of micro-urban heat islands in the Dallas area.

Description of Study Area

Three study areas were selected from the Dallas, Texas region (Fig. 1). The three subscenes, Addison, White Rock, and Oak Cliff, were chosen based on the varying amount of tree cover and urban development. The city of Addison is a newly developed area with relatively little tree cover, new residential neighborhoods, and an urbanized business district. Addison was chosen to represent an area with sparse tree cover. The White Rock area has well-established residential neighborhoods, an urbanized warehouse district, and a large lake (White Rock Lake), providing land use variation. The third subscene, Oak Cliff, was chosen because it represents an older, well-established region with an abundance of tree cover.
Fig. 1 Map of study areas within Dallas, Texas.
Landsat Technology

Originally operated by NASA, Landsat was transferred to EOSAT, a private corporation, in 1985. The current Landsat 5 was launched on March 1, 1984. Its major components include an MSS imaging system and the thematic mapper (TM). Landsat 5 can cover the earth in 233 orbits and 16 days. Landsat TM data has a spatial resolution of 30 m, contains 7 spectral bands and has an extended spectral range in the visible and reflected infrared regions. Table one summarizes the TM spectral bands.

<table>
<thead>
<tr>
<th>Bands</th>
<th>Spectral Range (μm)</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.45-.52</td>
<td>Some water penetration</td>
</tr>
<tr>
<td>2</td>
<td>.52-.60</td>
<td>Green wavelength for vegetation mapping</td>
</tr>
<tr>
<td>3</td>
<td>.63-.69</td>
<td>Red wavelength for geology, urban, &amp; vegetation</td>
</tr>
<tr>
<td>4</td>
<td>.76-.90</td>
<td>Reflected IR for vegetation mapping &amp; drainage</td>
</tr>
<tr>
<td>5</td>
<td>1.55-1.75</td>
<td>Reflected IR, soil moisture, geobotanical and vegetation, penetrates thin clouds</td>
</tr>
<tr>
<td>7</td>
<td>2.08-2.35</td>
<td>Reflected IR, rock and soil alteration mapping</td>
</tr>
<tr>
<td>6</td>
<td>10.4-12.5</td>
<td>Emitted thermal IR</td>
</tr>
</tbody>
</table>

(Morgan et al., 1992)
The blue spectral data of TM band 1 allows production of normal color composite images. TM has a thermal IR band, which is the primary band of interest when analyzing the temperatures/thermal characteristics of an urban area. Band 6 was useful for temperature determination of micro-urban heat islands because the detectors are capable of sensing a radiant temperature difference of approximately 0.6° C (Avery and Berlin 1985). Each TM band has an array of 16 detectors, with the exception of band 6, which uses only 4. A summary of the Landsat TM systems is detailed in Table 2.

Table 2
Landsat TM Systems

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>705 km</td>
</tr>
<tr>
<td>MSS on board</td>
<td>Yes</td>
</tr>
<tr>
<td>TM on board</td>
<td>Yes</td>
</tr>
<tr>
<td>Spectral bands</td>
<td>7</td>
</tr>
<tr>
<td>Resolution (visible &amp; IR)</td>
<td>30 m</td>
</tr>
<tr>
<td>Resolution (thermal)</td>
<td>120 m</td>
</tr>
<tr>
<td>Image coverage</td>
<td>34,225 sq.mi.</td>
</tr>
<tr>
<td>Pixels per scene</td>
<td>266,000,000</td>
</tr>
</tbody>
</table>

(Morgan et al., 1992).

There are many advantages to using thematic mapper data systems:

Synoptic View -- A single image covers 31,635 square kilometers that show features difficult or impossible to observe by other means. These images isolate areas needing more detailed study, thus reducing the amount of data required to cover large areas.

Worldwide Coverage -- The orbital path covers latitudes of 81° S to 81° N, therefore covering most of the inhabited areas of the
world. This is particularly valuable for politically and geographically remote areas.

