The Influence of Distance From the City Centre and Albedo on Air Temperatures in Metropolitan Washington DC

Extended Essay
Geography

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Abstract

This paper examines how distance from the city centre and albedo (solar reflectance) contribute to changes in air temperatures, in the Washington DC metropolitan area. These two factors will be analyzed in the context of the Urban Heat Island (UHI) effect, through the following hypotheses:

H1: There is an inverse relationship between air temperatures and distance from the city centre.
H2: There is an inverse relationship between the albedos of surfaces surrounding weather stations, and associated air temperatures.

The minimum air temperature data was gathered from 44 weather stations scattered in a 30 mile radius around the city centre, over five consecutive days in October 2008. To test hypothesis 1, daily minimum temperatures were plotted against the distances of the weather stations from the city centre. Significant negative correlation was observed, indicating the presence of an intense UHI in the Washington DC metropolitan area. As for hypothesis 2, an average albedo value for each weather station was calculated, and compared to the daily minimum air temperature data. However, results showed no significant trends. This was probably due to the inaccurate method used to calculate albedo values, although it is possible that albedo has little effect on air temperatures in Washington DC. It was therefore concluded that the Washington DC metropolitan area does exhibit an intense UHI, but that albedo of surfaces in the city does not contribute significantly towards it. In future studies, a more accurate method for measuring albedo (e.g. the analysis of infrared satellite photographs) should be used to provide more reliable data. Furthermore, factors such as altitude of weather stations should be controlled so as to produce more consistent data.

Word Count: 273

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Acronyms

BLM	Bureau of Land Management
CBD	Central Business District
CWOP	Citizen Weather Observation Program
DC	District of Columbia
MADIS	Meteorological Assimilation Data Ingest System
MDT	Maryland Department of Transportation
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research (NOAA's Office of)
UHI	Urban Heat Island
VDT	Virginia Department of Transportation
WTOP	Washington DC Radio Station

1. Introduction

In the United States, 82 percent of the population lives in urban areas (Geography: United States). There are many studies analyzing the impact that urban areas have on their surrounding environment. One issue examined is the Urban Heat Island (UHI) phenomenon, whereby urban areas experience hotter air temperatures compared to surrounding rural areas (Climate Protection Partnership Division 1). The UHI effect can negatively impact urban areas, for example by: increasing the number and intensity of heat waves, increasing energy consumption (thereby causing more greenhouse gas emissions) and increasing levels of ground level ozone pollution (Climate Protection Partnership Division 13). Researching the UHI effect will therefore generate more information about its causes and the ways it can be reduced. Several studies have documented the existence of a UHI in Washington DC: Cheung; Viterito, (1989); Woollum, (1964); and Hoekzema and Hicks. This paper builds on previous studies by analyzing more recent data (from October 2008), and aims to understand *the influence of distance from the city centre and albedo on air temperatures, in the context of the UHI effect.* To answer this statement, it will focus on the following two hypotheses:

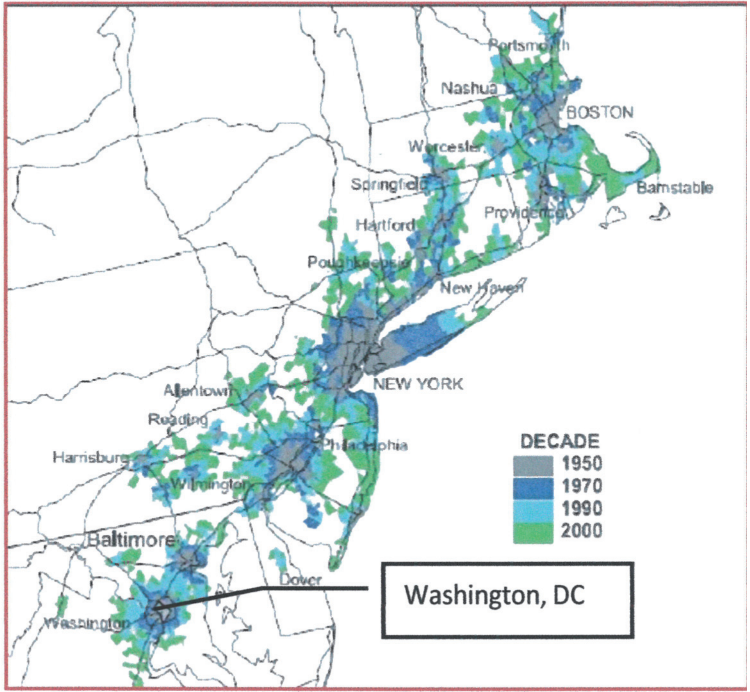
H1: There is an inverse relationship between air temperatures and distance from the city centre
– designed to measure the extent and intensity of the UHI.
H2: There is an inverse relationship between the albedos of surfaces surrounding weather stations and associated air temperatures
– designed to measure the contribution of albedo towards the temperature differentials observed in hypothesis 1.

This paper aims to study the Urban Heat Island in the Washington DC metropolitan area by analyzing air temperatures only, without also analyzing differences in humidity and wind speed between urban and rural areas. It concentrates on data gathered from a five day period in October 2008, referring to secondary published material in order to assess the validity of the data. This paper does not suggest possible mitigation strategies nor analyze the evolution of the city's UHI in a historical context. Neither does it attempt to measure the effects of the UHI on the city's environment and inhabitants. Thus, it is only a small contribution to a potentially larger study of the UHI phenomenon, which is likely to take on added significance in the context of global warming and adaptation strategies.

1.1 Geographical Context

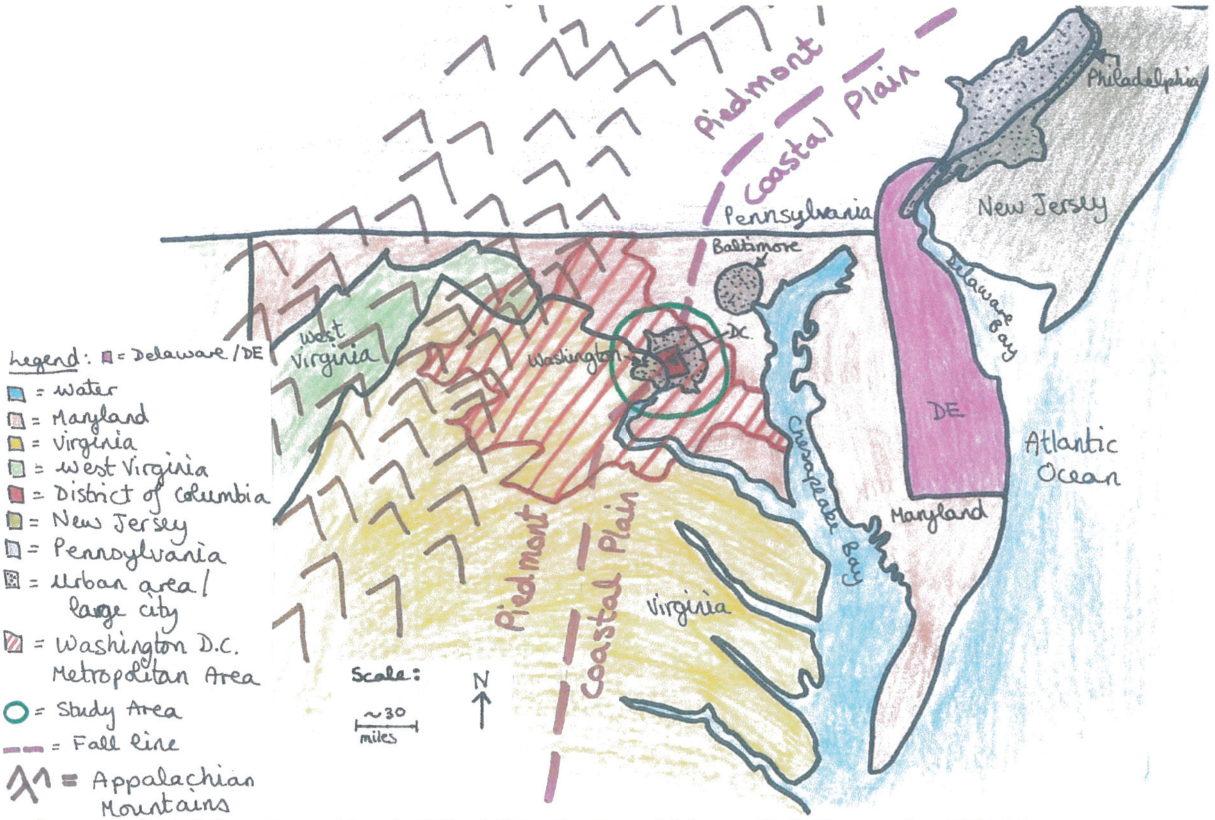
Washington DC is located on the East Coast of the United States of America (Figure 1), on the fall line between the coastal plain and the piedmont of the Appalachian Mountains (Lew). The city lies in the Chesapeake Bay watershed, and is intersected by the Potomac, Anacostia and Rock Creek Rivers. The District of Columbia itself is divided into four quadrants, with the Central Business District (CBD) lying principally in the Northwest quadrant (Cheung 1). The metropolitan area of Washington DC includes the District of Columbia, eleven counties or independent cities in Virginia, as well as five

***Figure 2:** Growth of the 'BosWash' Megalopolis*



Source: *Department of Geography*. University of North Texas, 11 June 2009. Web. 27 Nov. 2009. <http://www.geog.unt.edu/~rice/geog3100/3100slides/geog3100module5.pdf>.

***Figure 1:** Map of the Washington DC Metropolitan Area*



Source: adapted from Lew, Alan A. "The Mid-Atlantic and Megapolis." *Geography: USA*. N.p., 2004.Web. 12 Oct. 2009. <http://www.geog.nau.edu/courses/alew/ggr346/text/chapters/ch4.html>.

counties in Maryland (Figure 1; Cheung 1). It is part of the larger 'BosWash' megalopolis, which extends along the coast down from Boston to Washington and includes New York and Philadelphia (Figure 2; Webster's Third New International).

1.2 The Urban Heat Island Effect

Urban areas generally have higher surface and air temperatures than their surrounding rural environment, which leads to the formation of an Urban Heat Island (Climate Protection Partnership Division 1). The different characteristics of rural and urban environments, which lead to this temperature differential, are shown in the table below.

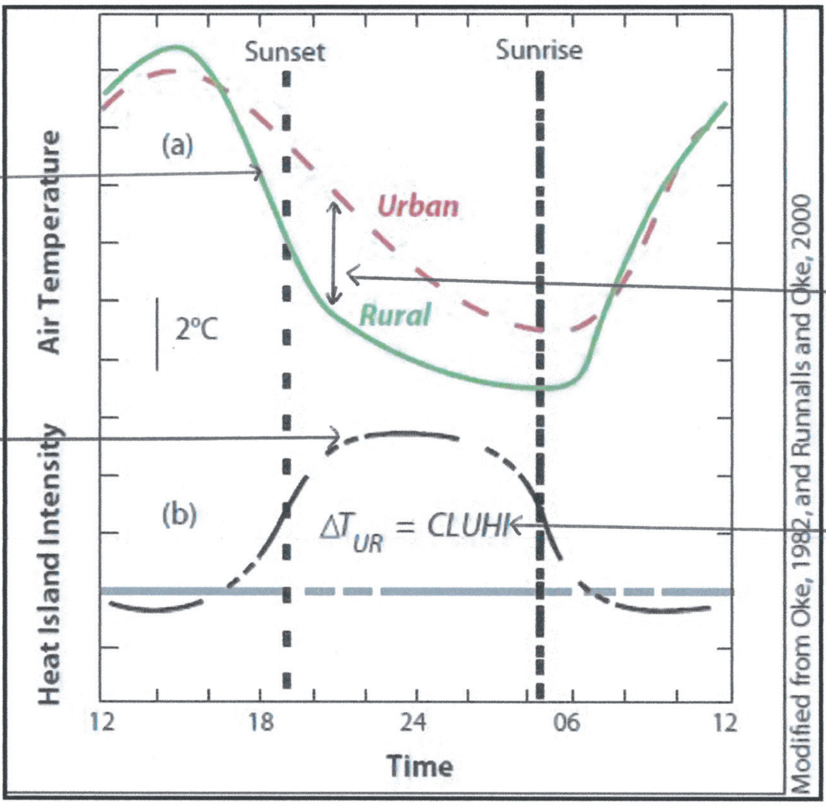
***Table 1**: Factors that contribute to the formation of the UHI*

Rural characteristic	**Effect on air temperatures**	**Urban characteristic**	**Effect on air temperatures**
Ground covered mainly by vegetation	-Evapotranspiration from vegetation reduces air temperatures -Trees produce shade, cooling the ground, leading to reduced surface temperatures -Vegetation has low heat capacity, decreasing surface temperatures *-Vegetation typically has a high albedo, decreasing surface temperatures*	Ground covered mainly by impervious surfaces	-Little evapotranspiration so air temperatures remain high -Concrete, asphalt etc have high heat capacities, increasing surface temperatures *-Construction materials typically have low albedo, increasing surface temperatures*
Lots of open space, high Sky View Factor (high percentage of sky visible from ground level)	Heat absorbed by vegetation can easily radiate outwards into the atmosphere, leading to high cooling rates	Buildings, cars etc close together lead to a small Sky View Factor (small percentage of sky visible from ground level)	Heat absorbed then radiated by buildings, cars etc is trapped in the canopy layer (layer of air between ground and the tops of trees or buildings), increasing air temperatures and reducing cooling rates
Few anthropogenic heat emissions	Little extra heat is added to the air by human activity	Many anthropogenic heat emissions	Cars, power plants, buildings etc produce heat, increasing air temperatures

Source: adapted from Climate Protection Partnership Division "Reducing Urban Heat Islands: Compendium of Strategies." *Heat Island Effect*. EPA, n.d. Web. 24 Aug. 2009. <http://www.epa.gov/hiri/resources/compendium.htm>.

