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Urbanization and Land Surface Temperature in Pinellas County, Florida

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Urbanization and Land Surface Temperature in Pinellas County, Florida

by

Bruce Coffyn Mitchell

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Arts
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ASTER ........... Advanced Spaceborne Thermal Emissions and Reflection Radiometer, 23
AVHRR ................................ Advanced Very High Resolution Radiometer, 23
CIR ................................................................. Color Infrared, 39
CRRC ............................................................... Cool Roofs Rating Council, 94
DEM ................................................................. Digital Elevation Model, 38
DOQQ ............................................................... Digital Orthophoto Quarter Quads, 41
EPA ................................................................. United States Environmental Protection Agency, 87
EPDM ............................................................... Ethylene-Propylene-Diene Monome, 94
FLUCCS .......................................................... Florida Land Use Land Cover Classification System, 37
GIS ................................................................. Geographic Information System, 47
GPS ................................................................. Global Positioning System, 51
GPSMET .......................................................... Global Positioning System Meteorology, 39
ICCUHI ............................................................. International Conference on Urban Heat Islands, 87
IEA ................................................................. International Energy Agency, 87
ISA ................................................................. Impervious Surface Area, 5
LANDSAT ......................................................... Land Remote Sensing Satellite, 23
LOWTRAN ........................................................ Low Resolution Transmission Model, 46
LST ................................................................. Land Surface Temperature, 4
LULC ................................................................. Land Use Land Cover, 38
METROMEX ....................................................... Metropolitan Meteorological Experiment, 16
MODIS ............................................................. Moderate Resolution Imaging Spectroradiometer, 23
MODTRAN ........................................................ Moderate Resolution Transmission Model, 46
MUHI ................................................................. Micro Urban Heat Island, 38
NDVI ................................................................. Normalized Difference Vegetation Index, 5
NHAP ............................................................... National High Altitude Photography Program, 56
NOAA ............................................................... National Oceanographic and Atmospheric Administration, 39
SUHI ................................................................. Surface Urban Heat Island, 4
SWFWMD ......................................................... Southwest Florida Water Management District, 37
TM ................................................................. Thematic Mapper, 23
TRUCE ............................................................. Tropical Urban Climate Experiment, 87
UCF ................................................................. University of Central Florida, 88
UCL ................................................................. Urban Canopy Layer, 42
UHI ................................................................. Urban Heat Island, 2
USGS ............................................................... United States Geological Survey, 38
UTC ................................................................. Coordinated Universal Time, 51
WGS ................................................................. World Geodetic System, 38
ABSTRACT

Since the early 1800’s, many studies have recognized increased heat in urban areas, known as the urban heat island (UHI) effect, as one of the results of human modification to the natural landscape. UHI is related to differences in land surface temperature (LST) between rural areas and urban areas where factors of the built environment such as the thermodynamic capacities of materials, structural geometry, and heat generating activities cause increased storage and re-radiation of heat to the atmosphere. This thesis examines the correlation between factors of urbanization and differences in land surface temperature (LST) in the subtropical climate of Pinellas County, Florida using remote sensing techniques. It describes the spatial pattern of LST, analyzes its relationship to factors of urbanization relative to NDVI, percentage of impervious surface, and land use land cover in the study area. It also assesses the effectiveness of remote sensing as an efficient method of identifying LST patterns at the local and neighborhood level for mitigation strategies.

Landsat TM thermal band imagery for three dates; April 1986, 2001 and 2009 was processed using Qin’s mono-window algorithm (MWA) technique to derive LST levels. This data was compared to in-situ readings, then normalized and statistically analyzed for correlation with vegetation ratio (NDVI) and
imperviousness percentages derived using linear spectral mixing/unmixing, and also with land use/land cover classification.

The resulting LST spatial pattern is a gradient across the peninsular landscape, from cooler water and wetland areas to a generally warmer interior, interspersed with micro-urban heat islands (MUHIs), corresponding to urban structures and “cool-islands” of parkland and lakes. Correspondence between LST pattern and urban structures and land use demonstrates the suitability of medium resolution remote sensing data and techniques for identifying micro-urban heat islands (MUHIs) for possible mitigation. Mitigation could include relatively low-cost measures like replacement of inefficient asphalt roofs with more reflective and emissive “cool roofs,” placement of “street trees” to enhance shade, and replacement of impervious pavements by permeable surfaces.

The thesis concludes that Landsat TM imagery processed with the MWA provides an efficient, relatively low-cost method for locating MUHIs. Satellite remote sensing, combined with aerial photography can facilitate neighborhood level analysis for the implementation of low-cost mitigation techniques. Previous studies have demonstrated that these are successful ways to mitigate the UHI effect at the micro-scale level; lowering urban heat and saving energy, and also facilitating the reintegration of natural elements into the urban environment.
CHAPTER 1: INTRODUCTION

Geographers have studied human and environment interaction since the time of Alexander von Humboldt, who commented on the effect of deforestation and consequent microclimate change on the South American landscape (Humboldt, 1819).¹ Later in the 19th century, the American geographer George Perkins Marsh wrote and lectured extensively about the effects of human agency on the natural landscape, warning of imprudence and urging caution in development (Martin, 2005). Since that time, human exploitation of the land and its resources has become more extensive, increasing the importance of quantitative study of the impact of these processes to the Earth. Humanity crossed an important threshold in the first decade of the 21st century; half of the world’s population now resides in urban areas according to United Nations estimate². The same estimate projects that by 2035 the number of urban dwellers will increase to 61%. This dramatic shift in population from rural to urban areas constitutes a process of global urbanization. This accelerating process is expected to occur mostly in developing countries, which are primarily

¹ Humboldt determined that deforestation altered the rainforest microclimate, hastening the process of evapotranspiration. The soil lost its moisture and eroded during subsequent torrents which swept hillsides (Humboldt, 1819, P.143). Later in his career, Humboldt developed the technique of connecting temperature observation points of equal value with lines, originating isotherm mapping (Martin, 2005).
in tropical and subtropical regions\textsuperscript{3}. Aside from the economic, social and psychological impacts of this increasing alienation from the natural environment and its processes, urbanization’s most noticeable aspects which can be described quantitatively are:

(1) Decline in vegetation levels as land is cleared.

(2) Expansion of impervious surface coverage as structures and road are built.

(3) Increased population density as people move to the developing area.

It also alters the climate at a local level, one of the better known results of which is the urban heat island effect.

The urban heat island effect (UHI) is easily understood as the difference in solar radiation reflectivity (albedo), and thermal conductivity and thermal storage capacity between surfaces which typify rural and urban environments. Imagine a square meter of asphalt, and of grass in the summer sun. Which would you prefer to walk across, and why? Grass is much cooler, while asphalt due to its black color which reduces its capacity to reflect the sun’s energy back to the atmosphere, is hotter and therefore much less desirable. Asphalt’s compact and homogenous structure is more effective at conducting and storing thermal energy than is grass and soil. This is the greatly increased thermal capacity of most materials which make up the built environment of an urbanized area. Because of this thermal capacity, asphalt is capable of storing greater

\textsuperscript{3} http://www.unfpa.org/public/publications/pid/408
amounts of energy and then reradiating back to the atmosphere, as long wave energy or heat long after sun down. In contrast, grass and the underlying soil reflect or diffuse more of the energy, and also use energy in the processes of photosynthesis and evapotranspiration. Additionally, vegetated surfaces have greatly reduced thermal capacity. Since less energy is conducted and stored, the surface does not get as hot, reradiating the thermal energy, and cooling more quickly at night.

Reduction of vegetation and its replacement by impervious surfaces, like asphalt and concrete, are directly related factors of urbanization which have environmental and societal consequences. Vegetation benefits the environment in many ways; reducing CO$_2$ levels, improving air quality by removing pollutants, mitigating storm water runoff, and reducing UHI through evapotranspiration and provision of shade\(^4\). Impervious surfaces are an important element of the urban built environment, but they seal the land’s surface from moisture penetration and because of their different thermodynamic properties from natural land cover, alter the local energy balance. It heats both the air and water which it contacts, causing temperature increases to the atmosphere and water resources. The increased runoff and higher temperature of urban and suburban streams and lakes impacts aquatic species however, this thesis will focus on the impact of urban heat to the lower atmosphere.

This alteration of the local energy balance has been recognized as one of the effects of urbanization since the early 19th century. Luke Howard, meteorologist and originator of the modern cloud classification system first noticed the effects of the UHI and documented a consistent 1°C difference between several rural locations and London (1820). He postulated that the building materials and industrial processes of urban areas stored and radiated heat energy in a different manner than areas with agricultural or natural land cover (Mills, 2008). After Howard’s pioneering efforts, more than 100 years elapsed before modern technology and methods were used to extend his hypothesis to fully describe and quantify the “urban heat island” effect (UHI). Scientists like Åke Sundborg, T. J. Chandler, Helmut Landsberg, and Timothy Oke pioneered efforts to identify, statistically assess, and study the energy dynamics of the UHI. Their efforts demonstrate that there is a correlation between urbanization and greater urban temperature typical of the UHI. Most of these efforts have been focused on in-situ measurements of near-surface (screen-level) air temperature of the atmospheric boundary layer UHI to establish the intensity of temperature differences, or ∆T between rural and urban areas.

While there are several causative factors to the atmospheric UHI, difference in land surface temperature (LST) depending on land cover type is the most fundamental one (Landsberg, 1981; Voogt & Oke, 2003). Urban areas are constituted of large amounts of impervious built surfaces, intermixed with
vegetation. As we saw with the examples of asphalt and grass, the reflective and conductive properties of impervious surfaces cause them to absorb and store more thermal energy than vegetated surfaces, which then radiates to the surrounding atmosphere for a longer period of time causing the atmospheric UHI. LST, the critical component of the atmospheric UHI can be observed with satellite or aerial remote sensing technology. Voogt and Oke (2003) proposed that the LST urban heating pattern observed by remote sensing should be known as the “surface urban heat island,” or SUHI. It is an indicator of the energy stored by natural and built surfaces that is then radiated to the surrounding air, impacting temperature of the lower atmosphere.

This thesis will examine the surface urban heat island of Pinellas County through remotely sensed measurement of LST across the area. Since the impact of future urbanization is likely to be most noticeable in sub-tropical and tropical regions, the Tampa Bay area presents a good site to test hypotheses related to regions with similar climate and topography. The following research questions will be examined:

1. What is the spatial pattern of land surface temperatures (LST) in Pinellas County?

2. What are the characteristics of the land surface temperature pattern relative to imperviousness (%ISA), vegetation (NDVI), and land use/land cover (LULC) in Pinellas County? Is there a correlation between LST and these factors of the urban landscape?

3. How effective are remote sensing techniques at assessing the LST pattern within the study area, and can they provide an efficient method of analyzing spatial patterns indicative of the surface urban heat island (SUHI) across the land surface?
Answering these questions for the Pinellas area, may assist with the development of an efficient and low-overhead method of analyzing LST in (sub)tropical regions. Combining more efficient methods of LST analysis with efficient, low-cost UHI mitigation techniques which could be employed in less developed regions would reduce the impact of increased heat as a side-effect of urbanization and lessen energy demand for cooling, which would also cut expenses and emissions due to fossil fuels.
CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

2.1. History of Urban/Rural Temperature Differences

Differences between urban and rural temperature have been generally understood since the early 19th –Century. While the mechanisms of what we now call the “urban heat island effect” had been described, urban heat was mainly the concern of the medical community and early urban planners who sought to remediate its health effects within the context of miasma theory. It was not until the early 20th –Century that systematic study of the issue and its implications were undertaken. This research extensively quantifies the UHI and its underlying causes.

2.1.1 Early Description of Rural/Urban Temperature Differences

It seems that what we now call the “urban heat island” was first described and documented as a phenomenon in the observations of meteorologist Luke Howard in The Climate of London: Deduced from Meteorological Observations, Made at Different Places in the Neighbourhood of the Metropolis, 1818-1820, Vol II (1820). Howard, who is best known for his systematic description and naming of clouds, noticed consistent differences between his temperature observations at several locations outside London and higher temperature readings made by the Royal Society within the city (Mills, 2008). He conducted a detailed analysis,
comparing monthly mean temperature from 1806-1816 for urban and rural locations, concluding that there is difference in temperature between the locations of 0.27°C in Spring to 1.19°C in Fall (Howard, 1820). His notes state that: “But the temperature of the city is not to be considered as that of the climate: it partakes too much of an artificial warmth, induced by its structure, by a crowded population and the consumption of great quantities of fuel…” (Howard, 1820, p. 103) So he attributed this difference in temperature to several factors unique to urban environments; human activities such as burning of fuel for domestic uses and industrial processes, the general crowding, and the structure of the city, its urban fabric. He speculates that structures in the city because of their vertical surfaces reflect heat on each other and impede airflow (Howard, 1820, p. 106). Additionally he describes how greater evapotranspiration contributes to the cooler temperatures in rural areas.

“When we consider that radiation to the sky, the contact of fresh breezes, and evaporation, are the three principle impediments to the daily accumulation of heat at the surface, we shall perceive that a city like London ought to be more heated by the summer sun than the country around it.” (Howard, 1820, p. 106)

This effect is most pronounced in the evening, when the surfaces in the city continue to radiate heat, causing the city to lose its heat more slowly than rural areas. From these early observations, Howard deduced three issues:

1. Temperature levels in London are directly impacted by anthropogenic change.

2. A mechanism of this temperature increase is the built surfaces which cause heating by radiating stored energy and allow less evapotranspiration.
3. Temperatures in the city should not be extrapolated to general climate change for the region.5

So, in Howard’s work rural and urban temperature differences are documented and several mechanisms of the process are discussed. While he did not describe the energy dynamics in detail, a general sketch of processes involved is provided. The extent of this understanding for atmospheric scientists would not advance for 100 years.

Differences in temperature between rural and urban areas were generally recognized during the 19th Century. Meyer, in “Urban heat island and urban health: early American perspectives” (1991) documents the sometimes vague recognition of climate differences between rural and urban areas in America. Differences in urban climate were usually part of a medical concern about epidemics, which periodically ravaged cities before the 20th-century. Common medical understanding at the time attributed these outbreaks to “miasma,” putrescent organic material which vaporized and polluted the air, made worse by summer heat. The fact that epidemics could also occur during winter months did not erode the credibility physicians gave this theory. Outbreak of diseases like malaria (literally “bad air”) and yellow fever did intensify with mosquito activity during the summer, lending credence to the theory. 19th-Century urban planning was impacted by the miasma theory, and cities were redesigned with broad boulevards, like Baron Haussmann’s work in Paris. This was justified on medical

5 Noah Webster noted the last issue in New York in 1799, (vol. 2, p. 311n)
and aesthetic grounds. It is clear that by 1880 the general causative factors of intensified urban heat were understood. The *New York Times* reported that “All other things being equal, great cities are warmer than small cities, on account of the larger heated mass, radiation from the streets, buildings, &c.” A rational approach to urban design emphasizing greater amounts of open space for parks and boulevards developed to lessen these effects. The principal response to increased urban temperature is seen in the work of urban planners during that era like Frederick Law Olmstead, who established public parks as a preeminent feature of their designs, as means of enhancing public health and recreation in growing cities.

For the meteorologists, other than Howard, who were concerned with urban/rural temperature differences, activity was focused on documenting the phenomenon and lamenting its impact on their climate observations. From his weather station outside Paris, Emilien Renou remarked on the air pollution of the city and its possible effect on temperature, also noting that “the temperature difference between the countryside (and the city) is about 1°C...” (Renou, 1868). An awareness of the moderating effect on diurnal high and low temperature is displayed when he states: “The cities, particularly the large ones, retard the march of temperature and thus alternate the oscillations, especially the most abrupt ones.” (1868) He also seems to have understood that this moderating effect was most notable in the evening and when the weather was clear and calm, and that winter temperatures were higher, hampering freezing in cities.

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6 New York Times, May 29, 1880
An American meteorologist, Oliver Fassig in "The Climate and Weather of Baltimore" (1907) used the resources of the Maryland Weather Service to document every aspect of the climate of that city, including differences between urban and rural temperatures. This effort was primarily descriptive, and he did not explore the issue further. What Meyer concludes is that assessments of differences between rural and urban temperature in the 18th, 19th, and early 20th century were primarily related to medical concerns, consequently, "...they left little imprint on the atmospheric sciences..." (p. 46). Indeed, while Howard had an understanding of the physical mechanics of energy storage and re-radiation by human built structures, Renou and Fassig were focused on observations that would enable them to discover climatic patterns. This seems to characterize the attitude of meteorologists at the time, whose primary concern with urban heating was local temperature variation masking large-scale climatic change. They understood that their observations at fixed meteorological stations were being impacted by encroaching urbanization, but failed to probe further.