**Uniform Illumination Angle** -- The Landsat orbit is sun-synchronous, providing a constant angle of illumination.

**Multispectral Content** -- Data are acquired simultaneously through the same optical system, facilitating overlaying the data from two or more bands. The bands cover a much larger spectral range than conventional cameras.

**Digital Analysis** -- The availability of TM in digital form permits large volumes of data to be processed quickly by computer.

**Planimetric Fidelity** -- The relatively high orbital altitude and narrow swath produces nearly orthographic images so that shapes, dimensions, and relative locations of features remain virtually constant across the entire image.

(Hughes, Santa Barbara Research Center, 1992).

TM data are useful for different types of applications related to urban heat islands, including land-use identification and classification (Phillips, 1992) and monitoring of impervious cover (Plunk, 1989). TM band 6 has been used to map water surface temperatures in Green Bay and Lake Michigan, (Lillesand and Kiefer, 1987). TM thermal data can also be utilized in agricultural applications such as estimation of surface moisture characteristics (Price, 1983), and in studies where temperature patterns are important, including the study of the urban heat island (Schott, 1989).

**Methodology**

The methodology for mapping micro-urban heat islands in an urban environment was divided into six steps: obtaining the Landsat image, data processing and classification, evaluation and accuracy checking of classifications, merging data
into a GIS, temperature calculations, and final production of a micro-heat island map. Figure 2 outlines the methodology.

**Obtain Landsat CCT**

A computer compatible tape (CCT), path 27 row 37, was obtained from EOSAT for data acquired on October 8, 1992 of Dallas-Fort Worth. The data had maximum full scene cloud cover of 30%, but there was no cloud cover over the study areas. The temperature ranged from a low of 48°F to a high of 71°F. There were heavy rains on October 7, 1992 (NOAA, 1992).

**Data Processing and Classification of Cover Types**

After obtaining the CCT, the data were loaded onto a Sun SPARC-1 for data extraction using ERDAS. This information was then transferred into MultiSpec on the Macintosh IIfx to classify cover types. MultiSpec is a multispectral analysis program developed by the EE department at Purdue University. It performs multispectral classifications on an image area. Because each pixel in an image can be characterized by its spectral signature, a multispectral classification performs an image-extraction that analyzes these signatures and assigns the pixels to different categories based on their similar spectral signatures (Sabins, 1987).

Because of the large area of coverage of the Dallas-Fort Worth scene, subscenes were carved out as representatives of the entire Dallas area. These subscenes were chosen based on the amount of trees present—areas were needed that represented newer areas with relatively little vegetation, and more developed neighborhoods with a relatively large amount of tree cover (Fig. 3).

In MultiSpec, the image was displayed in a stretched standard 4R, 3G, 2B (CIR) band combination. MultiSpec always works on raw data, however, so
Fig. 2 Schematic outline of methodology.
Fig. 3 4R 3G 2B (CIR) images of Oak Cliff, Addison and White Rock.
stretching the image had no effect on cover type classifications. Both supervised and unsupervised classifications were run to determine cover types in the subscenes and the Dallas scene. When using supervised classification, training fields were chosen by drawing rectangles or polygons around known cover types that represented the cover types of interest. Training sites were determined using aerial photos and ground truth. The five cover types were grass, trees, water, roads and buildings. Supervised classification verifies that the chosen training fields represent an association of pixels that have Gaussian distributions (Morgan et al., 1992). MultiSpec uses a maximum likelihood measure during classification that classifies the training fields and the entire image (Morgan et al., 1992). A maximum number of training sites are chosen that will allow the computer to determine adequately all pixel variations of one cover type.

Determining the correct number of training sites to use is a method of trial and error. For this study, enough training sites were chosen to correctly identify 90-100% of the pixels. Once training sites were selected, the computer classified the entire image based on the information in the training sites. A thematic map that displayed the five cover types was produced for each subscene. Each of the subscenes was compared to low-altitude aerial photographs of the areas to determine the accuracy of supervised classification in identifying areas with tree cover.

