ASSESSING URBAN HEAT ISLAND MITIGATION USING GREEN ROOFS: A HARDWARE SCALE MODELING APPROACH

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ABSTRACT

This project studies the properties of green roofs and their potential mitigating effects on the Urban Heat Island (UHI). The UHI is associated with many negative effects such as increases in air pollution, heat related illness and mortality, water temperatures in streams, and greenhouse gas emissions. These negative effects will become pronounced as it is estimated that over the next century, urban temperatures will increase by an additional 3 to 7°C.

To better mitigate the effects of the current and proposed temperature trends, green initiatives, including green roofs, are being implemented. Many studies have been conducted concerning the UHI effect and the benefits of green roof mitigation, but studies have been limited on the overall effects or benefits green roofs could have on an entire city.

This project used two hardware-scale models to simulate a real city to gain a better understanding of the effects green roofs have on an entire city. One model incorporated green roofs while the other was made of standard building materials. The model temperatures were monitored using temperature, humidity, rain, and wind sensors to assess the impact of green roofs on the overall temperature for the model. The data were collected from June 2009 to September 2009, on an hourly basis. The data showed that green roofs do have a beneficial effect on the UHI by lowering the temperature within the city by a couple degrees. The indoor average temperature data showed a 1.77°C difference between the green and black roofs. The outdoor temperature data showed a 0.24°C difference between the green and black roofs. The differences in the indoor and outdoor temperatures show that black roofs were warmer in both cases. Accounting for wind and rain effects on the temperatures showed that the benefits of the green roofs were still noticeable, but not as much as a clear and non-windy day.

This study will assist real cities conducting research to understand the benefits of green roofs on the UHI. The understanding will help these cities move forward in possible installation of green roofs though their cities.

CHAPTER 1: INTRODUCTION

With trends of increasing urban sprawl, air pollution, heat related illness and mortality, water temperatures in streams, and greenhouse gas emissions, new mitigation methods are being developed to help address these issues. One such method of mitigation is green roofs. There have been multiple studies done on the benefits of green roofs such as: the ability to assist stormwater management, acting as additional insulation for roof tops, providing outdoor areas for human as well as animals within urban areas, ability to help clean urban air by the reduction of $CO_{2,}$ and the possible reduction of the urban temperature associated with the Urban Heat Island (UHI). Of the benefits studied, there has been little documentation produced that shows the potential benefits of green roofs on the reduction of the UHI as a whole, in relation to a city. Smaller scale research has been done to show that green roofs can help lower surface and surrounding air temperature at that particular location, but what effects do green roofs have for an entire city? The hardware scale models used in this study will help in understanding the impact of green roofs in mitigating urban temperatures associated with the UHI. This project will help real cities understand the role of green roofs and plan for a future of developing plans that implement and design green roofs for a whole city.

1.1 Statement of Problem

The purpose of this study was to create two hardware scale models that would each be equipped with the appropriate equipment to monitor for indoor and outdoor temperatures, relative humidity, dew point temperature, wind, and rain, to assess green roofs' ability to assist in mitigating the effects of the UHI. The models were both built to scale, one with green roofs and the other with conventional roofing material. The models were monitored hourly from June through September 2009.

Hardware scale models are models based on real life features and materials and scaled down to a workable size. The models for this study were built due to the lack of data to compare two cities, one with green roofs and one with black roofs. There currently are no cities with green roofs that have a data base of temperature and associated data for analyzing on the scale needed to find the effects of mitigation on the UHI. The hardware scale models were based on the City of Hagerstown, Maryland. The models were used to study the following questions:

- Is there a difference in indoor and outdoor temperatures between the model cities, as well as humidity and dew point temperatures?
- How much of a temperature difference exists between the model cities?
- Do rain and wind affect the temperature difference between the cities?

These questions outline the purpose and the scope of this study, which was to determine if a city with green roofs has an overall beneficial effect of lowering the indoor and outdoor temperatures within that city compared to a city with black roofs. The beneficial effect of lowering the city temperature then will have a mitigating effect on the UHI effect.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Background

2.1.1 Urban Heat Island

Before human development began disturbing natural habitats, soils and vegetation constituted part of a balanced ecosystem that managed precipitation and solar energy effectively (Getter and Rowe 2006). These features have been replaced with impervious areas. In the United States, it is estimated that 10% of residential developments and 71% to 95% of industrial areas and shopping centers are covered with impervious areas. Today, two-thirds of all impervious area is in the form of parking lots, driveways, roads, and highways (Getter and Rowe 2006). The other one-third consists of homes, buildings, and other non-vegetated or open soil areas. These increasing impervious areas consist of cities, towns, and suburbs. This type of building material has the ability to hold in heat during the day more effectively than rural areas. It is documented that urbanization can have an significant affect on local weather and climate. Of these effects, one of the most familiar is the UHI (Streuker 2002).

The UHI is the effect on a metropolitan area that causes it to be significantly warmer than its rural surroundings (Figure 1). The thermal characteristics of materials used in the urban areas (asphalt, brick, concrete, glass, etc.) differ greatly from those found in the rural areas (trees, grass, water bodies, bare soil, etc.). In addition, the canyon structure created by tall buildings enhances warming by the sun (Figure 2).

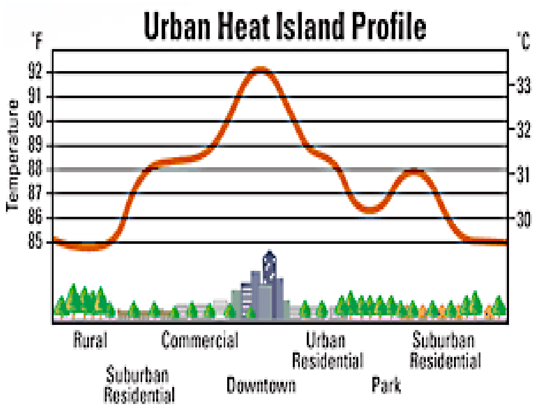


Figure 1. Late afternoon temperature profile over a city.
Source: Environmental Protection Agency,
http://www.epa.gov/hiri/about/index.html.

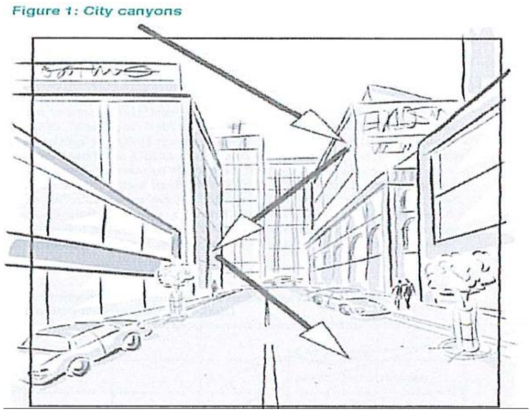


Figure 2. City Canyons. Reflection of solar energy off buildings.
Source: Chapman 2005.

During the day, the energy is trapped by multiple reflections and absorption by the buildings (Chapman 2005). This stored energy in urban areas is then reradiated as long-wave radiation less efficiently than in rural areas during the night (Solecki et. al. 2005), keeping the urban areas warmer than the surrounding rural areas. The buildings also play a role in reducing wind speed. The combination of reduced wind speed and reduced cloud cover aid in intensifying the UHI. Heat island intensities are largest under calm and clear weather conditions. Increasing winds mix the air and reduce the heat island effect. Increased cloud cover reduces radiative cooling at night and also reduces the heat island effect (Voogt 2004).

Air temperature also is reduced through evapotranspiration which is a naturally occurring process within vegetated areas, such as lawns, fields, and woods. Evapotranspiration occurs when plants secrete, or transpire, water vapor through pores in their leaves. The water draws heat as it evaporates, thus cooling the air surrounding the leaves in the process. Trees can transpire up to 100 gallons of water in a day. In a hot dry climate, this cooling effect is comparable to that of five air conditioners running for 20 hours per day (Gray and Finster 2008). In contrast to the natural landscape, cities tend to have little vegetation, and due to a large percentage of impervious surfaces there also tends to be less surface moisture in urban areas (Sailor and Dietsch 2005).

Another component that adds to the creation of an UHI is from waste heat. Waste heat is emitted from a range of human activities-automobiles, air conditioning equipment, industrial facilities, and a variety of other sources, including human metabolism (Sailor and Dietsch 2005). Waste heat can also be considered a byproduct of urbanization, which has greatly increased over the last century.

Though it may seem the study of the UHI is fairly new, it actually was noticed and documented as early as 1820. The first observation of the UHI was by an amateur meteorologist by the name of Luke Howard. He presented a nine-year comparison between temperature readings in London and in rural England in *The Climate of London* (1820). He concluded that night was 3.7^{o} warmer in the city than the country and the day temperature was 0.34^{o} cooler in the city than in the country (Chapman 2006).

Like Luke Howard’s data, recent data indicate that temperature differences are usually most noticeable in the non-daylight or night-time hours, and may exceed 10^{o}C (Chapman 2005). This increase in urban temperatures can affect public health, the environment, and the amount of energy that consumers use in summer cooling. Summer heat islands increase energy demand for air conditioning, raising power plant emission of harmful pollutants. Higher temperatures also accelerate the chemical reaction that produces ground level ozone and smog (EPA 2003). Over the next century, human induced warming is projected to raise global temperatures by an additional 3 to 7^{o}F (Chicago Climate Task Force 2007) adding to the Global Warming Effect.

In response to the increase in temperature, the Environmental Protection Agency (EPA) created the Heat Island Reduction Initiative (HIRI). Through its HIRI, established in 1997, the EPA is working with stakeholders to mitigate the heat island effect by promoting heat island reduction strategies which includes planting shade trees, increasing urban vegetation cover, and installing cool roofing and paving materials that are reflective and emissive (Wong 2008). Green roofs are one of the strategies being promoted within cities that are taking hold which helps reduce the UHI effect.

2.2 Green Roofs

2.2.1. Origin and Types

Green roofs involve growing plants on rooftops, thus replacing the vegetated footprint that was destroyed when the building was constructed (Getter and Rowe 2006). The earliest documented roof gardens were the Hanging Gardens of Semiramis in what is now Syria, considered one of the seven wonders of the ancient world. In the 1600s to 1800s, Norwegians covered roofs with soil for insulation and then planted grasses and other species for stability. Germany is recognized as the place of origin for modern-day green roofs (Getter and Rowe 2006). These were developed to help with protection for radiation on the roof, and even used as fire protection. In the 1970s, growing environmental concern, especially in urban areas, created opportunities to introduce progressive environmental thought, policy, and technology in Germany (Oberndorfer and others 2007). These innovations and technologies were quickly embraced. The use and understanding of green roofs have allowed the formation of building laws that now require construction of green roofs in many urban centers. Green-roof coverage in Germany alone now increases by approximately 13.5 million square meters (m^2) per year. Today, similarly elaborate garden projects are designed for high-profile international hotels, business centers, and private homes (Oberndorfer et. al. 2007).

Greens roofs are classified into two categories, intensive and extensive. Intensive green roofs involve intense maintenance and include shrubs, trees, and deeper planting medium. Extensive green roofs have less maintenance and usually consist of shallower soil media, different plants such as herbs, grasses, mosses, and drought tolerant succulents such as sedum (Getter and Rowe 2006). The creation of green roofs, whether they are intensive or extensive, has beneficial effects to the environment and on the UHI.

2.2.2 Benefits of Green Roofs

Green roofs have multiple benefits, one of which is shadowing the surfaces of roofs, which can reduce heat gain by nearly 100 percent. A green roof forms a buffer zone between the roof and the sun's radiation and shades the roof, preventing its surface from heating up and increasing outdoor and indoor air temperatures (FEMP 2004). Green roofs provide many other benefits such as storm-water management, improving roof membrane longevity, summer cooling of interior space, support of wildlife diversity, improvement in air quality, aesthetic views, and reduction of the UHI effect.

Studies and models have shown the ability of green roofs to reduce the UHI. A regional simulation model using 50% green-roof coverage distributed evenly throughout Toronto showed temperature reductions as great as 2^{o}C in some areas (Oberdorfer and others 2007). Also air adjacent to the River Thames in London, U.K., or with urban parks, is on average 0.6^{o}C cooler than air in neighboring urban areas (Wilby and Perry 2006).

The National Research Council of Canada (NRCC) conducted a field study over a two year period (2000-2002) to evaluate the thermal performances of green roofs. The study found that the daily maximum membrane temperature underneath the green roof was significantly lower than the daily maximum membrane of the reference roof (FEMP 2004). The temperature of the same green roof exceeded 30^{o}C on only 18 days out of 660-days, whereas the non-green rooftop exceeded 30^{o}C on 63 days out of the 660-days. Also, the NRCC predicted that if only 6 percent of Toronto's roofs, or 1,600 acres (6.5 square kilometers), were green roofs, summer temperatures could potentially be reduced by 1^{o}C to 2^{o}C in the urban center (FEMP 2004).

These reductions of temperatures in urban sites across the globe are gaining the attention of federal agencies in the United States. The EPA is one of those agencies incorporating initiatives to study the UHI and its effect on the environment. As previously mentioned, one of the initiatives the EPA was incorporating was the HIRI. The HIRI moved forward in 1998 with the National Aeronautics and Space Administration (NASA), and the Department of Energy's Lawrence Berkeley National Lab (LBNL) with the Urban Heat Island Pilot Project (UHIPP). They selected five cities to participate in the UHIPP: Baton Rouge, Chicago, Houston, Sacramento, and Salt Lake City (Wong 2008). The EPA selected these cities based on the intensity of the local ozone problem, the likelihood that the city could benefit from the use of heat island reduction measures, the availability of data, and local interest in initiating heat island reduction measures. Although the UHIPP ended in 2002, the data that these studies yielded have been serving as a foundation for current urban heat island activity in cities throughout the United States (UHIPP 2008). One of the cities from the UHIPP that has made great advancements in using green roofs for the mitigation of the UHI is the City of Chicago.