2.1.2 Modern Understanding of the Urban Heat Island

Understanding of the UHI evolved due to the improved instrumentation and statistical techniques developed in the last century. As the ability to quantify its effects has expanded, understanding of the underlying physical processes of urban heating with urbanization has improved. As a result, knowledge of the
UHI, the scale of its impact, and its relationship with change in land cover and land use is now well documented.

Study of the effect of climate on life processes is the focus of *Biometeorology*, which was pioneered in Europe. Since the lower atmosphere is most directly in contact with living things, biometeorologists sought ways to observe climate processes near the earth’s surface, which also typifies micrometeorology. It is thought that the Austrian biometeorologist, Wilhelm Schmidt pioneered the use vehicle mounted meteorological instruments sometime prior to 1927 (Sundborg, 1950). This technique allowed precise measurements to be taken in the near-surface atmosphere at exact locations from moving or stationary platforms, so results could be mapped using isotherm lines (Landsberg, 1981). It became the standard way to make temperature observations of rural/urban differences for the next 50 years. In Canada, Middleton and Millar (1936) used this method, attaching a resistance thermometer to an automobile and driving transverses in Toronto during different seasons. They recorded city boundaries and elevation, along with temperature. Wide fluctuations in temperature were documented, with one summer trial showing differences from 23.89° to 29.44°C, a variation of 5.6° C. In some cases they recorded temperature variances of 15°C from the bottom to the top of a hill. Their approach was purely descriptive, and concluded that “extreme care” need be taken in the placement of meteorological thermometers to control for variables like elevation of observation. The technical tools to study
the UHI were available, it remained for someone to combine these tools with quantitative techniques and fully document it.

A classic study of variation between urban and rural temperatures was completed by Åke Sundborg in the city of Uppsala, Sweden (1950). Schmidt and Middleton & Millar had proven the viability of the mechanical technology for data collection, which Sundborg then used to make comprehensive observations to test his hypotheses. Mobile traverses were systematically planned and driven through rural areas and into the city at different times of day, during all seasons. The collected data was then used to map temperature differences using isotherm lines and to complete a series of statistical regressions, beginning the comprehensive quantification of the relations of the UHI to land cover and seasonal differences. Topography impacted the results with greater standard deviation between readings taken at high and low elevations. Land cover was a factor with areas of vegetation playing a part in greater temperature variation. These factors were adjusted, and traverse routes which minimized them selected. Results were:

1) Temperatures in settled areas were higher than their surroundings, with the greatest difference at night.

2) Elevation played an important role, with cooler temperature at higher elevation.

3) Forest temperatures were lower during the day and higher at night.

Rural and urban temperature differences were expressed in a set of regression equations of day and night temperatures. A correlation between observed and
calculated day and night temperatures was estimated at $R=0.49$ and $R=0.66$ respectively. Sundborg’s empirical methodology combined with statistics was a major improvement of quantitative technique. Several scientists after him; J. Murray Mitchell and particularly T.J. Chandler expanded on this work during the 1950’s.

The term *heat-island* is thought to have been originated by Gordon Manley in the late 1950’s (Landsberg, 1981). Manley was an English climatologist who did extensive work on the historical temperature record of the British Isles. The term certainly appears in connection with Manley and Chandler in the introduction to a paper on “London’s Urban Climate” from 1961. Chandler expended considerable effort for “The London Climatological Survey” resulting in several papers and a comprehensive work, titled (perhaps in tribute to Howard) *The Climate of London* (1965). He followed then current methods, driving traverses through London, monitoring both temperature and humidity fluctuations along the route. Beyond this, he established a network of observers to take simultaneous readings at fixed locations throughout the city and surrounding areas, improving synoptic mapping of the UHI. He was able to document temperature differences between urban and rural areas between 1931 and 1960, producing isotherm maps (like Sundborg before him) of the London region along with sophisticated temperature traverse maps. Isotherm mapping\(^7\) provided the clear depiction of a temperature gradient, rising from rural areas to

\(^7\) A technique which Humboldt adapted from mathematics for use in climatology.
the urban region, appearing like an island of elevated readings amidst a sea of lower temperatures. Manley subsequently referred to this as a “heat-island”, establishing the term.

Aside from his comprehensive approach and improved data collection methods, Chandler improved on quantitative assessment and statistical methodology was to compute regression equations of temperature variation, or $\Delta T$ between rural and urban areas, with the variables of cloudiness, wind speed, and temperature. He found correlations for differences between urban and rural minimum summer and winter temperatures of $R= 0.608$ and $R= 0.563$ respectively. This relation is less for difference of maximum temperature with $R= 0.286$ for summer and $R= 0.114$ for winter. He also documented an occasional “cold-island” reversal of normal conditions, in which the urban area heats more slowly than surrounding rural areas. The overall effects on London are a termination of ground frost 23 days prior to the surrounding area, which consequently extends the growing season there. Overall, Chandler sees the heat island effect in London as “a leading element in the pattern of spatial change” from the surrounding area (p. 184). Chandler noted several benefits of the UHI for mid-latitude regions including lower heating energy requirements and benefits to transport. His later work for the World Meteorological Organization extensively quantified energy exchange relationships with urban structures (Urban climatology and its relevance to urban design, 1976).
William P. Lowry conducted a broad-brush review of issues in “The climate of cities” (1967), presenting then current state of knowledge with thermographic city images. This relatively new technology allowed the temperature signature of urban structures to be analyzed. In “Empirical estimation of urban effects on climate: a problem analysis” (1977) he critiqued then current understandings of urban climate change, proposing instead an empirical model to evaluate all factors of the urban climate through the use of synoptic typing applicable to the evaluation of many different regions. A central element was its ability to account for the “pre-urban” character of the land and effects of broader scale climatic change. It is conceptualized by the equation:

\[ M_{itx} = C_{itx} + L_{itx} + E_{itx} \]

where

- \( M \) is the measured value of the weather element
- \( C \) is the “background” climate
- \( L \) is the effect of local landscape
- \( E \) is the effect of urbanization
- \( i \) is the weather type
- \( t \) during time period
- \( x \) the station

Lowry uses the model for many purposes. He used it as a basis to critique Changnon and Huff’s work on urban precipitation regarding the controversial, (and now well-documented) “La Porte” anomaly, which indicated significantly higher levels of precipitation downwind of urbanized areas.\(^8\) Precipitation patterns are related to atmospheric heat, and subsequent studies, like

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\(^8\) The METROMEX experiment in St. Louis was designed to examine and clarify this issue, and did show increased precipitation in areas downwind of urbanized centers.
METROMEX have suggested a linkage with the UHI effect (Landsberg, 1981). Since this is a complex relationship, precipitation is outside this review’s scope. One problem with Lowry’s proposed model is that while it assumes $t = 0$ is the pre-urban status of the location, it is difficult to assess what the pre-urban climate of a location was like, or to quantify the extent of broader climatic change there. However, Lowry’s work is an early effort to produce general models capable of assessing a wide range of climate effects by urbanization. It is also a step beyond regression equations that express an existing relationship from which predictions can be extrapolated toward general models of urban climate effects.

Establishing the climate of an area prior to urbanization was a major component of Lowry’s effort to quantify urban climate science. This is specifically addressed by of Helmut E. Landsberg, who represents a continuation of the biometeorology tradition started by Schmidt. Landsberg enters the literature with an examination of urban and rural temperature differences related to microclimates in the Washington D.C. area (1950). His later studies (1972) (1978) of the rapidly urbanizing area of Columbia, MD, located along the Baltimore-Washington corridor, between 1967 and 1971 document how the thermal balance is rapidly upset and an UHI develops once natural land-cover is replaced by built surfaces. Columbia is a planned community that was developed by the Rouse Company starting in the late 1960’s. It was purposely designed to preserve and incorporate aspects of the existing landscape of then rural Howard
County. As the community grew, the heat island spread and intensified. Its effects were apparent even before mechanical systems in major urban structures like the Columbia shopping mall became operational. Changes in the heat balance, ambient temperature, and humidity were observed during the course of the study, substantially destroying the microclimates of the wooded clusters that had existed across the landscape of the area. This lead to the conclusion that: “Urbanization, even in early stages leads to the development of a heat island, caused by the alteration of the physical characteristics of the surface.” (Landsberg, 1981) Statistical regression of population growth to temperature increase showed that by the time the new town reached a population of 20,000 in 1974, the heat island was 4.5° C warmer than the surrounding countryside ($\Delta T$ 4.5° C.) Landsberg estimated no more than 30% of the heat generated in urban areas comes from mechanical processes and burning of fossil fuels. Most of the heat comes from destruction of vegetated land cover and replacement with impervious built surfaces which decrease the surface reflectivity, increased heat conductivity and capacity, and drastically altered the water cycle (1975). This research is a bottom up quantitative assessment of the UHI, by which Landsberg documents change to the rural environment and comprehensively describes the physical processes and change in energy balance of the area. With its longitudinal study method it links UHI to landscape change; replacement of natural vegetated land cover with an urban fabric of impervious surfaces thus
demonstrating a causal relationship between land cover change and temperature change.

The research of Timothy Oke started using the standard automobile traverse methodology in order to quantify the UHI and relate it to city population through linear regression (1973). In doing this analysis the variables of topography, proximity to water, climate differences, time, and identical instrumentation were controlled. A traverse through 10 towns and the city of Montreal were completed to compare urban areas of various population sizes. The results were that villages with as few as 1000 inhabitants showed a heat island effect. A strong positive linear relation was evident with an R² = 0.97 between aggregated measures of population and temperature. A logarithmic function was most appropriate for plotting the difference in urban and rural temperatures in this study with ΔT_{u-r(max)} = 2.96 log P – 6.41, with P being population. This yielded an r² = 0.96 and S_{ΔT} = ± 0.7°C. Comparison with urban to rural heat differences in other North American cities showed a strong fit with this function. It is interesting that European cities show a significant reduction of this linear relationship with ΔT_{u-r(max)} = 2.01 log P – 4.06. and an R² = 0.74 with S_{ΔT} = ± 0.9°C. At the conclusion of the paper, two limiting factors to magnification of the UHI are discussed:

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9 It would be interesting to determine whether the differences between North American and European cities are due to differences in the size of living quarters, population density, energy use, building materials, and/or evapotranspiration due to different arrangement of public space. Oke mentions some of these possibilities.
1. Intensity of urbanization has limits, and once an area is built to a certain extent, further construction becomes physically impractical.

2. Once a city reaches a high level of the UHI, rural to urban temperature differences generate a “convergent thermal breeze circulation” which prevents stagnation from occurring and limits further heat island growth. This may be a critical factor when determining how the UHI effect is playing out in cities in tropical and sub-tropical climates. Evidence of this may be present in the studies of and Gonzalez et al. in San Juan, Puerto Rico (2005) and Sullivan in Tampa (2010). It suggests limitations to the temperature gradient between rural (or water) and urban areas in tropical coastal mega-cities like São Paulo and Mumbai. Development of a “sea breeze” with intensification of temperature differences may moderate urban temperature by advection.

Oke’s subsequent work focused on energy and mass exchanges and their effect on the urban climate. *Boundary Layer Climates* (Oke, 1978) is an extensive investigation and explanation of energy exchanges in the atmosphere, natural, and human modified atmospheric environments. These exchanges are examined at the micro (organism) and local (city) scale, with emphasis on inadvertent climate modification and air-pollution. This work can be seen as a continuation and expansion of the biometeorology tradition started in the 1920’s.

A summary of the state of science and quantitative enquiry regarding the UHI is provided in “The energetic basis of the urban heat island” (Oke, 1982). It describes four stages of research:
1) Recognition and description
2) Linkage (statistical) of the feature to other factors
3) Study of processes causing the phenomenon
4) Construction of process-response models to predict behavior.

Oke finds that in the 150 years since Howard first described the phenomenon, most work has been at stage 1 and 2. Very few researchers have conducted stage 3 research, and then only since the 1970’s. Using this model research can be characterized as:

**Table 2-1** Taxonomy of UHI research

<table>
<thead>
<tr>
<th>Era</th>
<th>Description</th>
<th>Researcher</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>Recognition and description</td>
<td>Howard to Schmidt</td>
</tr>
<tr>
<td>Stage 2</td>
<td>Linkage to other factors (statistical)</td>
<td>Sundborg to Chandler &amp; Lowry</td>
</tr>
<tr>
<td>Stage 3</td>
<td>Study of processes</td>
<td>Landsberg to Oke</td>
</tr>
<tr>
<td>Stage 4</td>
<td>Modeling</td>
<td>Oke to current modeling projects examining relationship/interaction of UHI and global climate change and environmental processes</td>
</tr>
</tbody>
</table>

He cites several reasons for this apparent stalling of progress; inherent complexity of the problem, lack of a clear conceptual/theoretical frameworks for enquiry, and the expense and difficulty of observation in cities. Some of these issues are being addressed by students of Oke, like I.D. Stewart.

### 2.1.3 Current Work

Since many aspects of the UHI have been subject to extensive empirical study and quantification, current work can be categorized in five primary areas:

1. Improved classification of land cover and local climate considerations.

2. Improving data collection techniques and methodology.
3. Study in areas other than the mid-latitude regions which have been the focus of work until recently.

4. Linkage of the UHI to larger, meso-scale climate issues.

5. Study of mitigation strategies to lessen the effect of urban heat.

I.D. Stewart’s work is focused on the first issue, improving the quality of empirical observations, and identifying classification standards which can be used to typify aspects of cities and their impact on the UHI. This includes an urban to rural land type classification system (2006), and a local climate zone classification system (2006). Stewart’s review of the current status of UHI research (2010) asserts that there is “universal weakness in definition, measurement, and communication” in the literature (p.1). His recommendations to improve UHI research including; reduction of temporal and spatial span of studies, improved classification of study sites, and better disclosure of data limitations. He also advocates experiments which utilize fixed simultaneous observations, rather than mobile traverses. This last point moves from the traditional method of mobile traverses, a linear approach which does provide an advantage in visualizing the UHI in vertical space, but requires interpolation to gain a lateral view, using isotherm mapping for instance. Improved simultaneous sampling of temperature can be accomplished by increasing the number of data collection sites, or by acquiring a synoptic view of the study area which two technologies can facilitate; low-cost temperature date recorders and remote sensing.
Stewart’s point about the ability to take multiple, fixed, simultaneous observations is advanced in the technique employed by Joann Sullivan using thermocron temperature sensors (2009, 2010). This study introduces the use of miniaturized, automated temperature sensors which can be placed throughout a region, in rural and urban areas to assess and map changes in temperature over an extended time. These offer the advantage of being able to capture simultaneous readings of ambient air temperature, avoiding time corrections necessary with mobile traverses. Additionally, the sensors have a long life, and can record up to 2048 observations.

Another way of assessing temperature simultaneously across a wide surface area, and acquiring a synoptic view of a study area is by using remote sensing technology. Airborne and satellite remote sensing platforms offer away of capturing data related to land surface temperature through thermal sensors. Additionally, data in other bands of the spectrum can be used to assess land cover for levels of vegetation and the extent of urbanization through use of measures like the normalized difference vegetation index or NDVI. Satellites in particular offer an efficient mode of data collection, and those in the Landsat program have been collecting data on a world-wide basis since the 1970’s. Satellite data from Landsat, AVHRR, MODIS and the Terra satellite has all been used to study land surface temperature. The Landsat Thematic Mapper, or TM series of satellites has accumulated a particularly extensive archive of images. Landsat 5 has been in operation since March 1984, providing 120 meter spatial
resolution images, which is adequate for medium resolution urban temperature studies. Both MODIS and Advanced Very High Resolution Radiometer, or AVHRR satellites collect data in the thermal band, however their low spatial resolution of 1 and 1.1Km per pixel limits suitability for urban studies. Another instrument, Advanced Spaceborne Thermal Emissions & Reflection Radiometer, or ASTER mounted on the TERRA satellite was launched in 1999. It provides higher spatial resolution data, at 90 meter per pixel. Both Landsat and TERRA have 16 day ground coverage cycles.