Unsupervised classifications were run on all of the subscenes using the ISODATA algorithm. ISODATA is an iterative cluster algorithm that uses multiple passes through an image to establish multivariately stable clusters based on Euclidean distances (Langrebe and Biehle, 1993). This results in the identification of new classes from pass to pass that have closer association of pixels. Iterations end when fewer than a certain percent of pixels are changed from one iteration to another (Morgan et al., 1992). In unsupervised
classification, the computer identifies cover types of an area by grouping those pixels with similar digital number (DN) values. A thematic map was produced that identified the different pixel clusters the computer identified. These clusters were grouped into cover types to obtain a thematic map of the cover types of interest. The cover types for each subscene were different, but each identified trees.

The ISODATA algorithm offers four initialization options that allow a choice of initial clusters. These options are one-pass clusters, first covariance eigenvector, first correlation eigenvector and eigenvector volume. Only the options used in this study are discussed. The one-pass cluster option uses the first pixel in the first row of the column as the first cluster center. Then for each remaining pixel the closest cluster is found using Euclidean distance. If a pixel is too far away it becomes the center of a new cluster, and this becomes the cluster to which the remaining lines are compared (Morgan et al., 1992). When using one-pass cluster there is no way to set the number of clusters -- the computer generates these based on the number of cluster centers identified. The one-pass cluster initialization option was used to classify White Rock and Oak Cliff (Fig. 4). The eigenvector volume initialization option, used to classify Addison, chooses initial clusters based on distribution of points in eigenvector space described by the first three principle components calculated from a covariance matrix (Morgan et al., 1992). Convergence was set at 95%, the sampling interval was 10 x 10, and the number of clusters was set at 21. This number was determined by averaging the number of clusters obtained for White Rock and Oak Cliff. Tables of the results are located in Appendix A. Clusters were grouped into cover types for each area to obtain a thematic map (Fig. 5).
Fig. 4 Unsupervised classification clusters of subscenes.
Fig. 5 Cover types of subscenes.
Evaluation of Classifications and Accuracy Check

Each thematic map was evaluated for accuracy by visually comparing it to low-altitude aerial photographs of each study area. As an accuracy check, 20 random sites that contained trees were chosen on each thematic map and compared to the same sites on aerial photographs. A grid overlay was placed on the thematic map to determine accurate locations of comparison. The results are summarized in Appendix B.

Merge Classifications into a GIS

The thematic maps were transferred to the Macintosh GIS software Map II for merging into a GIS. Map II is a map processor program designed for map viewing, marking, measuring, transforming, and mapmaking (Pazner et al., 1992). The advantage of Map II over traditional GIS packages is that it is more user-friendly, allowing the user the ability to perform spatial processing using screen tools and menu choices in addition to the more traditional mode of text-based transformations (Pazner et al., 1992). Band 6, the thermal band, was transferred in a TIFF format unstretched into Map II from MultiSpec via Adobe Photoshop. In Map II band 6 was colorized for easy viewing, then recoded to extract micro-urban heat islands. A micro-urban heat island was determined to be any area with a higher DN value than the highest tree thermal value. This method of micro-urban heat island determination was used because trees provide a cooling canopy, and the areas in which this study was interested in mapping were those that were warmer than the warmest trees.
Temperature Calculation

After determination of micro-urban heat islands in each study area, equations provided by NASA were used to calculate relative on-the-ground temperatures of these hot areas based on DN values.