This paper focuses on the *atmospheric* heat island, i.e. the difference in *air* temperatures in the *canopy layer* (the layer of air between the ground and the tops of trees and buildings), rather than differences in *surface* temperatures. This is because specific *air* temperature data is much easier to find and collect than *surface* temperature data. Atmospheric heat islands are usually visible at night, because urban areas (which have higher air temperatures than rural areas – see Table 1) radiate heat slower (and therefore air temperatures remain high) than rural areas (Figure 3; Climate Protection Partnership Division 8).

Figure 3: *Graph of temperatures in rural and urban areas during a 24 hour period*



Rural areas cool at faster rate than urban areas

Largest temperature difference between rural and urban areas seen at night

Urban Heat Island is most intense at night

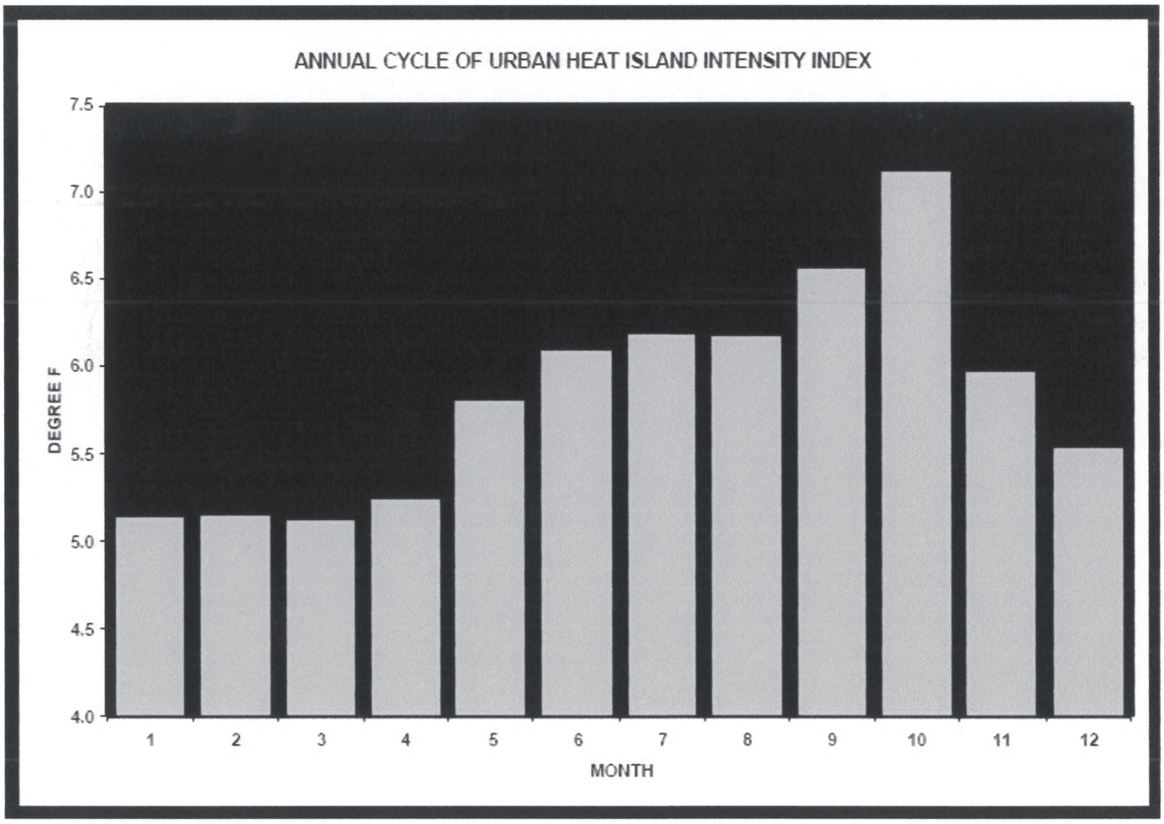
CLUHI = Canopy Layer Urban Heat Island

Source: Climate Protection Partnership Division "Reducing Urban Heat Islands: Compendium of Strategies." *Heat Island Effect*. EPA, n.d. Web. 24 Aug. 2009. <http://www.epa.gov/hiri/resources/compendium.htm>.

1.3 The Urban Heat Island in Washington DC

Between the 1950s and the 1980s, the intensity of Washington's UHI increased, particularly in the winter months (Cheung 3). Since then, there have been slight decreases in intensity, though these are not statistically significant (Cheung 3). They have been attributed to the sprawling of the city, which caused formerly rural weather stations to become increasingly urban (Cheung 3). Furthermore, it appears that the city's UHI follows an annual cycle, peaking in October, when average wind speeds are lowest (Figure 4; Cheung 2). The highest average difference between the city centre and rural outskirts, calculated over a 50 year period, is over 7ºF, based on a comparison between the Reagan National (urban) and Washington-Dulles (rural) Airports (Cheung 2). This is a relatively small difference in temperature, considering that the average difference in temperature for a city of one million inhabitants (the Washington metropolitan area has a population approaching 6 million) is 1.8 ºF to 5.4 ºF (Climate Protection Partnership Division 1).

Figure 4: *Graph of the average monthly intensity index of Washington DC's UHI from 1951-200*



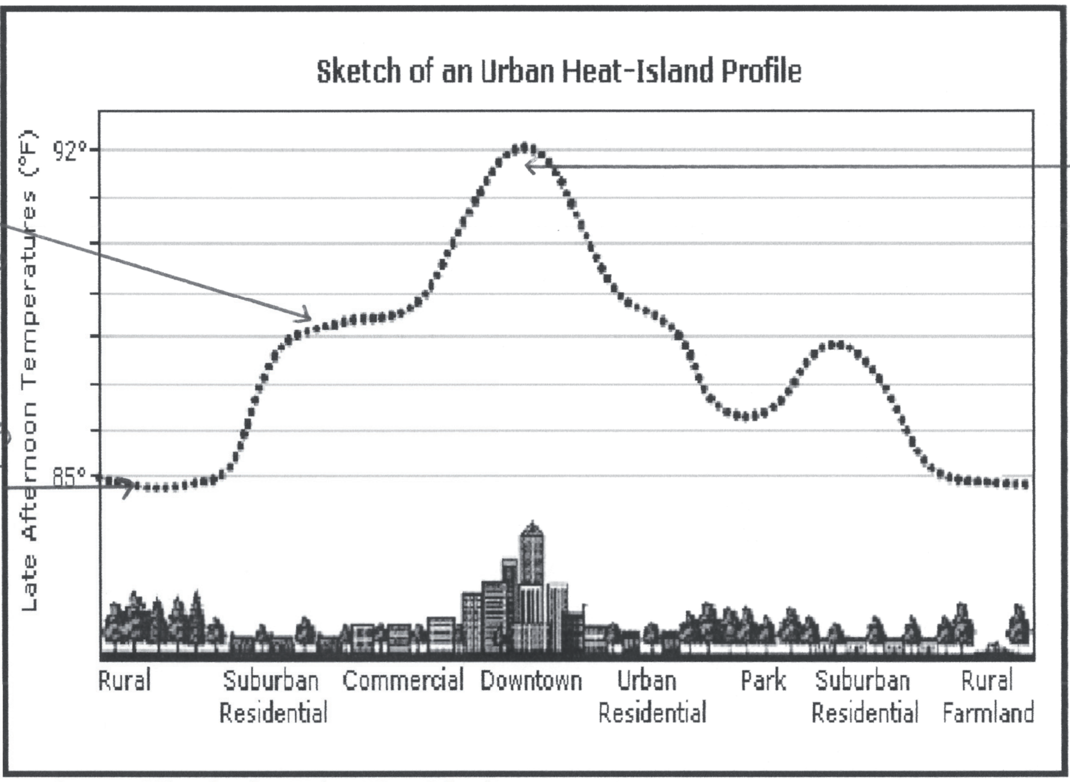
Source: Cheung, Ivan. *Extreme Heat, Ground Level Ozone Concentration, and the Urban Heat Island Effect in the Washington DC Metropolitan Area*. N. pag. PDF file.

2. Hypotheses

To analyze Washington DC's UHI, two hypotheses will be tested:

H1: There is an inverse relationship between air temperatures and distance from the city centre. This hypothesis is designed to measure the extent and intensity of DC's UHI. It assumes that urban density decreases from the CBD (Central Business District) outwards, as shown by Burgess' concentric model and Bid-Rent Theory (Nagle 273). Dense urban areas, such as the CBD (located in the centre of cities), are likely to have higher temperatures than areas that are mainly covered by trees or grass (and are therefore less dense), which are generally found outside the city (Figure 5). This is because the UHI effect is caused by the low albedo and heat emissivity, and high heat capacity of urban building materials (Climate Protection Partnership Division 7). A greater percentage of the ground will be covered by such materials in densely built up areas, thus leading to higher air temperatures. Furthermore, dense urban areas generally have little vegetation and small sky view factors, both of which would usually help decrease air temperature (Climate Protection Partnership Division 10).

Figure 5: *Urban Heat Island Profile*



Less dense areas of the city have lower air temperatures than in the CBD.

Lowest temperatures are observed in fully rural areas, because vegetation helps keep air and surface temperatures low

Highest temperatures present in the most densely built up area of the city (ie. the CBD).

Source: "Sketch of an Urban Heat-Island Profile." Chart. *Heat Island Group*. Lawrence Berkeley National Laboratory, 2000. Web. 27 Nov. 2009. <http://eetd.lbl.gov/HeatIsland/>.

H2: There is an inverse relationship between the albedo of surfaces surrounding weather stations and associated air temperatures.

This hypothesis is designed to measure the contribution of albedo towards the temperature differentials observed in hypothesis 1. Albedo (solar reflectance) is the amount of solar energy reflected by a surface, and is the main determinant of the temperature of that surface (Climate Protection Partnership Division 9). Therefore, since surface temperatures significantly affect ambient air temperatures, it is expected that areas with low albedos will reflect less energy, thus trapping more heat and raising air temperatures, while areas with high albedo will do the opposite (Climate Protection Partnership Division 4).

3. Methodology

Air temperature data was collected from 44 weather stations scattered around the DC metropolitan area (Figure 6). The weather stations are part of networks visible by accessing the website MesoWest (http://mesowest.utah.edu/), run by the University of Utah or from the DCNet network, run by NOAA (http://dcnet.atdd.noaa.gov/; Table 1). The stations were chosen because they provide reliable, quality-controlled data, but also because they have easily accessible archives, with data for October 2008, the period selected for analysis. All were located within an approximate 30 mile radius around the Hoover Building (chosen to represent the centre of the city).