Remote Sensing in the thermal band cannot directly reveal the UHI. The UHI is a phenomenon of atmospheric air temperature, and satellite remote sensing only observes the thermal upwelling of radiation from the surface below. Consequently, the term surface urban heat island, or SUHI has been coined by Voogt and Oke as descriptive of the heat island detectable from the land’s surface temperature (Voogt & Oke, 2003). Differences in land surface temperature, especially high temperatures are indicative of the SUHI, and are detectable by remote sensing. Many previous studies have been conducted, especially using AVHRR, though Landsat TM sensor data had limited accuracy and was not employed as much prior to development of a mono-window algorithm by Qin et al. in 2000. Their study found that the technique achieved accuracy within 0.4°C between assumed and retrieved temperature levels. These results indicate that Landsat TM thermal data provides a reasonably accurate method for measuring LST with a spatial resolution adequate for urban
studies. It offers a low-overhead and efficient land surface temperature survey method.

While considerable resources have been devoted to the study of the UHI in the mid-latitude regions of Europe and the U.S., it has not received as much attention in sub-tropical and tropical regions. Due to lack of financial, scientific and technical resources in developing tropical countries, the state of research in these regions has lagged. However, since predictions of urbanization indicate that these regions will experience the greatest increases with large population growth, the tropical UHI deserves increased study. Much of the literature regarding tropical UHI effects originated at the National University of Singapore. Janet Nichol’s GIS and remote sensing based assessment of urban heating and housing estates, C.P. Tso’s assessment of the UHI in two tropical cities, N. H Wong’s book, *Tropical Urban Heat Islands* (2008) concentrates of the results of research at that institution. Oke has devoted attention to this issue, authoring and co-authoring several studies on tropical UHI. Still, Roth, in his 2007 review of urban climate research found that less than 20% of studies focused on these regions (Review of urban climate research in (sub)tropical regions). It remains an insufficiently studied area of regional climatology.

The studies that have been done point to broad similarities between the UHI in mid-latitude and tropical areas, and also a few differences. One is the time of peak temperature differences between rural and urban areas. Generally it was thought that maximum differences occurred at night. Some researchers
(Gonzalez, Jorge et al., 2005; Sullivan, 2010) in subtropical and tropical areas have found that maximum difference between rural and urban temperature occurred during the mid-morning, with Sullivan finding a peak difference of 4.5°. Newton et al. found similar maximum temperature occurrence at about 12:00 in their 2007 study in Miami (Newton, Oke, Grimmond, Roth, 2007). This is counter to earlier findings by Oke and Landsberg (but most of those studies were focused on mid-latitude cities.) Sullivan postulated that regional topography and meteorological conditions might be a factor of this difference, citing the moderating effect of afternoon sea-breezes on the rural/urban temperature gradient referred to earlier. Newton et al’s Miami study (2007) found that wind speed increased in the morning, and peaked in the afternoon, lagging the temperature climb (though the conclusions of that study stressed that the similarities between the Miami surface energy dynamics and those found in other North American cities prevailed.) This is an area where further study is needed.

Early thought on local rural and urban temperature differences were preoccupied with the conflation of locally elevated temperature readings with indication of broader scale temperature change. Past researchers like Renou, Fassig, Sundborg, and J.M. Mitchell were concerned with this. It is only later with Landsberg that an awareness of possible linkage between urban growth, temperature elevation and larger scale effects begin. Some recent observers have addressed whether UHI effects have been conflated with warming due to climate change. In an analysis of the interaction between climate change and the
UHI, Parker (2010) found that there have been only minor impacts of UHI related warming on temperature estimates, because observers have been aware of urban rural temperature differences throughout the modern era and made efforts to avoid or adjust their observations for it. He warned that the combined effect of UHI and climate change “can be severe and justify urgent measures to initiate both mitigation and adaptation.” (p. 131). Grimmond, has done extensive work in energy dynamics of the UHI, examining the effect of urbanization on climate change and remarking that because of the relatively small area of urbanization of the Earth’s surface, the thermal and moisture dynamics extend only to areas near cities. However, the UHI effect in cities causes increased energy use which in turn causes increased emission of greenhouse gasses, and resource consumption which does have large scale effects (Grimmond, 2007). Additionally urban populations, especially low-income members of society are more exposed to heat waves and other weather extremes due to the UHI. Several issues of climate change and the UHI are relevant. Oke proposed that the UHI is limited by the pressure gradient that would develop between hotter urban and cooler rural areas. If climate change warms both areas then intensification of temperature to the overall region would occur and the UHI effect would be present, but it would be constrained by this relationship. Other effects associated with UHI could intensify including; greater energy/resource consumption, air pollution effects, local and regional weather effects related to evapotranspiration, and health effects associated with
intensified heat. The exposure of ever larger urbanized populations to the UHI and intensification of the effect through climate change is a troubling aspect to this issue requiring further study and description for purposes of mitigation.

This literature review reveals gaps in several areas. First, study and quantification of the tropical UHI deserves more emphasis due to the large population increases expected in these regions of the world. Second, the linkage between local level UHI effects and its impact on climate change requires more study, though the most immediate known impact seems to be increased electricity use for cooling which initiates more burning of fossil fuels in its generation. Additionally, present cooling technologies like air conditioning generate more heat by cooling interior spaces and expelling hot air to the external environment, increasing urban heat. Third, further research and promotion of mitigation strategies, especially low-tech, cost-effective ones capable of being implemented on a wide-scale in existing urban environments. Efficient techniques to measure and thereby delimit and quantify the extent of UHI effects are essential tools for research, development, and implementation of mitigation factors in tropical urban areas of the developing regions of the world.

2.2 The Structure of the UHI

The structure of the UHI, its scale and the surface energy dynamics which typify its pattern have been explained by researchers such as Chandler, Landsberg and Oke. Several general factors explain its appearance, but
fundamentally the urban heat island (UHI) is a localized increase of the temperature in urbanized areas with a varying spatiotemporal pattern. The term “heat-island” comes from the appearance of the feature when it is drawn on a map using isotherm lines. A region of elevated temperature appears amidst the surrounding rural area of relatively homogenous temperatures, creating an island-like effect (Landsberg, 1981). It is not a constant phenomenon, fluctuating in intensity and spatial distribution over time. The temporal fluctuations are diurnal, weekly and seasonal (Landsberg, 1981). Usually the UHI is most pronounced in mid-morning and evening, with seasonal variability depending on latitude and climate pattern in the area (Oke, 1978).

Urban heat islands can be defined at various levels of the atmosphere and surface of the urban environment, and have slightly different underlying mechanisms. In the vertical dimension, the atmospheric UHI is composed of elevated temperature in the canopy and the boundary air layers. The canopy layer starts just above the land surface and extends to roof-top level, and the boundary layer extends from 100 to 1000 meters above canopy layer (Oke, 1978). Most studies have measured and described the canopy level UHI, since it is the most accessible (Howard, 1820; Millar & Middleton, 1936; Sundborg, 1950; Mitchell, 1953; Chandler, 1965). Surface temperature gauges, thermometers mounted on automobiles and even small electronic devices like thermocrons have been used to measure this layer of the atmosphere. It is the level that is most directly affected by heat radiating from the surface, or LST.
While land surface temperature (LST) is not identical to UHI, it is the primary causal factor of temperature in the lower atmosphere. Voogt and Oke (2003) emphasize this association between elevated LST and the UHI by using the term “surface urban heat island,” (SUHI). LST is usually warmer than atmospheric temperature, sometimes by as much as 26°C, where asphalt and air temperature are compared in the summer (Landsberg, 1981). This variability of surface and air temperature is difficult to predict, and depends on such factors as albedo or reflectivity, emissivity and thermal capacity of the surface and also wind speed and moisture level of the atmosphere. Consequently, a precise transfer function between LST and atmospheric temperature at the canopy level does not exist (Weng et al., 2004).

There are several factors of anthropogenic change related to LST which are causal factors of the UHI. A predominance of heat absorbing materials on urban surfaces cause energy to be stored, and slowly radiated rather than reflected back to the atmosphere. Additionally, the vertical arrangement of structures in the city cause reflected and radiated energy to “bounce” between them, impeding energy flow directly into the atmosphere (Lowry, 1967). Since air is heated primarily by contact with warmer surfaces, structures in urban areas act like massive radiators, heating the air that flows thorough and directing it upward by the process of convection to the boundary layer (Lowry, 1967) (Chandler, 1976). Another anthropogenic change to land cover, replacement of vegetated land with impervious surfaces, decreases absorption of heat through
the process of evaporation. Impervious surfaces are a sealed layer, which prevent absorption of moisture into the soil and its evaporation by heat, which would dissipate the energy rather than radiate it. Modern industrial society produces heat through its modes of production, transportation, and the cooling and heating of structures. Urban structures often impede wind flow, obstructing the cooling effect of air exchange. All of these factors cause urban areas to be warmer than surrounding rural areas (Chandler, 1976). The scale and concentration of urbanization within cities magnifies or reduces the intensity of an UHI relative to the surrounding rural area.

The overall balance of energy in rural and urban locations can be expressed by the energy balance equation:

\[ R_n + F = H + G + A + LE \]

where
- \( R_n \) is net all wave radiation from the sun
- \( F \) is heat generated by artificial and anthropogenic processes, mechanical and industrial
- \( H \) is convective sensible heat transfer
- \( G \) heat stored in the urban fabric of concrete, asphalt and brick structures and pavements
- \( A \) net advected energy, reflected or transferred laterally by the wind
- \( LE \) Latent heat transfer

The UHI is subject to temporal patterns on both a daily, weekly and seasonal basis. Figure 2-1 describes the diurnal heat exchange cycle:
Diurnal Heat Exchange Rural/Urban Areas

Heat Balance Equation
\[ R_n + F = H + G + A + LE \]
- \( R_n \) is net all-wave radiation
- \( F \) is artificial and anthropogenic heat generated within the urban area
- \( H \) is the convective sensible heat transfer
- \( G \) is net heat storage within the urban fabric (buildings, roads, soil, etc.)
- \( A \) is net advected energy
- \( LE \) is the latent heat transfer

**Figure 2-1** Diurnal heat cycle with rural and urban land cover differences (after Chandler, Fuggle, & Oke (1976))
During the day, the sun’s energy is absorbed by rural and urban surfaces, but heats rural, vegetated surfaces more slowly, causing a difference in surface temperature between the two areas. As this difference intensifies, a breeze can develop across this gradient, flowing from the lower temperature rural area to the hotter urban area. Once maximum heating occurs, there is more stored energy in the urban area because of the conductive and thermal storage capacity of the materials in urban surfaces. After the sun sets, the energy in both areas radiates to the surrounding atmosphere, but the rural area cools more quickly. The intensity of this difference varies by season, depending on the daily warming pattern and cloud cover. Additionally, temperature differences have been found during the week, with Western industrial cities having less noticeable UHI on Sunday when commuting and industrial processes which produce heat are diminished (Mitchell, 1961)
CHAPTER 3: THE STUDY AREA AND METHODOLOGY

This section is a discussion of the study area, the data sources, and methods used in this analysis of the UHI. Introduction to the physical geography and population dynamics of the study area is first. The sources of data and the variables examined are introduced next. Then the methodology used to extract the data and analyze any statistical relationships is explained.

3.1 Study Area and Study Period

The scope of this study is focused on Pinellas County, Florida in the southeastern United States during the last 23 years. Pinellas County is part of the Tampa Bay region and occupies a peninsula on the west coast of south-central Florida (Figure 3-1). The Gulf of Mexico is on the western side of the

Figure 3-1 Pinellas County, Florida study area
peninsula, and it is bound by Tampa Bay to the south and east. Elevation varies from mean sea level on the coast to 32 meters at the central ridge (Figure 3-2). Total land area is 725 km\(^2\), ranking it as the second smallest county in Florida. The Gulf coast of the County has an extensive system of barrier islands stretching 55 km north to south constituting the Suncoast beaches. Although extensive segments of the Pinellas coast have been developed, there are undeveloped areas dominated by mangrove wetlands, especially to the south and on the Tampa Bay side of the peninsula. Much of this mangrove wetland is under State of Florida or County management as protected lands. The climate in Pinellas county is humid subtropical, typified by hot, rainy summers and drier, temperate winters. It is categorized as Cfa on the Köppen climate classification scale, signifying that mean temperature during the coldest month is between -3°C and 18°C, and the hottest month is above 22°C, typified by a dry winter and wet summer with precipitation greater than 30mm each summer month (The Times Atlas of the World, 1993)

The largest municipalities in the county are Saint Petersburg and Clearwater. County population increased from 728,731 in 1980 to 921,431 in 2000, or 20.9%. Despite losing population in the 2010 census, declining to 916,542, Pinellas remains as Florida’s most densely populated county, with 1264 persons per km\(^2\) (U.S. Census, 2010.) The geography of Pinellas has intensified the level of urbanization because of its peninsular shape which constricts development. Pinellas is the only county in Florida to have reached a “built-out” status earlier in
the decade (Policom Corporation, 2001). Build-out means that all of the large tracts of land available for development have been used. This makes the retention and improvement of existing green space critically important to the county. With its subtropical climate and intense level of urbanization, the Tampa Bay region and Pinellas County provide an interesting study area in which hypotheses about tropical and subtropical UHIs may be developed and tested.

**Pinellas County Population Growth**

![Graph showing Pinellas County population growth](image)

**Figure 3-2** Pinellas population growth peaked in 2000 concurrent with “build-out”

A study period comprising data from 1986 to 2009 was selected as a sufficient time frame to assess developments within the area, and also because of data availability and coordination of data sources. Satellite remote sensing data was selected on a basis of quality and seasonal consistency.
3.2 Data Sources and Variables

In order to conduct this study, primary data was gathered from a variety of official sources. Since much of the imagery was in standard government format, a number of steps were required to select, acquire, review and process it to prepare for interpretation and statistical analysis. This outlines the data sources and types of variables that were extracted for analysis.

3.2.1 Data Sources

Three primary sources of data are used to examine the relationship between land surface temperature (LST), vegetation (NDVI), imperviousness (%ISA) and land use and land cover (LULC); Satellite remote sensing data from the Landsat 5 Thematic Mapper (TM) sensor, 2008 Florida Land Use Classification Code System (FLUCCS) maps produced by the Southwest Florida Water Management District (SWFWMD). These sources provide the most comprehensive, accurate and up-to-date data for the study period which includes 1986 through 2009.

The choice of remote sensing data source was made on a basis of quality, consistency, resolution, duration of program, time of observation, frequency of observation and availability. Landsat 5 was launched in March 1984, and provides systematic periodic observation of the study area every 16 days through its TM sensor. This includes data recorded in 7 bands; 3 visible, 3 infrared, and 1 thermal. The thermal band covers radiance between 10.40 and 12.50 μm with 120 meter per pixel resolution. With its long operational mission, Landsat 5 provides an archive of images which is unmatched by other satellite remote
sensing instrument platforms. Landsat data is available free of cost through the United States Geological Survey “EarthExplorer” web interface, which enables the user to preview the data for quality issues like presence of clouds, data loss or sensor introduced errors. USGS quality control includes resampling of the data and projection using the Universal Transverse Mercator (UTM) system and the WGS-84 datum. Systematic radiometric correction is done along with geographic referencing and topographic correction using Digital Elevation Models (DEM) from several official sources.

Landsat TM imagery has been used in other studies of heat island effects and provides sufficient spatial resolution at 120m for analysis of the SUHI at a local (city-wide) and micro (large structure) level. Nichol’s study (1994) of urban microclimates and LST in the tropical city-state of Singapore used TM thermal data resampled to 30 meter. Another study of micro-urban heat islands (MUHI) conducted by Aniello et al. (1995) found the spatial resolution of Landsat TM useful when identifying local to micro scale heat islands in the urban area of Dallas. More recent studies, one in the Tampa Bay region by Xian and Crane (2005), found that TM data was useful in determining the relationship between LULC and thermal patterns of the landscape. Additionally, Yuan and Bauer (2007) used both TM and ETM (120m and 60m resolution thermal imagery) imagery in their analysis of the SUHI and impervious surfaces (ISA, with noticeable visual but negligible statistical differences in outcomes between
images. Considering these studies, Landsat TM thermal imagery is of sufficient resolution to analyze local and micro level LST patterns.

Land use/Land cover (LULC) data for 2008 was obtained from SWFWMD and used to make primary determinations in the study area. This data is based on photo interpretation at 1:8,000 scale using 1 foot color infrared (CIR) digital aerial photos of the study area. The land features are categorized by SWFWMD using standard FLUCCS codes which include 74 categories broadly divided into Residential, Agricultural, Upland Non-Forested, Upland Forested, Water, Wetlands, Barren Land, Transportation and Utilities.