The percentage of pixels that were classified as micro-urban heat islands was calculated using equation 1. For example, the total number of pixels classified in Addison was 128,656, with 76,179 pixels accounting for micro-urban heat islands. Addison, therefore was comprised of 59% micro-urban heat islands. When calculating the percentage of micro-urban heat islands in White Rock and Dallas, the number of pixels assigned to water were excluded from the equation because trees were assumed not to exist in these areas. Calculations for all scenes are listed in Appendix C.

\[
\frac{\text{Number of Hot Pixels}}{\text{Total number of pixels}} \times 100\% \quad (\text{Eq. 1})
\]

At-satellite temperatures (temperatures determined by the satellite) of the micro-urban heat islands were determined for the subscenes in a two step process using the following equations. Equation 2 calculates the spectral radiance of each DN value.

\[
L_w = L_{MIN_w} + \left( \frac{L_{MAX_w} - L_{MIN_w}}{QCAL\MAX} \right) QCAL
\quad (\text{Eq. 2})
\]

where:

- \(QCAL\) = Calibrated and quantized scaled radiance in units of DN, digital numbers
- \(L_{MIN_w}\) = Spectral radiance at \(QCAL = 0\)
- \(L_{MAX_w}\) = Spectral radiance at \(QCAL = QCAL\MAX\)
- \(QCAL\MAX\) = Range of rescaled radiance in DN
- \(L_w\) = Spectral radiance

(Markham and Barker, 1987)
Equation 3 calculates at-satellite temperatures using the spectral radiance values determined in Equation 2:

\[ T = \frac{K_2}{\ln(K_1/L_w + 1)} \]  

(Eq. 3)

where

\[ T \quad = \quad \text{Effective at-satellite temperatures in Kelvin, K} \]
\[ K_2 \quad = \quad \text{Calibration constant 2 in } ^\circ\text{K} \]
\[ K_1 \quad = \quad \text{Calibration constant 1 in mW} \cdot \text{cm}^{-2} \cdot \text{µm}^{-1} \]
\[ L_w \quad = \quad \text{Spectral radiance in mW} \cdot \text{cm}^{-2} \cdot \text{ster}^{-1} \cdot \text{µm}^{-1} \text{from Eq.2} \]

(Markham and Barker, 1987)

Table 3 compares the results of equations 1-3 for each of the scenes studied.

Table 3. Calculated Temperatures and Percent of Micro-Urban Heat Islands of the Four Scenes.

<table>
<thead>
<tr>
<th>Scene</th>
<th>Percent Micro-urban heat islands</th>
<th>DN Range</th>
<th>Temperature in °F of Micro-Urban Heat Islands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oak Cliff</td>
<td>15</td>
<td>131-139</td>
<td>73.43-79.89 ± 3</td>
</tr>
<tr>
<td>Addison</td>
<td>59</td>
<td>128-145</td>
<td>70.96-84.62 ± 3</td>
</tr>
<tr>
<td>White Rock</td>
<td>51</td>
<td>127-137</td>
<td>70.13-78.29 ± 3</td>
</tr>
<tr>
<td>Dallas</td>
<td>49</td>
<td>121-150</td>
<td>65.09-88.50 ± 3</td>
</tr>
</tbody>
</table>

At-satellite temperatures corresponding to each DN value are listed in Appendix D. It is important to remember that these are only relative temperature calculations. Studies have shown that satellite-derived surface temperatures are in error of 2° Kelvin due to systematic error in gain (Schott and Volchok, 1985). Because this study is only interested in the relative temperature differences between trees and micro-urban heat islands, this error was not taken into
consideration. If necessary, however, this error can be corrected for by underflight data and/or ground truth (Schott and Voichok, 1985).

In addition to micro-urban heat island determination, each thematic map was recoded in Map II to extract trees. A map displaying only the trees in each subscene was obtained. The tree maps and the micro-urban heat island maps were overlain to create maps displaying the relationship between trees and micro-urban heat islands.

