THE USE OF LOW-COST DATA LOGGING TEMPERATURE SENSORS IN THE EVALUATION OF AN URBAN HEAT ISLAND IN TAMPA, FLORIDA

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1. INTRODUCTION

The detailed study of the urban environment did not really begin until the start of the 20th century. Early studies by Fassig (1907), Saucier (1949), and Ligda and Bigler (1956) established the hypothetical down-wind effect of cities, while studies by Woollum and Canfield (1968) helped in localizing the hypothesized downwind effect of cities. As the evidence for the modification of weather by urban areas began to amass, Changnon (1968) produced a report on the La Porte precipitation anomaly downwind of Chicago. The Changnon La Porte study brought about an awakening of researchers and the general public to the possibility that urban areas were having an effect on the weather. In the wake of the Changnon report, in 1971 four research teams came together in St. Louis, Missouri, in an effort to study the weather modification induced by the urban-industrial environment. As a result of the collaboration, the St. Louis METROMEX field project was undertaken. Prior to the METROMEX project, urban-related climate modification had been studied only to a limited degree. In order to more fully document the Urban Heat Island (UHI) phenomenon and the effects that urban areas were having on weather modification, the METROMEX study employed a dedicated network of sensors over a period of 5 years.

By definition, a UHI is characterized as higher air temperatures in urban areas than in the surrounding rural locations. Historically, in UHI research, the records of local established weather monitoring sites have been used in the gathering of data for UHI analysis. To more fully document the characteristics of the urban environment, the St. Louis METROMEX study employed 220 rain gauges and hail pads distributed evenly over an area of 5700 square kilometers in and around St. Louis, Missouri. Three radar sites were employed to gather first-echo rain data in the study area. Radiosondes were deployed to gather data on upper atmospheric conditions, and aerosol samplers were used to detect cloud condensation nuclei concentrations and air pollutants in and around the city. The St. Louis METROMEX study was the first research effort to attempt to adequately document the specific characteristics within an urban area that might be influencing the climate. It should be noted that the METROMEX study initially employed just 7 weather stations to record temperature data. This was increased to 25 temperature reporting weather stations later in the study period. The low number of temperature recording stations in the METROMEX study, deployed in a large survey area, may have limited the research team's ability to accurately correlate any changes in weather characteristics that might have been attributed to the UHI.

Other researchers have also investigated the UHI using the traditional approach of gathering data from local weather stations in addition to the installation of small networks of field sensors. Bornstein and Lin (2000) studied summertime thunderstorms in Atlanta, Georgia, and found that the UHI induced a convergence zone that initiated thunderstorms. Dixon and Mote (2003) also investigated Atlanta, with similar results. A limiting factor in these two studies was the size of the temperature sampling network used. The Dixon and Mote study utilized 10 recording weather stations situated over a 21 county area, while Bornstein and Lin utilized 42 recording weather stations spread over a 105,000 km^2 study area. The number

of temperature sensors employed in these two studies allowed the researchers to establish a general perspective on the Atlanta UHI and its effects. However, in order to obtain a more detailed understanding of the spatial distribution of the UHI of Atlanta, a larger temperature sampling network would have been desirable.

The low number of temperature recording stations that seem to characterize many UHI studies may be attributable to the generally high cost of recording stations and the logistic complexity of deploying the stations in the field. Recently, researchers have begun to deploy denser sensor networks to study the UHI. A case in point, as detailed by Bassara *et al.* (2009), is the new Oklahoma City micronet. Thirty-five weather monitoring stations were deployed atop light fixtures and traffic signals in downtown Oklahoma City and the surrounding suburbs. While an advancement in sensor density, the high cost of advanced weather stations and the logistics required to install and monitor them does not make this a viable approach where such resources are lacking. With advances in technology, researchers have also turned to satellite thermal imaging systems in an effort to gather more detailed information on the UHI. Looking to quantify the urban characteristics contributing to UHI, Xian and Crane (2006) utilized LANDSAT satellite thermal data to examine the urban characteristics and associated land cover in Tampa Bay, Florida. Similar work was conducted by Yuan and Bauer (2007), utilizing LANDSAT images to compare normalized difference vegetative index and impervious surfaces as an indicator of surface UHI effects. Both studies utilized the thermal infrared (TIR) capabilities of LANDSAT in their examination of the urban heat signature in their respective study areas. With a 60 m by 60 m spatial resolution in the thermal infrared band, the recent series of LANDSAT satellites provides a detailed view of land surface temperatures within a study area. The resolution is significantly greater than that provided by geosynchronous satellites or orbiting satellites such as MODIS (with its 1000 m by 1000 m resolution in the TIR band).