USGS data evaluating imperviousness as a percent at the pixel level was acquired for 2002 (Crane, 2011). Data is 30m resolution, and covers the entire study area for 2002. It was used to validate 2001 imperviousness levels calculated for this thesis using linear spectral mixing/unmixing.

Atmospheric data was sourced from several sites. The National Weather Service provided radiosonde data of atmospheric water vapor content for 1986 and 2001 from its upper atmosphere sounding program through a portal hosted by the University of Wyoming, College of Engineering. NOAA’s GPSMET, or Global Positioning System/Meteorology program provided temperature and atmospheric water vapor data. The Florida Climate Center at Florida State University provided temperature and rain observations in Pinellas County beginning in 1900.
3.2.2 Dependent Variable

Land Surface Temperature (LST) – A measure of the thermal energy stored in surface land cover. This is radiation in the range from 10.4µm to 12.5µm. It is the chief determinant of temperature at the lowest level of the atmosphere, and the primary factor of the SUHI and urban warming. This is an effective way to quantify the relative intensity of surface radiation and temperature in an area. It is a quantitative variable with a scalar form of measurement.

3.2.3 Independent Variables

All of the independent variables were drawn from the same Landsat imagery as the LST data was. Some explanation of the processing of the impervious surface data is required to cover the assumptions and technical details involved in its production.

3.2.3.1 %ISA and Linear Spectral Mixing/Unmixing

Impervious Surface Area (ISA or %ISA) – Land cover classified by percent impervious within each pixel. Since impervious surfaces are built structures they are primarily composed of concrete, asphalt, rock or brick. Their structural density comprises a sealed surface which water cannot penetrate to reach the subsurface soil layer. The Landsat TM images for 1986, 2001 and 2009 were classified at the subpixel level using linear spectral mixing/unmixing as described by Wu (2004) and Schowengerdt (2007). This process relies on the identification of a sample of spectrally pure endmembers for representative land cover types (See Figure 3-3):
Workflow for processing impervious images using linear spectral mixing/unmixing

REMOTE SENSING DATA SELECTION & ACQUISITION
A) Landsat TM imagery, bands 1-5 & 7
B) Verification of quality control for georeferencing and radiometric correction
C) Clipping of images to study area

IDENTIFICATION OF PURE SPECTRA ENDMEMBERS
Use 1986, 2001, and 2009 high resolution photographs to locate and isolate pixels for land cover:
1) Vegetation – trees & wetland
2) Impervious – high albedo
3) Impervious – low albedo
4) Sand – high albedo

MASKING
Create water mask using Band 4 (near-infrared) and a threshold of digital number 27

LINEAR SPECTRAL MIXING/UNMIXING ALGORITHM
1) Apply water mask and conduct subpixel level linear spectral mixing/unmixing for 6 bands (1-5, 7)
2) Separates into 4 categories as above

RESULTS FILE
1) Apply constraint $0 > b_1 < 1$ to results where $b_1$ is the land cover type
2) Add per pixel totals for high and low albedo impervious
3) Apply equation: Impervious total/(Impervious total+Vegetation)
4) Per-pixel results with percentage impervious surface
5) Create sand image using .90 threshold with value of 0 for beach
6) Assign 101 as classification code for water area and mask water from statistics and maps

Figure 3-3  Workflow of Linear Spectral Mixing/Unmixing process for %ISA
In this case vegetation, high-albedo impervious (new concrete), low-albedo impervious (asphalt and old concrete), and sand were identified as sample areas within each separate image using high resolution aerial imagery (NHAP photographs from 1984 and 1 meter resolution DOQQs from 2000 and 2009). The images were then classified using the ENVI 4.5 “linear spectral mixing/unmixing” utility with a sum constraint of 1.00. A water mask was applied during the process to exclude pixels in those areas, giving them a default “0” percent impervious. Once the ENVI 4.5 algorithm was run, a constraint of $0 > \text{band}1 < 1$ was applied to exclude negative and values greater than 1. The low-albedo ($f1$) and high-albedo ($f2$) impervious amounts were summed ($f12$) and then compared to vegetation quantity ($f3$) using an equation to establish the impervious proportion:

$$\text{% Impervious} = \frac{f12}{f12+f3}$$

Sand areas (exceeding 90% at subpixel level) in the image were then assigned a “0” percent impervious surface value. The 2001 image was sampled and compared to a 2002 USGS imperviousness image which had been produced using a regression tree program. The mean of the 2001 image was 36.75%, while the 2002 USGS image was 34.58%. Correlation was statistically significant at the .01 level with a Pearson’s $r = 0.639$. The 1986, 2001, and 2009 images produced using linear spectral mixing/unmixing showed impervious means of 36.51, 36.75 and 44.60% respectively. %ISA is a quantitative variable in scalar format. The resulting images are displayed as Figures 3-4 to 3-6:
Figure 3-4 1986 %ISA calculated using linear spectral mixing/unmixing
Figure 3-5 2001 %ISA calculated using linear spectral mixing/unmixing
2009 PINELLS IMPERVIOUS

Figure 3-6 2009 %ISA calculated using linear spectral mixing/unmixing
3.2.3.2 Normalized Difference Vegetation Index

Normalized Difference Vegetation Index (NDVI) - Index used to assess the relative level of vegetation per pixel as a ratio, so this is a quantitative variable measured as a ratio.

3.2.3.3 Land Use/Land Cover

Land use/Land Cover (LULC) - Land use data from 2008 SWFWMD classified according to FLUCCS codes. This is categorical data at the pixel level which can be expressed as a percentage or ratio when aggregated using census tracts or block groups. LULC categories were grouped into “rural” and “urban” types. This is broadly based on residential, industrial, commercial and services being urban uses, while vegetation, recreational, and intertidal land covers can be typified as rural.

3.3 Methods

The technical methods involved in assessment of the SUHI involve standard techniques taken from remote sensing and statistical measures of the results. These methods enable us to make hypotheses that help describe the pattern of the SUHI in the study area and examine its relationship to other parameters which may be related. Remote sensing affords a synoptic view of the extent of the study area, so that factors scale, micro to meso scale can be examined. They also offer the advantage of examining data over an extended period. Statistical methods offer a way to test hypothesis about this data.
3.3.1 Remote Sensing

Past methods of evaluating the UHI generally relied on near surface air temperature measurements of the urban canopy layer (UCL) of the atmosphere. The UCL extends from the surface to approximately mean building height (Voogt & Oke, 2003). Sensors mounted at screen-level (approximately 1.5 m from the surface) are used to compare temperatures at fixed rural and urban locations or thermometers mounted on automobiles conduct traverses from rural to urban areas (Schmidt, 1927; Middleton and Millar, 1936; Sundborg, 1950; Chandler, 1965; Oke 1973). Both of these methods provide air temperature readings in the boundary layer of the atmosphere, which is subject to air flow and turbulence, potentially causing advection of thermal energy downwind. These techniques were used to describe what we know of as the UHI, and constitute the standard methodology for observing the phenomena. They are also limited to providing point data, which must be interpolated over an area, usually by involving the use of isotherm lines, or in the case of automobile traverse they are limited to measurements along a line of travel. Remote sensed images provide continuous data across a surface, which allows different spatial relationships to be evaluated.

Satellite based remote sensing measures the temperature of the actual surface, independent of the turbulence and advection. This is called the “Surface Urban Heat Island” or SUHI by Voogt and Oke (2003), and represents detection of thermal surface upwelling through the atmosphere. There are several
advantages and disadvantages to this technique. The synoptic temporal and spatial view provided by satellite observation can be an advantage. Satellites can take images of large spatial extents in one frame. One image records the near simultaneous reading of surface temperature across a broad region at a specific time, with a swath width of 185 km. Satellite based images also have a long history, with programs like LANDSAT archiving almost 30 years worth of imagery, from 1972 to the present. Since LANDSAT 5 (launched 1984) has an orbital frequency over Pinellas twice a month, it has acquired an extensive image archive extending almost 3 decades. Most of the LANDSAT archive has been made available for free through the USGS *EarthExplorer* web site and can be searched for suitable images before download.

3.3.1.1 *Landsat TM and the Mono-Window algorithm*

There are several limitations to Landsat imagery related to its orbital frequency and path, but also some advantages. Satellite over-flight is limited to a specific recurring time, every 16 days. This prevents acquisition of data at different times and intervals. In the case of the Tampa Bay region, a mid-morning over-flight provides advantages. Since solar angle is relatively higher in tropical and subtropical regions, surfaces capture greater amounts of energy, heating them more quickly than in mid-latitude areas. Landsberg’s studies of Columbia, MD (1981) found that on warm cloudless days, rural to urban temperature contrasts are well developed 1.5 hours before solar noon. Sullivan’s
(2010) study of the Tampa UHI found that air temperature differences between rural and urban areas were greatest between 10:30 and 13:30. Gonzalez et al. (2005) studied tropical San Juan, Puerto Rico determining that the spatial pattern of the UHI was most apparent during midmorning and early afternoon, not at night like most researchers in mid-latitude regions have found. Since spatial pattern of the SUHI is the primary emphasis of this study, the Landsat over-flight time should provide an adequate data source.

The greatest disadvantage of Landsat TM thermal imagery is that it requires precise atmospheric correction and estimation of surface land cover emissivity.\textsuperscript{10} Satellite sensors cannot directly capture the surface temperature, since it is not being directly observed. Rather, it is the thermal upwelling through the lower atmosphere which is captured, and the at-sensor radiance must be adjusted to account for atmospheric transmission. Early attempts to employ a heat balance equation to calculate outgoing radiative energy flux use the calculation:

\[ Q_{L\square} = \varepsilon \sigma T^4 \]

where
- \( Q_{L\square} \) is the upwelling radiative flux
- \( \varepsilon \) is surface emissivity
- \( \sigma \) is the Stefan-Boltzman constant
- \( T^4 \) is at-sensor temperature

One impediment to the successful adaptation of this equation for remote sensing use is the wide diversity of urban surfaces, with differing albedo and emissivity (Landsberg, 1981). Another issue was the lack of an accurate algorithm for

\textsuperscript{10} All materials possessing energy (above absolute zero, or 0 K) emit radiation. Emissivity is the relative ability of a material at a given temperature to emit the maximum possible amount of radiation per unit of surface area. Planck’s law of blackbody radiation describes this function, and establishes a spectral distribution curve of energy emitted by a full radiator at 6000 K.
atmospheric correction of the at-sensor radiance value for the single channel Landsat TM thermal sensor. This problem was resolved with publication of a robust mono-window algorithm by Qin, Karnieli, and Berliner (2000.) The algorithm is expressed as:

\[ T_s = \frac{1}{c}[a(1-C-D) + b(1-C-D)+C+D)T_{sensor}-DT_a] \]

where

\[ C=\varepsilon \tau \]

\[ D=(1-\tau)[1+(1-\varepsilon)\tau] \]

\( a \) and \( b \) are coefficients taken from the slope for the relationship of change in Planck’s radiance and with temperature (Qin et al., p. 3723.)

\( a = -67.355351 \)

\( b = 0.458606 \)

\( \varepsilon \) = emissivity of land surface

\( \tau \) = total atmospheric transmissivity

\( T_s \) = at-sensor brightness temperature

\( T_0 \) = mean atmospheric temperature given for USA 1976, or tropical, or mid-latitude summer, or mid-latitude winter (Qin et al., p. 3731.) Example for tropical 17.9769+0.91715\( T_o \), where \( T_o \) is near-surface air temperature.

\( \tau \) is the total atmospheric transmissivity measured from \( \omega \), the atmospheric water vapor content of between 0.4 and 1.6 \( g cm^2 \) as:

\( \tau = 0.974290 - 0.08007 \omega \) for high air temperature

\( \tau = 0.982007 - 0.09611 \omega \) for low air temperature

This algorithm utilizes the LOWTRAN or MODTRAN atmospheric correction program to model atmospheric transmittance levels with reasonable accuracy, attaining \( R^2 \) values >0.99 for estimation of the relationship between atmospheric transmittance and water vapor content (Qin et al., 2000,). Validation the algorithm showed differences between assumed and retrieved ones to be less than 0.4˚C in the temperature range 0-55˚C. An additional advantage of the model is its relative insensitivity to ground emissivity error, with the authors claiming these high levels of accuracy “in spite of some possible emissivity
errors.” (p. 3734.) The algorithm is much more sensitive to atmospheric transmittance error, making accurate atmospheric water vapor and temperature readings critical. The authors stipulate that accuracy under the model is highest for atmospheric conditions where the water vapor content is less than 2.5 $g \text{ cm}^2$ and temperature is below 40°C (p. 3738.)

The mono-window algorithm has been coded to a C language program by Pu and Gong (2004). This program utilizes MODTRAN 4 atmospheric profile modeling to calculate a text file of LST values which can be displayed by remote sensing programs like ENVI 4.5 or GIS like ArcGIS 9.3.1. Inputs include Landsat TM band 6 at-sensor radiance digital numbers, estimated surface emissivity values, atmospheric near-surface temperature, water vapor content of the atmosphere, and the appropriate MODTRAN 4 atmospheric model for the region. A work-flow for processing the LST images was established as seen in figure 3-7:
Workflow for processing TM thermal imagery to LST image

REMOTE SENSING DATA SELECTION & ACQUISITION
A) Landsat TM imagery, bands 1-6.
B) Verification of quality control for georeferencing and radiometric correction.
C) Clipping of images to study area.

ATMOSPHERIC DATA COLLECTION
A) Water vapor content $g \text{ cm}^2$
B) Near-surface temperature data at satellite over-flight date/time from GPSMET & radiosonde

CONSTRUCTION OF EMISSIVITY IMAGE
A) Construction of water layer with 0.99 emissivity
B) Construction of vegetation layer with 0.985
C) Construction of impervious surface layer with emissivity of 0.945
D) Combination of layers in emissivity image

LANDSAT TM BAND 6 – Thermal at-sensor radiance image

ATMOSPHERIC DATA COLLECTION
A) Water vapor content $g \text{ cm}^2$
B) Near-surface temperature data at satellite over-flight date/time from GPSMET & radiosonde

MONO-WINDOW ALGORITHM PROGRAM
A) Input of at-sensor radiance text file
B) Input of emissivity text file
C) Input of water vapor content
D) Input of near-surface temperature
E) Input of MODTRAN atmospheric model
   1) 1976 USA
   2) Tropical (selected)
   3) Mid-lat N Summer
   4) Mid-lat N Winter

TEXT FILE OF LAND SURFACE TEMPERATURE IMAGE

Figure 3-7 Work flow for processing the Landsat imagery for LST
3.3.1.2 Image Processing

As stated in the Data Sources section, images were selected from the USGS on the basis of quality and study period needs. Three suitable images were found as seen here, in table 3-1:

**Table 3-1** Landsat 5 imagery used

<table>
<thead>
<tr>
<th>Image Label</th>
<th>Image Date</th>
<th>Over-flight Time</th>
<th>Cloud Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT50170412009098EDC00</td>
<td>04/08/09</td>
<td>11:48 EDT</td>
<td>34</td>
</tr>
<tr>
<td>LT50170412001108XXX04</td>
<td>04/18/01</td>
<td>11:42 EDT</td>
<td>0</td>
</tr>
<tr>
<td>LT501704111986115AAA05</td>
<td>04/25/86</td>
<td>10:26 EST</td>
<td>0</td>
</tr>
</tbody>
</table>

Satellite over-flight occurs during late morning varying from 15:26 to 15:48 UTC, or from 10:26 EST to 11:48 EDT (The 1986 images were taken during Eastern Standard Time.) April was selected as the month of acquisition because of decreased cloud cover over Florida’s west coast during early spring, maximizing the availability of high quality images. All of the selected images were cloud-free over the study area. Weather conditions recorded at MacDill Air Force Base in Tampa were consistent across the images, with no precipitation during the previous 24 hours, and maximum wind speeds varying no more than 4 mph. Air temperature differences between the 4/25/1986 and later images are notable, and it is 5°C higher, as displayed in table 3-2:
Table 3-2 Lower atmosphere conditions at time of satellite over-flight

<table>
<thead>
<tr>
<th>Image Date</th>
<th>Over flight Time</th>
<th>Air Temp MacDill</th>
<th>Max Wind MacDill</th>
<th>Precip. MacDill (24 hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/08/09</td>
<td>11:48 EDT</td>
<td>16.05°C</td>
<td>13 mph (W)</td>
<td>0 in</td>
</tr>
<tr>
<td>04/18/01</td>
<td>11:42 EDT</td>
<td>16.0°C</td>
<td>14 mph (N)</td>
<td>0 in</td>
</tr>
<tr>
<td>04/25/86</td>
<td>10:26 EST</td>
<td>21.67°C</td>
<td>10 mph (N)</td>
<td>0 in</td>
</tr>
</tbody>
</table>

Acquisition of near anniversary images was essential to standardize the phenological cycle and the length of solar heating time of the land’s surface for each image. The images differ by less than 9 minutes from each other for consistent solar heating time. The 1986 image was produced later in the spring than the others, with a consequent increase of sun angle, though the heating time was actually less between sunrise and acquisition. This is seen in table 3-3:

Table 3-3 Solar heating time and elevation at satellite over-flight

<table>
<thead>
<tr>
<th>Image Date</th>
<th>Sunrise</th>
<th>Over flight Time</th>
<th>Heating Time</th>
<th>Sun Elevation</th>
<th>Sun Azimuth</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/08/09</td>
<td>07:12 EDT</td>
<td>11:48 EDT</td>
<td>4hrs 36min</td>
<td>58.0192</td>
<td>110.0070</td>
</tr>
<tr>
<td>04/18/01</td>
<td>07:02 EDT</td>
<td>11:42 EDT</td>
<td>4hrs 40min</td>
<td>59.4020</td>
<td>117.0882</td>
</tr>
<tr>
<td>04/25/86</td>
<td>05:55 EST</td>
<td>10:26 EST</td>
<td>4hrs 31min</td>
<td>57.8974</td>
<td>110.0070</td>
</tr>
</tbody>
</table>

There is a time differential with the satellite overpass time because the 2001 and 2009 images were taken when Eastern Daylight Savings Time was in effect, while the 1986 image was taken during Eastern Standard Time. Since the 1986 image had a higher mean temperature than the other two, image normalization was conducted, which will be discussed later.