Production of Final Micro-Heat Island Map

After trees were extracted and combined with a map of micro-urban heat islands, these maps were imported into the Macintosh graphics program Canvas. The final step in this methodology was to overlay a GIS layer of the major roads in each scene onto the tree/micro-urban heat island image (Fig. 6). Two methods were used to accomplish the road overlay. For White Rock, portions of a city map was scanned into Canvas, and the roads were digitized onto a second layer. This road map was then warped to fit the image. This method of overlaying roads was tedious and time-consuming. An alternate method of road overlay was thus used for Addison and Oak Cliff, in which roads were digitized directly onto the image. This method ensured that the road layer and the micro-urban heat island/tree map were the same scale. To accomplish this, band 1 was exported as raw data from MultiSpec and imported into Canvas. A second layer was created over the road layer and the roads were manually digitized using the polygon tool. The road layer was then extracted and overlain on the tree/micro-urban heat island map. Although Band 1 was used to digitize roads, other bands can be used to display roads, depending on the scene, (Møller-Jensen, 1990).
Fig. 6. Schematic diagram of GIS process.
Roads were labeled and a final map representing the exact location of each micro-urban heat island was obtained.

Once it was determined that micro-urban heat islands could be reliably mapped for small neighborhood areas, the above procedures were performed on the entire Dallas area to demonstrate that this methodology can successfully be applied to a large urban region. Roads for the entire Dallas scene were digitized from band 1. Because of the large area of study and the high cost of obtaining low altitude aerial photographs of the entire city limits of Dallas, accuracy checks were performed using the aerial photographs of the Oak Cliff, Addison and White Rock subscenes.

Classification Results

Although supervised classification was adequate in classifying most cover types, it did a poor job of identifying trees in neighborhoods. This was because it was extremely difficult to obtain "pure" tree training sites in neighborhood areas. Because the primary interest of this study was the relationship between trees and micro-urban heat islands, a supervised classification was not adequate for cover type identification. When performing unsupervised classifications, the one-pass cluster initialization option was chosen to classify White Rock and Oak Cliff. If repeating this study in the future, it will be necessary to experiment with the different initialization options to determine which works best for the scene. Using the one-pass cluster initialization option produced thematic maps that accurately identified cover types in White Rock and Oak Cliff, but in Addison some of the asphalt and water were cross-classified. It was therefore necessary to experiment with the different initialization options to determine whether another option would work better. Eigenvector volume was used and it performed a
better classification on the Addison scene because this option performs multiple
passes over an area, giving a higher confidence level. Based on visual accuracy
evaluations, unsupervised classification did an accurate job of identifying all
cover types, and was better able to detect trees in neighborhoods than
supervised classification techniques, (Appendix B).

Results and Discussion of Micro-Urban Heat Island Maps

Final maps of the three subscenes are displayed in Figures 7, 8 and 9.
Results of unsupervised classification of each subscene are listed in Appendices
A and B. Table 4 illustrates how the data compare between the different scenes.
Each scene is discussed below.

Oak Cliff

The percentage of tree cover in Oak Cliff was calculated at 43.8%, and in
addition, 15% of the scene consisted of micro-urban heat islands. These
statistics indicate that Oak Cliff had the smallest temperature variation of the
three subscenes, with a temperature range of 73.43-79.89°F. Because Oak Cliff
is more established than the other study areas, it has an abundance of mature
trees, thus leading to reduced temperatures and less micro-urban heat islands.
The micro-urban heat islands that exist in the Oak Cliff area are comprised of
buildings, warehouses and parking lots located along the major roads. Parts of
the airport at the south of the scene also appear as a micro-urban heat island.
Because of the high percentage of tree cover that exists throughout the Oak Cliff
scene, all residential neighborhoods and forested areas are consistently cool,
with temperatures below 73°F.
Fig. 7 Final micro-urban heat island map of Oakcliff.
Fig. 8  Final micro-urban heat island map of Addison.
Fig. 9 Final micro-urban heat island map of White Rock.
Table 4. Comparison of results for all scenes.