While satellite data analysis can provide useful information on components of the UHI, it is limited in three areas. First, overflight times of LANDSAT and other satellite platforms for the continental United States occur in the early morning hours, well prior to the maximum heating effects of the day, and provide no coverage during the maximum UHI night time period. Second, land surface temperatures recorded by the satellites do not directly reflect the air temperature in the urban environment, which is a major forcing function on the generation of a UHI. Third, the temporal frequency of imaging by LANDSAT and other satellite platforms only allows for observations every 2 to 16 days, assuming no periods of cloud cover, limiting the amount of data that can be collected.

What seems to be needed to more fully characterize the spatial and temporal aspects of the UHI is a low-cost temperature logging sensor that can be deployed in a spatially dense network and with sufficient data logging capacities to capture the relevant UHI temperature data. This paper details the usage of such a sensor in the study of the UHI in Tampa, Florida. To highlight the use of a low cost sensor, this paper presents several of the condensed results from a much larger study of the relationship between the percent of impervious surface and the rural to urban temperature differences (delta temperatures) within a Tampa study area.

2. DATA AND METHODS

The search for an appropriate low cost temperature data logging sensor led the authors to the Dallas Semiconductor company. An examination of the Dallas Semiconductor data catalogue revealed a small form temperature data logging sensor which contained an internal power source and is environmentally sealed. The device is the Dallas DS1921 Thermochron series of data loggers. This device is available in several different temperature ranges. The device chosen for this study was the DS1921H which has a temperature measurement range of 15 to 46°C, which is a good match to the expected summertime temperature range of 21 to 32°C in the Tampa study area. The Dallas DS1921H is capable of logging temperature data at user-defined rates of 1 to 255 minutes between measurements, and can store 2048 such measurements. The unit has a resolution of 0.125°C and an accuracy of

better than 1°C over its entire range. In addition, each DS1921H sensor has a unique serial number embedded within its firmware, allowing for tracking of deployed sensors. With a cost of $16 per sensor in bulk, the total cost of implementing the 100 sensor network of this study was $1,600 (significantly less than the weather stations deployed by Bassara (2009) mentioned earlier). Figure 1 depicts the relative size of a Thermochron sensor.
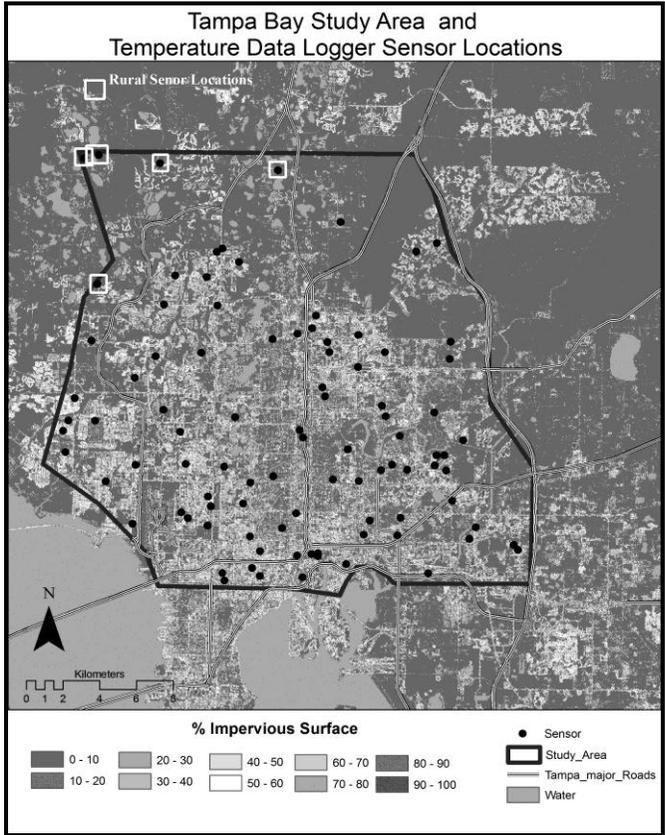