2.3 Chicago-A Case Study City

The City of Chicago is located on Lake Michigan in northeast Illinois (Figure 3). The city itself has a population of 2.8 million people according to the 2000 United States Census and covers over 225 square miles. The Chicago metropolitan region includes 7 million people in a six-county area and covers approximately 3,750 square miles (Chicago 2007).

In 1999, researchers used data from the National Climatic Data Center to identify the location of Chicago's heat island. The researchers found that the Chicago heat island consistently appeared in the western suburbs and not downtown. This is because Lake Michigan, to a great extent, influences Chicago's climate and the UHI (Figure 4), along with the western suburbs that continue to develop rapidly.

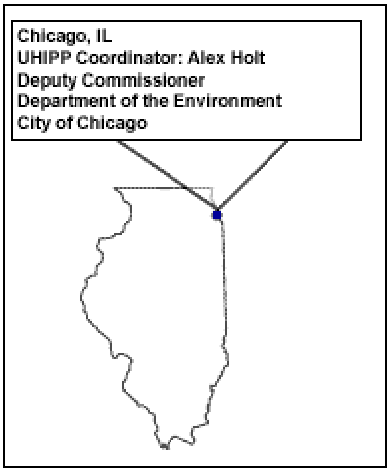


Figure 3. Chicago, Illinois.
Source: U.S. Environmental Protection Agency.
http://www.epa.gov/heatisland/pilot/chicago.html.

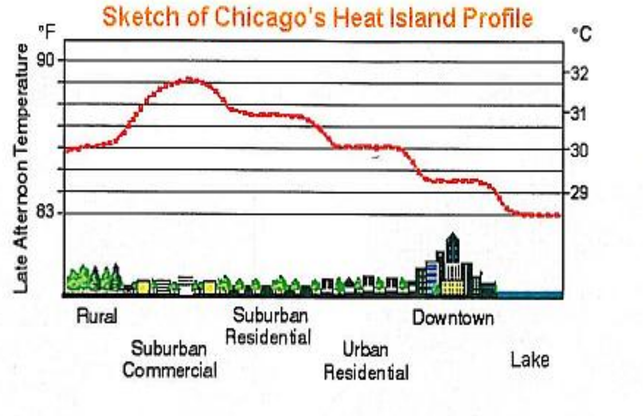


Figure 4. Late afternoon temperature over the City of Chicago.
Source: Gary and Finster 2008.

The temperature gradient between areas in the far west suburbs and downtown Chicago was on average 1.7°-2.8°C (Chicago 2007). The local climate in relation with the terrain also affects the UHI. The flat terrain of Chicago and Lake Michigan make Chicago's weather unpredictable and frequently extreme. Summer is very warm and often humid. The highest temperatures occur throughout July and August and can reach 35-38°C. The coldest days are usually in January when the temperature can drop below -18°C. Average monthly temperatures for Chicago range from -6°C in January, to 23°C in July (Chicago 2007).

Chicago temperatures have warmed by about 1.1°C since 1945 (Chicago Climate Task Force 2008). This information was developed from 14 different weather stations in Chicago and the surrounding areas, taken over the past 80 years. The following are also other signs that the temperatures have increased in the past few decades pertaining to the UHI of Chicago which coincide with the current trends of global warming:

- There have been fewer 'cold waves' during the 1990s than in previous decades.
- Growing seasons are getting longer, as long as a week in the last 100 years.
- Ice on Lake Michigan forms later in the year and lasts shorter periods of time. Sometimes no lake ice at all.
- A number of heat waves have occurred in the last few decades. (Chicago Climate Task Force 2008)

Of the above group, the increase of heat waves, especially one that occurred in 1995, pushed the issue to study the increase in temperature and remediation of the urban heat island effect in Chicago.

The 1995 heat wave occurred in a 5 day span over the central United States during mid-July 1995. Of the more than 800 deaths nationally as a result of the heat wave, 525 deaths were in Chicago, an event appropriately labeled, "a citywide tragedy." These death tolls contributed to the fact that many people had incorrect perceptions of weather dangers and are unaware of the relative differences of weather threats to human life (Changnon and others 1996). The increase in temperature during the 1995 heat wave was greatly increased. Chicago's non-lake-effect areas were 38^{o}C or higher every day and averaged 41^{o}C and the daily minimums averaged 24^{o}C, 5-6 degrees higher than suburban temperatures every day (Changnon and others 1996). The natural increase in temperature was not alone in creating the extreme heat conditions, the UHI effect aided in this process. The formation of the UHI increased temperatures not only during the day but also at night.

Urban heat islands exhibit much less nocturnal cooling than occurs in rural areas. Hence, large cities do not cool off at night during heat waves like rural areas do, and this can be a critical difference in the amount of heat stress within the inner city. The heat island was cited as an important factor in the deaths an Chicago (Changnon and others 1996).

As a result of this heat wave, Mayor Daley appointed a Commission on Extreme Weather Conditions to ascertain what went wrong and what should be done in the future (Changnon and others 1996). This created a new "heat warning plan" on July, 20, 1995. Following the initiation of the heat warning plan, Mayor Daley and the City of Chicago moved forward to implement green initiatives to better the city. The green initiatives movement came from a $700 million settlement in 1999 from utility company Commonwealth Edison (ComEd) in an arbitration case (Czarnecki 2003) where ComEd failed to make good on a 1991 franchise agreement (Chicago City Hall 2008). This arbitration case established a $100 million 'fund for the future,' administered by the Department of the Environment (DOE). Of the $100 million dollars, $2.5 million was committed to fund the DOE's Urban Heat Island Initiative in late 1999 (Chicago City Hall 2008).

The Chicago Urban Heat Island Initiative was established to reduce urban air temperatures, ameliorate effects of dark surfaces, and reduce pollution. More than 60 percent of Chicago's rooftops are dark and absorb and trap heat emitted from the sun. To lessen the effect, the city is beginning to replace asphalt in alleys with light-colored paving, construct light-colored roofs, and install rooftop gardens (Czarnecki 2003). The mayor decided to demonstrate an example of a green roof on the City Hall building in 2001 for several reasons:

1. To showcase green roof technology in Chicago and lead by example
2. To study its effectiveness in lowering ambient air temperature
3. To promote public interest in this new technology (FEMP , 2004).

2.3.1 Green Roof Case Study-Chicago City Hall Building

Chicago's City Hall shares a 12-story building in downtown Chicago with Cook County's administrative offices (FEMP 2004). The overall roof measurements are about 38,800 square feet, with 22,000 square feet of green roof (Figure 5).

Figure 5. Chicago's City Hall Greenroof.
Source: http://www.worldbusinesschicago.com/newsletters/art/CityHall.jpg

The first interesting effect, the reduction in heat flow resulting from the green roof, was observed during the first winter. The snow lasted for an extended period of time on the green roof, as observed by engineers in the city's environment Department, while the snow on the adjacent buildings roof melted in just two weeks, indicating reduced heat flow on the green roof (FEMP 2004). Actual data have been collected for this particular rooftop to show temperature reduction. City Hall along with 12 other public buildings and through a unique combination of mayoral commitment, policy development and implementation, and incentive, have incorporated more than 300 green roofs that are establishing roots in this densely developed Midwestern city, adding more than 3 million square feet of vegetation (Berkshire 2007). Through the development of these projects the city continues to encourage green roof incorporation through a number of activities:

- The Building Green/Green Roof Policy
- The Green Permit Program
- Green Roof Grant Program
- Fostering Green Roof Products and Services
- The Green Roof web site
- The Green Roof Improvement Fund (GRIP)
- Streamlining City Effects

The result of these projects and initiatives is to create a well-established, healthy, and vital green roof market and ultimately make green roofs a more standard building feature, but also to ensure a healthy future for the city as a whole. As it stands, Chicago currently has the most green roof space of any city in North America (Bershire 2007). Reconfirming this statistic in 2009 was *Living Architecture Monitor Online Magazine* (Summer 2009, Volume II, No. 3). Besides Chicago other cities have studied the effects of the UHI and green initiatives but only on a smaller scale or by computer aided analyisis. These studies have helped in understanding the benefits of green roofs and have helped in defining the purpose and scope for this project, by creating interest in finding out how the benefits of green roofs have an effect on an entire city and not just in one or two particular areas.

2.4 Methods of Studying the Urban Heat Island and Benefits of Green Roof Mitigation

2.4.1 Urban Heat Island Methods-Dataloggers

One way to study the UHI is to use technology to measure the change in temperatures. Some of this technology includes, electric remote reading thermometers, dataloggers, and weather stations. The following studies use the above methods to gain a better understanding of the UHI processes.

A study was conducted by Kent State University in which 31 years of temperature data were studied for Toledo, Ohio. In this study an electronic remote reading thermometer was used with a thermograph that was maintained as a back-up system and was used occasionally when personnel were not available to read thermometers on weekends prior to 1983 (Schmidlin 1989). The study utilized two stations, one downtown and one at a rural site (airport). The study found the average annual temperature was 2.0^{o}C warmer at the urban site than the rural site. The heat island was most intense during the summer months and least evident during winter and spring (Schmidlin 1989). The research also suggested there maybe some variance do to the effect of Lake Erie. The lake effect on urban areas will be looked at later in this review. The freeze-free season, when corrected for the local effect of Lake Erie, was approximately 24 days longer at the urban site (Schmidlin 1989).

Another study used a network of temperature dataloggers that were deployed across metropolitan Phoenix for a 61-day period during the summer of 2001. This encompassed the Phoenix Sunrise Experiment. The data were used to compute pseudodovertical temperature profiles and the UHI (Fast and others 2005). The average UHI during the measurement period was between 2.5^{o}C and 3.5^{o}C; however, there was day-to-day variability in the magnitude, and it was as large as 10^{o}C on one evening. The peak UHI usually occurred around midnight; however, a strong UHI was frequently observed 2-3 hours after sunrise (Fast and others 2005). This study also looked at two other factors that affected the UHI, wind and cloud cover.

In this study, the UHI did not decrease much with increasing wind speeds, except for speeds exceeding 7 m s^{-1}. Also, the average UHI during the night was between 3^{o}C and 6.5^{o}C during clear-sky conditions, and gradually decreased to between 2.5^{o}C and 3.5^{o}C when the average cloud cover was 75% (Fast and other 2005).

2.4.2 Green Roof effects on Urban Heat Island Methods-Dataloggers

In a study conducted by Singaporean researchers, it was determined that gardens reduced roof ambient temperature by 4^{o}C and that heat transfer into the rooms below were lower. The team analyzed climatic data collected from various regions of Singapore and historical climatic data obtained from meteorological services. The researchers found that commercial- and business-district areas were hotter than the green areas by 2°C (Hein 2002).

Another study looked at the City of Chicago's City Hall green roof compared to the attached Cook County black tar roof. Weather stations were established on the city and county sides of City Hall to compare air temperature and other data as it related to the garden rooftop. The information was compared to the County's black roof. In addition, an infrared thermometer was used to measure surface temperature (City of Chicago 2008). The results were taken on August 9, 2001 and were as follows:

City Hall Roof (paved) 52-54°C
City Hall Roof (planted) 33-48°C
County Roof (black tar) 76°C

An additional study analyzed historical data (1900-present) and recent (year 2002) data on New York city's UHI effect to characterize changes over time and spatially within the city (Gaffin and others 2008). For this estimate, 1900-to-present historical record from Central Park was used and was compared to the average of 23 non-urban stations, over the same period, that were included in the regional climate assessment of Rosenzweig and Solecki 2005.

The study revealed a growth of the Central Park UHI temperature intensity from ~2.0°C in 1900 to ~2.5°C today (Gaffin and others 2008). The effect of the urbanization, increase in the urban skyline by building heights, and reduction of windspeed has increased the UHI for the City of New York. The one beneficial indicator for a Central Park cool island was summer night-time temperatures, which seemed to be cooler than the non-park stations.

2.4.3 Green Roof Study of Chicago's UHI

In 2003, Chicago's Department of Environment and MWH consulting designed the Green Roof Test Plot Project and constructed nine 36-square-foot test plots at the Chicago Center for Green Technology. The test plots were outfitted with a variety of green roof and conventional roof materials and were imbedded with sensors to measure roof thermal performance and the ability to retain stormwater (MWH 2007). Up to three sensors were installed at different layers; rooftop, soils, and/or membrane horizons, with a maximum of eight sensors installed per test plot.

The results showed that the daily peak temperatures at the membrane horizon were, on average, approximately 1°C warmer at the 36 square foot test plot. The same findings were also found at the 96 and 36-sqaure foot plot samples (Table 1) (MWH 2007).

Table 1. Mean Differences in Daily Peak Temperatures at the Membrane Horizons, 2006.
Source: MWH 2007.

Warmer Test Plot	**Cooler Test Plot**	**Mean temperature Difference (°C)**
New 2-inch thick green roof (36 square feet)	New 4-inch thick green roof (36 square feet)	0.2
New 4-inch thick green roof (36 square feet)	New 4-inch thick green roof (96 square feet)	1.0
New 4-inch thick green roof (36 square feet)	Mean of three green roofs with vegetation established in 2003	1.6
Black Tar	Mean of all six green roofs	12.9
WRS (White Reflective Surface Roof)	Mean of all six green roofs	3.0
Black Tar	WRS (White Reflective Surface Roof)	9.8

2.4.4 Temperature Variation

A study in Toronto, Canada, on Lake Ontario, was conducted to study the mesoscale interaction with an emphasis on the interaction between city and lake-shore climate. Lake breezes are common in late spring and early summer. The data were collected with automobile temperature transverse conducted on a mostly clear day with slight winds and with a network of mesoscale cooperative observer stations. Also four years of temperature records (1964-67) from climatological stations within and around Toronto were used (Munn and others 1969). The results showed how the UHI was shifted to the northwest when winds from the lake were evident. Also, when winds from shore were evident the UHI was shifted the opposite direction.