<table>
<thead>
<tr>
<th>Scene</th>
<th>Percent Micro-urban heat islands</th>
<th>Percent Trees</th>
<th>Hottest Areas</th>
<th>Coolest Areas</th>
<th>Micro-urban heat island Temps. (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Rock</td>
<td>51%</td>
<td>39%</td>
<td>-Warehouses -Apartments -New neighborhoods -Buildings -Asphalt</td>
<td>-Forested Areas -Established neighborhoods -Water</td>
<td>70.13-78.29</td>
</tr>
<tr>
<td>Oak Cliff</td>
<td>15%</td>
<td>48%</td>
<td>-Airport -Warehouses -Buildings -Asphalt</td>
<td>-Forested Areas -All neighborhoods</td>
<td>73.43-79.89</td>
</tr>
<tr>
<td>Addison</td>
<td>59%</td>
<td>19.4%</td>
<td>-New neighborhoods -Business/warehouse district -Shopping mall -Asphalt</td>
<td>-Forested areas -Established neighborhoods -Golf courses</td>
<td>70.96-84.62</td>
</tr>
<tr>
<td>Dallas</td>
<td>41%</td>
<td>34%</td>
<td>-CBD -Universities -New neighborhoods -Shopping areas</td>
<td>-Forested areas -River corridor</td>
<td>65.09-88.50</td>
</tr>
</tbody>
</table>
Addison

Of the three subscenes, Addison had the warmest temperatures and the broadest temperature range of micro-urban heat islands, 70.96-84.62°F. Because tree cover comprised only 19.4% of the pixels in the scene, 59% of the Addison area was made up of micro-urban heat islands, the largest amount of the three subscenes. Cover types associated with these high temperatures included newly developed neighborhoods, the business/warehouse district, the airport, and all asphalt parking lots and roads. All the micro-urban heat islands in the Addison scene have little to no tree cover, and therefore do not benefit from shading that trees provide. Like Oak Cliff, the coolest areas in Addison were those with significant tree cover, such as older, established neighborhoods and forested areas scattered throughout the scene.

White Rock

While White Rock had the coolest overall temperatures, with a range of 70.13-78.29°F, micro-urban heat islands comprised 51% of the area, with only 39% of the remaining pixels assigned to trees. The hottest areas were those with a large amount of impervious cover, especially parking lots, buildings and warehouses. Like Addison, new neighborhoods were significantly warmer than tree-covered areas. Also like Addison, the hottest areas of White Rock were the warehouse district, buildings, asphalt parking lots and roads, and the large number of apartment complexes to the left of the image. These micro-urban heat islands shared the common characteristic of the hottest areas in all the scenes in that they have little to no tree cover. Other micro-urban heat islands were found in areas with bare soil and open grass-covered fields bordering the lake. As in all the scenes, the coolest areas were those with heavy tree cover, including the forested park just north of White Rock Lake. These areas were significantly
cooler due to the shading effects of tree cover. The older residential neighborhoods in the southern portion of the scene were also cool.

The above methodology shows that satellite imagery is a useful tool when mapping micro-urban heat islands in selected small areas. The image used in this study covered a much larger area than the small neighborhoods studied. It was thus possible to perform the methods of this study to map individual micro-urban heat islands for an entire urban area. The above methodology was therefore applied to Dallas, Texas to map the micro-urban heat islands throughout the city (Fig. 10).

Dallas

In the entire Dallas area, the temperature scale was slightly broader than the subscenes, from a low of 65.09° F to a high of 88.50° F. Trees covered 34% of the Dallas scene, and 41% of the area was classified as micro-urban heat islands. Because the Dallas scene encompassed a large area, a subscene of the central business district (CBD) was created to display the individual micro-urban heat islands that are not visible when viewing the entire Dallas image (Fig. 11). The warmest areas in Dallas were the CBD, parking lots and roads, shopping centers, university campuses, and some bare fields. Again, all micro-urban heat islands have little to no tree cover to reduce the temperatures in the area.