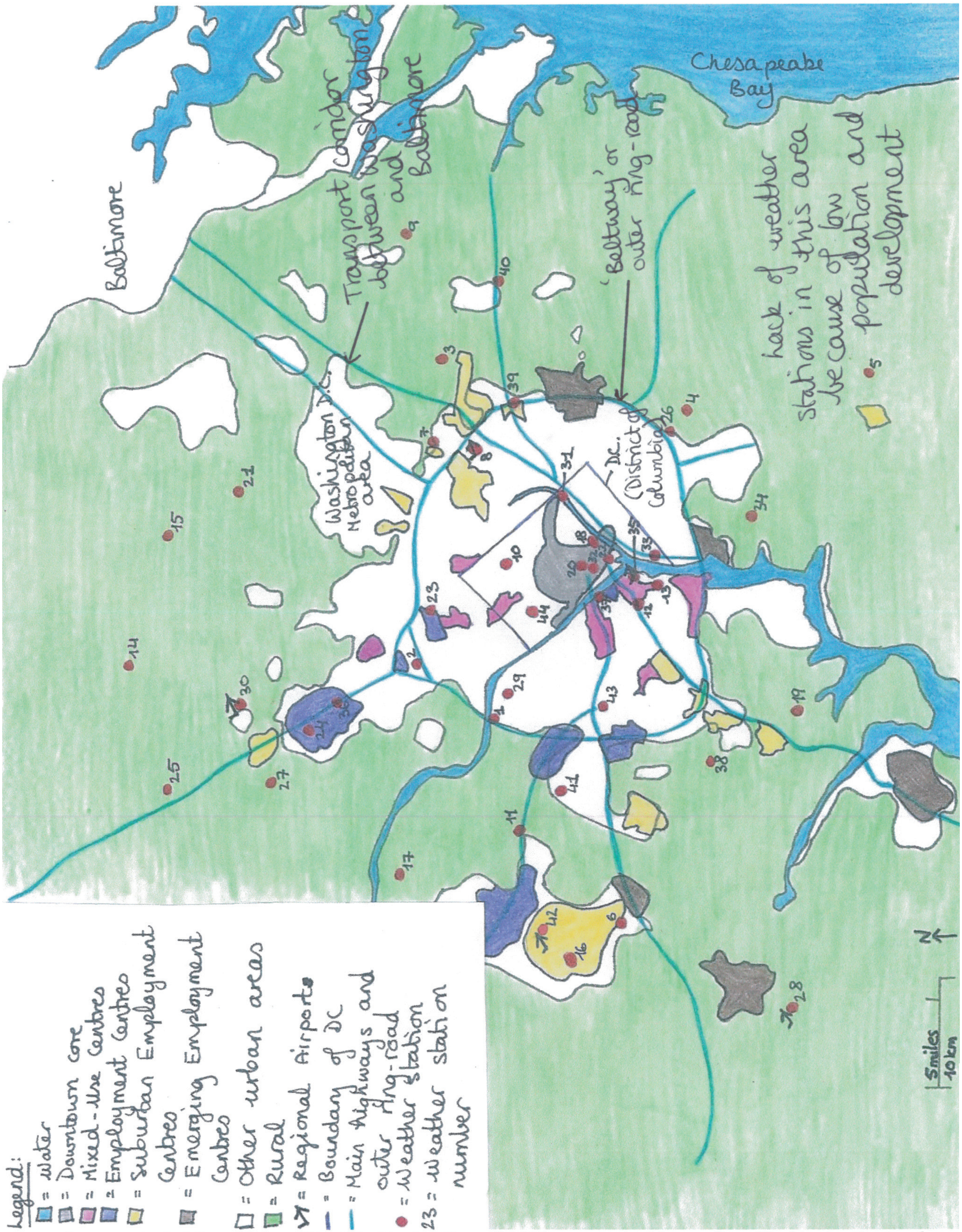
***Table 2:** Weather stations used for data collection*

Station number (Figure 6)	Weather station name	Association providing data
1	Am Lgn Br	MDT, MADIS
2	Bethesda	CWOP, MADIS
3	Bowie	CWOP, MADIS
4	Camp Springs/Andrews Air Force Base	NWS
5	Cedarville	BLM
6	Centreville	CWOP, MADIS
7	College Park	CWOP, MADIS
8	College Park Airport	NWS

9	Crofton	CWOP, MADIS
10	CSPAN South*	NOAA, OAR
11	CW3816 Reston	CWOP, MADIS
12	CW8838 Arlington	CWOP, MADIS
13	CW9740 Alexandria	CWOP, MADIS
14	Damascus	CWOP, MADIS
15	Dayton	CWOP, MADIS
16	Dulles Toll Road	VDT, MADIS
17	DW0851 Great Falls	CWOP, MADIS
18	DW1189	CWOP, MADIS
19	Fort Belvoir	NWS
20	Frank Reeves Municipal Centre*	NOAA, OAR
21	Highland	CWOP, MADIS
22	Hoover Building*	NOAA, OAR
23	I495 Connecticut	MDT, MADIS
24	I270 I370	MDT, MADIS
25	I270 MD109	MDT, MADIS
26	I495 MD4	MDT, MADIS
27	KB3HHA Germantown	CWOP, MADIS
28	Manassas Regional Airport	NWS
29	McLean	CWOP, MADIS
30	Montgomery County Airpark	NWS
31	National Arboretum*	NOAA, OAR
32	National Education Association*	NOAA, OAR
33	Naval Research Lab*	NOAA, OAR
34	Potomac	MADIS
35	Reagan National Airport	NWS
36	Rockville	CWOP, MADIS
37	Rosslyn	VDT, MADIS
38	Springfield	CWOP, MADIS
39	US50 I95	MDT, MADIS
40	US50 US301	MDT, MADIS
41	Vienna	CWOP, MADIS
42	Washington-Dulles International Airport	NWS
43	Westlawn	CWOP, MADIS
44	WTOP*	NOAA, OAR

*DCNet weather station

***Figure 6**: Map of the study area and weather stations*



Source: adapted from Metropolitan Washington Council of Governments. *Metropolitan Washington Regional Activity Centers and Clusters*. 2007. PDF file.

All data were collected over a five day period, from the 19th to the 23rd October, 2008. This is because October is generally the time when the UHI effect is most intense in Washington DC, since it is the month with the lowest average wind speed (Figure 4; Cheung 8). Furthermore, these dates represent several days with little cloud cover - as recorded at the Washington-Dulles Airport, Table 3 – weather conditions which produce the most intense UHI effect (Climate Protection Partnership Division 1).

Table 3: *Type of cloud cover recorded at Washington-Dulles International Airport, for the five days in October being studied.*

Date	**Number of hours recorded with each type of cloud cover**					
	Clear	**Mostly Clear**	**Partly Cloudy**	**Mostly Cloudy**	**Overcast**	***Mode type of cloud cover***
19th October '08	21	3	0	0	0	*Clear*
20th October '08	11	3	4	6	0	*Clear*
21st October '08	4	10	8	2	0	*Mostly Clear*
22nd October '08	8	11	1	2	2	*Mostly Clear*
23rd October '08	13	1	6	4	0	*Clear*

Source: University of Utah. *MesoWest*. University of Utah Department of Atmospheric Sciences, 2009. Web. 30 Nov. 2009. <http://mesowest.utah.edu/index.html>.

The first round of temperature data was recorded at 6pm for each of the five days being studied. This was the time immediately after sunset (Table 4), which is when the UHI effect is sometimes most intense (Kimura).

Table 4: *Sunset times for Washington DC*

Date	**Sunset time**
19th October '08	17:23
20th October '08	17:22
21st October '08	17:21
22nd October '08	17:19
23rd October '08	17:18

Source: "Rise and Set of the Sun for 2008." Chart. Astronomical Applications Dept, US Naval Observatory. *Microsoft Word* file.

However, when analyzed, the 6pm air temperature data showed no significant trends when compared to distance from city centre or albedo (Figures 26-35, Appendix). It was therefore decided to record the minimum daily temperature at each of the 44 weather stations, for the five between urban and rural areas (Figure 3; Climate Protection Partnership Division 8). Thus rural areas, which have high nighttime air temperature cooling rates, should cool to a lower minimum temperature than urban areas, which have slower nighttime cooling rates (Climate Protection Partnership Division 5).

3.1 Hypothesis 1

There is an inverse relationship between air temperatures and distance from the city centre.

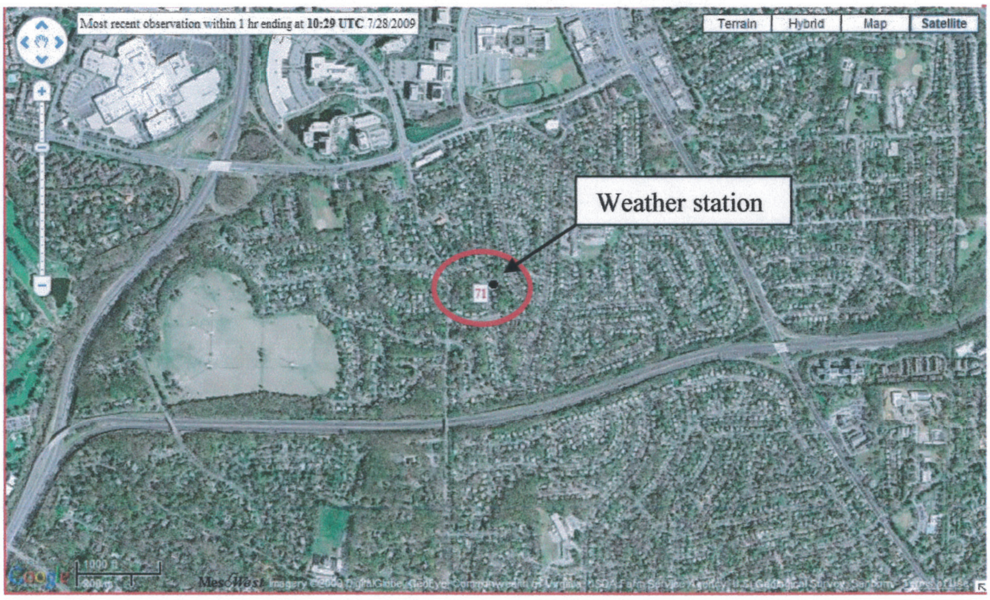
The Hoover Building weather station (number 22, Table 2), was chosen to represent the centre of Washington DC. This is because it is near the geographical and political centre of the city, and had been used in a previous study measuring the extent of DC's UHI, as the centre of the metropolitan area (Hoekzema and Hicks 1). The distance of each weather station from this point was then calculated using the "ruler" feature in Google Earth, which measures the distance 'as the crow flies'. For each of the five days being studied, the air temperature of each station was plotted against its distance from the Hoover Building on a scatter graph. The Spearman's Rank test was used to assess the statistical significance of the correlation between air temperature and distance from the city centre. Significance levels for the Spearman's Rank value were determined by using a table of Critical Values (Table 8, Appendix).

3.2 Hypothesis 2

H2: There is an inverse relationship between the albedos of surfaces surrounding weather stations and associated air temperatures.

To determine an average albedo value for each weather station, aerial photographs from Google Maps were analyzed. Each photo was taken from the same altitude, with the same resolution and scale (Figure 8).

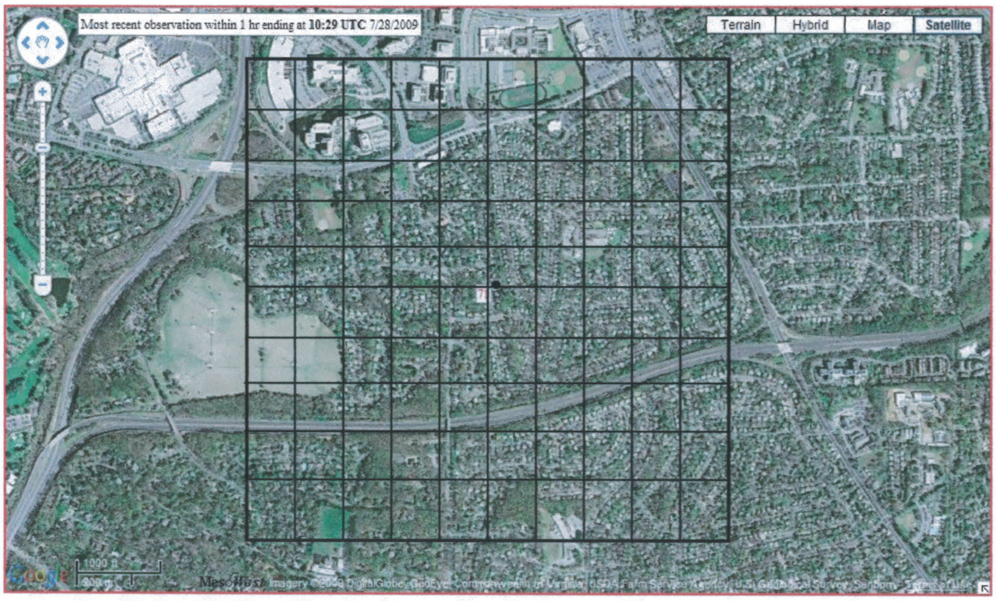
Figure 7: *Example of Google Earth aerial photo used to measure land use around the weather stations*



Source: Satellite Map of Bethesda Weather Station. Map. *Google Maps*. Google, 2009. Web. 27 Nov. 2009. <http://maps.google.com/maps?ie=UTF-8&hl=en&tab=wl>.

A quadrat was placed over the photo, with the weather station located in the exact centre of the quadrat. The quadrat was 1km by 1km in dimension, and was divided into a hundred squares, each representing 1% of the total 1km² surface surrounding the weather station (Figure 9). The number of squares fully covered, or more than 50% covered by each of five land use categories, was counted. The five land use categories are grass, woodland, impervious surfaces, water and bare ground.

Figure 8*: Google Earth photograph with a 1km by 1km quadrat over it*



Source: Satellite Map of Bethesda Weather Station. Map. *Google Maps*. Google, 2009. Web. 27 Nov. 2009. <http://maps.google.com/maps?ie=UTF-8&hl=en&tab=wl>.