FIGURE 1
DS1921 THERMOCRON SENSOR SIZE

Other researchers have also used the Dallas Thermochron sensor in their studies. Hubbart *et al*. (2005, p. i) evaluated the performance of the Thermochron sensor and their results indicated that, "the Thermochron IButton is an accurate, inexpensive alternative to more expensive temperature data logging systems, and is well suited for obtaining quality spatially distributed data ...". Johnson *et al.* (2005) used the Thermochron sensor to document groundwater and river interactions, and Hartman (2006) used the Thermochron sensor to remotely monitor bird nesting. The HOBO series of data loggers was also investigated; however, the least expensive HOBO outdoor temperature sensor had a cost of $36 (with quantity purchase), over double the cost of the Thermochron sensor. In addition, it did not have the capability to synchronize recording start times or a variable sampling rate, and its 90 percent temperature settling time was 10 minutes, compared to the two minute settling time of the Thermochron sensor. Therefore the DS1921H temperature logging sensor was chosen for the Tampa area UHI study.

The determination of the sensor placement within the study area was accomplished using Hawth's tools for ArcGIS (Beyer, 2006). As part of the Hawth's random point generation routine, random point generation can be influenced by the cell values within a raster layer. As the study of the UHI in Tampa was ultimately concerned with the relationship between the percent of impervious surface and the temperature difference between rural and urban locations, a 2002 impervious surface raster image (USGS, 2007) of the study area was used as a weighted probability layer in the random point generation. Each cell within the impervious surface raster image could have a value of between 0 and 100. Utilizing the study area impervious surface raster as the weighted probability distribution raster layer, a random point set of 100 points was generated, where the cells having a higher percentage of impervious surface were more likely to have a sample point in that location. This method met the needs of using a random sampling routine while still investigating those areas that had a higher percentage of impervious surface and therefore more likely to contribute to the generation of a Tampa UHI. Other sampling methods could have been used, such as random transects of the study area. However, because of Hawth's tools random stratified sampling method's ability to incorporate a weighted probability raster image in the sample point generation, it was deemed

to be more appropriate in the study of the relationship of percent of impervious surface and urban delta temperatures. Figure 2 depicts the sensor placement in the study area. Within the study area, utility poles appeared to be a good mounting structure for the temperature data logging sensors. Therefore permission was obtained from Tampa Electric Company (TECO) to attach the Thermochron sensor to their utility poles. Sensors were attached to the north face of each utility pole to minimize direct sunlight and any induced heating effects. Figure 3 depicts a typical sensor installation.

FIGURE 2
STUDY AREA SENSOR LOCATIONS

   Prior to installation of the temperature data logging sensors in the field the sensor must first be programmed with the current local time, the required sampling rate, required sampling start date and time, and location identification number. A commercial software package offered by Scanning Devices, Inc., is available to manage the setup and to later download and format the collected temperature data. During this study temperatures were logged every thirty minutes.

   Temperature data sampling was conducted in the summer of 2007 when one hundred temperature data logging sensors were deployed in the Tampa study area. The sensors were located in accordance with the designed sampling scheme. A second sampling period in the summer of 2008 was used to validate the data collected in the summer of 2007. Of the 100 sensors initially deployed, two sensors stopped recording prior to the end of the sample period and four sensors were removed by unknown parties. The data from the two stopped sensors were discarded. The remaining 94 sensors provided data over the entire 2007 sampling period.

FIGURE 3
SENSOR INSTALLATION

During the sampling period each temperature sensor logged 2048 temperature readings. With a complement of 94 valid sensors, this resulted in a total of 192,512 30-minute period temperature readings being recorded during the 2007 sampling season.