Another study concerning lake effect and the UHI was conducted in the Minneapolis-St. Paul, Minnesota area. Mean monthly temperatures for the 10-year period 1967-76 were collected from the Minneapolis-St. Paul National Weather Service station and from 20 cooperative weather stations in a ~18,000 km^2 area surrounding Minneapolis-St. Paul. These stations were adjusted for background climate, differences in observation time, and changes in station location. The adjusted temperature data depicted a larger UHI that conformed more closely to the urban structure. The influence of the adjustments on the strength of the heat island was estimated by comparing urban-rural temperature differences calculated from both data sets for the three time periods. The mean urban minus mean rural temperature differences calculated from the adjusted data were as much as 50%

larger than the differences calculated from the unadjusted data (Winkler and Skaggs 1981).

2.4.5 Hardware Models for Collecting Data

A study was conducted to find the spatial patterns of urban dew and surface moisture in Vancouver, Canada, during the summer in an urban residential neighborhood. A 1/8th scale, out-of-doors model with a simplified geometry was constructed and tested. The Internal Thermal Mass (ITM) approach to scaling was used to modify the thermal inertia of the model buildings so that nocturnal surface temperatures would be duplicated in real time. Three wooden houses and two false walls were constructed and placed along the north edge of a grassed plot (9x12m in width). Concrete paving slabs were used to model a street (1.0m wide). Trees were present in the model (Richards 2000). Ambient conditions in the model (air temperature, humidity, and wind speed and direction) were similar to those seen at the full-scale sites, except the model site was windier. Moisture accumulation on the model was also realistic, and surface temperature appeared to mimic reasonably well those observed at the full-scale. Some residential effects of shading differences were evident in the early evening, e.g. for roof surface temperatures. In complicated environments such as cities, modeling can be a useful alternative to measurement (Richards 2000).

Another study using scale modeling of nocturnal cooling in urban parks was conducted. A hardware scale model was used to simulate the effects of radiation geometry thermal properties and surface wetness upon nocturnal surface cooling in urban parks of different size, vegetative cover and soil conditions. The idea was to simulate surface cooling after sunset for the case with little or no wind. Physically the hardware model consisted of a slab of dense wood (solid Douglas fir) with a square removed from its centre. On all occasions the urban background remained dry and was made of fir so that it had constant thermal properties. Sometimes the urban background was flat while and at other times blocks of fir placed around the park simulated the presence of buildings and streets that affect the radiative geometry. Also the park was bare whilst on other occasions model 'trees' fashioned from foam rubber arranged in and around the park, in rows, or randomly scattered, to mimic borders and other tree distributions. The wooden model was placed on a thick sheet of polystyrene to insulate it from spurious heat fluxes through the base, and the whole apparatus was enclosed in a polyethylene 'tent' to minimize convective exchange with the surrounding air. The approximate model: full scale ratio was 1:625 (Spronken-Smith and Oke 1999).

This model used copper constantan thermocouples insulted with Teflon sheathing for surface and air temperature measurements. The park surface sensors were sampled every 2 s while the remaining thermocouples were sampled every10 s using a multiplexer. Data were continuously measured on a Campbell Scientific CR21X data logger. The standard error of temperature measurement was estimated to be 1.0°C. Also model surface temperature were also remotely-sensed using an AGEMA Thermovision 880 system. The AGEMA estimated surface temperature to within 0.5°C (Spronken-Smith and Oke 1999).

The results of this paper developed and demonstrated the use of a very simple hardware model to stimulate nocturnal cooling in urban parks under calm and clear conditions. Also scale modeling has the special merit of allowing fairly complex urban environments to be considered, i.e., including realistically varied geometric configurations and mixtures to surface materials. These models allow for a variety of studies to be completed, such as the benefits of green roof mitigation on the UHI effect. Due to the scale of most cities and lack of data, a scale model is warranted to study the benefits.

CHAPTER 3: STUDY AREA

The study area for the models was located at Guilford Hills Elementary School in Guilford Township in Franklin County, approximately 2 miles east of Chambersburg, Pennsylvania, adjacent to Route 30 (Figure 6). The models were built and installed within a 17′ x 35′ fenced area located approximately 50 ft west of the school building (See Figure 7).

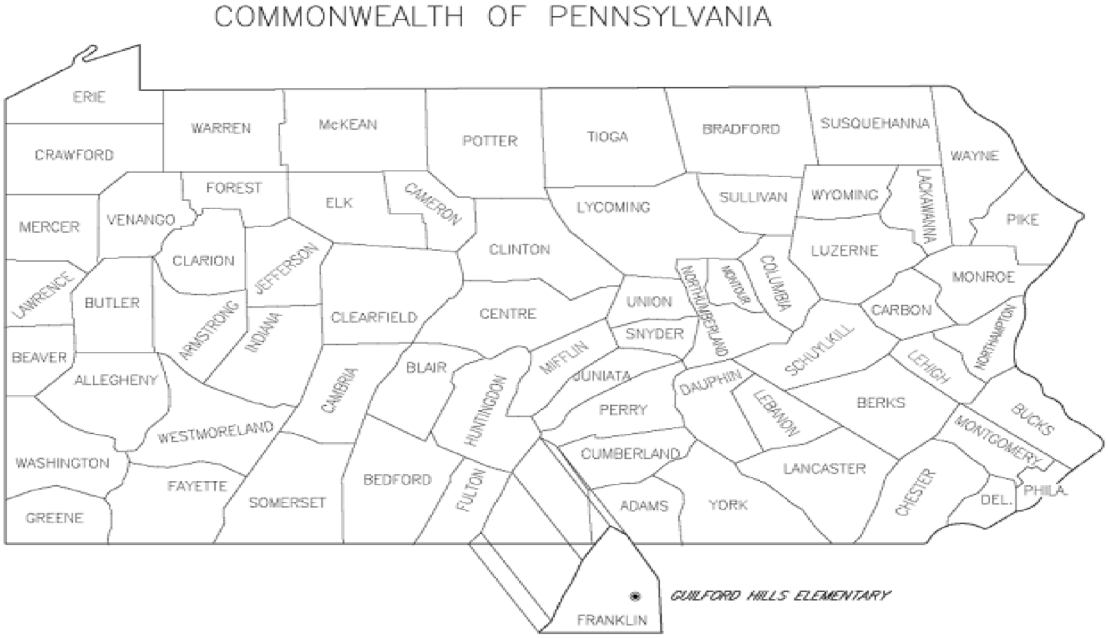


Figure 6. Study Area Location.

The current use of the study area at the time the model was being monitored was a flower garden that the school used for outdoor teaching. The two models, one with green roofs and the other without, were placed within this fenced area towards the southern side (Figure 8) so not to interfere with the garden’s plantings, school teaching classes, and for security. The garden has low growing plants, mulch, and mulched walkways. The area outside the fence consists of maintained grass, and blacktop within 6 ft. of the area.

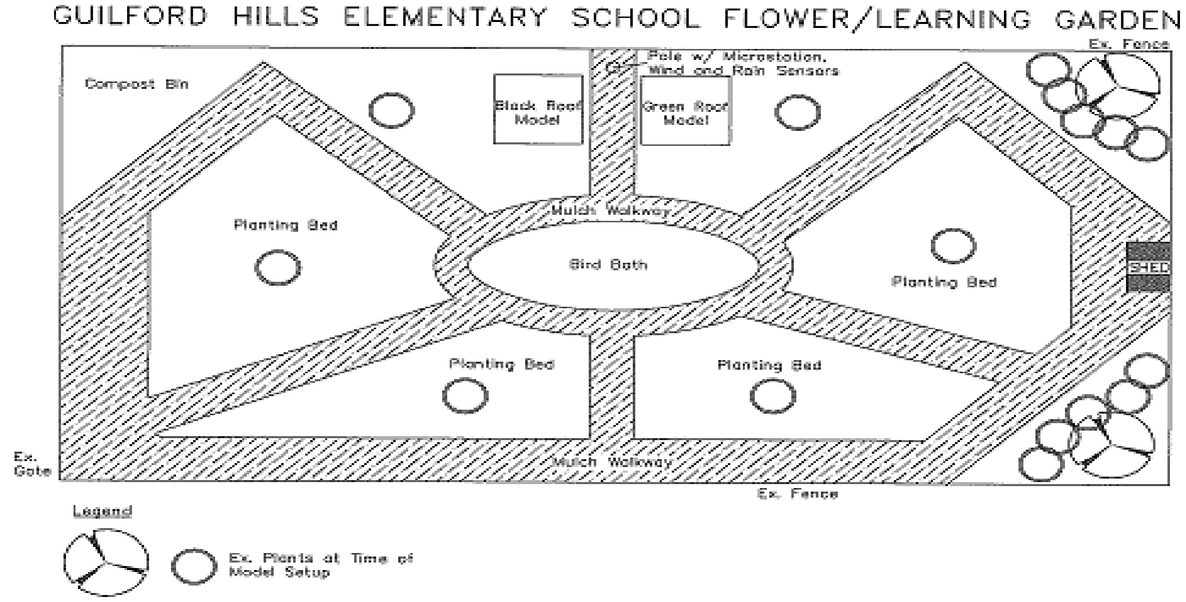


Figure 7. Model Placement within fenced area.

The placement of these models within this area allowed for real time temperature, rainfall, relative humidity, and wind measurements. The models were removed after the monitoring of the two model cities and the area where the models were placed was replanted for outdoor class room use.

CHAPTER 4: METHODS AND DATA

4.1 Models

Two hardware scale models were created to replicate an urban downtown setting and to better assist in researching the benefits of green roofs on the UHI. For the building of the models I used the City of Hagerstown, Maryland (See Figures 9, 10, 11, and 12) as the urban downtown setting. The use of Hagerstown was for scaling and building purposes only and was not studied in any particular way concerning the UHI and green roofs.

Figure 8. Downtown Hagerstown looking West, South side of street.

Figure 9. Downtown Hagerstown looking West, North side of street.

Figure 10. Downtown Hagerstown looking North, East side of street.

Figure 11. Downtown Hagerstown looking East, South side of street.

The models were built as close to identical as possible at a horizontal scale of 1″=8′ and vertical scale of 1″=3′, using the same building materials. One model incorporated green roofs while the other incorporated normal roofing methods for black roofs (See Figures 13, 14, 15, and 16).

Figure 12. Green Roof Hardware Scale Model being built.

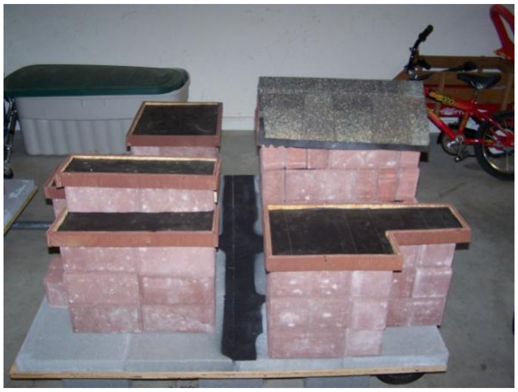


Figure 13. Black Roof Hardware Scale Model being built.

Figure 14. Black Roof Hardware Scale Model.

Figure 15. Green Roof Hardware Scale Model.

Each model consisted of typical building material such as plywood, concrete pavers, brick pavers, roof felt, outdoor paint, and live plants. Each model was built upon a 4′x4′x3/4″ piece of plywood that rested approximately 8″ above the ground on typical cinder blocks. The plywood was then wrapped in roof felt to help protect it from the weather during the duration of the experiment. On top of the roofing felt, 12″x12″x1″ concrete pavers were used to simulate sidewalks and roads. The roads themselves were spray painted using outdoor black spray paint and a template of the road layout in downtown Hagerstown. Once the roads were sprayed on, the rest of the model was built, which included the building and the incorporating of the monitoring equipment. The buildings were built out of brick pavers and capped with plywood roofs that were covered with roofing felt and green roof material. The edges of the roof caps were painted with outdoor paint to protect the plywood from the elements.

The plants for the green roofs consisted of a typical green roof species known as Sedum acre 'Aureum' (See Figure 17). The plants were taken from my yard and transplanted into a special soil mix consisting of compost, peat moss, and topsoil (See Figure 18).

Figure 16. Green Roof plant material-Sedum Acre ‘Aureum’.

Figure 17. Soil Media consisting of compost, peat moss, and topsoil.

Due to the size of the green roofs it was not practical to contact a green roof plant nursery to get plants which come in pre planted containers. Though on large roofs these containers can be laid and attached to the roof. Watering was required for the first week or two to get the transplanted plants established on the new roofs. Once established and due to the mild summer, no other watering was required. Other than watering for the first two weeks, some minor trimming and maintenance was done during the monitoring of the project as needed. The model itself was inspected every week for damage or problems when readings were taken from the monitoring equipment.