For each category, an approximate albedo was calculated, using values from published literature (Table 3; JRC-IPSC and CRA-CIN). Then, the number of squares from each category was multiplied by the albedo calculated for it. The total albedo was then calculated for each weather station (see below).

Table 5: *Albedo for each type of ground coverage*

Type of ground coverage	**Albedo**
Grass	0.25
Trees	0.125
Impervious	0.175
Water	0.22
Bare ground	0.24

Source: JRC-IPSC, and CRA-CIN. “Albedo.” *Tools for Agro-Meteorology and Biophysical Modelling*. N.p., 2009. Web. 25 Aug. 2009. <http://www.apesimulator.it/help/models/solarradiation/Albedo.html>.

Sample Calculation:

Weather station: Bethesda (number 2 in Table 2)

Number of squares counted for each land use category:

Grass: 5

Trees: 9

Impervious: 86

Water: 0

Bare ground: 0

Total albedo value:

(5*0.25)+(9*0.125)+(86*0.175) = **17.43**

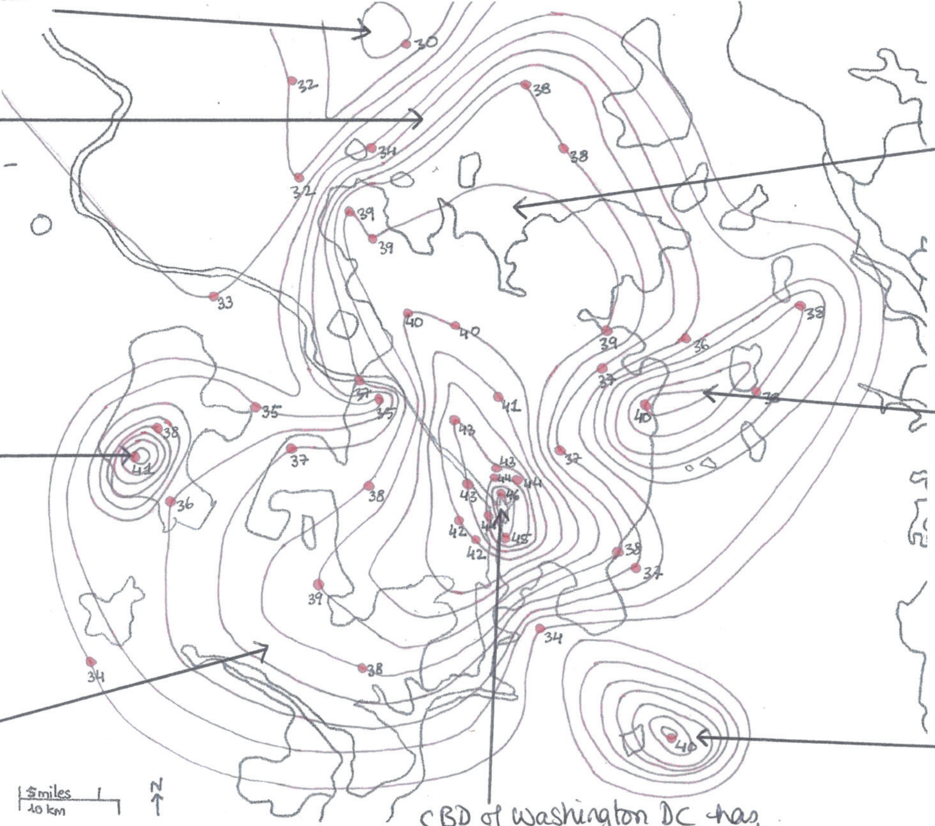
The range of possible albedo values is between 12.5 (completely covered by trees) and 25 (grass). For the five days observed, the air temperature recorded at each weather station was plotted against this calculated albedo value. A linear regression was drawn on the graphs in Microsoft Office Excel.

4. Results

4.1 Hypothesis 1

There is an inverse relationship between air temperatures and distance from the city centre

***Figure 9:** October 19th isotherm map*



Zone of coldest temperatures

Rapid decrease in temperatures marks the rural-urban fringe

Area of air temperature stability

"Dulles Toll Road" weather station hotspot

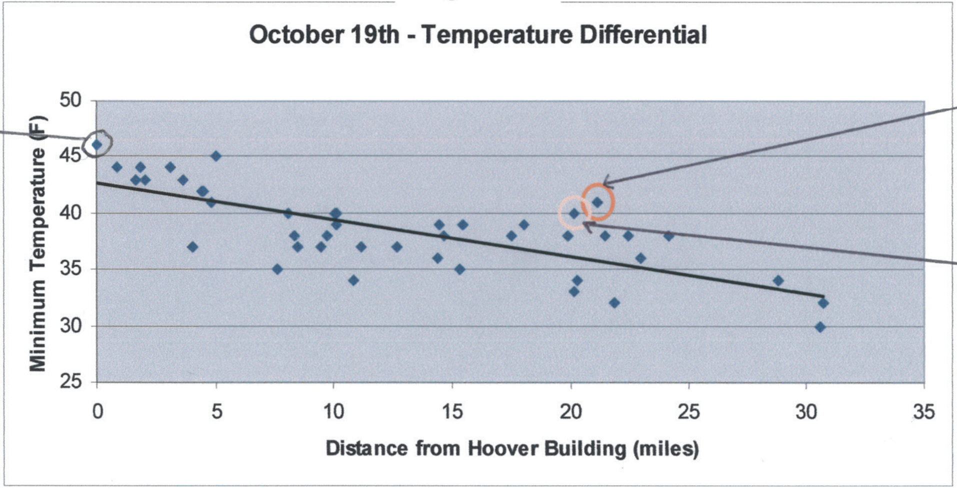
zone of higher temperatures follows highway leading from outer-ring-road to Chesapeake Bay

Area of gradual temperature decrease

"Cedarville" weather station hot spot

CBD of Washington DC has highest temperatures

Figure 10

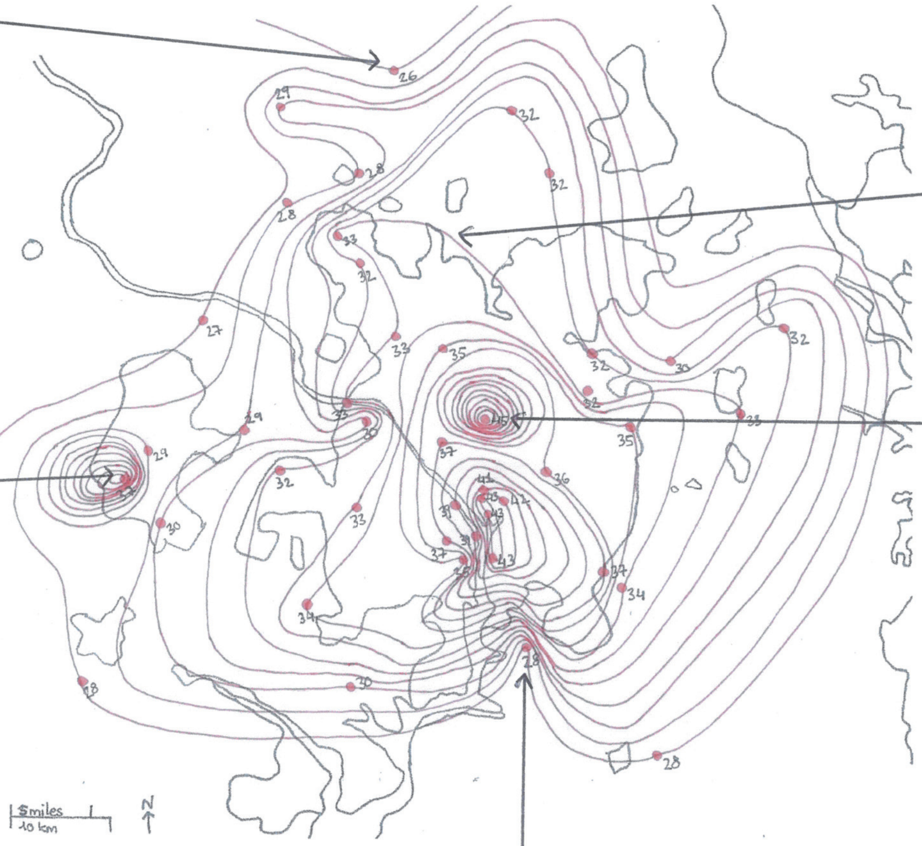


"Hoover Building" weather station records highest air temperature

"Dulles Toll Road" weather station hot spot anomaly

"Cedarville" weather station hot spot anomaly

Figure 11: October 20th isotherm map



Coolest temperatures recorded to the North of city

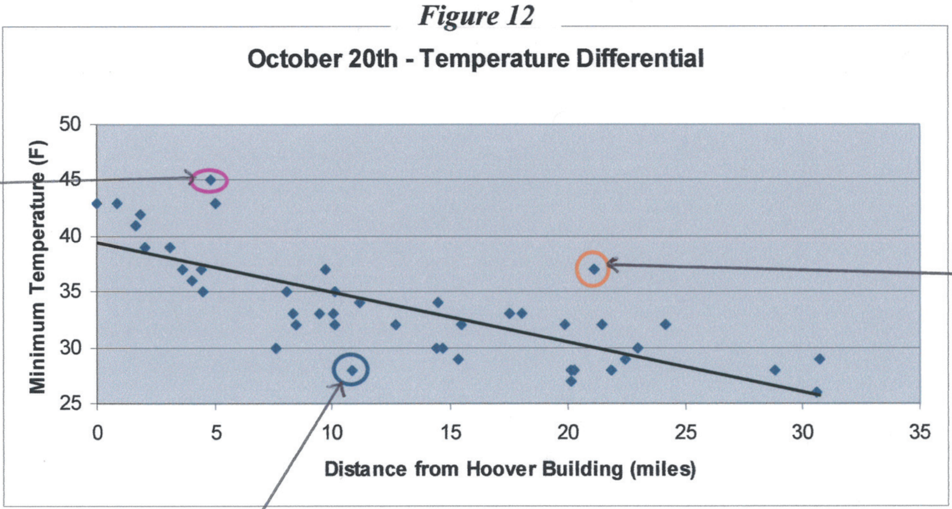
Area of air temperature stability

"Dulles Toll Road" weather station hot spot

Hottest temperatures recorded on the outskirts of DC at "CSPAN South" weather station

"Potomac" weather station cool spot

Figure 12

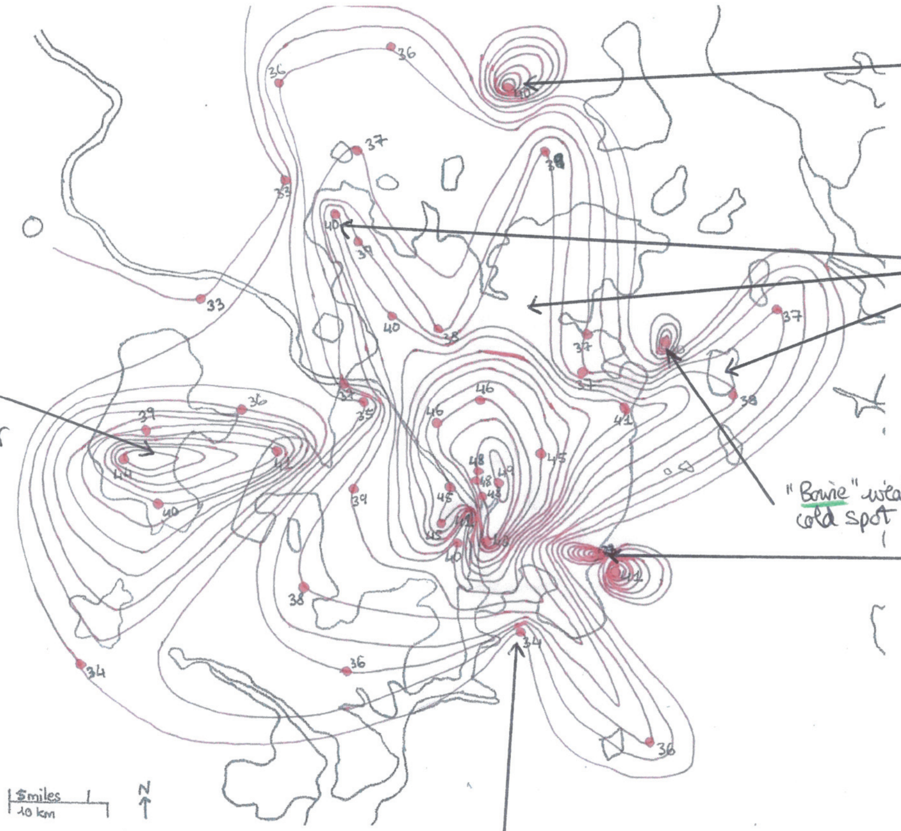


"CSPAN South" hot spot anomaly

"Dulles Toll Road" weather station hotspot

"Potomac" weather station cool spot

Figure 13: *October 21st isotherm map*



zone of high temperatures around "Dulles Toll Road" weather station

"Dayton" weather station hotspot

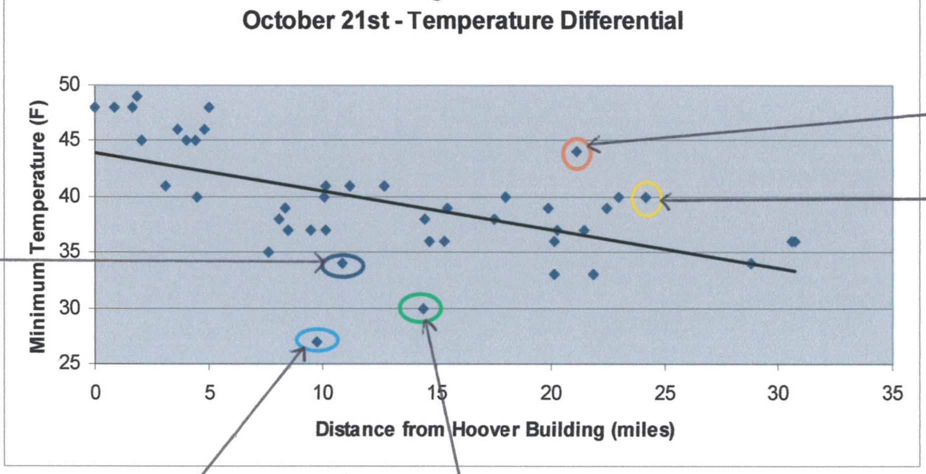
Distinct branches of high air temperatures extend out of the city, following roads and new areas of development