3. RESULTS

For the purposes of this study, five sensors were specifically sited in rural locations outside of the Hawth's-generated random sensor placement scheme for the urban placements. These five rural sensors were placed in locations with similar ground cover and less than 15 percent impervious surface within a 100 meter radius. To minimize the differences in siting characteristics, a mean value of the five rural sensors temperature was calculated for each 30 minute sample period. These mean values then served as the 30 minute rural temperature value in later calculations. Subsequently, the 30 minute mean rural temperature value was then subtracted from each 30 minute urban sensor temperature value. The result was a delta temperature reading for each urban sensor location at 30 minute intervals. To obtain a basic delta temperature profile of the Tampa study area, all of the study area urban delta temperature readings were averaged over the entire 2007 sample period to gain an average 24-hour temperature profile. Figure 5 depicts a basic delta temperature profile of the Tampa study during a 24-hour day, starting at 00:00 (midnight) EDT.

An examination of individual sensor location mean study period values was conducted. A representative commercial and residential sensor location are highlighted here. Figure 6 depicts the 2007 delta temperature plot of the sensor #71 data. Sensor #71 was located in a commercial land use area. The designation of a commercial land use area was based on observations taken during installation of the sensors. An area was deemed to be in the commercial land use category if the surrounding area consisted of high-rise office buildings, a large shopping center or larger strip mall. Examining Figure 6, starting after sunrise at 06:30 hours there is a marked drop in the rural to urban temperature difference. This drop can most likely be attributed to the greater thermal mass and heat capacity corresponding to a larger
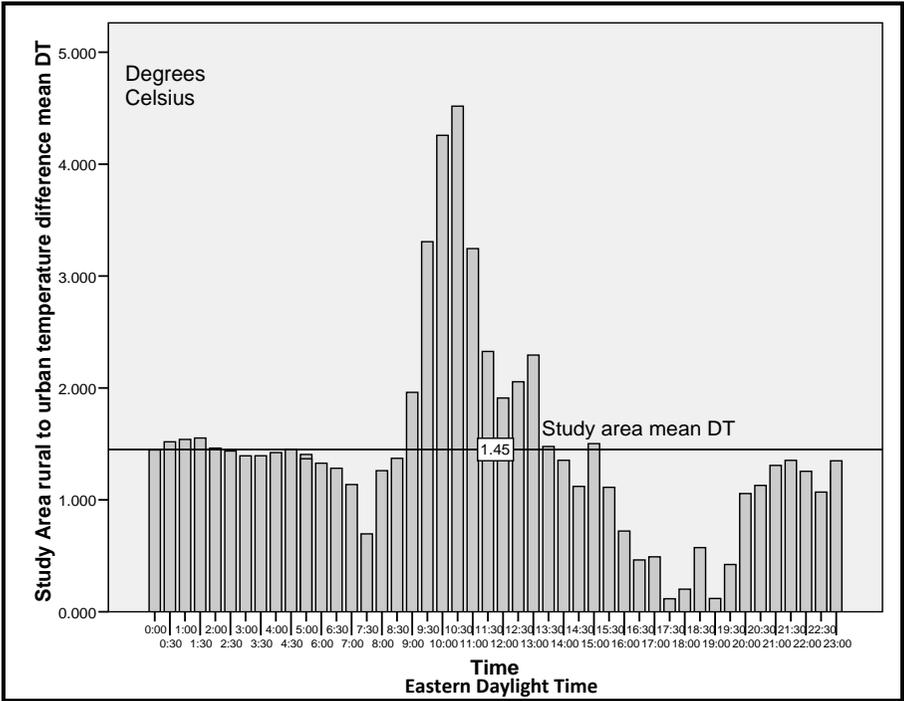
256