The mono-window algorithm relies on the MODTRAN 4 atmospheric model to accurately predict atmospheric transmittance. They require data on water
vapor content and near-surface air temperature acquired near the study area at
or near the time of satellite over-flight. The Global Positioning
System/Meteorology or GPS/MET system operated by the National Oceanic and
Atmospheric Administration (NOAA) provides atmospheric water vapor content
data based on GPS time differential methodology. This data is based on
continuous all weather sensing that is not affected by precipitation or cloud
cover. It has a temporal resolution of 30 minutes to one hour, and is accurate to
within 1mm (US Department of Commerce/NOAA, 2011). MacDill AFB hosts the
local GPS site, which is near the vertical center of the study area, though about
10 kilometers further east. This provided near real-time data for the 2009
satellite over-flight, but it was not operational in 2001 and other data sources
needed to be found. Atmospheric data collected by radiosonde launched from
the National Weather Service site in Ruskin, Florida was used for the 1986 and
2001 observations. These observations are conducted twice daily at 00:00 and
12:00 UTC, so they were made 3 hours 26 minutes and 3 hours 42 minutes
before satellite over-flight of the 1986 and 2001 images. They are shown in
table 3-4:

Table 3-4 Source of MODTRAN 7 required parameters

<table>
<thead>
<tr>
<th>Date</th>
<th>Time  (UTC)</th>
<th>Type</th>
<th>IPW g cm²</th>
<th>NS TEMP at over-flight</th>
<th>13m Temp - Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/08/09</td>
<td>15:45 Z</td>
<td>GPSMET</td>
<td>1.150</td>
<td>16.05</td>
<td>N/A</td>
</tr>
<tr>
<td>04/18/01</td>
<td>12:00 Z</td>
<td>Radiosonde</td>
<td>0.585</td>
<td>16.0</td>
<td>10.20</td>
</tr>
<tr>
<td>04/25/86</td>
<td>12:00 Z</td>
<td>Radiosonde</td>
<td>1.020</td>
<td>21.67</td>
<td>9.8 (14.4 at 45m)</td>
</tr>
</tbody>
</table>
A high near-surface temperature on 4/25/1986 is significant (over 5°C higher than the other measurements), and was a factor in normalizing that image later.

The next step in processing the remote sensing data was to create a surface emissivity image using the basic procedure outlined by Okwen et al. (in press 2011). This involved producing an NDVI image using the basic formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Or in terms of Landsat TM sensor bands

$$NDVI = \frac{TM\ band\ 4 - TM\ band\ 3}{TM\ band\ 4 + TM\ band\ 3}.$$  

A vegetation layer image was created using all pixels with an NDVI value greater than 0.18. This was selected after viewing high resolution (1 meter) DOQQs of vegetation and impervious surfaces. It sufficiently isolated pixels that are composed mostly of impervious surfaces from impervious ones. Next, a water layer image was created using a near-infrared image from TM band 4. Data with a digital number less than 27 was determined to be water from comparison between the near-infrared and visible bands 1, 2, and 3. Finally, an impervious layer image was created from all pixels with an NDVI value less than 0.18. The water layer was then subtracted from the result, so that only the impervious pixels remained in the image\(^\text{11}\). Each layer image was the multiplied by a standard emissivity value for their land cover type; water by 0.99, vegetation by 0.985, and the impervious layer by 0.945. It became apparent that the sandy

\(^{11}\) The 2001 image had greater visible sand and sandbars in the image. Satellite over-flight seems to have coincided with low-tide. As a result the next image taken in April 2001 was used to construct a water mask and block out the sand in the imperviousness image used calculating emissivity and statistical calculations.
coastal areas were being categorized as impervious. However since the 
emissivity level of quartz sand in the 10 to 12 \( \mu m \) wavelength is \(~0.95\), it was 
not an issue for the LST images (Pampaloni, 1995; Qin, 2000). Finally, the three 
layers were combined to construct the finished emissivity image using the band 
math function of ENVI 4.5.

Landsat TM band 6 is the thermal data band. This data, along with the 
emissivity image was converted to a text file for processing. Since this data was 
of 120 meter resolution, when it was placed in text format, it was resampled to 
30 meter. Its resolution then coincided with that of the 30 meter emissivity 
image. They were input to the mono-window algorithm program (MWA.) Then 
the temperature and water vapor values appropriate to each image were entered 
in the program; the GPSMET water vapor and temperature observations for 
2009 and the radiosonde data for 1986 and 2001 with air temperatures 
measured at MacDill closest to time of satellite over-flight. Because the climate 
is sub-tropical, the “Tropical” atmospheric model of MODTRAN was selected. The 
program produced the required text files which after editing were converted to 
images and georeferenced. Image statistics are shown in table 3-5:

**Table 3-5** Land Surface Temperature image statistics prior to normalization

<table>
<thead>
<tr>
<th>Image Date</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/08/09</td>
<td>30.2841</td>
<td>17.1730</td>
<td>50.9199</td>
<td>4.7858</td>
</tr>
<tr>
<td>04/16/01</td>
<td>28.0876</td>
<td>13.2199</td>
<td>46.2700</td>
<td>4.1459</td>
</tr>
<tr>
<td>04/25/86</td>
<td>32.8377</td>
<td>17.9699</td>
<td>64.7999</td>
<td>4.1726</td>
</tr>
</tbody>
</table>
3.3.1.3 Validation

The 1986 image has a much higher mean LST than the other two images. Possible causes include that it was taken later in the season than the other two. As noted earlier, the air temperature measured at MacDill on that date was also warmer. Methods of validating the data were explored. One method of validating LST is by using in-situ observations of sea water temperature data. This method was used to check calibration of Landsat TM 5 and TM 7 satellites by Barsi et al. (2003). A total of six observations were found that occurred on the day of over-flight in 2009 and two for 2001. Unfortunately, no observations were found for 1986. Results are displayed in table 3-6:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>St. Pete, Bayboro</td>
<td>27.760 N 82.627 W</td>
<td>N/A</td>
<td>N/A</td>
<td>24.65/24.41</td>
</tr>
<tr>
<td>Clearwater Beach</td>
<td>27.977 N 82.832 W</td>
<td>22.10/22.22</td>
<td>21.2334</td>
<td>19.90/19.70</td>
</tr>
<tr>
<td>Middle TBay</td>
<td>27.7238 N 82.5338 W</td>
<td>23.22/24.16</td>
<td>22.6286</td>
<td>N/A</td>
</tr>
<tr>
<td>Middle TBay</td>
<td>27.826 N 82.5675 W</td>
<td>N/A</td>
<td>21.52/21.29</td>
<td></td>
</tr>
<tr>
<td>Old TBay</td>
<td>27.9002 N 82.592 W</td>
<td>N/A</td>
<td>18.96/19.17</td>
<td></td>
</tr>
<tr>
<td>Old TBay</td>
<td>27.9278 N 82.6397 W</td>
<td>N/A</td>
<td>19.24/20.76</td>
<td></td>
</tr>
<tr>
<td>Old TBay</td>
<td>27.9528 N 82.6416 W</td>
<td>N/A</td>
<td>19.63/21.29</td>
<td></td>
</tr>
</tbody>
</table>

A t-test of paired samples for the observed and LST measured means was conducted using the 2009 data. The hypothesis states that the LST measured mean is significantly different from the observed mean (H₁: μ₁≠μ₂). The null hypothesis is that there is no significant difference in observed and LST

---

12 Water quality measurements in Tampa Bay made by Hillsborough County Environmental Protection Commission on the day of the 2009 over flight were used, along with observations at the NOAA stations in Clearwater Beach and St. Petersburg. Unfortunately these stations were not operational in 1986.
measured means ($H_0: \mu_1=\mu_2$). In this two-tailed test, there is not enough evidence to reject the null hypothesis. With $t = -1.550$, and $df=5$ there is a significance of .182, meaning there is no statistically significant difference between the LST measured and observed means, as table 3-7a shows:

**Table 3-7 a & b**  T-test for paired samples of observed and measured water temperature on 4/08/2009.

<table>
<thead>
<tr>
<th>Paired Samples Test</th>
<th>Mean</th>
<th>Std. Dev</th>
<th>95% Confidence interval of the difference</th>
<th>t</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed 2009 &amp; Measured 2009</td>
<td>-0.533</td>
<td>0.84308</td>
<td>Lower -1.418 Upper 0.3514</td>
<td>-1.550</td>
<td>5</td>
<td>.182</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Paired Samples Correlation</th>
<th>N</th>
<th>Correlation</th>
<th>Significance</th>
</tr>
</thead>
</table>

Bivariate comparison of the LST measured and observed 2009 data show a statistically significant (at .05 level) positive linear correlation ($r= 0.913$). The equation of the slope is: $y=0.8495x + 3.6357$, where $y$ = LST measured temperature and $x$ = the observed temperature, and the $R^2 = 0.834$. Factors in the 16.6% variation that are not explained by the relationship could include the low number of observations and the comparison of observed values taken at a precise geographic location in the field, while the LST measure entails aggregation of values over a 120 meter resolution.

**3.3.1.4 Image Normalization**

Because of the lack of sufficient observed values to serve as validation points in the 1986 and 2001 images, the 2009 image was used as a basis to normalize them. Using the three surface types from the emissivity image: water,
impervious, and vegetated, test regions were established on the images using high resolution imagery by NHAP from 1984 for the 1986 LST image, and SWFWMD DOQQ from 2000 and 2009 for the 2001 and 2009 LST images. A stratified random sample of 500 pixels from each test region (vegetation, water, impervious) was drawn using ENVI 4.5’s random sample generator. A linear equation for the LST values of 1986 and 2009, and the 2001 and 2009 image was calculated for each surface type. The 1986 and 2001 LST images were then reprocessed using the appropriate linear equation for each surface type (shown in the scatter plots in Appendix B, with linear regression line: x-1986 or 2001 data, y-2009 data.) This resulted in the following normalized values:

<table>
<thead>
<tr>
<th>Image Date</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/08/09</td>
<td>30.2841</td>
<td>17.1730</td>
<td>50.9199</td>
<td>4.7858</td>
</tr>
<tr>
<td>NORMALIZED</td>
<td>04/16/01</td>
<td>30.3239</td>
<td>13.9812</td>
<td>49.2747</td>
</tr>
<tr>
<td>04/16/01</td>
<td>28.0876</td>
<td>15.9677</td>
<td>46.2700</td>
<td>4.1459</td>
</tr>
<tr>
<td>NORMALIZED</td>
<td>04/25/86</td>
<td>30.4549</td>
<td>18.3879</td>
<td>57.4399</td>
</tr>
<tr>
<td>04/25/86</td>
<td>34.4082</td>
<td>20.4586</td>
<td>57.6882</td>
<td>2.9837</td>
</tr>
</tbody>
</table>

For the 1986 image this is a substantial reduction in mean temperature of 3.9533°C and an increase of standard deviation from 2.9837 to 3.8043 along with a downward shift in the range of temperature values. The effect on the 2001 image was less, with a 2.2363°C increase in mean temperature, and an increase in standard deviation from 4.1459 to 4.3711, while the temperature range expanded somewhat. The resulting normalized images were used as reference in assessment of the results (see figures 3-8 through 3-10):
Figure 3-8 Image of 1986 normalized LST values
Figure 3-9 Image of 2001 normalized LST values
Figure 3-10 Image of 2009 LST values
3.3.2 Statistical

Once the land surface temperature images were produced, analysis of the dependent variable – LST, and independent variables was carried out. A series of descriptive statistics for the dependent and independent variables produced data summarizing basic findings for the study area. This included summary data for the dependent variable – LST, and the independent variables, particularly the categorical variable of land use/land cover, then the other quantitative variables %ISA and NDVI. Analysis of the relationship between dependent and independent variables can be accomplished through correlation analysis, using Pearson’s r as long as the sample of the variables meet the assumptions of random sample selection, normal distribution, homoskedasticity, and independence. Finally, changes in the study area were assessed using LST values derived from sampling the earlier 1986 and 2001 images.

Analysis of LST took place at two levels; descriptive statistics for the 2009 LST image are developed, the independent variables for NDVI, %ISA, and LULC were then examined for relationships and linear trends. This first level used data in point form. A lateral analysis using transects stretching across the study area was then conducted.

3.3.3 Sample Design

Two levels of analysis were done, but only one required a sampling strategy since point data was being evaluated. A stratified random sample was conducted. The 2001 image was used to define the sample area since it is
temporally between the 1986 and 2009 images. A sample size of .005% of land pixels (or 4,136) was established, since a smaller sample size would have been inadequate for the large area (2,506,728 pixels) and a larger sample size would have been less manageable. Selection was on a random stratified basis, excluding water and areas outside of the political boundaries of Pinellas County. The random sample generator in ENVI 4.5 was used to produce the sample from the 2001 image, which is shown in Figure 3-11.

![PINELLAS SAMPLE SELECTION](image)

**Figure 3-11** Pinellas sample points were taken from the 2001 image
Sample points were superimposed on georeferenced images of LST, NDVI, Impervious, and LULC so that data in these categories could be analyzed. Additionally, three transects were evaluated in Pinellas. They were selected on the basis of land cover and major transportation routes, displaying from east to west, one forested to urban and water transect, and two water to urban to water transects. This was done to determine whether the UHI could be visualized using remote sensing techniques in a manner similar to ground transects. LST is displayed on the vertical axis with land cover type and distance on the horizontal axis.
CHAPTER 4: ANALYSIS OF LST AND LANDSCAPE FACTORS

4.1 Descriptive Statistics

An analysis of the descriptive statistics and correlation statistics can assist us in understanding LST and its relationship with the landscape factors of vegetation, imperviousness, and land cover land use. For the descriptive statistics, comparisons of variables between the different images show similarities and changes over time. Sample size varied because of coastal shifts during the study period. LST of the samples for the three dates shows consistency of the means, which is expected since the images were normalized. Standard deviation is least for the 1986 and most for the 2009 image with 0.6531 difference between those dates. The minimum LST value is lowest for the 2009 image at 18.40°C, and most for 1986 at 21.35°C. Table 4-1 displays these values:

Table 4-1 LST of samples for the three image dates.

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009 LST*</td>
<td>18.4000</td>
<td>42.9800</td>
<td>30.6876</td>
<td>4.5340</td>
</tr>
<tr>
<td>2001 LST**</td>
<td>18.8455</td>
<td>42.5313</td>
<td>30.3145</td>
<td>4.0232</td>
</tr>
<tr>
<td>1986 LST**</td>
<td>21.3490</td>
<td>41.3972</td>
<td>30.5381</td>
<td>3.8809</td>
</tr>
</tbody>
</table>

* n=4114  ** n=4059 different sample sizes due to coastal shifting
Vegetation levels as measured by NDVI for the same sample points used to evaluate LST were examined next. These show consistency of the mean value, with a difference of only 0.0049 between the 1986 and 2001 images. Standard deviation differs a maximum of 0.018 between 2001 and 2009 images.