4.2 Monitoring Equipment

The collection of data within the models were compiled using HOBO® data loggers, monitoring sensors and a HOBO® mirco station which were created by Onset Computer Corporation. The HOBO® data loggers used outdoors to collect temperatures, relative humidity, and dew point were the HOBO® Pro v2 (U23-001) data loggers (See Figure 19). The indoor temperature data were collected using HOBO® 12-Bit (S-TMB-M017) Temperature Smart Sensors (See Figure 20). Along with indoor and outdoor temperatures, relative humidity, and dew point temperatures, wind and rain were monitored using a HOBO® Wind Sensor (S-WSA-M003) (See Figure 21) and a HOBO® Rainfall Sensor (S-RGA M002) (See Figure 22). The outdoor data loggers were installed within a Solar Radiation Shield (M-RSA) (See Figure 23). The indoor sensors, along with the wind and rainfall sensors where connected by cables to the HOBO® Micro Station which has 4 sensor inputs (See Figure 24). The outdoor data loggers were wireless and collected data within the logger. Table 2 shows the specifications for the HOBO® data loggers and sensors.

Figure 18. HOBO® Pro v2 (U23-001) Data Logger.

Figure 19. HOBO® 12 Bit (S-TMB-M017) Temperature Smart Sensor.

Figure 20. HOBO® Wind Sensor (S-WSA-M003).

Figure 21. HOBO® Rainfall Sensor (S-RGA M002).

Figure 22. HOBO® Solar Radiation Shield (M-RSA).

Figure 23. HOBO® Mirco Station.

Table 2. HOBO® sensors and data loggers specifications.

Equipment	Range	Accuracy	Resolution	Starting Threshold	Data Channels	Response Time
Pro v2 Loggers (Temp.)	-40° to 70°C	0.2°C over 0° to 50°C	0.02° at 25°C	N/A	N/A	40 minutes
Pro v2 Loggers (Relative Humidity(RH))	0-100% RH, -40° to 70°C	±2.5% from 10% to 90% RH to ±3.5% max.	0.03%	N/A	N/A	40 minutes
12-bit Indoor Sensor	-40° to 75°C	±0.2° from 0° to 50°C	.03° from 0° to 50°	N/A	N/A	< 3 minutes
Wind Sensor	0 to 45 m/s	± 1.1 m/s or ± 4%	0.38 m/s	≤ 1 m/s	2	N/A

The data loggers, monitoring sensors, and mirco station were laid out within and along the side of the model as shown in Figures 25 and 26. The outdoor data loggers as noted where placed within the solar radiation shields approximately two inches from the ground in the center of each model. This allowed for free air flow around the shields for accurate readings. The indoor temperature sensors were mounted in the only pitched roofs within the models using a screw and loop mount and then connected to the micro station with a cable. The micro station was mounted, using u-bolts, approximately five feet from the ground on a one and half inch metal pipe that was installed for the models. The wind and rain sensors where also mounted on the same metal pipe and was connected to the micro station by cables.

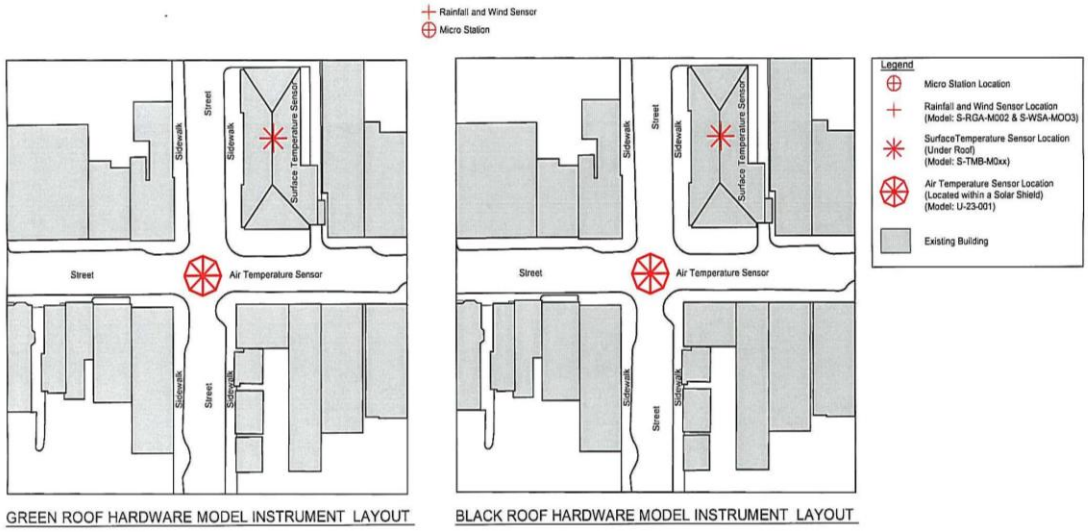


Figure 24 . Layout of the proposed buildings with instrumentation. Both models were built identically and the instruments were located in the same position with both models sharing the micro station, rainfall, and wind sensor.

Figure 25. Models with monitoring equipment.

Along with the all the HOBO® monitoring equipment a laptop computer was used to collect the data each week from the HOBO® Mirco Station and the HOBO® outdoor data loggers. The computer was connected via USB connector and a plug into the bottom of the micro station. The information was downloaded to HOBOware computer program. This information was then exported as an Excel file for further analysis. The wireless outdoor data loggers were connected to the laptop via HOBO® USB Base Station (Base-U-4) and a coupler. The HOBO® Pro v2 data loggers were inserted into the coupler and synced with the computer into BoxCar Pro 4.3 software. Once downloaded, the information was exported as an Excel file for further analysis.

4.3 Data Methods

The data from the micro station and from the outdoor data loggers were collected hourly for a time period of approximately three and half months beginning May 27 and ending September 4, 2009. The overall data file contained 2,396 readings. The data collected were analyzed to help support the overall purpose of this project. The following section will explain how the data was analyzed to gain the results. The results of these 2,396 readings will be presented in a more concise form, which include hourly averages for the indoor temperatures, outdoor temperatures, relative humidity percentages, and dew point temperatures. Also, the analyzed daily average comparisons will be examined.

4.3.1 Hourly Data

One of the easiest ways to compare the monitoring results of the models was to look at the indoor and outdoor temperatures between the green roof and black roof models on an hourly basis. Also, dew point temperature and relative humidity (RH) comparisons will be examined between the models. This will help in understanding how vegetation can affect the RH and dew point and therefore temperatures within cities. These data were collected with the HOBO® 12-Bit Temperature Smart Sensors that were mounted inside the pitched roofs and the

HOBO® Pro v2 data loggers there were placed within the solar radiation shields approximately two inches from the ground in the center of the model. With 101 days of collected data, the data condensed into a more workable data set. The hourly data for each day was added together and averaged with the same hourly data for all 101 days. For example: All noon data readings for the 101 days were added together and averaged to get the data. The hourly data were analyzed even further to find the differences between the green and black roofs. These differences were then compared to find the largest and smallest differences plus daytime and nighttime difference averages. The daytime difference average consisted of a time frame during the day from 9:00 to 20:00. The nighttime difference average consisted of a time frame during the night from 21:00 to 8:00.

4.3.2 Daily Average Data

The other way to analyze the data collected over the three month period was to look at the daily averages. Comparing daily averages helped create a more even data set. Of the 101 daily averages, the highest 5% or top 5 readings (e.g. rainiest) and lowest 5% or bottom 5 readings (e.g. non-rainiest) of each data set were found and then averaged. The data sets compared were for wind, rain, and outdoor temperatures. The highest and lowest reading averages were compared to see the effect upon each other, most importantly how wind and rain affected the outdoor temperature.

Besides finding the average for the top and bottom readings, the differences were also found for the top and bottom readings for each category and averaged together. The differences were computed by taking the black model data minus the green model data.

The third way the daily data were analyzed was looking at the average differences between the black and green roofs for both indoor and outdoor temperatures for the entire monitoring period. Also the largest difference in temperatures for both the black and green roofs will also be presented.

4.3.3 Statistical Analysis

A statistical analysis was also conducted on the data. The data were analyzed using the program IBM SPSS Statistics 18. The data were first processed to find out if they were normally distributed. To find out if the data were normally distributed, the data were split (by time) within the SPSS program and analyzed using the descriptive techniques of skewness and kurtosis. Skewness is the degree of asymmetry of a histogram. Kurtosis is degree of peakness. To determine if the data were normally distributed the absolute values of the statistics had to be less than twice the standard error. The results showed that the data were not normally distributed and so a non-parametric two-sample Mann-Whitney U Test was performed for each average hourly data to determine if the differences were significant. The Mann-Whitney U test was used because it is fairly robust and nearly as powerful as a parametric test. It also was used because it takes two random independent samples of the same size and compares them to find out if they are different.

CHAPTER 5: RESULTS

5.1 Hourly Data Results

The temperatures measured in Figure 26 shows the average hourly data for indoor temperatures comparison for green and black roofs starting at midnight and running for 24 hours. The temperatures for both black and green roofs gradually rose throughout the day starting at approximately 9:00 and increased to the highest average temperature of 33.87°C for the black roof and 28.07°C for the green roof at approximately 15:00 and 16:00, respectively. After 15:00 and 16:00 both black and green roof temperatures decreased due to evening and nighttime cooling. The black roof temperatures decreased at a faster rate than the green roofs. The black roof temperatures were warmer until approximately 22:00, when the green roof temperatures became warmer due to the green roof infrastructure acting as insulation. The green roof infrastructure acted as insulation to keep the green roofs inside temperatures warmer until 8:00. Though the temperatures for both areas peaked at approximately 15:00 and 16:00, the largest temperature difference occurred at 14:00 with a difference of 6.41°C, with the black indoor temperature being warmer. The smallest difference occurred at 21:00 with a difference of 0.09°C with the indoor black roof being warmer. Also, the average daytime difference was 4.19°C while the average nighttime difference was -0.65 °C. This indicates that the indoor temperatures for black roofs were warmer during the day and the green roofs were warmer during the night.

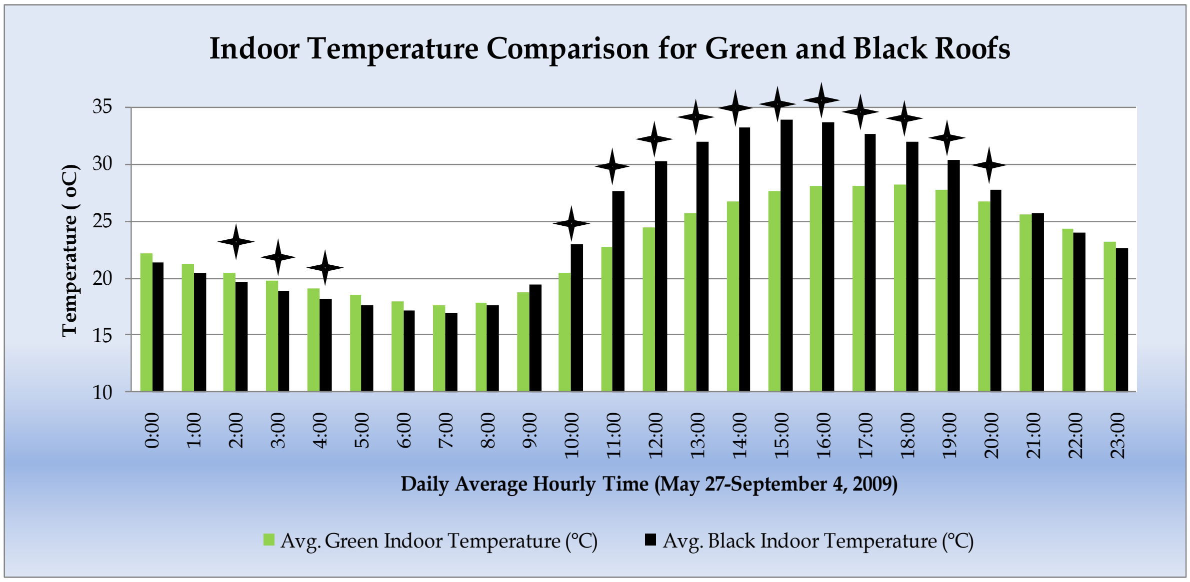


Figure 26. Indoor Temperature Comparison for Green and Black Roofs. The (✦) indicates the statistically significant difference in comparisons between the green and black roofs when anaylzed using SPSS program and conducting the Mann-Whitney U test.

Figure 27 is similar to Figure 26 in that it shows the average hourly data. The difference between the two graphs is that Figure 27 shows the outdoor temperature comparison for green and black roofs starting at midnight and running for 24 hours. The temperatures for both black and green roofs gradually rose throughout the day starting at approximately 6:00 and increased to the highest average temperature of 26.77°C for the black roof and 26.26°C for the green roof at approximately 15:00. After 15:00 both black and green roof temperatures decreased due to evening and nighttime cooling. Both roof temperatures decreased at a fairly constant rate. The black roof temperatures were warmer from 10:00 until approximately 7:00, when the green roof temperatures became warmer due to the green roof infrastructure acting as insulation or buffer. The green roof infrastructure acted as insulation or a buffer to keep the green roofs outdoor temperatures warmer until 9:00. Though the temperatures for both areas peaked at approximately 15:00, the largest temperature difference did occur at 15:00 with a difference of 0.50°C, with the black outdoor temperature being warmer. The smallest difference occurred at 10:00 with a difference of 0.01°C with the outdoor black roof being warmer. Also, the average daytime difference was 0.33°C while the average nighttime difference was 0.15°C. This indicates that the outdoor temperatures were warmer during most of the day and night for black roofs compared to the green roofs.