"Bowie" weather station cold spot

"I495 MD4" weather station cold spot

"Potomac" weather station cool spot

Figure 14



"Dulles Toll Road" station hot spot

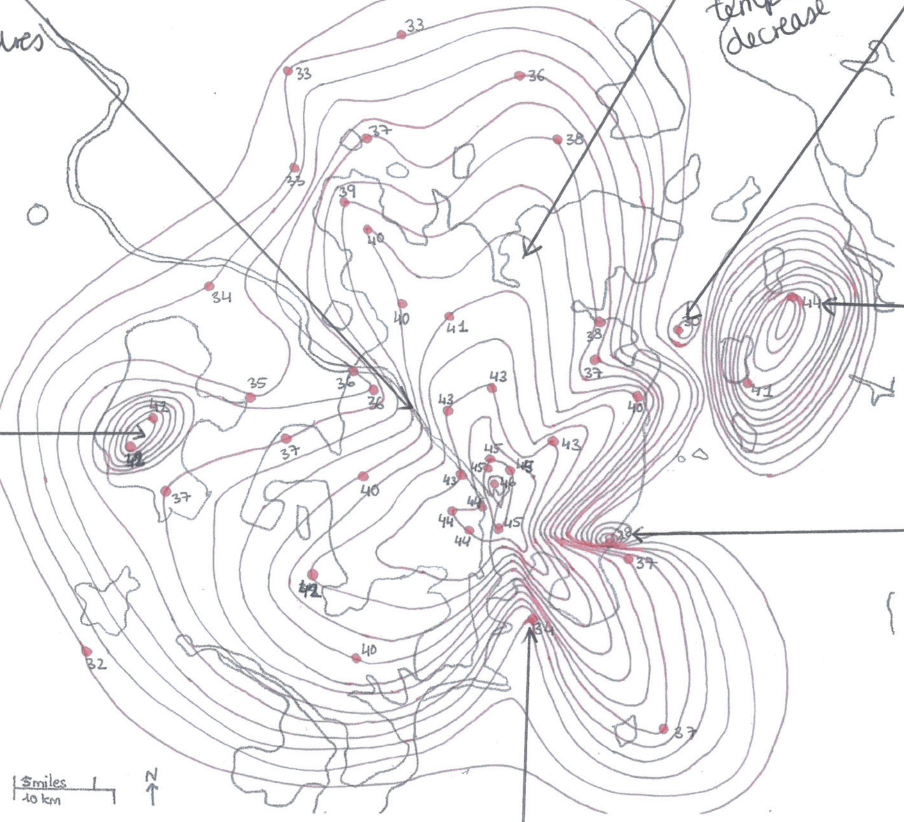
"Dayton" weather station hot spot

"Potomac" weather station cool spot

"I495 MD4" weather station cool spot

"Bowie" weather station cool spot

Figure 15: *October 22nd isotherm map*



Isotherm bends show the cooling effect of the Potomac River on air temperatures

Area of steady temperature decrease

"Bowie" weather station cool spot

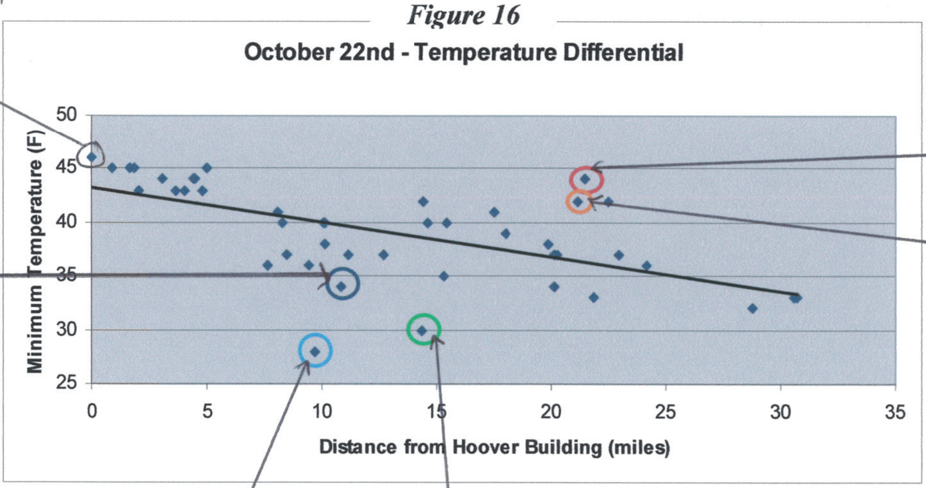
"Crofton" weather station hot spot

Hot zone around "Dulles Airport" and "Dulles Toll Road" weather stations

"I495 MD4" weather station cool spot

"Potomac" weather station cool spot

Figure 16



"Hoover Building" weather station records highest temperatures

"Potomac" weather station cool spot

"Crofton" weather station hot spot

"Dulles Toll Road" station hot spot

"Bowie" weather station cool spot

"I495 MD4" weather station cool spot

***Figure 17:** October 23rd isotherm map*

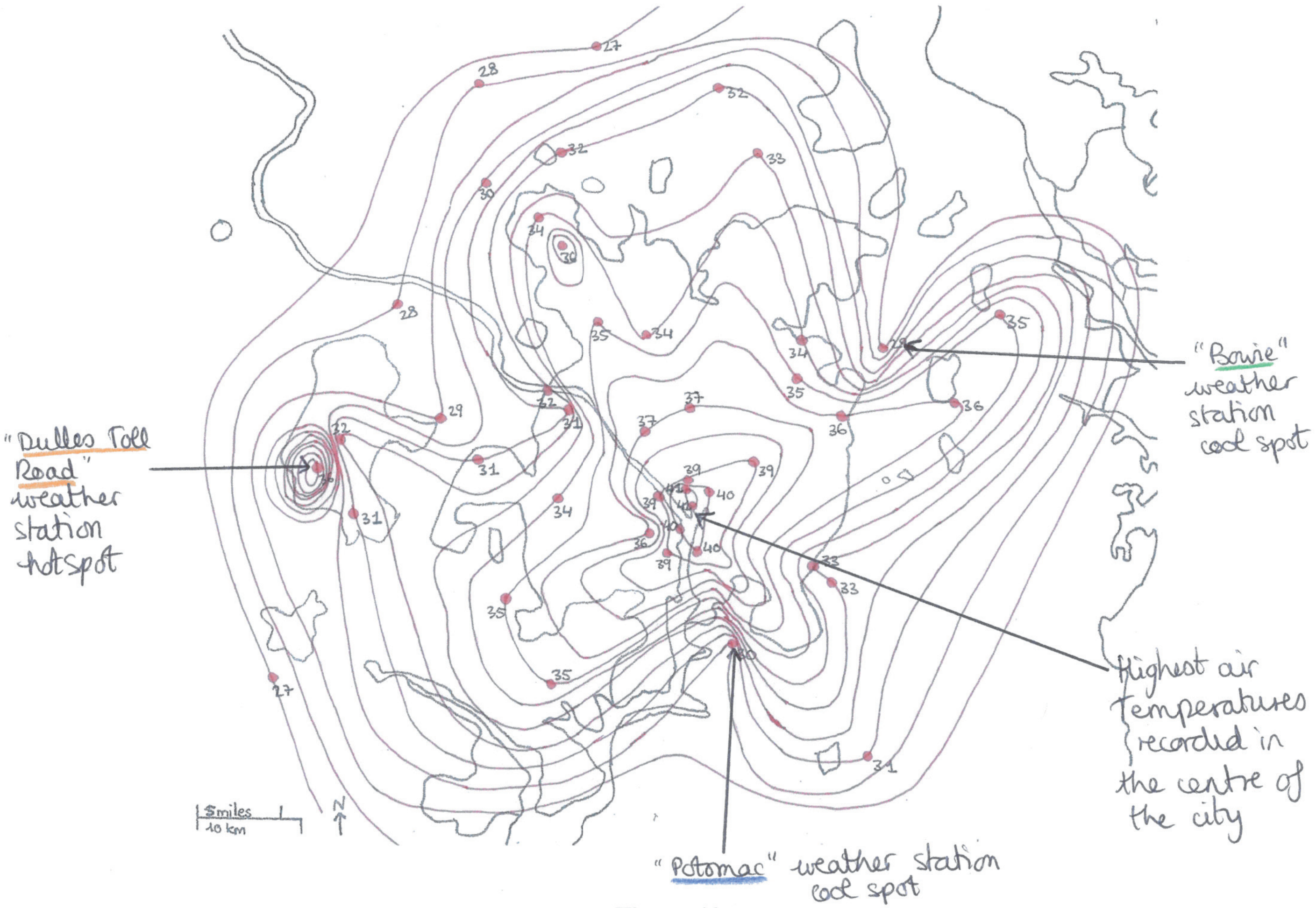


Figure 18

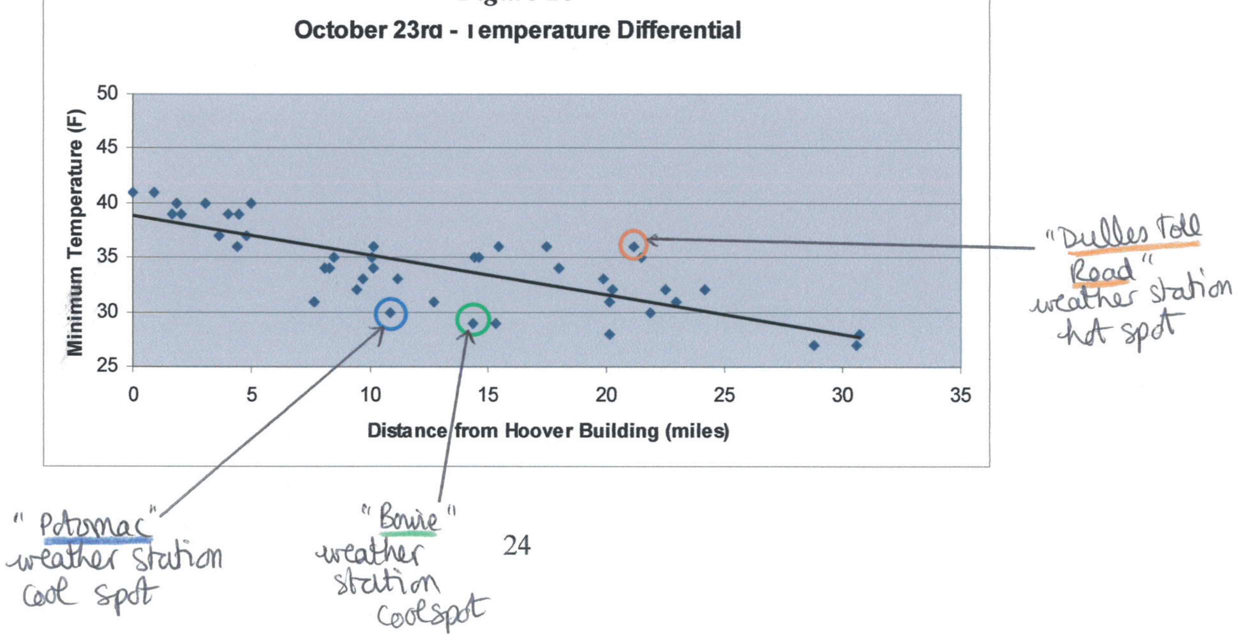


Table 6: *Spearman's Rank values and significance levels for distance from city centre versus minimum temperature data*

Date	**Spearman's Rank**	**Significance Level**
October 19th	-0.66	> 0.1%
October 20th	-0.69	> 0.1%
October 21st	-0.59	> 0.1%
October 22nd	-0.66	> 0.1%
October 23rd	-0.76	> 0.1%
Average	-0.67	> 0.1%

As can be seen from Figures 10, 12, 14, 16, 18 and Table 6, the minimum daily temperature data produced very strong negative trends for all of the days measured. These scatter graphs all show a significant inverse relationship between distance from the Hoover Building and minimum temperature. Moreover, the significance level of the data is above 0.1% for all the days being studied, so the research hypothesis can be accepted.