A difference in the range between minimum and maximum is most notable in the 1986 image. Table 4-2 summarizes the 2001 findings:

**Table 4-2** NDVI of samples for the three image dates.

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009 NDVI*</td>
<td>-0.2754</td>
<td>0.7143</td>
<td>0.2763</td>
<td>0.1733</td>
</tr>
<tr>
<td>2001 NDVI**</td>
<td>-0.2414</td>
<td>0.6667</td>
<td>0.2788</td>
<td>0.1553</td>
</tr>
<tr>
<td>1986 NDVI**</td>
<td>-0.3770</td>
<td>0.7031</td>
<td>0.2739</td>
<td>0.1639</td>
</tr>
</tbody>
</table>

* n=4114  ** n=4059  different sample sizes due to coastal shifting

%ISA shows an increase between 1986 and 2009, with the mean value going from 36.51% in 1986 to 44.896% in 2009. The minimal change in mean between 1986 and 2001 is a factor which deserves further analysis since it is unlikely that changes during the 15 year period could be this minor. It is possible that inadequate identification of spectra for endmember identification, sample selection, or other processing issues is responsible for this. Other than this issue, the standard deviation differs by 2.0656 between 2001 and 2009 images. Minimum and maximum values are as expected. These results are displayed in Table 4-3:
Table 4-3 %ISA of samples for the three image dates.

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009 %ISA*</td>
<td>0</td>
<td>100</td>
<td>44.8959</td>
<td>27.1628</td>
</tr>
<tr>
<td>2001 %ISA**</td>
<td>0</td>
<td>100</td>
<td>36.75</td>
<td>29.2284</td>
</tr>
<tr>
<td>1986 %ISA**</td>
<td>0</td>
<td>100</td>
<td>36.5135</td>
<td>28.6354</td>
</tr>
</tbody>
</table>

n=4114  **n=4059 different sample sizes due to coastal shifting

Descriptive statistics for the 2008 LULC classifications revealed that high-density residential was the largest type comprising 43.2% of the sample. Next were commercial & services with 8.1%, then medium density residential at 6.4% and recreational with 5.8%. Sample counts for these categories are displayed in Figure 4-1:

![Figure 4-1 Counts of 2008 LULC using FLUCCS level 2 classification](image-url)

Figure 4-1 Counts of 2008 LULC using FLUCCS level 2 classification
LULC was subdivided into two further categories of “rural” and “urban” reflecting uses of the land. Analysis of “Rural/Urban” showed that 20.6% and 79.4% of the sample were in the respective categories, as displayed in Table 4-4:

<table>
<thead>
<tr>
<th></th>
<th>Frequency</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>849</td>
<td>20.6</td>
</tr>
<tr>
<td>Urban</td>
<td>3265</td>
<td>79.4</td>
</tr>
<tr>
<td>Total</td>
<td>4114</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Both the FLUCCS classification results and the “Rural/Urban” analysis reflect the urbanized character of the study area. Additionally, most of the “rural” areas occur along the coast, or in scattered pockets of park and preserved land in the study area which becomes evident viewing maps of NDVI, LULC and %ISA.

4.2 Correlation of LST and Landscape Factors

Since imperviousness and vegetation levels are closely associated factors they are unsuited for combination in a model that might describe the relationship between LST and landscape change. Instead, examination for bivariate correlation using Pearson’s r is the most appropriate measure. The same sample data which produced the descriptive statistics were used to analyze correlation between LST and the independent variables of NDVI and %ISA for the three images. In all cases a two-tailed test for statistical significance is used.

Starting with the 2009 data scatterplots for LST and NDVI and %ISA were constructed as shown in Figures 4-2a & 4-2b:
Figures 4-2a and 4-2b 2009 sample LST plotted with NDVI and %ISA

An anomaly occurs in the 2009 LST to NDVI scatterplot (Figure 4-2a), where a slight “shift” is seen in the values on the x-axis at 0.18. This is probably due to the cutoff point of 0.18 NDVI for impervious and vegetated surface emissivity which was used in processing all the LST images with the mono-window algorithm. It is evident in scatterplots of all three images.

Considering correlation in the 2009 image, there is a significant, negative linear relationship between higher LST and decreasing vegetation ($r = -0.722$.) Additionally, a statistically significant, positive linear relationship was shown for impervious surfaces ($r = 0.580$.) As expected, NDVI and imperviousness indicate negative linear relationship ($r = -0.819$.) Table 4-5 displays the information regarding correlation:

<table>
<thead>
<tr>
<th></th>
<th>LST</th>
<th>NDVI</th>
<th>%ISA</th>
</tr>
</thead>
<tbody>
<tr>
<td>LST</td>
<td>Pearson’s r</td>
<td>1</td>
<td>-0.722**</td>
</tr>
<tr>
<td>NDVI</td>
<td>Pearson’s r</td>
<td>-0.722**</td>
<td>1</td>
</tr>
<tr>
<td>%ISA</td>
<td>Pearson’s r</td>
<td>0.580**</td>
<td>-0.819</td>
</tr>
</tbody>
</table>

** Correlation significant at the $\alpha = 0.01$ level (2-tailed)
The 2001 sample data set shows a similar distribution to the 2009 set, with a more pronounced shift distribution at the NDVI 0.18 value as seen in Figure 4-3a:

Figures 4-3a & 4-3b 2001 sample LST plotted with NDVI and %ISA

There was a statistically significant negative linear correlation for LST and NDVI \((r = -0.710)\) and a statistically significant positive correlation of LST and %ISA \((r = 0.501)\). Also NDVI and %ISA show a statistically significant negative correlation \((r = -0.762)\). Table 4-6 summarizes these values:

<table>
<thead>
<tr>
<th></th>
<th>LST</th>
<th>NDVI</th>
<th>%ISA</th>
</tr>
</thead>
<tbody>
<tr>
<td>LST</td>
<td>Pearson Correlation</td>
<td>1</td>
<td>-0.710**</td>
</tr>
<tr>
<td>NDVI</td>
<td>Pearson Correlation</td>
<td>-0.710**</td>
<td>1</td>
</tr>
<tr>
<td>%ISA</td>
<td>Pearson Correlation</td>
<td>0.501**</td>
<td>-0.762**</td>
</tr>
</tbody>
</table>

** Correlation significant at the \(\alpha = 0.01\) level (2-tailed)
For the 1986 dataset, the shift in values for the LST and NDVI evident in the scatterplot at 0.18 is very pronounced. A line is drawn to highlight the value point of this change in Figure 4-4a:

Figures 4-4a & 4-4b 1986 sample LST plotted with NDVI and %ISA. Line at 0.18 NDVI value which defined the cutoff in emissivity for the LST MWA processing.

Correlation of LST and NDVI is significant and negative linear, with an $r = -0.716$. LST and %ISA show a significant positive correlation with $r = 0.612$. NDVI and %ISA show a significant negative correlation with $r = -0.836$. Table 4-7 displays these relationships:

Table 4-7 Pearson's correlation for 1986 LST, NDVI, and %ISA

<table>
<thead>
<tr>
<th></th>
<th>LST</th>
<th>NDVI</th>
<th>%ISA</th>
</tr>
</thead>
<tbody>
<tr>
<td>LST</td>
<td>Pearson Correlation</td>
<td>1</td>
<td>-0.716**</td>
</tr>
<tr>
<td>NDVI</td>
<td>Pearson Correlation</td>
<td>-0.716**</td>
<td>1</td>
</tr>
<tr>
<td>%ISA</td>
<td>Pearson Correlation</td>
<td>0.612**</td>
<td>-0.836**</td>
</tr>
</tbody>
</table>

** Correlation significant at the $\alpha = 0.01$ level (2-tailed)
4.3 LULC and LST

Examination of possible differences of mean LST for different LULC in 2009 was explored using FLUCCS level 2 classifications. The previously selected stratified random sample points for evaluation of LST, NDVI and %ISA were used. Several LULC categories were excluded due to low sample size, so this does not reflect samples less than 10. The histogram displaying the values compared to the mean is displayed as figure 4-5:

![Histogram of Mean 2009 LST for LULC classified by FLUCCS level 2 codes](image)

**Figure 4-5** Sample mean temperature for LULC classified by FLUCCS level 2 codes
The histogram shows the generally lower mean temperature of forest and wetland land cover types, and also for low-density residential. Land cover typical of the urban environment, like high density residential, commercial, industrial and institutional and also transportation and utilities all exceed the sample mean.

In order to better visualize the relationship between land cover and LST, transects were produced which provide an improved spatial perspective. The northernmost transect, which follows an east to west line starting at Brooker Creek Park, passing south of Lake Tarpon and terminating at the Gulf of Mexico in the west is presented in Figure 4-6 a & b. A mid-county transect which runs from Tampa Bay, along Gulf-to-Bay Boulevard to Clearwater and the Gulf of Mexico is shown in Figure 4-6 a & c. The southernmost transect is in St. Petersburg and runs from Tampa Bay to the Gulf of Mexico along Central Avenue in Figure 4-6 a & d. All transects show a pattern of temperature variation with low water temperatures which steeply increase past coastal wetland areas. Temperature plateaus in areas of high-density residential land use, with sharp increases in commercial areas, and declines in lake, wetland and forest areas.
**Figure 4-6a** Areas displayed in Pinellas transects
**Figure 4-6b** Results of the north Pinellas transect, Brooker Creek Park to Honeymoon Island

**Figure 4-6c** Pinellas transect in Clearwater, Tampa Bay to the Gulf of Mexico
**Figure 4-6d** South Pinellas transect, downtown St. Petersburg to Treasure Island
The statistical relationship between impervious surfaces, the NDVI and LST suggest that they are predictive factors in the UHI pattern. The higher mean LST values of LCLU typical of the urban environment and lower mean values of natural vegetated surfaces further confirm of an association. Transects of the region help visualize this association as LST varies across the surface with the different land cover types.

The land cover types were further generalized to categories for “rural” and “urban”. Low-density residential, wetlands, forested and agricultural land use were assigned to the “rural” and medium and high-density residential, commercial, industrial, transportation (primarily the airports in downtown St. Pete and St. Pete/Clearwater), utilities were assigned to “urban”. The means for the two different categories were then compared, with rural equaling 25.05°C and Urban 32.15°C. This produces a difference in mean temperature, or ΔT between rural and urban categories of 7.1°C on 4/08/2009 at 11:48 EDT, the time of satellite over flight. The difference should not be construed as an overall indicator of rural/urban LST differences, but does show significant differences in temperature during the mid-morning. Further evaluation over time using air temperature readings is needed to establish an understanding of the intensity of the UHI in Pinellas.
4.4 Descriptive Mapping of the UHI

The resulting LST map for 2009 was analyzed at the local and micro scale level. Oke defines micro scale events as occurring between from sub-meter to 1 kilometer scale, and local scale from 100 meters up to 50 kilometers (Oke, Boundary Layer Climates, 1978). This definition creates broad overlap between the two scales. For the purposes of this study the micro scale is defined from the lowest resolution of the thermal imagery, 120 meters up to a kilometer, and local scale extends between a kilometer and up to 20 kilometers.

4.4.1 Micro-scale Analysis

LST patterns in Pinellas at the micro-scale level are typified by a series of “hot” and “cool islands” related to landscape and LULC factors. This can be seen in figure 4-10, a detailed view of Pinellas Point. This area is in south St. Petersburg, at the tip of the peninsula, surrounded by water on three sides. A distinct temperature gradient is evident, with the coolest temperatures near the water and extending to wetland, and wooded areas (parks) close to the water. In these areas LST is typically between 22 and 28°C. Temperatures from 28 to 32°C are evident in the areas extending, comprising of medium-density residential areas. The next temperature zone, 32 to 36°C is made up of high-density residential, commercial and institutional areas. A zone of temperatures from 36 to 40°C is typified by the areas surrounding shopping plazas, schools, and also commercial districts. Finally, the areas with the highest temperatures, above 40°C consist of specific structures like schools and shopping plazas. The
lakes and parks interspersed through the interior portion of the peninsula also appear to be the center of temperature gradients, with a zone of increasing surface temperatures extending from the cooler, central area (Figure 4-7.)

LST "MUHI" & "Cool-Islands" Pinellas Point

**Figure 4-7** The spatial pattern of MUHIs and "cool islands" is evident in this detail of south St. Petersburg
This pattern is seems similar to the one in Aniello et al’s study of the Dallas area found a similar pattern of “hot spots” surrounded by a gradient which they refer to as “Micro-Urban Heat Islands, ...isolated urban locations that produce ‘hot spots’ within a city” (Aniello et al., 1995, P. 965.) There is no description of the scale of these features, rather they are described on the basis of their thermal intensity relative to the surrounding area.

Distinctive “cool-island” features are centered on ponds, lakes and woodlands in areas distant from the Gulf and Bay. As an example, Sawgrass Lake is easily distinguishable in the south-central Pinellas area (Figure 4-8.) This rural remnant area is a SWFWMD water control site and recreation area, with extensive forest cover. Sandwiched between neighborhoods of high-density residential, commercial, and industrial land uses this park area is
Figure 4-8 A "Cool Island" effect is evident in the pattern of this park centered on a lake. The immediately surrounding areas are residential, with MUHIs centered on the commercial and industrial buildings to the north and west of the park.
A distinctive feature of the LST images. The park is a minimum of 4°C cooler than the surrounding residential areas, which are near mean temperature for that date. It is difficult to determine how far its temperature moderating influences extend beyond its boundaries. In a study conducted by Rosenzweig et al. of New York’s 850 acre Central Park, it was found that its temperature moderating influence did not extend further than 60 meters into the surrounding urban area (Rosenzweig, Solecki, Slosberg, 2007).

This pattern of MUHIs and “cool islands” scattered throughout the peninsula is repeated, showing the considerable variation in land surface temperature based on LULC. This cannot be extrapolated to near-surface temperature to determine whether similar variation exists for atmospheric temperature over the region.

To better examine the types of structures associated with MUHIs and determine where “cool-islands” were present a series of maps were produced highlighting areas where they are clustered (Figures 4-10a&b, 4-11a&b). A total of 36 MUHIs (temperatures 3 standard deviations above the mean) were identified in the 2009 image and classified according to location and activity (figure 4-9.)
Most were shopping plazas, followed by industrial and then institutional sites which were mostly school buildings. All were large structures, usually surrounded by extensive parking facilities, however the greatest heat intensity was concentrated on the buildings themselves, possibly due to heat producing activities and air conditioners located on or near their roofs. Additionally, many of the structures have or had black roofs.

The locations of “cool-islands” are shown in figures 4-11 a & b. These sites are usually associated with coastal wetlands, or parks on the interior of the peninsula. Most have dense vegetation, and are the sites of natural preserves. The largest are Brooker Creek in north Pinellas along the border of Hillsborough County, and then Weedon Island/Gateway coastal preserves on Tampa Bay. When analysis was being conducted, many of these areas were at,
Figure 4-10a MUHIs in the north portion of the Pinellas study area 2009
Figure 4-10b MUHIs of the southern portion of the Pinellas study area 2009
Figure 4-11a "Cool-Islands" of the north Pinellas study area 2009
Figure 4-11b "Cool-Islands" of the south Pinellas study area 2009
or even slightly below water temperature levels in Tampa Bay. The coastal sites
generally are intertidal mangrove forests. Sites in the interior usually are
associated with an extensive water feature like Sawgrass Lake, and Boyd Hill
Park on Lake Maggiore. Dunedin Hammock and Brooker Creek Parks are
exceptions to this.