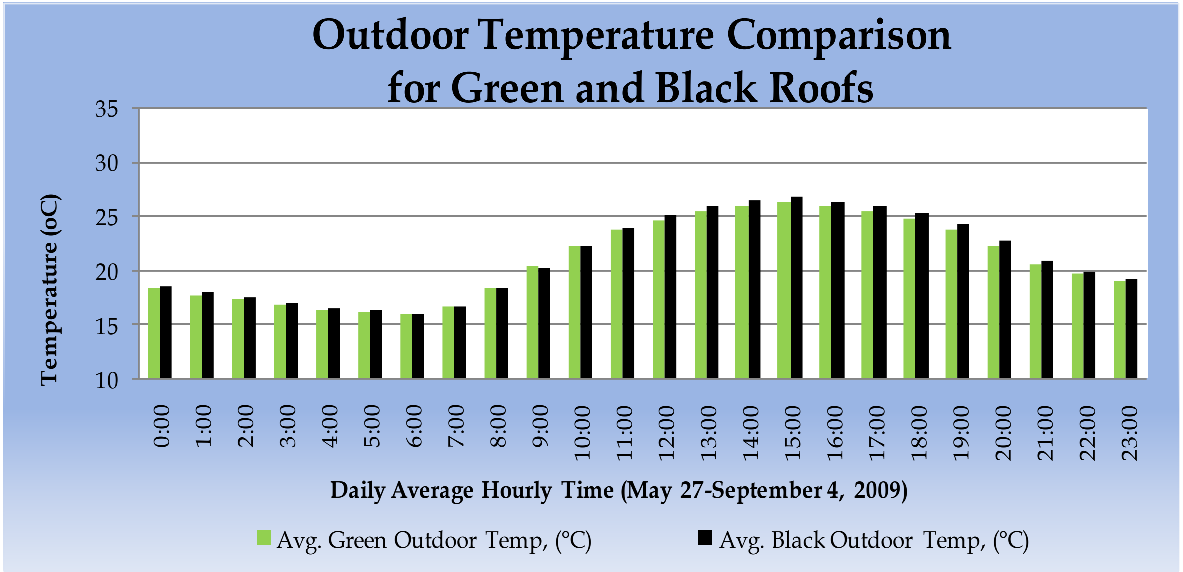


Figure 27. Outdoor Temperature Comparison for Green and Black Roofs.

The third set of hourly data that were analyzed was relative humidity (RH) (Figure 28). The graph shows the RH comparison for green and black roofs starting at midnight and running for 24 hours. The percentage for both black and green roofs gradually rose throughout the afternoon and into the evening starting at approximately 16:00 and increased to the highest average percentage of 94.75% for the black roof and 94.87% for the green roof at approximately 7:00. After 7:00 both black and green roof RH percentages decreased. Both roof RH percentages decreased at a fairly constant rate. The green roof RH percentages were higher from

11:00 until approximately 7:00, when the black roof RH percentages became higher. The black roofs RH percentages stayed higher and continued until 10:00. Though the RH percentages for both areas peaked at approximately 7:00, the largest percentage difference did occur at 20:00 with a difference of -1.92% with the green roofs having a larger RH percentage. The smallest difference occurred at 7:00 with a difference of -0.11% with the green roofs having a larger RH percentage. Also, the average daytime difference was -0.92% while the average nighttime difference was -0.57%.

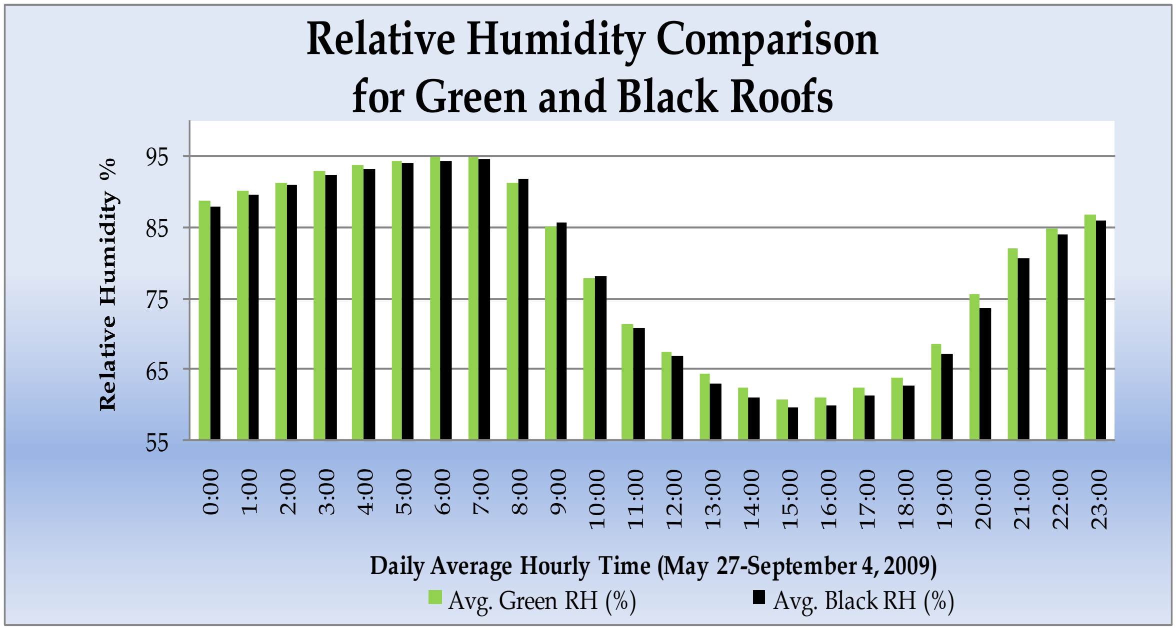


Figure 28. Relative Humidity Comparison for Green and Black Roofs.

The fourth and final hourly data that was analyzed was dew point temperature (Figure 29). The graph shows the dew point temperature comparisons for green and black roofs starting at midnight and running for 24 hours. The temperatures for both black and green roofs gradually rose throughout the day starting at approximately7:00 and increased to the highest average temperature of 18.35°C for the black roof and 18.20°C for the green roof at approximately 12:00.

After 12:00 both black and green roof temperatures decreased due to evening and nighttime cooling. Both roof temperatures decreased at a fairly constant rate. The black roof temperatures were warmer from 10:00 until approximately 6:00, when the green roof dew point temperatures became warmer. The green roofs dew point temperatures continued to be warmer until 9:00. Though the temperatures for both areas peaked at approximately 12:00, the largest temperature difference did occur at 12:00 with a difference of 0.14^{o}C, with the black dew point temperature being warmer. The smallest difference occurred at 13:00 with a difference of 0.0006^{o}C with the black dew point temperature being warmer. Also, the average daytime difference was 0.06^{o}C while the average nighttime difference was 0.05^{o}C.

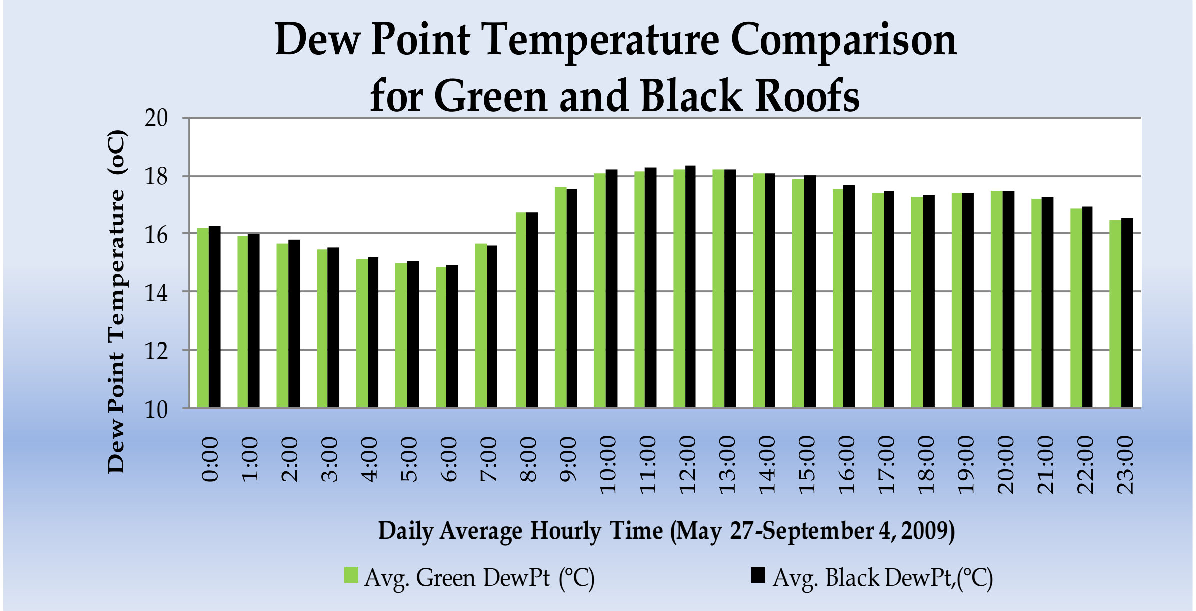


Figure 29. Dew Point Temperature Comparison for Green and Black Roofs. (* indicates Significantly Different)

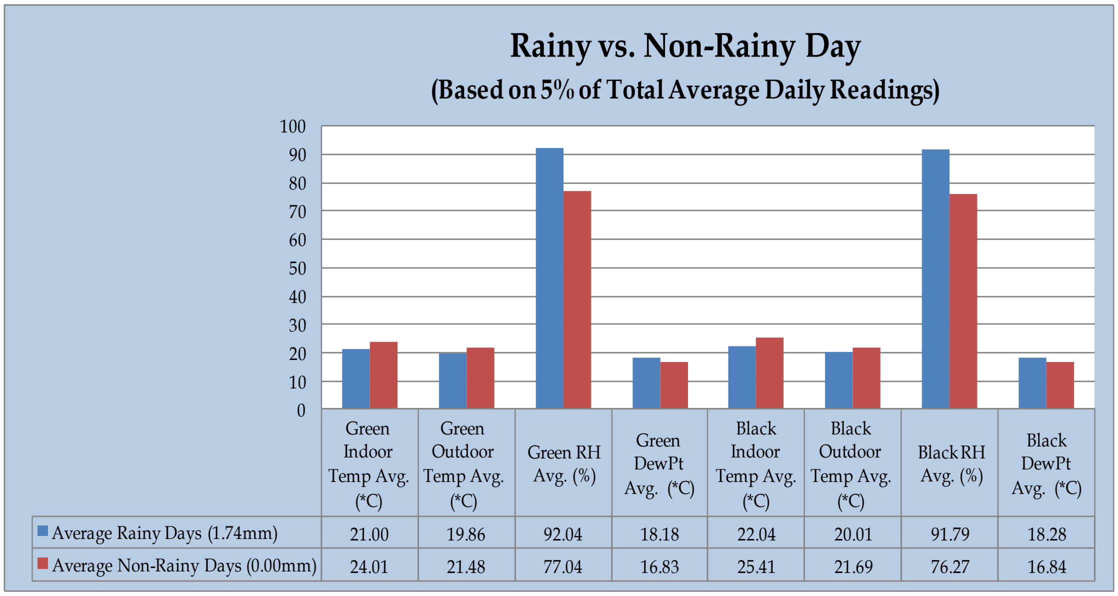
5.2 Daily Average Comparison

Figure 30 and Figure 31 shows the 5% highest and lowest of the daily average data for rainy versus non-rainy days and windy versus non-windy days, respectively, while Figure 32 shows the 5% highest and lowest of the daily average data for warmest and coolest days outdoors.

Figure 30 shows an overall difference of 1.74 mm for the amount of rain that occurred during the monitoring period. The rainy day averages show cooler temperatures for the green and black indoor temperatures and the green and black outdoor temperatures compared to the non-rainy days. The largest difference in temperatures was the black indoor temperature of 3.37^{o}C. The smallest difference in temperatures was the green outdoor temperature of 1.62^{o}C. The average difference for the indoor green and black roofs was 3.19^{o}C and the average difference for the outdoor green and black roofs was 1.65^{o}C.

The opposite occurred for the dew point temperatures. The green and black dew point temperatures were warmer for the rainy days with the black roofs having the largest difference of 1.44^{o}C and the green roof having the smallest dew point temperature difference of 1.35^{o}C.

The same effect occurred on the RH percentages. The RH percentages were higher for the rainy days with the black roof having the largest difference of 15.52% and the green roof having the smallest RH percentage difference of 15.00%.



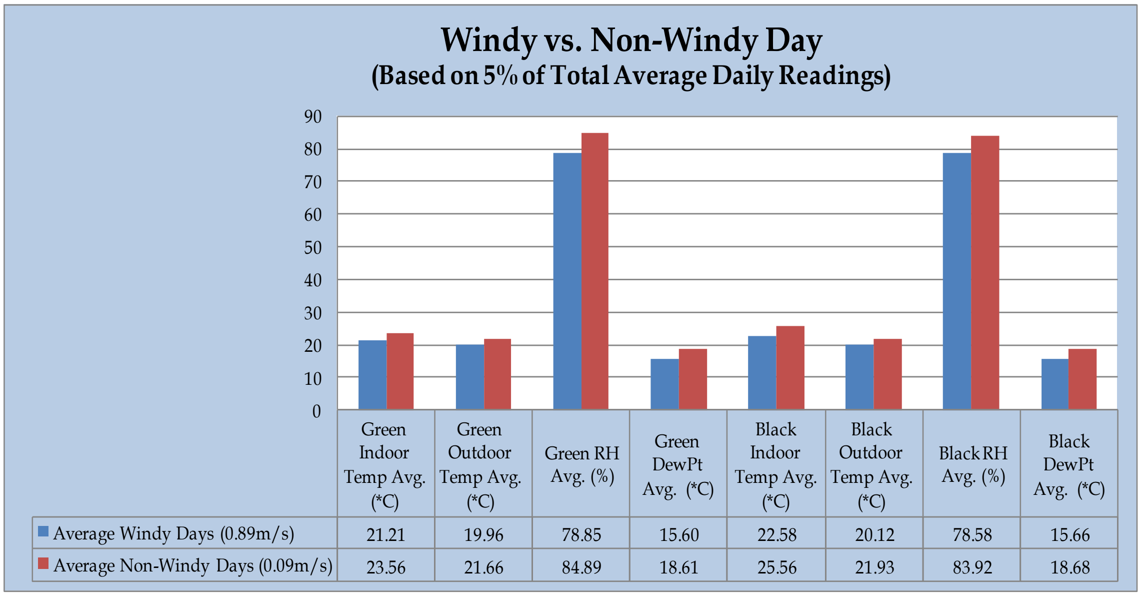
	Green Indoor Temp Avg. (*C)	Green Outdoor Temp Avg. (*C)	Green RH Avg. (%)	Green DewPt Avg. (*C)	Black Indoor Temp Avg. (*C)	Black Outdoor Temp Avg. (*C)	Black RH Avg. (%)	Black DewPt Avg. (*C)
🟦 Average Rainy Days (1.74mm)	21.00	19.86	92.04	18.18	22.04	20.01	91.79	18.28
🟥 Average Non-Rainy Days (0.00mm)	24.01	21.48	77.04	16.83	25.41	21.69	76.27	16.84

Figure 30. Rainy vs. Non-Rainy Days.