FIGURE 5
TAMPA STUDY AREA 24-HOUR MEAN RURAL-TO-URBAN
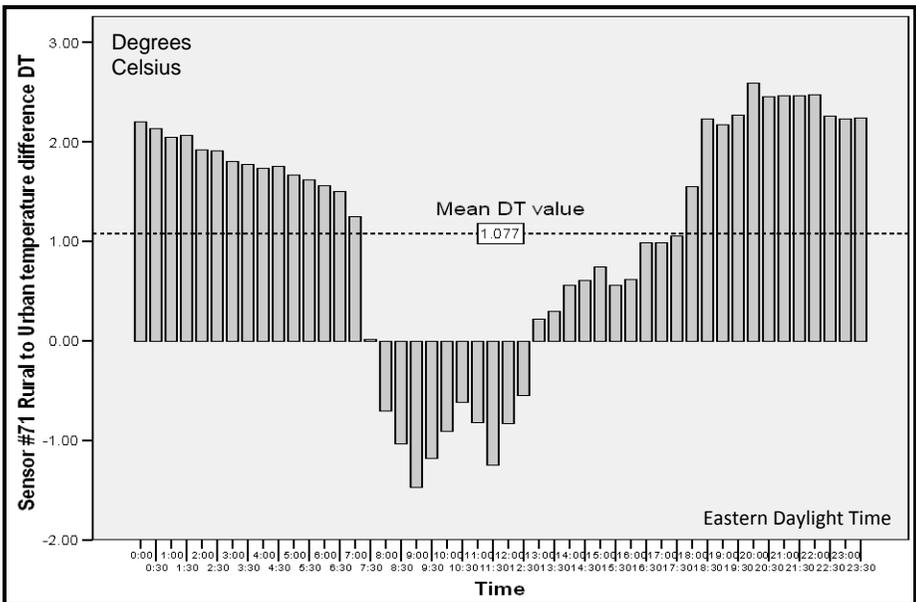DELTA TEMPERATURE VALUES (°C)

FIGURE 6
AVERAGE TEMPERATURE RECORD FOR SENSOR IN A COMMERCIAL AREA (°C)

thermal charge time constant of the commercial area as compared to the rural area. Grimmond and Oke (1999, p. 922) found that "Results indicate the storage heat flux is a significant component of the surface energy balance at all sites and is the greatest at downtown and light industrial sites." In addition, they found that there is a distinctive time lag between delta thermal storage and net radiative flux. Urban areas, with their greater thermal mass, have a slower response time (thermal hysteresis), requiring a greater amount of energy input for a corresponding rise in temperature as compared to a rural location. When examining urban to rural temperature differences, the lagging temperatures of the urban area will manifest themselves as a negative temperature difference. This may account for some of the unexpected urban cool island that was seen by Haffner and Kidder (1999). As detailed in Oke (1982) rural areas will tend to express residual energy flux as increased latent heat of evapotranspiration, and a smaller value as sensible heat, whereas the urban area with its dryer environment will express residual energy flux primarily as sensible heat. After initial thermal capacitance charge, the difference in generation of sensible heat will result in the rural-to-urban temperature differences being positive.

Figure 7 depicts the 2007 delta temperature plot of the sensor #76 data. Sensor #76 is located in a residential land use area. An area was deemed to be in the residential land use category if the surrounding area was composed of single family or duplex residences. The rural to urban delta temperature value goes negative shortly after sunrise in a similar fashion to the commercial area. However, the duration of negative delta temperature values is less than the commercial area. In addition to lower thermal mass, as compared to the commercial area, residential areas tend to have more vegetative cover and more characteristics in common with rural areas, which may account for the smaller temperature differences between the rural and residential areas.
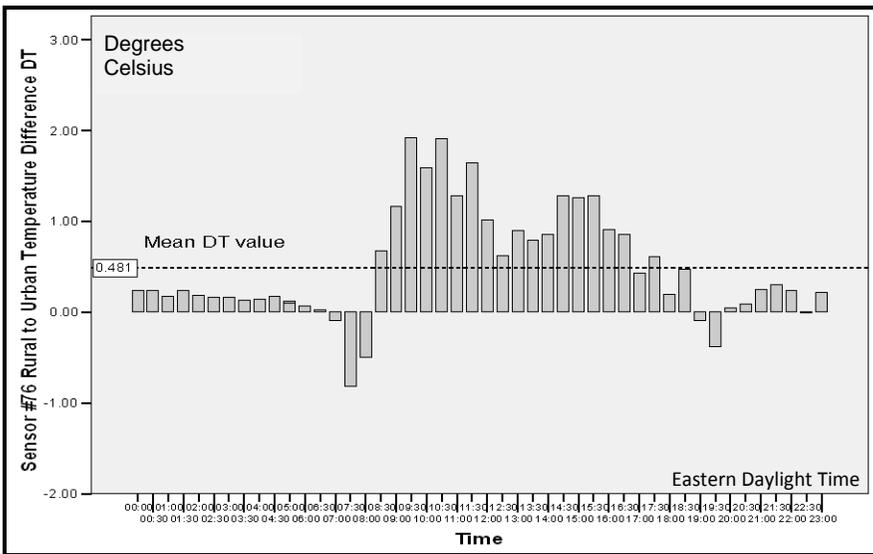