4.4.2 Local-scale Analysis

Changing the scale of analysis to examine the LST structure of the overall
region reveals several different patterns. Statistical analysis and the LST
transects indicate that overall patterns are linked to LULC in the region. The
transects provided a lateral view of those temperature differences, lower LST
around water and forested areas, rising to a plateau over the high-density
residential areas, interspersed with peaks and valleys depending on land cover
differences. Study area LST images tend to verify this pattern, and also show its
variations, particularly along major transportation routes, where the prevalence
of commercial and service related land uses creates “bands” of increased LST
along their routes. These are then punctuated by MUHIs, centered on major
commercial or industrial structures. There are several areas where this pattern
of temperature differences dissolves into more homogenized areas of elevated
temperature such as around St. Petersburg/Clearwater Airport, the area of Gulf
to Bay Boulevard extending to downtown Clearwater, the Tyrone Mall area and
notably the Central Plaza area of St. Petersburg (Figure 4-12.) The last feature
is at the center of an extensive SUHI which appears on the land surface.
Figure 4-12 This 2009 image of the Central Plaza district of St. Petersburg displays areas of elevated LST surrounded by relatively cooler areas. The scale and structure are evidence the SUHI with smaller MUHI in this area, which is distant from the moderating influence of Tampa Bay and the Gulf of Mexico.
A pattern of MUHIs is evident in the Central Plaza area of St. Petersburg. It is located the southern, center of the Pinellas peninsula, about 5 km from Tampa Bay to the east and 7 km from the Gulf to the west far from possible the water, which would be a moderating factor. The area of greatest LST intensity is a highly urbanized area, which was developed as a commercial center in the 1960’s, with extensive asphalt and concrete parking lots and commercial buildings. Figure 4-9 shows LST typically in the 28 to 40°C range, the cooler areas being in the residential districts which are interspersed with some small lakes and ponds. The overall spatial pattern covers roughly 4km x 5km, and is a prominent feature in both the 1986 and 2009 LST images. Because of the distance from the water, the extensive homogenized urban land cover in which high-density residential and commercial land uses are mixed it is the center of the most easily distinguished pattern of urban heating on the peninsula, and indicative of a SUHI.
CHAPTER 5: MITIGATION STRATEGIES

At this point the relationship between land cover and the UHI (and SUHI) has been demonstrated repeatedly in the literature, from Howard’s hypothesis to Chandler and Lowry. Surface energy dynamics have been extensively researched and explained by Landsberg and Oke, to a point where a linkage can be made with land cover change as one factor of the UHI. The UHI is not a theoretical construct, but an established phenomenon of the urban microclimate. Its economic and societal impact, and its potential mitigation require examination. Since urban land cover is a factor in LST and the formation of the UHI, then specific changes to land cover can mitigate it.

5.1 Urban Heat Effects

Urban heat is a factor of public health, economics, and indirectly, global climate change, so it is important to examine ways its impact is decreased. It is obvious that very hot temperatures affect personal comfort, and intense prolonged heat, human health because of the body’s inability to tolerate extreme heat for long periods of time. From a public health perspective, periods of intensified prolonged heat lead to higher mortality rates for populations living in physical environments that are not well heat adapted, as the 1995 Chicago
(Klinenberg, 2002), the 2003 European (Stott, Stone, Allen, 2005), and last year’s eastern Russia heat wave (Lokoshchenko, 2011) demonstrated. While the health effects of the UHI have been understood within the context of heat waves, there are other potential impacts if urban heating is coupled with the effects of global climate change (EPA Climate Change Division, 2006). Also, there is concern that heat intensification will elevated the risk of climate sensitive diseases, especially “vector-borne,” or mosquito transmitted disease like malaria, dengue fever, encephalitis, and yellow fever. High levels of heat also increase the occurrence of algal blooms and water borne diseases like cholera. One study has examined the UHI and possible effects on respiratory illness, but without conclusive results (Lo, Quattrochi, 2003).

The UHI acts to compound broader regional heating patterns intensifying them at the local level (Grimmond, 2007). The most direct way for people in developed countries to cope with intensified urban heat is to turn up the air conditioner. However, adaptation strategies which rely exclusively on mechanical cooling through air conditioning are counterproductive both at the local and global level (Richardson, Otero, Lebedeva, Chan, 2009). Air conditioners exhaust heat to the urban environment thereby intensifying the UHI and increasing energy use which requires burning greater quantities of fossil-fuels for power generation. This adds to CO₂ emissions, possibly contributing to global climate change. Cooling to mitigate heat island effects comes at a high economic cost too. For each 1°C increase in temperature above a threshold of
15 to 20°C, electricity demand in cities increase 2-4% (Akbari, Pomerantz, Taha, 2001). Additionally, one study predicts that sales of air conditioners will escalate in markets that are not already saturated by them if the number of degree cooling days climbs attendant with global climate change, further increasing energy use (Sailor, & Pavlova, 2003). Because of these factors, the UHI has been recognized as an important issue requiring mitigation or remediation by international, US Federal and State level agencies.

Internationally, the World Meteorological Organization (WMO) has been a publisher and clearing house for UHI related research. Publications by Chandler, Oke and Grimmond have been underwritten and distributed. The WMO also sponsors a series of international workshops on the UHI. One effort since the 1993 WMO Dhaka conference is the Tropical Urban Climate Experiment (TRUCE), which promoted increased research on tropical urban climates, however it’s difficult to find much recent output (post 2003) from this specialty group. Also at the international level, the International Energy Agency (IEA) has hosted the International Conference on Countermeasures to Urban Heat Islands (ICCUHI). Even though most of its efforts are directed toward global climate change rather than the UHI per-se, the IEA has hosted the ICCUHI in the past.

At the Federal level, since 1997 the EPA Heat Island Reduction Initiative has focused on supporting voluntary heat island reduction efforts such as demonstration projects, state, local and private incentive programs, urban forestry, weatherization, and outreach programs. They also act as a clearing
house for information on policy efforts like; revision of zoning codes, ordinances, building codes, and green building requirements. Their strategy for UHI reduction boils down to:

1. Increasing vegetation
2. Promotion of green roofs and cool roofs
3. Cool or permeable pavements

Lawrence Berkeley National Laboratory Heat Island Group maintains a cool roofing material database, conducts research on materials, demonstration projects, researches the UHI. Federal incentives have included a 30%, or maximum $1500 credit for material costs of ENERGY STAR certified metal or asphalt roofing. It has also promoted demonstration projects for green roofs, cool roofs, and urban forestry in cities throughout the US. In Florida, incentives at the state government level relate to building code reductions of insulation requirements for meeting a minimum 70% solar reflectance. Florida’s 2006 State Energy plan gave no consideration to heat island effects or cool roofs (Florida EPA, 2006). Private incentives exist, like the Florida Power & Light economic incentives for reflective roofs, which is active. The Florida Solar Energy Center associated with UCF is conducting Florida specific research in the area of roofing materials and local effects, and also acts as a clearinghouse for information on the UHI.
5.2 Specific Mitigation Strategies

As stated above, the EPA has promoted a mitigation strategy based on increasing urban vegetation (urban forestry), cooling the roofs of structures, and cooling pavements. In 2005 it was estimated that the total economic effect of complete mitigation of UHI in the United States potentially could lower use of air conditioners by 20%, amounting to $5 Billion in yearly savings (Akbari, 2010) (Akbari, Konopacki, 2005). Secretary of the Department of Energy, Steven Chu has advocated this program, specifically promoting increasing albedo (surface reflectivity) as a strategy to lessen the impact of global climate change (Department of Energy, 2010). All new Department of Energy buildings have been mandated to have high-albedo roofs, with replacement of older roofs as they reach the end of their service life.

The Department of Energy strategy is an example of both direct and indirect beneficial effects. Direct effects alter the surface energy balance and minimize the cooling requirements of a particular building. So planting shade trees and implementing cool roofs lowers energy demand and costs for commercial, institutional and residential structures. If this occurs throughout an entire city, indirect effects occur, altering the overall surface energy balance and potentially lowering the temperature at the local scale. Additional indirect effects occur with the decreased CO₂ emissions from a reduction in energy demand. Direct effects can have immediate benefit to the building owner, lowering
temperature and energy costs due to cooling. The indirect effects can have greater impact by lowering temperature city wide.

5.2.1. "Cool Roofs"

Two different types of roofing systems have been promoted to lower surface temperature; cool roofs and green roofs. The EPA has published a guide focused on green roofs which compares their relative advantages to cool roofs (EPA, 2009). Green roofs are roof structures that support the growth of vegetation consisting of plants, a growing medium, drainage and a waterproof membrane, with underlying structural support. These types of roofs are divided into extensive (low-profile), sod-like and intensive (high-profile) roof garden types which can support shrubbery or even small trees. Advantages of this type of roof are their low temperature profile, insulating properties, possibility of increasing evapotranspiration to roof tops, reduction of stormwater runoff, and greater capacity to filter the air. They are also expensive to install, starting at $10.00 a square foot for an extensive green roof, versus $.50 to $6.00 a square foot for a cool roof, and can require more maintenance (EPA, 2009). Green roofs require a great deal of planning for construction or conversion, while it is easy to retrofit an existing roof to a cool one. Because of green roofs greater cost and the early stage of their development (in this country), this paper focuses on cool roofing materials as the most practical choice for most applications.
Cool roofs are designed to maintain a lower surface temperature during the day, than conventional roofs can. They do this by combining the properties of high-albedo, or surface reflectivity with high emittance - the ability to radiate absorbed heat. This way they reflect most of the thermal energy from their surface, and the thermal energy which is absorbed is efficiently radiate back rather than stored. White surfaces are highly reflective of solar radiation in the 400 – 2500 nm region of the spectrum, and are emissive in the far-infrared of 4000 – 18,000 nm (FSEC, 2000). They also reflect the ultraviolet portion of the spectrum, which is responsible for degradation of polymers (Department of Energy, 2010). Their high emittance reduces diurnal expansion and contraction, enhancing their long-term durability. Their problems include increased glare and visual discomfort when sloped roofs are covered. They also reduce thermal absorption during the winter, and can increase heating cost. Reduction of albedo over time is also a problem for some cool roofs. White roofs may need to be maintained and periodically repaired, recoated or washed. Existing tar roofs are not capable of being painted with elastomeric cool roof “paints”.

Additionally, their aesthetics may not appeal to all and there are limited color choices\textsuperscript{13}. However, despite these problems, they substantially lower surface temperatures as seen in this image of Tropicana field (Figure 5-1).

\textsuperscript{13} Though this is being addressed with the introduction of “cool dark color” roofing materials which have higher albedo and emittance than their conventional counterpart. Still they are less efficient than white color “cool roofs.” (US DOE, 2010)
Figure 5-1 Tropicana field with its white "cool roof" has a temperature below the mean of 28°C, and 12°C less than the parking lot in this 4/08/2009 thermal image over aerial imagery. (Landsat TM, and SWFWMD DOQQ)
The direct effects of changing roof albedo are well established. Both Akbari and Parker have extensively tested the results of different roofing materials on energy demand and cost. Parker’s 1998, study of 11 Florida houses found a 17% average reduction in energy use (Parker, McIlvaine, Barkaszi, Beal, Anello, 2000). They also monitored summertime energy use in seven Florida strip mall stores finding a 25% reduction in energy use by applying reflective roof coating. 30% reduction in summer energy use after a reflective roof was placed on a school in Florida. Akbari et al. extrapolated savings of this sort nationwide, estimating them at about 10 TWh a year, or about 3% of the total national demand from cooling electricity (Akbari, Konopacki, 2005). Another indirect advantage of cool roofs, with the addition of cool pavements involves their implementation on a massive scale worldwide. Akbari calculated that an increase in albedo of all roofs and paved surfaces in urban areas, worldwide could result in negative radiative forcing, reflecting sufficient sunlight back to the atmosphere, thereby reducing solar heating of the atmosphere equivalent to 44 Gt of CO₂ emissions. He estimates the economic benefits as $1,100 billion yearly. This does not include savings in energy costs from reduced air conditioning (Akbari, Menon, Rosenfeld, 2008). This is being promoted as the “100 cool cities initiative,” the goal of which is to have the 100 largest cities in temperate and tropical regions develop a program for conversion of their pavements and rooftops to cool or white surfaces (Akbari, 2011).
There are several types of cool roofing materials available. These include cool roof coatings, membranes, built-up roofs, modified bitumen sheet membranes, spray polyurethane, cool asphalt shingles, tile and coated metal roofs. Parker evaluated many of these types in a study conducted in Florida in 2000 (Parker et al., 2000). At that time, the materials that best combined high-albedo and high emittance were white elastomeric coatings, white membrane systems, white concrete tile, white cement shingles, white coated metal roofing, and EPDM products like *Hypalon*\(^{14}\). Table 5-1 compares some of the top performers in Parker’s study with conventional roof materials.

**Table 5-1** Evaluation of common roofing materials and "cool roof" materials. (Parker, 2000)

<table>
<thead>
<tr>
<th>Type</th>
<th>Product Notes</th>
<th>Solar Reflectance %</th>
<th>Infrared Emittance</th>
</tr>
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<tr>
<td>Grey asphalt shingle</td>
<td>Owens Corning</td>
<td>21.7</td>
<td>0.91</td>
</tr>
<tr>
<td>Wood shingle</td>
<td>Brown painted</td>
<td>21.9</td>
<td>0.90</td>
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<tr>
<td>Unpainted galvanized</td>
<td>generic</td>
<td>60.9</td>
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<tr>
<td>White metal - Kynar</td>
<td>Atlanta Metal Products</td>
<td>66.5</td>
<td>0.85</td>
</tr>
<tr>
<td>Elastomeric on shingle</td>
<td>Kool-Seal</td>
<td>71.4</td>
<td>0.91</td>
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<tr>
<td>White concrete tile</td>
<td>Generic</td>
<td>72.8</td>
<td>0.90</td>
</tr>
<tr>
<td>Hypalon membrane</td>
<td>DuPont - CSPE</td>
<td>75.5</td>
<td>0.91</td>
</tr>
<tr>
<td>White cement shingle</td>
<td>Generic</td>
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<td>0.88</td>
</tr>
<tr>
<td>White membrane</td>
<td>T-EPDM</td>
<td>80.6</td>
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</table>

This shows that conventional materials that are white, like concrete and cement tile and shingle are highly reflective and have high emittance, and well suited for “cool roofs.” Modern materials like the EPDM membrane and elastomeric sealant "Kool-Seal” are also rated highly on these properties and offer some insulation.

\(^{14}\) DuPont ceased manufacturing Hypalon (chlorosulfonated polyethylene) in April 2010, though it may continue to be manufactured elsewhere.
and moisture resistance advantages. The industry based group, Cool Roof Ratings Council (CRRC) maintains a database of materials and their performance characteristics, and Lawrence Berkeley National Laboratories posts the results of their testing in this area\textsuperscript{15}. An example of a local conversion to a “cool roof” in Pinellas is seen in Figure 5-2, where a retail hardware store was converted from black asphalt to a white “cool roof”. A similar warehouse hardware store directly across the street and north retains its black asphalt roof. The LST difference between the sites as measured by a Landsat thermal image is 15°C. The image shows notable reduction of a MUHI that was centered where the converted store is located, reducing its temperature to background levels.

\textsuperscript{15} CRRC http://www.coolroofs.org/products/search.php LBNL http://eetd.lbl.gov/CoolRoofs/
Figure 5-2 Mitigation of the MUHI, before and after replacement of black asphalt roof with white "cool roof." LST of building to the north in 2009 image is 51°C, and the "cool-roof" is 36°C. Home Depot at 22nd Ave. N., St. Petersburg. (Landsat TM imagery from 2001 and 2009. Google Earth photo from 2010 shows new white roof)
Overall, cool roofs have been shown to have significant effect in reducing roof surface temperature. This leads to direct economic benefits in reduced cooling and energy use in tropical and temperate regions. They can be minimally more expensive to install than conventional roofing, and require only a little more maintenance for surface repair and cleaning. Their durability may be superior to conventional roofs because of their thermal properties and resistance to UV radiation. In addition to direct benefits they indirectly benefit the environment by lessening energy use thereby reducing fossil-fuel emissions. They also have the potential, if employed on a massive scale to, lessen solar warming to the atmosphere, thus reducing the impact of CO₂ on the atmosphere.

5.2.2. Increase Vegetation - "Urban Forestry"

The “urban forest” already comprises a significant portion of the space within urban areas, with tree canopy covering 20-40% of the average North American city (Oke, The micrometeorology of the urban forest, 1989). Urban trees are an important factor in their environment by reducing CO₂ directly (sequestration) and to the micrometeorology of cities by absorption and reducing overall heat by refracting sunlight and shading of pavements and structures and effecting wind flow (Dwyer, McPherson, Schroeder, Rowntree, 1992). While some early work suggested that the impact of urban forests on overall urban climate might be substantial (Huang, Akbari, Taha, Rosenfeld, 1987), recent work by Rosenzweig in New York (2007) suggests only minor impacts, with the cooling effect of Central Park extending only slightly beyond its boundary.
Nevertheless, when trees and vegetation are placed in a planned manner, they provide significant shading to structures and can be an important factor in mitigating urban heating (Richardson, Otero, Lebedeva, Chan, 2009).