Figure 31 shows an overall difference of 0.80 m/s for the amount of wind that occurred during the monitoring period. The windy day averages show cooler temperatures for the green and black indoor temperatures and the green and black outdoor temperatures compared to the non-rainy days. The largest difference in temperatures was the black indoor temperature of 2.98°C. The smallest difference in temperatures was the green outdoor temperature of 1.70°C. The average difference for the indoor green and black roofs was 2.67°C and the average difference for the outdoor green and black roofs was 1.76°C.

The same effect occurred for the dew point temperatures. The green and black dew point temperatures were cooler for the windy days with the black roofs having the largest difference of 3.02°C and the green roof having the smallest dew point temperature difference of 3.01°C.

The same effect occurred on the RH percentages. The RH percentages were lower for the windy days with the green roof having the largest difference of 6.04% and the black roof having the smallest RH percentage difference of 5.34%.



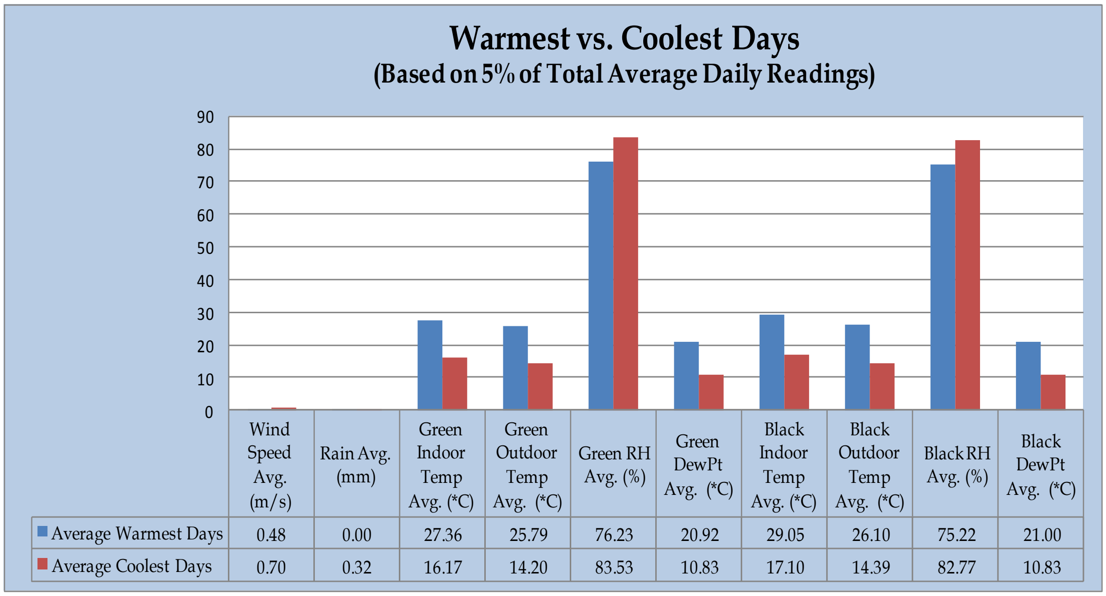
	Green Indoor Temp Avg. (*C)	Green Outdoor Temp Avg. (*C)	Green RH Avg. (%)	Green DewPt Avg. (*C)	Black Indoor Temp Avg. (*C)	Black Outdoor Temp Avg. (*C)	Black RH Avg. (%)	Black DewPt Avg. (*C)
🟦 Average Windy Days (0.89m/s)	21.21	19.96	78.85	15.60	22.58	20.12	78.58	15.66
🟥 Average Non-Windy Days (0.09m/s)	23.56	21.66	84.89	18.61	25.56	21.93	83.92	18.68

Figure 31. Windy vs. Non-Windy Days.

Figure 32 shows an overall difference of 11.71°C for the outdoor temperatures during the monitoring period. The warmest day averages show warmer temperatures for the green and black indoor temperatures and the green and black outdoor temperatures compared to the coolest days. The largest difference in temperatures was the black indoor temperature of 11.95°C. The smallest difference in temperatures was the green indoor temperature of 11.19°C. The average difference for the indoor green and black roofs was 11.57°C and the average difference for the outdoor green and black roofs was 11.65°C.

The same effect occurred for the dew point temperatures. The green and black dew point temperatures were warmer for the warmer days with the black roofs having the largest dew point temperature difference of 10.17^{o}C and the green roof having the smallest dew point temperature difference of 10.09^{o}C.

The opposite occurred on the RH percentages. The RH percentages were higher for the cooler days with the black roof having the largest difference of 7.55% and the green roof having the smallest RH percentage difference of 7.30%.



	Wind Speed Avg. (m/s)	Rain Avg. (mm)	Green Indoor Temp Avg. (*C)	Green Outdoor Temp Avg. (*C)	Green RH Avg. (%)	Green DewPt Avg. (*C)	Black Indoor Temp Avg. (*C)	Black Outdoor Temp Avg. (*C)	Black RH Avg. (%)	Black DewPt Avg. (*C)
🟦 Average Warmest Days	0.48	0.00	27.36	25.79	76.23	20.92	29.05	26.10	75.22	21.00
🟥 Average Coolest Days	0.70	0.32	16.17	14.20	83.53	10.83	17.10	14.39	82.77	10.83

Figure 32. Warmest vs. Coolest Days.

Table 3 is a summary of differences for the highest 5% and lowest 5% of all data for the monitoring period. The table shows and reconfirms some of the same findings above. For the windy and rainy days, the indoor and outdoor temperatures for both green and black roof models show a lower temperature difference compared to calm and clear days. Though both indoor and outdoor temperatures show a smaller difference, there was a noticeable change for the indoor nighttime difference. The difference at this time showed that the green roofs indoor temperatures were warmer than the black roofs. This indicates that the green roofs acted as insulation at night, keeping the buildings indoor temperature warmer and insulation during the day, keeping the indoor temperatures cooler.   The effect on the indoor temperatures was seen for the calm and windy days as well as the clear and rainy days. The RH and dew point temperatures for windy days were also lower than calm days, due to the wind effect. Similar results occurred for rainy days and clear days, except for the dew point temperatures. The data for rainy days show that the rain helped lower the temperatures for both models and both indoor and outdoors. The dew point temperatures where higher due the rain. The green roofs had higher RH differences for both the day and nighttime percentages when compared to the black roofs. The green roof percentage differences being higher was due to the vegetation and the ability to hold the water and release it back into the air, compared to the black roofs.

The temperature difference readings for hot and cold show that the daytime indoor temperatures were warmer for black roofs and the nighttime indoor temperatures were warmer for green roofs. This was due to the plant material acting as insulation during the daytime and nighttime. The outdoor temperature daytime and nighttime differences show that it was larger difference between temperatures during the daytime than the nighttime. The RH percentage and dew point temperature differences are larger during the day, indicating that water moisture during the night keeps the nighttime differences more balanced.

The humidity differences show the same except for the dew point nighttime difference, the larger differences were during the dryer readings. The humidity differences also show that the nighttime had lower humid and dry recordings compared to the daytime humid and dry recordings, except for the dew point temperature.

Table 3. Average Differences for Highest and Lowest 5% of Total Average Daily Readings.

Average Differences between Black and Green Roofs (Based on 5% of Total Average Daily Readings)								
	Wind (m/s)		**Rain (mm)**		**Temperature (^{o}C)**		**Humidity (%)**	
	Windy	**Calm**	**Rainy**	**Clear**	**Hot**	**Cold**	**Humid**	**Dry**
Indoor Temp. Day	3.26	4.57	2.49	3.82	3.66	2.73	1.06	4.20
Indoor Temp. Night	-0.54	-0.57	-0.40	-1.02	-0.30	-0.86	-0.07	-0.79
Oudoor Temp. Day	0.22	0.36	0.20	0.31	0.39	0.23	0.19	0.30
Outdoor Temp Night	0.09	0.19	0.11	0.11	0.24	0.15	0.10	0.24
Relative Humidity Day	-0.37	-1.31	-0.44	-1.20	-1.02	-0.92	-0.44	-1.36
Relative Humidity Night	-0.16	-0.63	-0.07	-0.33	-0.99	-0.59	0.09	-1.08
Dew Point Day	0.08	0.04	0.10	-0.03	0.11	-0.04	0.10	-0.15
Dews Point Night	0.05	0.08	0.10	0.05	0.06	0.05	0.11	0.00

Figure 33 is an overall comparison for the whole monitoring period. The figure shows the average indoor and outdoor temperatures for both green and black roofs. It shows a difference of 1.77^{o}C. for indoor and 0.24^{o}C for outdoor temperatures with the black roofs being warmer. The indoor difference was statistically significant based on the Mann-Whitney U test. The largest difference in indoor temperatures occurred on June 15, 2009 at 14:00, with a difference of 12.82. The largest difference for outdoor temperatures occurred on August 21, 2009 at 11:00, with a difference of 2.08.

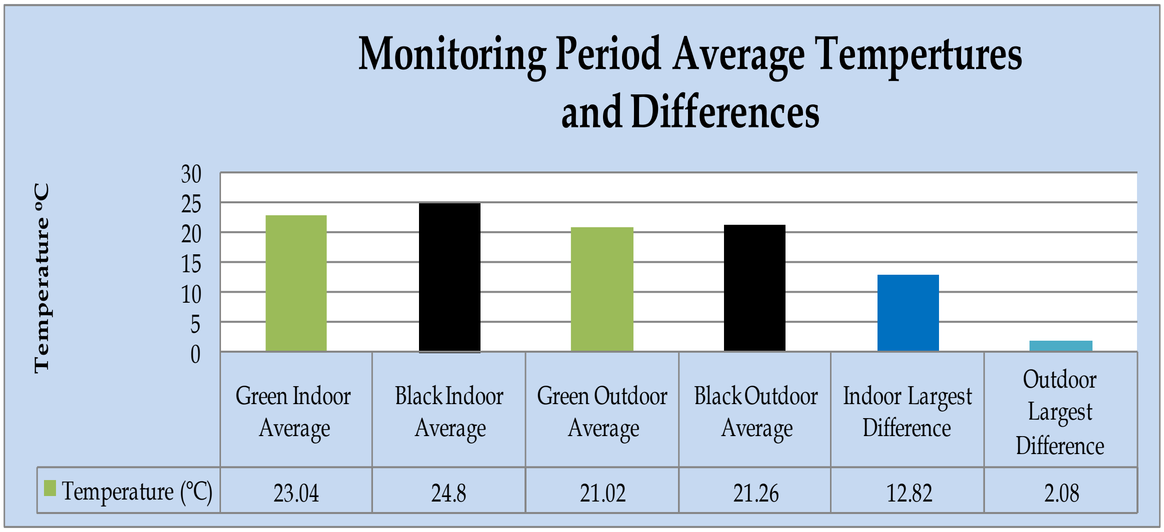


Figure 33. Monitoring Period Average Temperatures and Differences.

CHAPTER 6: DISCUSSION OF THE RESULTS

The data collected through the monitoring of the models provided answers to the understanding of green roofs effect on the UHI. The data in general showed that green roofs do have a mitigating effect on the temperatures by lowering the urban temperature within a city, which can help reduce the UHI effect. There was a noticeable difference between the model with green roofs and the model without green roofs as well as a noticeable temperature difference between the cities when rain and wind came into effect. A statistically significant difference of $p<0.05$, occurred between the indoor temperatures where noted, though all data, including indoor temperatures, outdoor temperatures, relative humidity percentages, and dew point temperatures were statistically analyzed. This was found using the Mann-Whitney U test. The same data were also used and analyzed on an hourly basis.