FIGURE 7
AVERAGE TEMPERATURE RECORD FOR SENSOR
IN A RESIDENTIAL LOCATION (°C)

The spatial distribution of delta temperature values was examined. Figure 8 depicts the spatial distribution of the 2007 delta temperature values in the Tampa study area at 11:30 hours. With the density of sensors deployed, discernable patterns begin to emerge. These patterns are correlated with the percent of impervious surface at the sensor location. Seen in a spatial perspective, data from the temperature sensors would tend to indicate that a UHI is not

homogeneous and in fact varies spatially within an urban area. The area of the Tampa study area is approximately 525 km^2. With a compliment of 100 sensors, this equates to approximately one sensor for every 5.25 km^2. In comparison, the Bornstein and Lin (2000) Atlanta study utilized 42 recording weather stations spread over a 105,000 km^2 study area. This equates to 1 sensor for every 2500 km^2. The Tampa study area sensor density is 500 times as dense as the Bornstein and Lin study.

Comparison of the 11:30 temperature pattern (Figure 8) with the 15:00 temperature pattern (Figure 9) indicates that the Tampa study area UHI not only varies spatially, it also varies temporally. Additional research (not described here) has shown that there is a very significant direct spatial and temporal relationship between the percent of impervious surface in the Tampa study area and the delta temperature of the Tampa UHI.
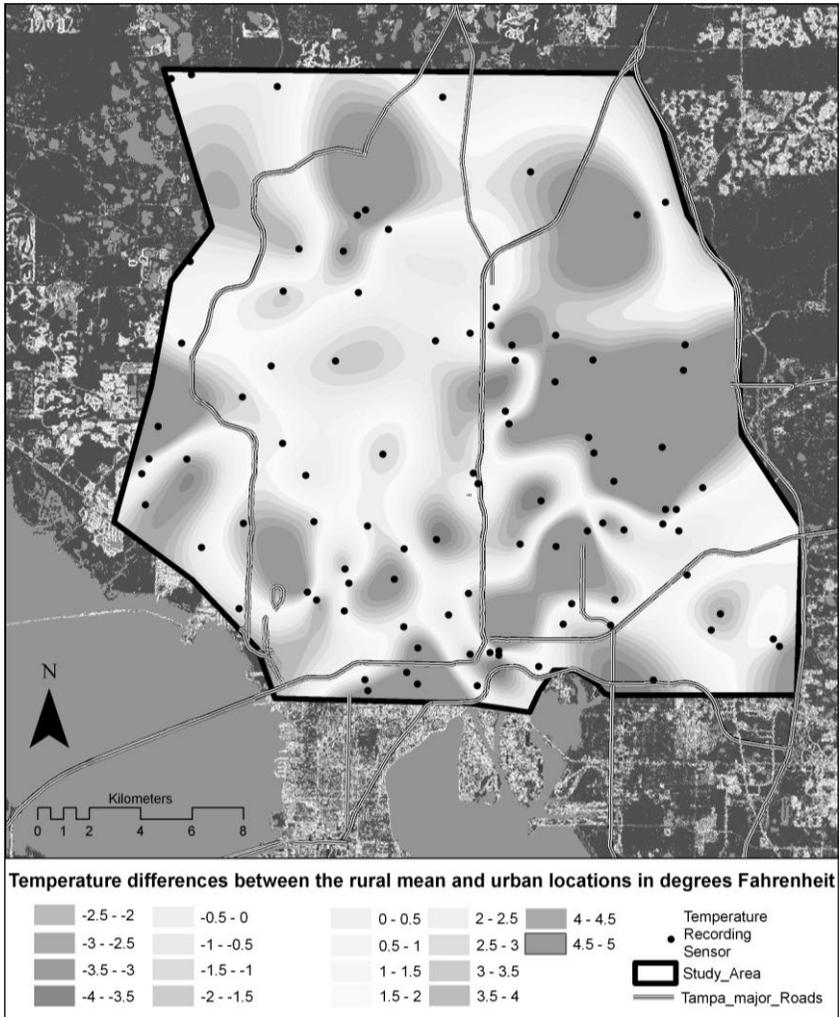