Discussion and Conclusions

This study indicates that the TM thermal band is a useful tool for accurately mapping micro-urban heat islands in an urban area. This is evident
Fig. 10 Final micro-urban heat island map of Dallas.
Fig. 11 Enlarged portion of Dallas Central Business District.
from comparisons of the micro-urban heat island maps to aerial photographs and
ground truth verification of each scene. TM bands 3 and 4 were useful in
accurately mapping cover types in each of the scenes. This study concentrated
on the accuracy of tree cover mapping, and since unsupervised classification
proved 90% accurate, it can be assumed that the classification methodology also
correctly identified other cover types to at least the same high accuracy
evaluation.

When comparing the three subscenes, several similarities were evident.
In all areas the coolest portions of the image were those with heavy tree canopy
cover. These forested areas were either found in a park setting, such as the area
above White Rock lake, or in older, established neighborhoods, which could be
found in all scenes. While all subscenes contained older neighborhoods that
were cooler than the surrounding environment, Oak Cliff was unique in that most
of the scene was occupied by neighborhoods with a high tree density. The Oak
Cliff results highlight the fact that not only does increased tree cover significantly
reduce the number of micro-urban heat islands, they also reduce the intensity.
Oak Cliff had fewer micro-urban heat islands than the other scenes, and the ones
it did have were not as hot as those in Addison and White Rock.

When examining the final maps produced for each scene it was noted that
the micro-urban heat islands throughout the city were radiative in nature. That is,
the centers of the micro-urban heat islands were the hottest, with the cooler
regions located along the periphery. Micro-urban heat islands were most
prevalent in areas with a high percentage of impervious cover, including strip
malls, indoor malls, parking lots, intersections, and newly-developed
neighborhoods with little or no vegetation. Other significantly hot areas included
some golf courses, bare soil and airports. The final maps produced in this
thermal study also indicate that, while micro-urban heat islands heat radiatively,
trees, in turn, cool in a radiative manner. As evident in all the scenes, the cooling effects of trees extend well beyond their immediate vicinity, so that a stand of trees would reduce the amount of micro-urban heat islands in an area. Another facet of the results is that not only does it appear that trees significantly reduce the amount of micro-urban heat islands in a particular area, they also lower the intensity of the ones that do exist. In Oak Cliff, the scene with the highest percentage of tree cover (48%), the temperatures of the micro-urban heat islands only spanned a 6.46°F range. In Addison, only 19.4% of the scene was occupied by trees. Not only did Addison have the highest temperatures of the three subscenes, but the broadest range of micro-urban heat island temperatures. These hot areas spanned a 13.66°F temperature difference.

Based on the data obtained in this study, predictions can be made as to the occurrence of micro-urban heat islands in any region based on the percentage of tree cover. Figure 12 is a regression curve showing the relationship between the percentage of trees present in each scene, and the subsequent percentage of micro-urban heat islands existing in each area. It should be noted that the data point of the entire Dallas scene falls directly on the slope of the graph. This indicates that the three subscenes provided wide variability of tree cover that is found throughout the city. Because a linear relationship exists among the four data points, the graph can be used as a preliminary model to predict the amount of micro-urban heat islands present based on a certain percentage of tree cover. Although this graph is accurate within the confines of the above data, more data points will be needed to make it accurate for all data. The information that this model provides will be beneficial to city planners or other organizations that are interested in planting trees to combat the negative effects of micro-urban heat islands. This new model will
indicate the amount of trees that need to be planted in an area to reduce the number of micro-urban heat islands to a given percentage.

Improvements to this analysis would consist of taking ground temperatures at the time the satellite is flying over Dallas-Fort Worth. This would provide exact temperatures of the micro-urban heat islands instead of relative temperature differences because each DN value would represent an exact temperature value. Further improvements will occur with the launch of Landsat 7. This satellite will increase the resolution of the bands 1-5 and 7 from 30 m to 15 m.

This study opens the door for further analyses of the micro-urban heat islands. Studies need to be undertaken to determine the ideal time of year in which to map micro-urban heat islands, as well as the effects of urbanization on micro-urban heat island development.