6.1 Data Comparison

6.1.1 Indoor and Outdoor Hourly Average Temperature Comparison

The results from the readings and analysis of the data revealed that green roofs have a mitigating effect on the indoor temperature of buildings (Figure 27). Figure 27 shows that the black roofs were warmer throughout the day and the night except for a period between 22:00 and 8:00. The transition to the green roof indoor temperatures becoming warmer occurred due to the fact that the heat was absorbed by the green roofs during the day and into the night. This absorbed heat was then kept within the green roof media during the night. The media of the green roof acted as insulation and did not release as much heat as the black roofs. The insulation factor allowed for the green roof model to stay warmer inside in the morning. At 8:00, the transition occurred for the green roof indoor temperatures going from being warmer to the becoming cooler compared to the black roofs. The green roofs after this time acted again as insulation and protected the indoor temperatures from rising. The results of the indoor temperature being able to stay cool during the day and warmer in the night provides supporting documentation that green roofs reduce the amount of heat transferred through the roof, thereby lowering the energy demands on the buildings heating and cooling system (Oberndorfer et. Al. 2007). The reduction of energy demands on the buildings heating and cooling help in reducing unnecessary waste heat created by using the mechanical mechanisms to heat and cool buildings. The unnecessary wasted heat is then taken away from the overall outdoor urban temperature which contributes to the creation of the UHI.

The mitigating results and effects on the indoor temperatures observed through the models coincide with the same beneficial results observed for the outdoor temperatures. The outdoor temperatures measured through the models showed the green roof model had lower outdoor temperatures as well. Figure 28 shows that the black roofs were warmer throughout the day and the night except for a period between 8:00 and 9:00. The reason that the green roof model was warmer during that time period was that this was the transition from night to day or sunrise. The absorbed heat from the black roof model in this time period had gradually released to the point that it was cooler than the green roof model. The reason the green roof model stayed warmer through this time period was the same reason the indoor temperatures acted the way they did, insulation. The buildings and materials within the green model were insulated by the plant material keeping it warmer until the sun rose and stared to radiate onto both models. Once the sun rose and both models started to receive the energy from the sun, the green roofs again acted as insulation to keep things cooler and not absorb as much solar waves as the black roof model. Though there was period were the green roof model was warmer than the black roof model, the temperatures show that the green roofs do have a mitigation effect on temperatures that can help reduce the UHI effect. Also another noticeable effect in both Figure 27 and Figure 28, especially in Figure 27, was the amount of temperatures differences that occurred later in the late afternoon and into the evenings. This is consistent with Luke Howard's data that indicated that the temperature differences are usually most noticeable in the non-daylight or night-time hours (Chapman 2005).

The outdoor temperature differences explained above, though noticeable, was not as extreme as the indoor temperature differences. The expectation was that there would have been more of a noticeable difference in the outdoor temperatures as there was in the indoor temperatures. This could have been a result of the scaling of the models. I would expect to see the same results, with the green roofs having mitigation effects on both indoor and outdoor temperatures on a large scale, but I would expect that the differences for outdoor temperatures would be more noticeable on a larger scale.

6.1.2 Relative Humidity (RH) and Dew Point Hourly Average Comparison

The outdoor temperature also had an effect on other atmospheric properties such as relative humidity and dew point temperature. These features were monitored for both the green roof and black roof models to see how they differ with the addition of vegetation to the green roof model and how evapotranspiration played a role in the results. Relative humidity is considered the amount of water vapor that exists within the air and measured by percentage (Horstmeyer 2010). Dew point is the temperature at which the air becomes saturated with water vapor when air is cooled by removing sensible heat (Snyder 2010). Relative humidity of 100% indicates that the air parcel has cooled to the dew point temperature and the air is maximally saturated with water. In terms of relative humidity, as the parcel of air is cooled, the relative humidity increases (Horstmeyer 2010). The results shown in Figures 29 and 30 correspond with the definitions above. Figure 29 shows that the green roof RH was higher throughout the day and night except for a period of approximately 8:00 to 10:00. This is approximately the same time period where the outdoor temperatures changed. The same reason applies for this change. The overall RH was higher for the green roofs because the plants released water into the air through the process of evapotranspiration. The process occurred in greater amounts from approximately 13:00 to 22:00. The RH for the remaining 24 hours except for the time between 8:00 to 10:00 remained higher than black roofs because it was night time and there was no radiant energy to burn off the moisture. The overall flow of the RH daily averages also relates to outdoor temperature and the dew point. The RH was higher throughout the night when outdoor temperatures and dew point temperatures were relatively lower and constant with one another. The RH was lower throughout the day when the outdoor temperatures and dew point temperatures were relatively higher and constant with one another. As RH relates to the dew point and outdoor temperatures, so does the dew point relate to RH and outdoor temperature as explained above. The dew point temperatures shown in Figure 30 show how they coincided with the RH and outdoor temperatures. The dew point temperature for green roofs was slightly lower throughout the whole 24 hour period because of evapotranspiration. With dew point temperatures, greater partitioning of the absorbed solar energy into evapotranspiration reduces the amount of energy used for evaporation and is transformed into latent heat, because it is only released as heat when the water vapor molecules condense back into water, they are cooled into the atmosphere (Bass and others 2009). This cooling effects are shown in the results in Figure 30.

6.1.3 Daily Average Comparison

The results from the indoor and outdoor temperature readings as well as the RH percentages and dew point temperatures corresponded to the results shown in Figure 31, 32, and 33. These figures looked at the same data but in a different way. The data was computed taking the highest 5% and lowest 5% of the daily averages. These data was analyzed to answer another problem statement question, does rain and wind affect the temperature difference between the cities? This type of analysis was done for wind, rain, and outdoor temperatures. Figure 31 shows the comparison for rainy vs. non-rainy days and Figure 32 shows the comparison for windy vs. non-windy days. As expected, the data shows that on the rainy and windy days, both green indoor and outdoor temperature were still cooler than black indoor and outdoor temperatures. The indoor temperature differences for both green and black showed a larger temperature difference between the two compared to the outdoor temperature difference. This larger difference is because of the insulation that the green roofs provide. The differences for outdoor temperatures were not as large because of the affects rain and wind had on the outdoor temperatures. The wind and rain had a cooling affect on the outdoor temperatures such as in the results shown for the City of Toronto (Munn and other 1969).

The other atmospheric properties also showed the anticipated results. The data for rainy days vs. non-rainy days showed the RH for both the green and black roof models were relatively the same. The only difference between the two was that the green roof model RH percentage was a little higher. This was due to the rain adding moisture to the air. The dew point also showed the anticipated results with the rainy days for both the green and black roof models being higher than the non-rainy days. This again is due to the amount of rain. The same atmospheric properties for windy vs. non-windy days showed the same anticipate results. The results in this case were that windy days would lower the RH percentage and the dew point temperature. These results were the same for both the green roof model and the black roof model.

The data from both Figure 31 and Figure 32 are reinforced with data from Figure 33. The data from all three figures were anticipated and answers the question concerning, does rain and wind affect temperatures within the cities. Not only did this data show how the wind and rain effected temperatures it also showed how it affected RH and dew point temperature. Though rain and wind affected the temperature, RH, and dew point and brought the outdoor temperature differences closer together, the overall results still show that green roofs have a beneficial effect on the model.

The results from the average hourly data show mitigating effects on the temperatures, with results in all aspects including the indoor and outdoor temperatures, relative humidity and dew point temperature.

6.1.4 Daily Average Differences Comparison

All the information used for the daily average comparison was analyzed a little further to construct Table 3. Like the information above, the highest 5% and lowest 5% were used for Table 3. All the differences for the highest and lowest 5%, plus the most beneficial and most negative for each difference during the daytime and nighttime hours, can be reviewed in Appendix A. This table also shows that green roofs to have a beneficial effect on mitigating urban temperatures by helping to reduce the UHI effect. The beneficial effects can be seen even when rain and wind affect the temperatures. The indoor daytime temperatures were warmer for black roofs for both the calm and windy days. The windy days showed a smaller temperature difference due to the wind. The indoor nighttime temperatures were warmer for green roofs for both the calm and windy days. The windy days showed a smaller temperature difference due to the wind. The green roof indoor temperatures were warmer during the night and the black roof indoor temperatures were warmer during the day, indicating that the green roofs act as insulation, keeping the indoor building cooler during the day and warmer during the night. The indoor daytime temperatures were warmer for black roofs for both the clear and rainy days. The rainy days showed a smaller temperature difference due to the rain and moisture. The indoor nighttime temperatures were warmer for green roofs for both the clear and rainy days. The rainy days showed a smaller temperature difference due to the rain and moisture. The green roof indoor temperatures were warmer during the night and the black roof indoor temperatures were warmer during the day, indicating that the green roofs act as insulation, keeping the indoor building cooler during the day and warmer during the night.

The outdoor temperatures showed the same results with the calm and clear days being warmer then the windy and rainy days. Unlike the indoor nighttime temperatures though, the outdoor nighttime black roof temperatures were still warmer than the green roofs. This shows that the windy and the rain do affect the temperatures, but the green roof does not have insulating affect on the outdoor temperatures.

6.2 Limitations of Study

The data collected produced anticipated results to show the benefits of green roof mitigation on the UHI. The original challenges of building the model, setup, and equipment familiarity were met with surprisingly little problems. The new challenges came from actually scaling the model and what were the best data to use to present and represent all the processes that occurred throughout the monitoring period. In reference to scaling the model, there was little information on the correct or incorrect way to proceed on building a scale model that would yield the best results. There have been multiple scale models completed and studied that did help in creating the models for this project. Some of these models from previous studies consisted of studies on wind, urban canyons, dew, and nocturnal cooling. These studies did help in understanding and learning how the models were setup and monitored such as in Richards (2000). Other studies which were not scale models, also helped in understanding how the data were collected with different type of equipment used for green roofs. These studies used areas on an existing rooftop to house a small section of green roof material and monitor it. All these resources assisted in understanding the information to complete the project.

The other challenge consisted of how to present the data. The amount of data was rather large. The creation of an hourly data for a 24 hour period made the most logical sense in that it was the set reading each day. This allowed for an average of all the times throughout the day, which created more fair and balance readings. The other data was looked at as the same, but instead of using the hours the highest 5%

and lowest 5% days were used. The highest and lowest averages again help to create fair and balance results. The use of 5% was a general number and not a specific standard that was used to create this percentage. The choosing of the percentage was a challenge, due to there not being a set standard. The whole purpose though was to create figures and tables that showed how rain and wind affected the models. The use of 5% or 10% would have yielded the same results needed to answer the questions.

Chapter 7: Conclusion

The intention of this project was to study the UHI mitigation using green roofs. This project used hardware scale models equipped with HOBO® monitoring equipment to study the models over a three month period, from June to September 2009. The models consisted of one green roof model and one black roof model, or one with traditional building material.

The data results from the indoor and outdoor temperatures showed that the green roof model temperatures were lower than the black roof model. Along with the temperatures, associated atmospheric properties such as relative humidity and dew point temperature showed that green roofs also had a beneficial effect on these properties as well. The comparison between the two models showed that the RH percentages were higher for the green models. Though higher RH is uncomfortable to most people, the larger RH percentages in the green roof model showed how the plants from the green roofs released water into the air through evapotranspiration. This process raised the RH but lowered the urban temperature and the UHI. A similar effect occurred on the dew point temperatures through evapotranspiration. Evaportranspiration on the green roofs carried the heat off through the water release, which cooled the air at the same time as seen in the results.

Other studies have been done on the effects that wind and rain have on the overall temperatures as well. Rain and wind data for this project showed affects on the temperatures in both cites, but only by reducing the effects of the differences between the temperatures. The difference in temperature for the green roofs compared to the black was less when rain and wind was evident.

These results show the benefits that green roofs have on the reduction of the urban temperatures that lead to the UHI effect. The findings from this project will help others in understanding how green roofs benefit urban areas by the reduction of the urban temperatures. The findings will also help others that are trying to understand larger issues that affect cities or entities, that a hardware scale model is a valid and possible way to collect data for future studies. The overall outcome of this study will assist larger cities conducting research to understand the benefits of green roofs on the UHI and the beneficial effects of reducing air pollution, heat related illness and mortality, water temperatures in streams, and greenhouse gas emissions.

This project was intended to help governing boards, organizations, other universities and associated faculty and students, and private residents of real cities understand the benefits of green roof mitigation. On a smaller scale, such as the green roof plots, to a scale model like the one created for this project, the data shows how green roofs have a mitigating effect on the urban temperature and the UHI. The scale model was created at a scale that was feasible for monitoring, moving, and for its location to fit within the fenced in area. Some recommendations for future studies of this kind would be to build the models a little larger, such as the buildings used at Penn State University Green Roof Research area. This would allow for creation of indoor spaces that use a/c, heating units, and insulation within the walls.

This would create a more realistic scenario. Another recommendation is to monitor the models for a whole year or longer. Though most previous data shows that during the winter months there is not much effect from the UHI, it would be nice to see if there actually is when done on a scale model approach. Besides the study of the benefits of green roofs on the UHI, the scale models could lead to other types of studies concerning green roofs and their benefits. These types of studies could also help cities in planning for the use of green roofs within their ordinances. As in the City of Chicago, their ordinances contain a Sustainability Section. Also, the city has funding set aside for developers to incorporated green roofs. These types of planning procedures and incentives will only further the use of green roofs and will further the education about the mitigating effects of mitigation on the UHI.