Furthermore, the weather station at the Hoover Building (representing the centre of the city) recorded the highest minimum temperature for three out of the five days measured, while the Damascus station (second furthest from the Hoover Building), recorded the lowest minimum temperature for three out of the five days measured. This supports the hypothesis that temperature decreases with distance from the centre of a city. In fact, the average difference in temperature between the Hoover Building and the weather station furthest away from it is 13.2°F, while the average maximum range in temperatures for the five days recorded is 17.8°F. These are significant differences in temperature, only a few degrees short of the commonly accepted maximum temperature differential of 22°F produced by an UHI (Climate Protection Partnership Division 1). Therefore the results show that an intense UHI forms over the Washington DC metropolitan area. Nevertheless, it is important to remember that the average temperature difference between the city centre and its rural outskirts will generally be a lot smaller, since this data shows the temperature range for days that were specifically chosen to show the most intense UHI.

In his study of the Washington DC heat island, Cheung found a difference of just over 7ºF between Reagan and Dulles Airports. This paper found this average to be 5.6ºF, suggesting that the data collected here is relatively consistent with earlier findings. The smaller difference in temperatures found here probably reflects the hypothesis stated in Cheung's research that the temperature difference between these two locations is decreasing due to the increasing amount of urbanization around Dulles Airport.

The isotherm maps drawn using the minimum temperature data for each of the five days measured add a spatial dimension to the results (Figures 9, 11, 13, 15 and 17). On most of the maps, the downtown zone and CBD of the city around the Hoover Building is the hottest area. The coolest temperatures recorded are generally found to the north and north-west of the city. Isotherm lines follow the different zones of development around the city, producing several branches of elevated air temperatures: one directly to the north of the city, one branch to the east, one to the south west and a small one to the south east of the city. Temperatures tend to decrease steadily as distance from the centre of the city increases. Hot- or cold-spots dotted around the study area produce areas of rapid temperature increase or decrease. For example, on all the isotherm maps, the Dulles Toll Road weather station (circled orange) appears as a hot spot, with air temperatures significantly higher than those of surrounding weather stations. This may be because the weather station is located on the main road to the Washington-Dulles International Airport, and therefore air temperatures increase from the heat pollution caused by traffic. It is also a new area of industrial development and suburban sprawl, both of which would raise air temperatures (due to the increase in amount of impervious surfaces and associated anthropogenic heat emissions, as well as the decrease in the amount of vegetation). Two cold-spots also often appear on the isotherm and scatter plots, to the south-east of the city. One is the weather station at I496 MD4 (circled light blue), which is located on a busy intersection between the beltway (outer ring road) and another main road; therefore the low air temperatures it recorded have been attributed to instrument malfunction. It may be however that the relatively high altitude of the station (495ft) caused the lower air temperatures. Potomac (circled dark blue), the other anomalous weather station, is an area of low air temperatures because it is a rural weather station, near low-density housing, and surrounded by woods and open fields. It is interesting to note that to the south of the city, there is generally less urban sprawl (visible as a rapid decrease in temperatures), whereas to the north and north-west, there are large areas of suburban development (visible as a slow decrease in air temperatures).

4.2 Hypothesis 2

H2: There is an inverse relationship between albedo of surfaces surrounding weather stations and associated air temperatures.

Figure 19

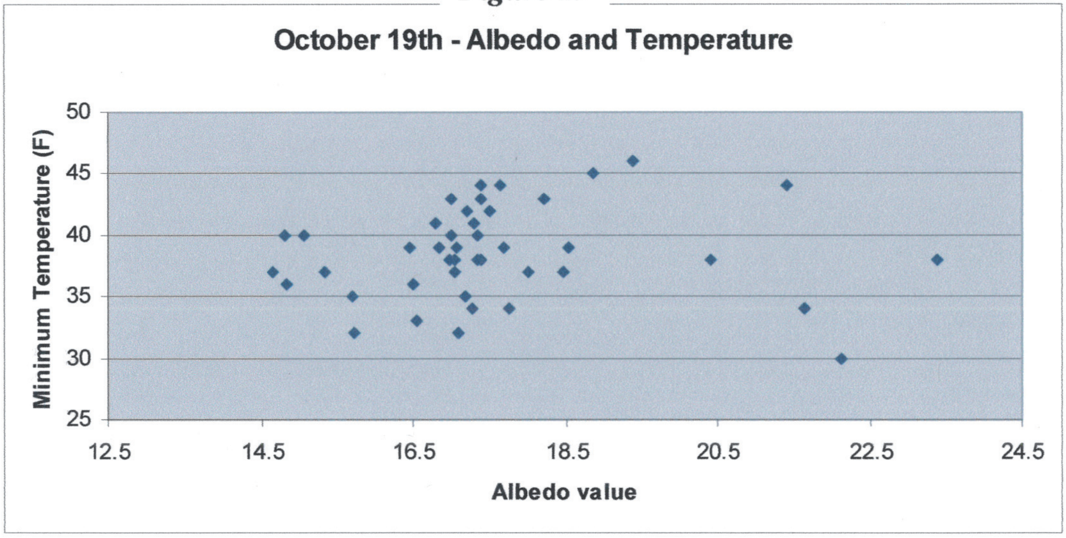


Figure 20

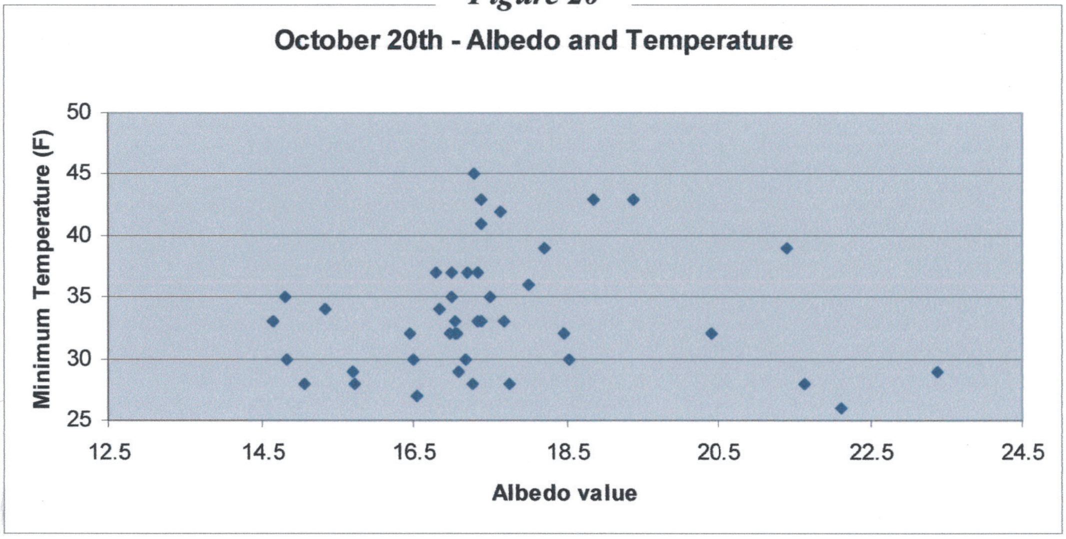


Figure 21

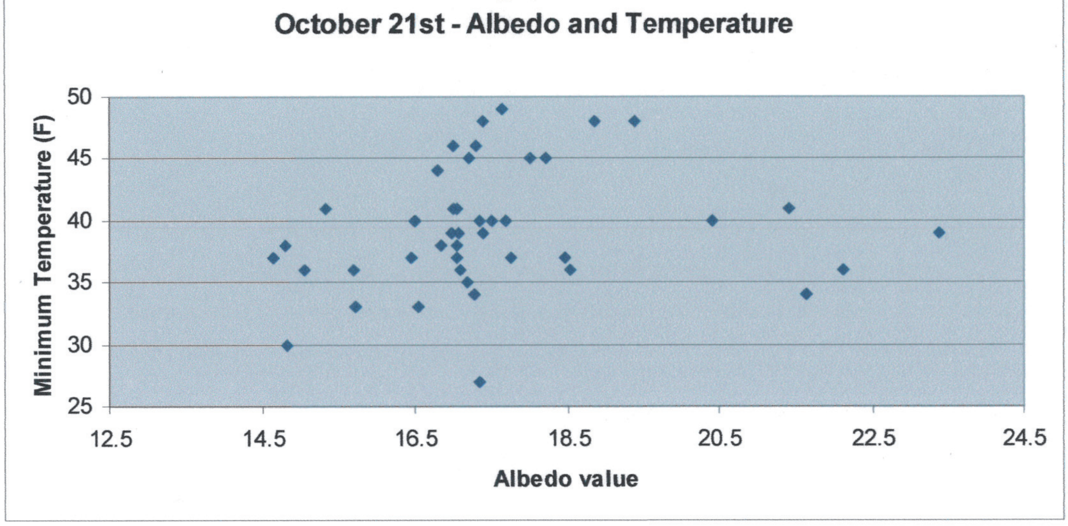


Figure 22

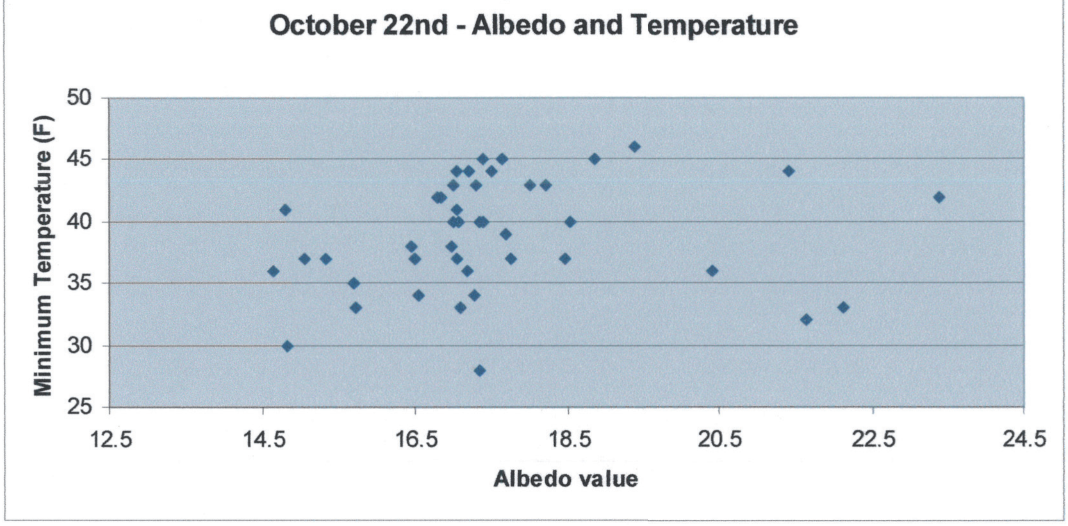


Figure 23

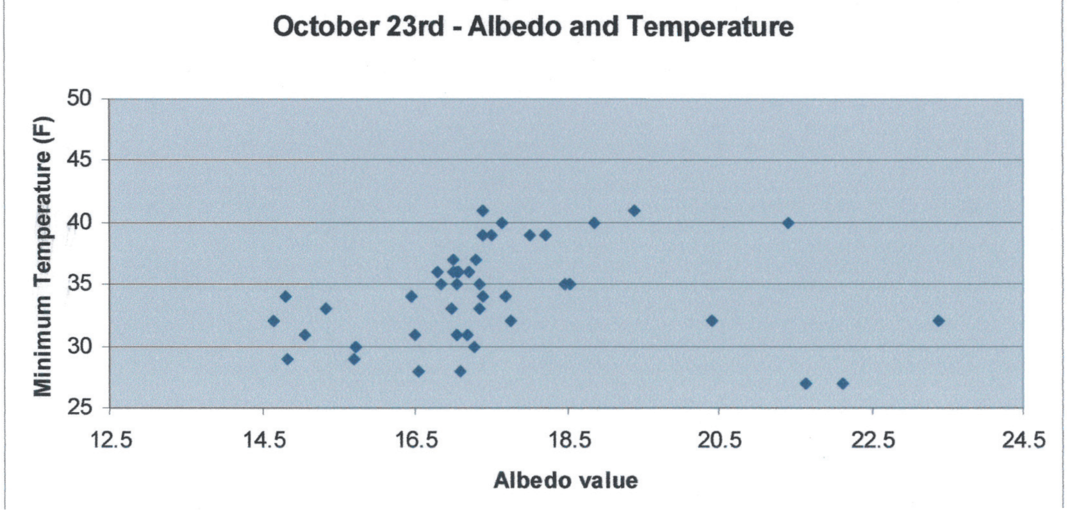


***Table** 7: Spearman's Rank value and significance levels for the albedo versus temperature data*

Date	**Spearman's Rank Value**	**Significance Level**
October 19th	0.17	< 5%
October 20th	0.13	< 5%
October 21st	0.23	< 5%
October 22nd	0.25	< 5%
October 23rd	0.27	< 5%
Average	0.21	< 5%

As can be seen from Figures 19-23, the albedo versus minimum temperature data shows little or no correlation. There is a cluster of data points with albedo values of between 16.5 and 18.5. These data points all have very similar albedo values despite their great differences in temperature. In addition, the Spearman's Rank values calculated for each of the five days measured are all below the 5% significance level. Therefore, the null hypothesis that there will be no significant relationship between albedo and air temperature, must be accepted.