FIGURE 8
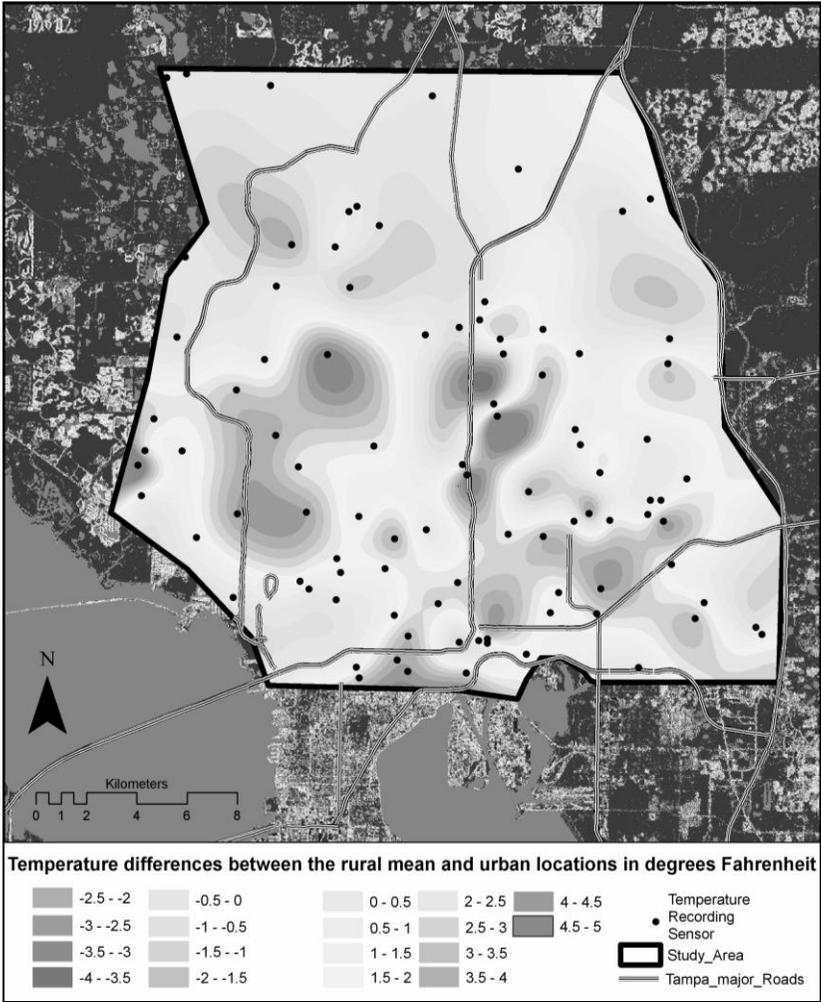TAMPA STUDY AREA 11:30 EDT TEMPERATURE DIFFERENCES

FIGURE 9
TAMPA STUDY AREA 15:00 EDT TEMPERATURE DIFFERENCES

4. CONCLUSIONS

The Dallas Semiconductor Thermochron series of data logging temperatures appear to be a useful tool for the study of the spatial and temporal aspects of a UHI and has many advantages over other types of sensors which should be considered when performing a UHI analysis. The use of these low cost temperature data logging sensors enables one to deploy more sensors and at a lower cost. The increased density of sensors enables one to investigate spatial and temporal aspects of a UHI not available using a conventional low density weather station method and does not have any of the timing correction problems associated with a vehicle transect sampling method. The Thermochron sensors also provide a significant improvement in temporal resolution as compared to satellite thermal infrared imaging in addition to measuring the actual air temperature in comparison to land surface temperatures measured via satellite. The use of the Thermochron sensors should be considered in planning any study that requires logging of temperature data.

5. ACKNOWLEDGEMENTS

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