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Appendix A

Average Differences for Highest and Lowest 5% of Total Average Daily Readings

Average Differences for Highest and Lowest 5% of Total Average Rain Daily Readings

Date/Time	Rain Avg. (mm)	Black-Green Indoor Most Negative	Black-Green Indoor Most Positive	Black-Green Indoor Daytime Average	Black-Green Indoor Nighttime Average	Black-Green Outdoor Most Negative	Black-Green Outdoor Most Positive	Black-Green Outdoor Daytime Average	Black-Green Outdoor Nighttime Average	Black-Green RH Most Negative	Black-Green RH Most Positive	Black-Green RH Daytime Average	Black-Green RH Nighttime Average	Black-Green Dew Most Negative	Black-Green Dew Most Positive	Black-Green Dew Daytime Average	Black-Green Dew Nightime Average
07/23/09 23:00:00.0	3.41	-0.93	5.659	2.840583	-0.52417	-0.215	0.517	0.14325	-0.00208	-6.315	1.262	-0.75933	0.466917	-0.945	0.562	-0.02683	0.06775
08/02/09 23:00:00.0	2.05	-0.43	7.759	3.821417	-0.21708	-0.024	0.781	0.2935	0.087333	-2.198	2.522	-0.07683	0.261417	-0.182	0.884	0.277667	0.137417
05/29/09 23:00:00.0	1.34	-1.38	5.565	3.070833	-0.58683	-0.381	0.69	0.247667	0.144917	-3.73	3.6	-1.00275	-0.3165	-0.448	0.693	0.013	0.072083
06/05/09 23:00:00.0	1.07	-0.33	0.978	0.518083	-0.02425	0.024	0.145	0.071917	0.105917	-0.776	0.375	-0.00842	-0.02167	0.029	0.148	0.081917	0.107917
07/11/09 23:00:00.0	0.84	-1.05	5.401	2.19925	-0.66242	-0.145	0.705	0.226667	0.212083	-2.927	2.207	-0.33158	-0.72642	-0.263	0.619	0.144083	0.092167
Average	**1.74**	**-0.83**	**5.07**	**2.49**	**-0.40**	**-0.15**	**0.57**	**0.20**	**0.11**	**-3.19**	**1.99**	**-0.44**	**-0.07**	**-0.36**	**0.58**	**0.10**	**0.10**
07/18/09 23:00:00.0	0.01	-1.26	6.504	2.907333	-0.64267	-0.357	0.794	0.246	0.085667	-4.994	5.793	-0.20083	-0.01208	-1.254	1.62	0.157667	0.069583
08/20/09 23:00:00.0	0.01	-1.69	5.107	3.599167	-0.80483	-0.072	0.782	0.288083	0.118583	-3.827	4.569	0.0455	-0.263	-0.383	1.857	0.279667	0.078083
07/10/09 23:00:00.0	0.00	-1.14	7.726	4.26225	-0.72333	-0.143	0.686	0.394083	0.1765	-5.764	2.354	-2.342	-0.3695	-1.242	0.563	-0.20042	0.100917
08/17/09 23:00:00.0	0.00	-1.73	6.216	3.626667	-1.30633	-0.167	0.714	0.355083	0.145583	-5.51	2.61	-1.53567	-0.62667	-1.987	1.567	-0.091	0.031417
9/3/2009 23:00:00 P	0.00	-2.07	7.983	4.6905	-1.60892	-0.599	0.913	0.2695	0.02375	-3.989	2.201	-1.98258	-0.37775	-0.782	0.335	-0.28858	-0.02683
Average	**0.00**	**-1.58**	**6.71**	**3.82**	**-1.02**	**-0.27**	**0.78**	**0.31**	**0.11**	**-4.82**	**3.51**	**-1.20**	**-0.33**	**-1.13**	**1.19**	**-0.03**	**0.05**

Average Differences for Highest and Lowest 5% of Total Average Wind Daily Readings

Date/Time	Wind Speed (m/s)	Black-Green Indoor Most Negative	Black-Green Indoor Most Positive	Black-Green Indoor Daytime Average	Black-Green Indoor Nighttime Average	Black-Green Outdoor Most Negative	Black-Green Outdoor Most Positive	Black-Green Outdoor Daytime Average	Black-Green Outdoor Nighttime Average	Black-Green RH Most Negative	Black-Green RH Most Positive	Black-Green RH Daytime Average	Black-Green RH Nighttime Average	Black-Green Dew Most Negative	Black-Green Dew Most Positive	Black-Green Dew Daytime Average	Black-Green Dew Nightime Average
06/22/09 23:00:00.0	0.976	-0.976	7.927	4.325	-0.635	-0.429	0.743	0.344	-0.057	-4.651	3.881	-0.321	0.378	-0.617	1.506	0.233	0.009
06/05/09 23:00:00.0	0.335	-0.335	0.978	0.518	-0.024	0.024	0.145	0.072	0.106	-0.776	0.375	-0.008	-0.022	0.029	0.148	0.082	0.108
06/29/09 23:00:00.0	1.503	-1.503	5.344	3.245	-0.739	-1.023	0.718	0.162	0.033	-5.437	7.507	-0.593	0.343	-1.771	2.431	-0.109	0.034
06/21/09 23:00:00.0	1.003	-1.003	7.330	3.026	-0.465	-0.190	0.764	0.282	0.145	-2.580	4.578	0.046	-0.366	-0.268	0.861	0.252	0.079
06/23/09 23:00:00.0	1.403	-1.403	8.166	5.195	-0.824	-0.571	0.687	0.222	0.213	-6.640	6.502	-0.952	-1.157	-1.545	1.777	-0.052	0.005
Average	**1.04**	**-1.04**	**5.95**	**3.26**	**-0.54**	**-0.44**	**0.61**	**0.22**	**0.09**	**-4.02**	**4.57**	**-0.37**	**-0.16**	**-0.83**	**1.34**	**0.08**	**0.05**
06/08/09 23:00:00.0	0.127	-0.832	10.386	6.535	-0.279	-0.215	0.923	0.449	0.259	-6.681	7.943	-1.487	-1.135	-1.688	2.676	-0.004	0.059
06/10/09 23:00:00.0	0.111	-1.075	10.191	5.345	-0.621	-0.358	0.757	0.384	0.135	-3.173	1.832	-1.360	-0.584	-0.351	0.493	0.083	0.046
07/17/09 23:00:00.0	0.111	-1.170	6.153	1.388	-0.837	-0.362	0.587	0.145	0.177	-4.105	3.705	-0.177	0.076	-0.314	1.177	0.130	0.192
08/03/09 23:00:00.0	0.095	-1.262	10.680	6.833	-0.590	-0.239	1.754	0.592	0.260	-8.727	4.389	-1.976	-1.156	-0.891	1.714	0.088	0.066
08/22/09 23:00:00.0	0.016	-0.697	6.087	2.765	-0.538	-0.169	0.488	0.225	0.110	-5.359	0.707	-1.542	-0.365	-0.736	0.331	-0.081	0.049
Average	**0.09**	**-1.01**	**8.70**	**4.57**	**-0.57**	**-0.27**	**0.90**	**0.36**	**0.19**	**-5.61**	**3.72**	**-1.31**	**-0.63**	**-0.80**	**1.28**	**0.04**	**0.08**

Average Differences for Highest and Lowest 5% of Total Average RH Daily Readings

Date/Time	Black RH, (*C)	Black-Green Indoor Most Negative	Black-Green Indoor Most Positive	Black-Green Indoor Daytime Average	Black-Green Indoor Nighttime Average	Black-Green Outdoor Most Negative	Black-Green Outdoor Most Positive	Black-Green Outdoor Daytime Average	Black-Green Outdoor Nighttime Average	Black-Green RH Most Negative	Black-Green RH Most Positive	Black-Green RH Daytime Average	Black-Green RH Nighttime Average	Black-Green Dew Most Negative	Black-Green Dew Most Positive	Black-Green Dew Daytime Average	Black-Green Dew Nightime Average
06/05/09 23:00:00.0	99.55171	-0.335	0.978	0.518083	-0.02425	0.024	0.145	0.071917	0.105917	-0.776	0.375	-0.00842	-0.02167	0.029	0.148	0.081917	0.107917
06/04/09 23:00:00.0	96.635	-0.479	2.123	1.068	-0.20033	-0.024	0.216	0.11775	0.088583	-1.139	2.032	0.06975	0.125167	-0.013	0.397	0.126083	0.10575
08/28/09 23:00:00.0	94.93496	-1.147	3.463	-2.76475	0.537583	-0.048	0.333	0.224583	0.1095	-1.434	0.751	-1.54242	-0.36483	-0.042	0.356	-0.08133	0.049083
06/11/09 23:00:00.0	93.70129	-0.88	5.318	2.63675	-0.46817	-0.071	0.409	0.223833	0.097333	-4.521	2.138	-0.65167	0.472333	-0.567	0.355	0.09575	0.163917
08/02/09 23:00:00.0	92.95275	-0.43	7.759	3.821417	-0.21708	-0.024	0.781	0.2935	0.087333	-2.198	2.522	-0.07683	0.261417	-0.182	0.884	0.277667	0.137417
Average		**-0.65**	**3.93**	**1.06**	**-0.07**	**-0.03**	**0.38**	**0.19**	**0.10**	**-2.01**	**1.56**	**-0.44**	**0.09**	**-0.16**	**0.43**	**0.10**	**0.11**
07/07/09 23:00:00.0	63.48758	-1.261	6.615	3.70425	-0.87558	-0.166	0.717	0.229667	0.228333	-4.408	2.908	-0.00258	0.176833	-1.205	1.171	0.1005	0.21775
07/04/09 23:00:00.0	63.41642	-0.976	5.717	3.421083	-0.64575	-0.286	0.614	0.2925	0.123167	-4.485	2.749	-0.83275	-0.41217	-1.065	1.139	-0.011	0.027583
07/13/09 23:00:00.0	63.34317	-1.095	10.569	6.451083	-0.74517	-0.095	0.679	0.337833	0.202333	-6.637	4.614	-2.13742	-0.83842	-1.894	1.136	-0.45958	0.015167
06/01/09 23:00:00.0	60.29033	-1.746	6.167	3.56575	-1.0675	-0.626	0.735	0.313583	**0.395333**	-6.334	2.833	**-2.09242**	-2.3235	-1.563	1.023	-0.34758	-0.02592
05/31/09 23:00:00.0	59.25346	-1.507	6.41	3.850167	-0.62567	-0.357	1.232	0.499667	0.239833	-8.025	2.825	-1.743	-2.00483	-2.1	1.193	-0.02817	-0.23658
Average		**-1.32**	**7.10**	**4.20**	**-0.79**	**-0.31**	**0.80**	**0.33**	**0.24**	**-5.98**	**3.19**	**-1.36**	**-1.08**	**-1.57**	**1.13**	**-0.15**	**0.00**

Average Differences for Highest and Lowest 5% of Total Average Outdoor Temperature Daily Readings

Date/Time	Black Outdoor (^{0}C)	Black-Green Indoor Most Negative	Black-Green Indoor Most Positive	Black-Green Indoor Daytime Average	Black-Green Indoor Nighttime Average	Black-Green Outdoor Most Negative	Black-Green Outdoor Most Positive	Black-Green Outdoor Daytime Average	Black-Green Outdoor Nighttime Average	Black-Green RH Most Negative	Black-Green RH Most Positive	Black-Green RH Daytime Average	Black-Green RH Nighttime Average	Black-Green Dew Most Negative	Black-Green Dew Most Positive	Black-Green Dew Daytime Average	Black-Green Dew Nightime Average
08/10/09 23:00:00.0	27.18642	-0.897	5.53	3.304083	-0.1865	-0.049	1.036	0.41675	0.28275	-3.277	4.15	-0.54267	-1.33842	-0.703	1.829	0.243333	0.034
07/16/09 23:00:00.0	26.19042	-0.571	6.232	3.546	-0.0255	-0.364	0.692	0.37575	0.245583	-4.051	3.922	-0.62517	-0.77417	-1.232	1.539	0.106583	0.090583
08/09/09 23:00:00.0	26.10583	-0.358	6.456	4.009333	0.082917	-0.145	0.925	0.39725	0.304833	-4.841	1.125	-1.94442	-1.51683	-0.709	0.75	-0.05758	0.038583
08/20/09 23:00:00.0	25.70275	-1.694	5.107	3.599167	-0.80483	-0.072	0.782	0.288083	0.118583	-3.827	4.569	0.0455	-0.263	-0.383	1.857	0.279667	0.078083
08/11/09 23:00:00.0	25.32313	-0.932	6.211	3.836333	-0.54467	-0.123	0.851	0.4545	0.24725	-5.365	1.026	-2.05075	-1.073	-0.588	0.588	-0.0325	0.065667
Average		**-0.89**	**5.91**	**3.66**	**-0.30**	**-0.15**	**0.86**	**0.39**	**0.24**	**-4.27**	**2.96**	**-1.02**	**-0.99**	**-0.72**	**1.31**	**0.11**	**0.06**
08/31/09 23:00:00.0	15.53617	-1.605	6.414	4.057583	-1.25883	-0.12	1.118	0.388833	0.143167	-5.775	2.2	-1.52075	-0.48117	-1.011	0.94	0.039333	0.068833
06/01/09 23:00:00.0	15.16633	-1.746	6.167	3.56575	-1.0675	-0.626	0.735	0.313583	0.395333	-6.334	2.833	-2.09242	-2.3235	-1.563	1.023	-0.34758	-0.02592
06/05/09 23:00:00.0	14.01033	-0.335	0.978	0.518083	-0.02425	0.024	0.145	0.071917	0.105917	-0.776	0.375	-0.00842	-0.02167	0.029	0.148	0.081917	0.107917
09/01/09 23:00:00.0	13.89613	-2.11	7.169	4.356917	-1.70642	-0.385	0.714	0.276	0.001167	-3.913	3.965	-1.15167	-0.18917	-0.773	0.722	-0.10983	-0.02733
06/04/09 23:00:00.0	13.34321	-0.479	2.123	1.12825	-0.26475	-0.024	0.216	0.11175	0.096667	-1.139	2.032	0.158833	0.046917	-0.013	0.397	0.131917	0.103333
Average		**-1.26**	**4.57**	**2.73**	**-0.86**	**-0.23**	**0.59**	**0.23**	**0.15**	**-3.59**	**2.28**	**-0.92**	**-0.59**	**-0.67**	**0.65**	**-0.04**	**0.05**