Several factors may explain why no trends were visible for the albedo versus minimum temperature data. Firstly, albedo controls surface temperatures, which then indirectly (but significantly) affect ambient air temperatures (Climate Protection Partnership Division 1). Thus, if the influence of surface temperatures on air temperatures was weakened (e.g. by wind), there may appear to be no connection between albedo and air temperatures (Climate Protection Partnership Division 4). Secondly, there was only a small range of different albedo values, with most stations having values between 16.5 and 18.5. This shows that the weather stations were all located in areas of similar levels of urban development, and may be due to the fact that Washington DC is a very sprawling and relatively 'green' city, with 46% tree cover compared to 27% impervious surface cover (American Forests 3). A study conducted measuring the difference in albedo between 20 major cities and their rural fringes found that the difference could be as little as 0.02, especially in "green" cities, located in temperature regions, such as Washington DC (Fuller, Roy and Cohen). Finally, it is probable that the method used to determine the albedo value for each station was insufficiently accurate to produce any detailed data (see Evaluation). This is suggested by the observation that weather stations that had similar albedo values exhibited vastly different air temperatures. Moreover, most published literature suggests that there should be an inverse relationship between albedo and air temperature, since surfaces with low albedo trap more heat (than areas surfaces with high albedo), thus increasing surface temperatures which in turn increases ambient air temperatures (Climate Protection Partnership Division 9).

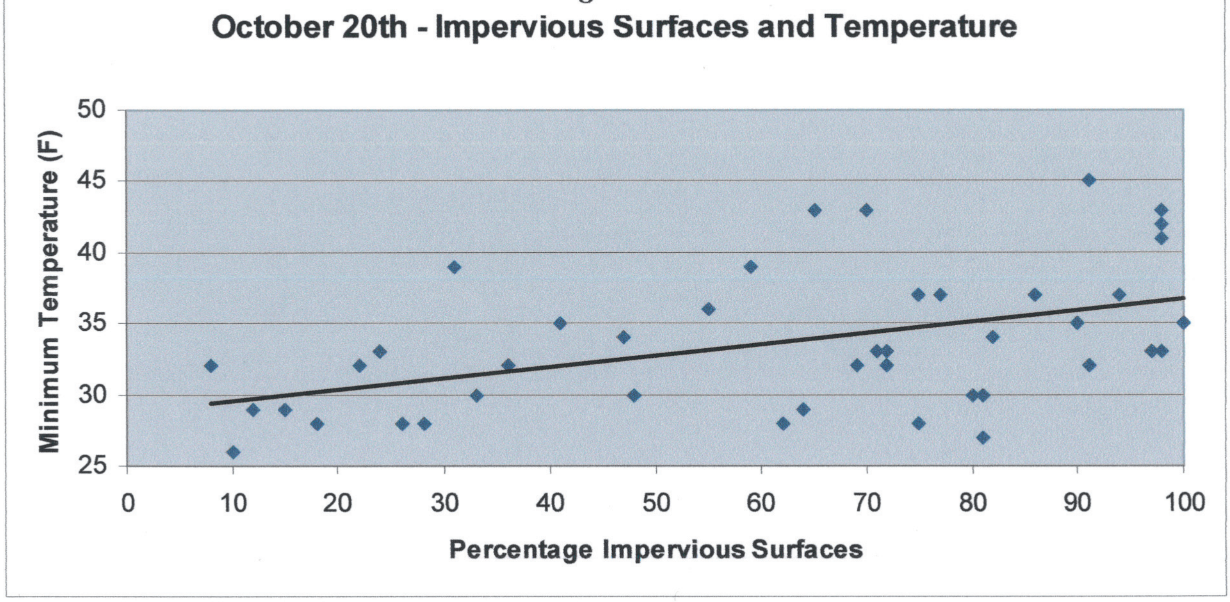
5. Evaluation

Although the data collected did show statistically significant trends for the relationship between temperature and distance from the city centre, it represents only the patterns present on the days of data collection, meaning it is still insufficient enough to draw conclusions about the general characteristics of Washington DC metropolitan areas UHI. However, since there are no major disparities between the different temperature data sets from the five days being studied, it can be assumed that this is a reliable method for data collection. Using so many weather stations also allowed for detailed isotherm maps to be drawn, and hence for the analysis of anomalies that appeared. However, Spearman's Rank, the main statistical tool used for analysis, decreases in accuracy for such large sample sizes, which may have affected the reliability of results.

As for the method used to determine the albedo of the area surrounding each weather station, this provides only a very rough estimate of the actual albedo. The value calculated acts as an average for the 1km² area measured, thereby blanketing any major changes in albedo of that area, which may have affected its air temperature. The determination of the percentage of ground covered by each category of land use (grass, woodland, impervious surfaces, water and bare ground) was somewhat subjective, because of the low definition of the Google Earth photos being used. Furthermore, the method was not accurate enough to take into account variations in land use cover for areas smaller than 0.01km² (the size of one square of the quadrat), meaning, for example, that gardens and tree-lined streets were all counted as 'impervious surfaces', if they constituted less than 50% of a quadrat square. Moreover, it must be taken into account that Google Earth photos may date back several years, and are sometimes made up of a patchwork of photos from different years. Therefore, what is seen on the photos may not be the exact lay of the land as it was in October 2008. In addition, the albedo values used to represent each land use category were very generalized averages.

Another problem with this method is that although trees lower air temperatures because they produce shade and take part in evapotranspiration, they have an albedo (0.125) lower than that of impervious surfaces (0.175). Therefore areas with a large percentage of tree cover appear to have a lower total average albedo value than areas covered with impervious surfaces, and are therefore expected to produce higher temperatures than those more urbanized areas, which is not the case. This helps explain why the albedo data produced no trends, whereas when examining the percentage of each individual type of land use cover, correlation does become evident. For example, Figure 24 below shows the percentage of impervious surfaces surrounding each weather station compared to its air temperature, for October 20th.

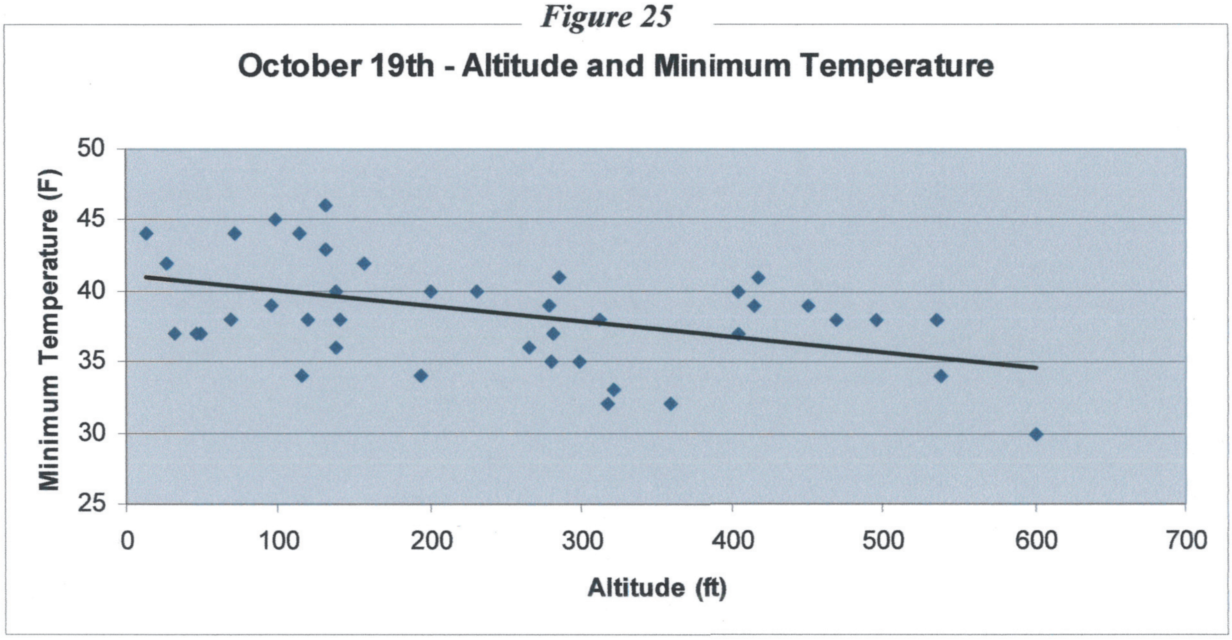
Figure 24



Although only weak correlation may appear on the scatter plot, this dataset has a Spearman's Rank value of 0.48, which is above the 0.1% significance level (for a sample size of 44; Table 8 Appendix). Therefore it may be more accurate in future studies to compare the actual land use around each weather station to its air temperature. Another method for determining the effect of albedo on air temperatures would be to analyze infrared satellite photos using special algorithms. However, this technology was not available to the author.

Other factors that may have affected the temperature data collected are aspect and altitude. Neither of these were controlled when choosing weather stations to gather data from, meaning that there is a 571ft difference in elevation between the lowest and highest weather station used in this study. Figure 25 displays the weak correlation between altitude and minimum temperature for October 19th, and shows that altitude should be controlled in future studies because it does impact temperature data.

Figure 25



As stated in the conclusion, there are many other factors apart from distance for the city centre and albedo that contribute to UHI formation. These include time of day and year, weather, urban geometry, sky view factor, thermal emittance, heat capacity and anthropogenic heat emissions (Climate Protection Partnership Division 7-12). These factors influence each other, making it hard to isolate one particular aspect and study it out of context, as was done when measuring albedo.

6. Conclusion

This paper has examined the intensity and extent of the UHI of the Washington DC metropolitan area, and the influence of albedo on the formation of the UHI. The results show a statistically significant decrease in temperatures as distance from the city centre increases – with average maximum temperature differences of 17.8°F between central urban areas and the rural fringe. This indicates the formation of a very intense UHI over the city for the 5 days in October being studied. However, although differences in albedo between urban and rural areas are known to be one of the causes of UHI formation, this study found no correlation between albedo and air temperature. This may be due to several factors, in particular the inaccurate method used to gather albedo data for the areas surrounding each weather station and the low level of observed variation in albedo. However, it also indicates that the surface albedo in itself has only a weak influence on air temperatures, and that the formation of such an intense heat island in the Washington DC metropolitan area is due to other factors (e.g. land use cover, anthropogenic heat emissions and sky view factor). Altitude and aspect also play a role in determining air temperature, and all these factors are discussed in the Evaluation. It is most likely that the UHI of Washington DC is caused by a combination of different factors.

Bibliography

American Forests. *Urban Ecosystem Analysis for the Washington DC Metropolitan Area*. 2002. PDF file.

Cheung, Ivan. *Extreme Heat, Ground Level Ozone Concentration, and the Urban Heat Island Effect in the Washington DC Metropolitan Area*. N. pag. PDF file.

Climate Protection Partnership Division. "Reducing Urban Heat Islands: Compendium of Strategies." *Heat Island Effect*. EPA, n.d. Web. 24 Aug. 2009. <http://www.epa.gov/hiri/resources/compendium.htm>.

"Critical Values of the Spearman Rank Order Correlation Coefficient: The Rs Tables ." Chart. 1972. PDF file.

Fuller, D O, S S Roy, and A Cohen. *Land Surface Albedo of Large Urban Agglomerations from Landsat Observations*. N. pag. *Astrophysics Data System*. SAO/NASA, May 2006. Web. 26 Oct. 2009. <http://adsabs.harvard.edu/abs/2006AGUSM.B43A..03F>.

"Geography: United States." *CIA World Factbook*. CIA, n.d. Web. 24 Aug. 2009. <https://www.cia.gov/library/publications/the-world-factbook/geos/us.html>.