Several studies have been conducted to quantify the effect of shade on the cooling of structures. A Florida based study by Parker (1983) measured energy use for the cooling of a structure before and after shade from plants was added and found a 50% reduction. An early literature review of the topic, Meier found that energy savings between 25-50% were common (1991). In Sacramento, CA, Akbari et al. conducted a similar study with two houses, finding seasonal cooling energy reduction of 30% (2001). These studies concentrate on integrating trees into the landscape for their shade producing quality, emphasizing the need for proper planning if full benefit is to be derived from them. Several studies suggest that trees be placed along the southern exposures of structures in lower mid latitude regions and the tropics.

Since large parks do not provide cooling benefits far beyond their boundaries, tree planting to cool buildings and mitigate the MUHI should be approached at the structure or neighborhood level (Richardson et al., 2009). Additionally, improper management strategies and placement of trees and other vegetation can have adverse economic impacts. Regional climate, sun exposure, water and maintenance needs must be evaluated to determine appropriate tree species and planting location. The overall expense of siting, maintaining, pruning, and clean-up of trees must be considered and weighed against
economic benefit. Trees can also take decades to reach maturity, so the growth patterns of individual species requires consideration. Consequently, plantings of trees should be planned at the neighborhood level to maximize urban forestry benefits.

5.3 Remote Sensing as a Survey Tool

As we have seen with cool roofs and urban forestry, mitigation measures can have immediate, direct impact at a small-scale, conserving energy and lowering costs. These effects are generally apparent at the scale of MUHI, large structures or complexes of structures with much higher land surface temperature than the surrounding area, as seen in the reroofing example in figure 5-2. When these local effects are combined, mitigation of the UHI takes place at the local level. This, in turn has indirect impacts which if done on a large enough scale, could have global effect (Akbari et al., 2008). This multiplication of effects starts with neighborhoods; altering land cover and structures at small scales.

Mitigation measures can be aided by effective and low cost survey of LST using remotely sensed imagery like the free Landsat TM data. Addition of NDVI and LULC maps can aid urban planners as they modify the urban environment to reduce the effect of urban heat. The cities of Chicago and New York are already using UHI mapping to pinpoint urban “hot spots” and remediate their impact (Hertsgaard, 2011) (Rosenzweig et al., 2007). This method is especially useful when combined with socio-economic data so that vulnerable populations like the
elderly or low-income who have less means to afford the energy costs could benefit most directly from lower thermal load. Mitigation strategies involving the creation of additional green-space, strategic planting of urban forest, and increase in the surface albedo of structures. Additionally, low cost, remotely sensed LST images are an efficient survey technique for locating MUHIs and general indications of the SUHI in developing countries. Many of these countries are in tropical climates with growing populations and expanding urban infrastructure. Greater emphasis on green-space in the urban planning of these areas may lessen energy demands, having direct economic benefit, and lessening electricity generation and consequent fossil fuel use and CO₂ emissions. LST mapping combined with the use of low costs air temperature recorders like thermocrons, would establish an efficient, low cost survey method to plan specific interventions at the local and neighborhood level. Combined with efficient techniques, like the application of white roof coating and planting neighborhood scale vegetation, this could provide a basis for future UHI mitigation efforts.
CHAPTER 6: CONCLUSION

This analysis, based on remote sensing derived data has shown the spatial complexity and pattern of land surface temperature (LST) in Pinellas. The pattern was found to be highly related to land cover and land use in the region, and is partly determined by the quantity of vegetation and impervious surface in the unit of analysis, which are 30 meter pixels. Images from all three dates, 1986, 2001, and 2009 displayed broadly similar patterns with distinct micro urban heat islands (MUHI), usually related to specific structures, and “cool islands” of densely vegetated land or intertidal areas and lakes. The remote sensing processing techniques used, which rely on thermal data from the Landsat TM sensor, are well suited for locating large-scale structures and parklands which are at the center of these thermal features of the landscape. It could provide an effective survey method for locating neighborhood and local scale features for mitigation efforts.

The first research question, “what is the spatial pattern of land surface temperature in Pinellas,” can be answered by visually examining the LST images produced. Temperature patterns are seen to resolve themselves as a gradient across the landscape. This pattern exists at a micro-scale and local scale level (micro up to 1000 meters, local 100 to 50,000 meters). The local pattern
exhibits lower water and wetland temperatures, which climb as distance from the coast increases, creating an ascending gradient with higher land surface temperatures mostly in the center of the Pinellas peninsula. This pattern fragments into a series of smaller heat and cool islands at the micro-scale level. This is characteristic of the MUHI or a "cold-island and warm spot" pattern as described by Aniello et al. (1995) and Tso (1996). MUHIs have been classified for the purposes of this study as areas with temperature over 40°C and correspond with specific urban structures in the region. These structures are typified by low albedo roofs or extensive asphalt parking lots. "Cool islands," consisting of lakes surrounded by vegetation create a lower temperature gradient, which gradually climbs as land cover transitions to residential areas with more intensive impervious surface.\(^\text{16}\) So an overall landscape surface pattern in Pinellas emerges; homogenized residential areas, interspersed with large commercial and institutional structures and lake and park areas with more natural land cover, creating a "patch-like" temperature pattern. This pattern seems well resolved by the late morning, the time of satellite over-flight (~15:30 UTC) though further hypothesis testing regarding temporal pattern is not possible due to limitations of the data. It also seems consistent over time in the images, showing the same general pattern of coastal coolness and urban warmth at the center of the peninsula, especially in the southern portion where it is widest, which is most evident in the 1986 image.

\(^{16}\) C.P. Tso describes these as “cold islands” his 1996 study of Singapore and Kuala Lumpur.
The second research question is, “what are the characteristics of the LST pattern relative to %ISA, NDVI and LULC, and is there a correlation between LST and these factors of the urban landscape?” Statistical analysis using Pearson’s correlation coefficient indicates statistically significant positive linear relationships between LST and %ISA in all three years, 1986, 2001 and 2009. There was a statistically significant negative linear relationship between LST and NDVI in all three years. These relationships are consistent in all the statistical analysis of the datasets used in this thesis. Additionally, when land use was separated into “rural” and “urban” categories for the 2009 image, the urban LST was found to be 7.01°C warmer than rural ($\Delta T = 7.01^\circ C$). So, there is a consistent relationship in which areas of greater percentage of impervious surfaces correlate with elevated LST, and areas with more vegetation correlate with lower LST. This supports the literature relating LST to land cover and the hypothesis that urban areas have higher LST than rural. A pattern of localized MUHI and “cool islands” is related to LULC patterns. The extensive impervious surfaces in areas of MUHI, and large vegetated expanses of “cool islands” display this relationship on visual examination of map overlays and transects.

Finally, the third research question regarding remote sensing as an assessment method for finding indications of a surface urban heat island (SUHI) can be answered by examining the results. Using Landsat 5 TM thermal sensor data and the mono-window algorithm required collecting several parameters to produce accurate LST. While most of the parameters of the mono-window
algorithm can be calculated from sensor settings and by deriving an emissivity image, the atmospheric transmissivity parameter requires in-situ measurement of near surface temperature and atmospheric water vapor content. Near surface temperatures are widely available, but the atmospheric water vapor content must be calculated from radiosonde flight data, or from the new GPSMET, global positioning system signal differential measurement technique. If data from either of these sources is available the mono-window algorithm is capable of calculating highly accurate LST readings. Validating the 2009 image using water temperature readings revealed an mean difference of 0.53°C with an $R^2 = 0.834$. With a 120 meters pixel size, the Landsat thermal data offers sufficient resolution to identify neighborhood level features and large structures at the center of MUHIs. Because of its synoptic coverage, accuracy, spatial resolution, reduced requirement for in-situ measurements of temperature, Landsat TM thermal data is a useful component in LST surveying.

This thesis makes a contribution by being the first comprehensive survey of land surface temperature pattern in Pinellas County to use remote sensing technology. It reveals distinct patterns related to the coastal landscape of the Pinellas peninsula, and its highly urbanized interior. Furthermore, this survey technique using the mono-window algorithm provides an efficient, relatively low-cost method for locating micro urban heat islands for remediation. Satellite remote sensing, combined with aerial imagery can facilitate neighborhood level analysis for the implementation of low-cost mitigation techniques. These have
been shown to be effective ways to mitigate the UHI effect at the micro-scale level; lowering urban heat, saving energy, and facilitating reintegration of natural elements back into the urban environment.

Since human changes to land cover are responsible for altering the urban microclimate, making different choices about the materials used to construct, and the configuration of the built environment can reduce urban heating. Mitigation techniques using cool roofs and increased vegetation have been shown to lower surface temperature by purposely altering the energy dynamics of the urban landscape at a micro and local scale. Conscious choices can make structures and neighborhoods cooler, reducing their need for air conditioning, which has a direct benefit of lowering energy use and its associated cost. An additional indirect benefit is derived by lowering fossil-fuel emissions and carbon output to the atmosphere. This benefit has been extrapolated by some, like Akbari, Menon, and Rosenfeld (2008) as a way to increase the worldwide urban albedo to produce negative radiative forcing as an offset to carbon emissions. Regardless, the direct economic benefit of cool roofs and the direct and aesthetic benefits of urban forestry are well established, providing a compelling reason for their large scale implementation in hot climates of the lower mid-latitudes and tropical regions. Market reasons alone are sufficient to justify their implementation, and because of their utility, there is no need to invoke the precautionary principle as justification for their use.
Remote sensing and aerial surveys provide an efficient method of mapping areas where mitigation techniques would have the greatest immediate effect at the neighborhood scale by reducing temperature of MUHIs. A combination of high resolution aerial/satellite photography with thermal imagery provides an ideal survey tool, applicable in both developed and developing regions of the world. These techniques are already being studied or used in some cities like Montreal, Chicago and New York. With the increasing urbanization of tropical regions, this combination of surveying techniques and low-cost mitigation methods provides a useful tool to maintain or improve the microclimate and reduce energy use in these expanding urban areas.
REFERENCES


www.whiteroofs.org.nz/media/7f5b35a5ffe921e9fff81edf523.pdf.


Also


Mono-window algorithm processing code from by Peng Gong and Ruiliang Pu.

Spectral Sciences, Inc., MODTRAN4 atmospheric modeling and correction algorithm.
APPENDIX A

REMOTE SENSING IMAGES PROCESSED
Figure A-1 Original Landsat images by date displayed in RGB
Figure A-2 Landsat images by date displaying NDVI value
Figure A-3 Emissivity images for 1986, 2001, 2009 with NDVI value 0.18 as threshold for vegetation
**Figure A-4a**  Stratafied random sample sites of all images. 4136 sample pixels, or 0.005% of 2009 water mask.  **A-4b** -Composite 3 band image of 2009 Landsat TM impervous surface types used for: water, vegetation, high and low albedo impervious, and sand.
Figure A-5a, b, & c Test sample sites for 5 land classification types. Green=vegetation sample, Blue=lake, gulf and bay water samples, Red=low albedo impervious, Maroon = High albedo impervious, Yellow = sand (from 2009 Landsat TM 3 band image.)
**Figure A-6** Water masks used for processing images, displayed by date
Figure A-7 Land Surface Temperature images displayed by date
Pinellas County Elevation From NED

Figure A-8 Pinellas County elevation map taken from the National Elevation Dataset (NED). Brown areas represent areas of highest elevation at approximately 32 meters. (Source: USGS)
Figure A-9 Land cover classification of Pinellas County according to 2008 Southwest Florida Water Management District survey. (Source: SWFWMD)
Figure A-10 2002 USGS Imperviousness image with calculated percentages (Source: USGS http://gulfsci.usgs.gov/tampabay/data/1_imperviousness/index.html)
Table B-1 2010 Florida Counties by population density, calculated from US Census

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<th>County</th>
<th>2010 Population</th>
<th>Area Km²</th>
<th>Density pop/Km²</th>
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**Figure B-2a-c** Mean air temperature by decade taken from daily readings at Albert Whitted St. Petersburg weather station. Tmin is average daily minimum, Tavg is average daily, and Tmax is average daily maximum temperature. (Data from Office of Florida State Climatologist)
**Figure B-3a-c** Mean air temperature by decade taken from daily readings at the Tarpon Springs sanitation weather station. Tmin is average daily minimum, Tavg is average daily, and Tmax is average daily maximum temperature. (Data from Office of Florida State Climatologist)
Figure B-4a-c  Slope of the line and regression equations used to normalize the 1986 image.
Figure B-5a-c  Slope of the line and regression equations used to normalize 2001 image
Table B-6a-c  Sample statistics for LST, NDVI and Imperviousness for all images, same sample sizes.

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<td>@2009LST</td>
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<td>.0707764</td>
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<tr>
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<td>.7143</td>
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<td>4059</td>
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<td>44.603234</td>
<td>.4218729</td>
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<tr>
<td>Valid N (listwise)</td>
<td>4059</td>
<td></td>
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<td></td>
</tr>
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</table>
Figure 7a-c 1986 standardized residuals chart, Normal P-P regression plot and standardized regression scatterplot
Figure 8a-c  2001 standardized residuals chart, Normal P-P regression plot and standardized regression scatterplot
Figure 9a-c  2009 standardized residuals chart, Normal P-P regression plot and standardized regression scatterplot
Figure B-10  Boxplot of 2009 LST sample distribution for 2008 LULC using FLUCCS classification (n=4114).
Table B-11 2008 Pinellas land use classification of samples (N=4114) with percentage.

<table>
<thead>
<tr>
<th>Type</th>
<th>Frequency</th>
<th>Valid Percent</th>
<th>Percent</th>
<th>Valid Percent</th>
<th>Cumulative Percent</th>
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<td>5.7</td>
<td>5.7</td>
<td>5.7</td>
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<tr>
<td>RESIDENTIAL MED DENSITY</td>
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<td>6.4</td>
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<tr>
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<td>43.2</td>
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<td>COMM &amp; SVCS</td>
<td>333</td>
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<td>8.1</td>
<td>66.2</td>
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<td>1.7</td>
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<td>.3</td>
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<td>.5</td>
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<tr>
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<tr>
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<td>8</td>
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<td>.2</td>
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<tr>
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<td>93.1</td>
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<tr>
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<td>3.2</td>
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<td>UTILITIES</td>
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<td>100.0</td>
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Table B-12 2009 Pinellas MUHI classification from images. Areas classified over 40°C on 4/8/2009.

<table>
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<th>Structure</th>
<th>Location</th>
<th>Location</th>
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<td>1</td>
<td>Shopping Plazas</td>
<td>Tarpon Springs</td>
<td>TARPON SPRINGS</td>
</tr>
<tr>
<td>2</td>
<td>Power Plant</td>
<td>Mobbly Bayou</td>
<td>OLDSMAR</td>
</tr>
<tr>
<td>3</td>
<td>Shopping Mall</td>
<td>Countryside Mall</td>
<td>CLWTR</td>
</tr>
<tr>
<td>4</td>
<td>Shopping Plazas</td>
<td>Missouri Ave corridor</td>
<td>CLWTR</td>
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<td>5</td>
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<td>Bayshore Blvd.</td>
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<td>6</td>
<td>Shopping Plazas</td>
<td>Cleveland St.</td>
<td>CLWTR</td>
</tr>
<tr>
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<td>Sunset Pt. Rd.</td>
<td>CLWTR</td>
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<tr>
<td>8</td>
<td>Industrial</td>
<td>Amer. Tool &amp; Mold</td>
<td>CLWTR</td>
</tr>
<tr>
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<td>Institutional</td>
<td>YMCA</td>
<td>CLWTR</td>
</tr>
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<td>Missouri Ave Corridor</td>
<td>CLWTR</td>
</tr>
<tr>
<td>11</td>
<td>Industrial</td>
<td>E Bay &amp; US 19</td>
<td>PINPARK</td>
</tr>
<tr>
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<td>Airport</td>
<td>PINPARK</td>
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<td>Services</td>
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</tr>
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<td>Industrial</td>
<td>Catalent Ind</td>
<td>ST PETE</td>
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<td>Unk</td>
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<td>ST PETE</td>
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<tr>
<td>27</td>
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<td>Tyrone Gardens</td>
<td>ST PETE</td>
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<td>Shopping Mall</td>
<td>Tyrone Mall</td>
<td>ST PETE</td>
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<td>Tyrone Plaza</td>
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<td>Shoppes Park Place</td>
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