Growth of the Bos-Wash Megalopolis. Map. *Department of Geography*. University of North Texas, 11 June 2009. Web. 27 Nov. 2009. <http://www.geog.unt.edu/~rice/geog3100/3100slides/geog3100module5.pdf>.

Hoekzema, Mark, and Bruce B Hicks. *Using Urbanet Data to Quantify the Nocturnal Heat Islands of US Cities*. N. pag. PDF file.

JRC-IPSC, and CRA-CIN. “Albedo.” *Tools for Agro-Meteorology and Biophysical Modelling*. N.p., 2009. Web. 25 Aug. 2009. <http://www.apesimulator.it/help/models/solarradiation/Albedo.html>.

Kimura, Fujio. “Thermal Effects of Urban Canyon Structure on the Nocturnal Heat Island: Numerical Experiment Using a Mesoscale Model Coupled with an Urban Canopy Model.” *Applied Meteorology* 43.12 (2004): 1899-1910. Abstract. *American Meteorological Society Online Journals*. Web. 25 Aug. 2009. <http://ams.allenpress.com/perlserv/?request=get-pdf&doi=10.1175%2FJAM2169.1>.

Lew, Alan A. “The Mid-Atlantic and Megapolis.” *Geography: USA*. N.p., 2004. Web. 12 Oct. 2009. <http://www.geog.nau.edu/courses/alew/ggr346/text/chapters/ch4.html>.

Metropolitan Washington Council of Governments. *Metropolitan Washington Regional Activity Centers and Clusters*. 2007. PDF file.

“Mid-Atlantic Region: Physical Geography.” Map. *Geography: USA*. N.p., 2004. Web. 27 Nov. 2009. <http://www.geog.nau.edu/courses/alew/ggr346/text/chapters/ch4.html>.

Nagle, Garrett. *Advanced Geography*. Singapore: Oxford University Press, 2000. Print.

NOAA/OAR. *DCNet*. NOAA/OAR, n.d. Web. 30 Nov. 2009. <http://dcnet.atdd.noaa.gov/>.

“Rise and Set of the Sun for 2008.” Chart. Astronomical Applications Dept, US Naval Observatory. *Microsoft Word* file.

Satellite Map of Bethesda Weather Station. Map. *Google Maps*. Google, 2009. Web. 27 Nov. 2009. <http://maps.google.com/maps?ie=UTF-8&hl=en&tab=wl>.

“Sketch of an Urban Heat-Island Profile.” Chart. *Heat Island Group*. Lawrence Berkeley National Laboratory, 2000. Web. 27 Nov. 2009. <http://eetd.lbl.gov/HeatIsland/>.

University of Utah. *MesoWest*. University of Utah Department of Atmospheric Sciences, 2009. Web. 30 Nov. 2009. <http://mesowest.utah.edu/index.html>.

Webster's Third New International Dictionary, Unabridged Online. N.p., n.d. Web. 25 Aug. 2009. <http://www.websters-online-dictionary.org/me/metropolitan_area.html>.

Appendix

Figures 26-35 are the scatter plots created using the 6pm air temperature data, which showed little or no correlation against distance from the Hoover Building or albedo.

Figure 26

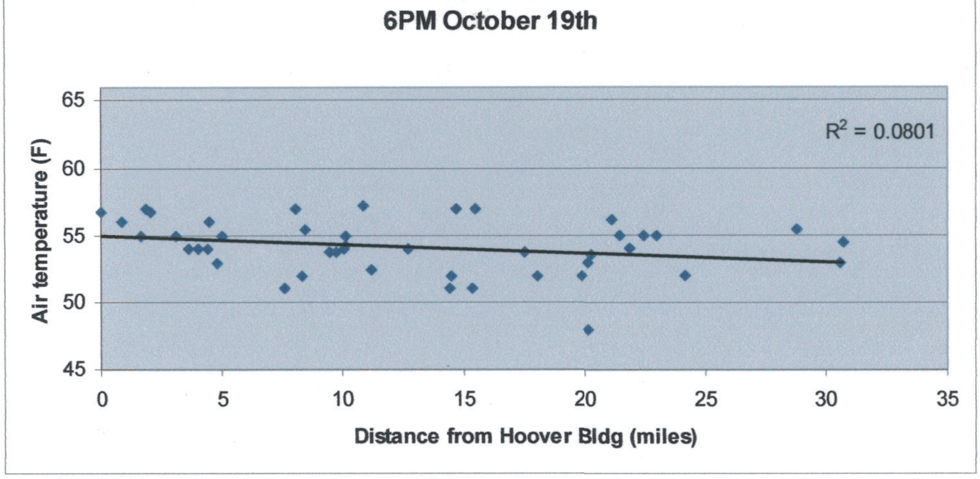


Figure 27

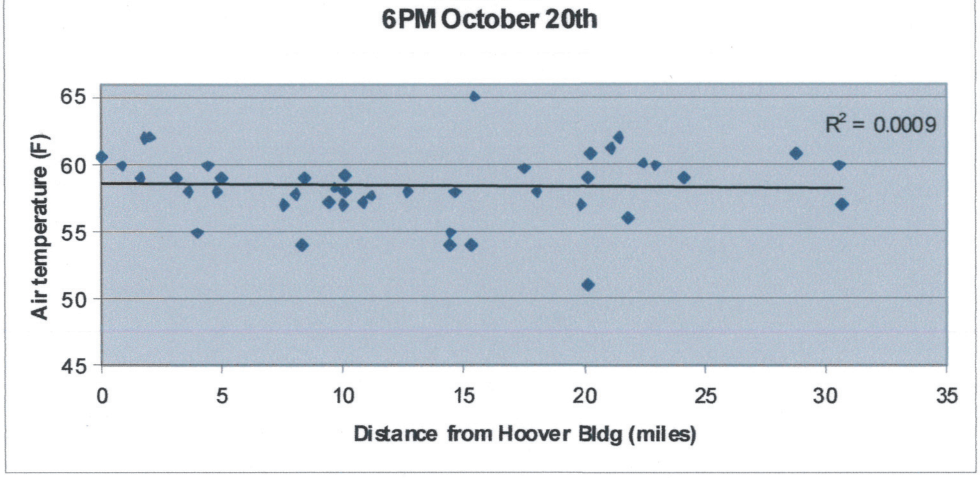


Figure 28

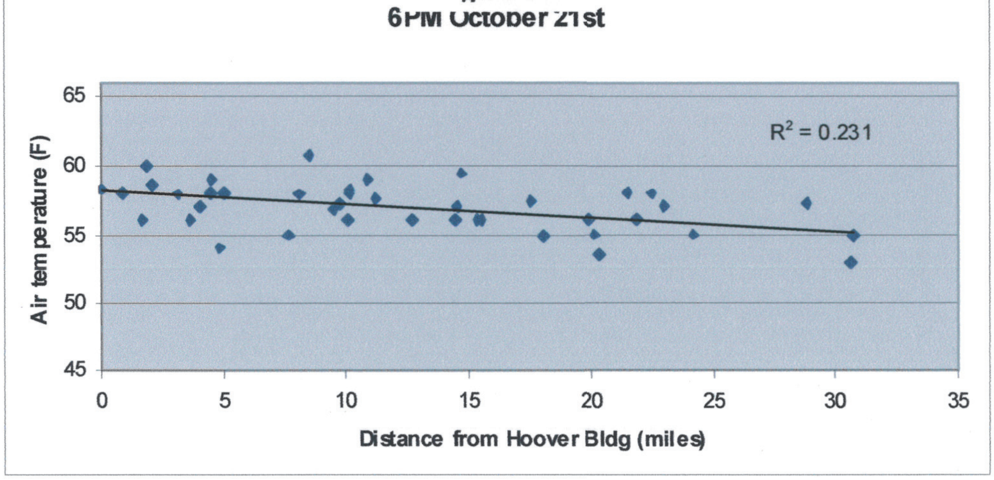


Figure 29

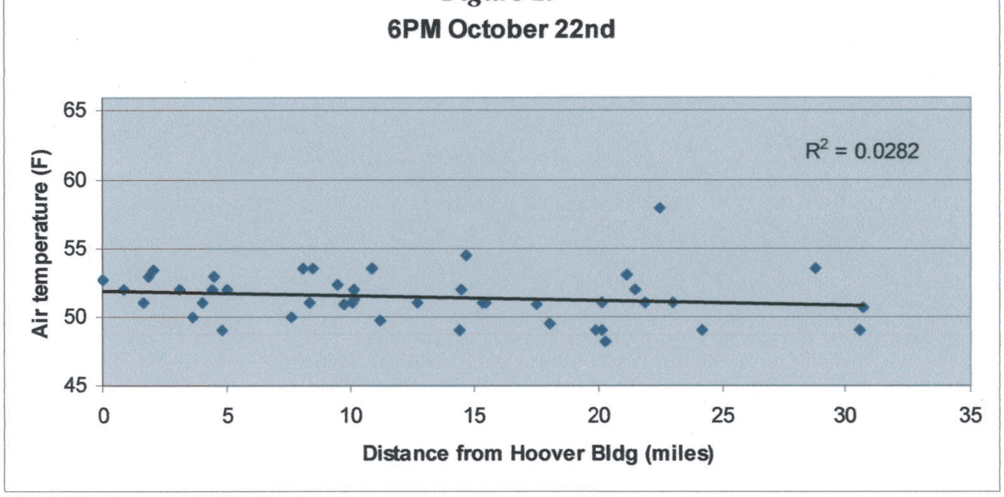


Figure 30

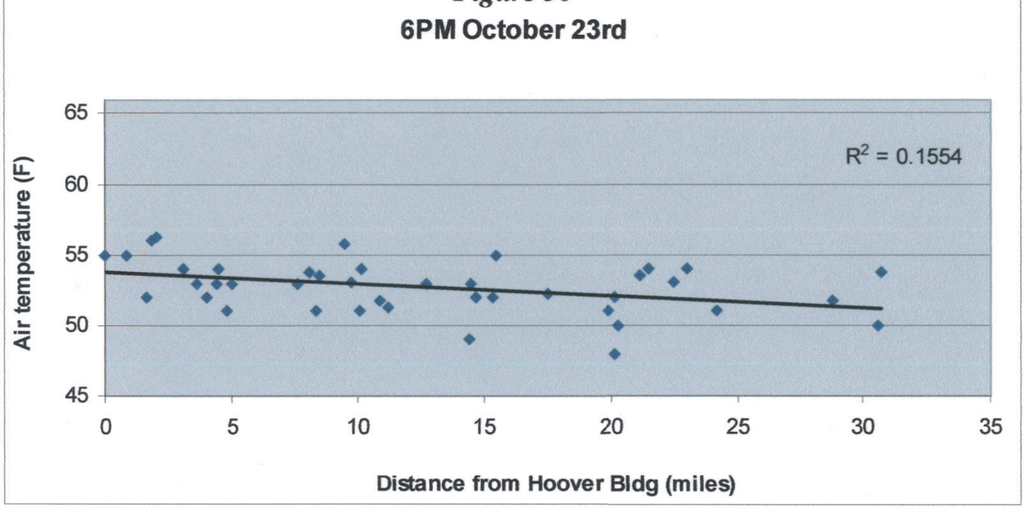


Figure 31

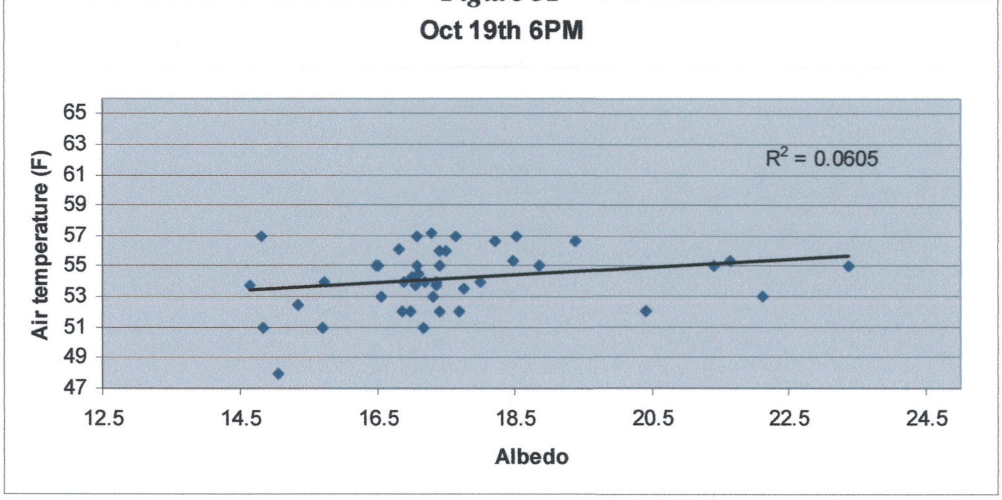


Figure 32

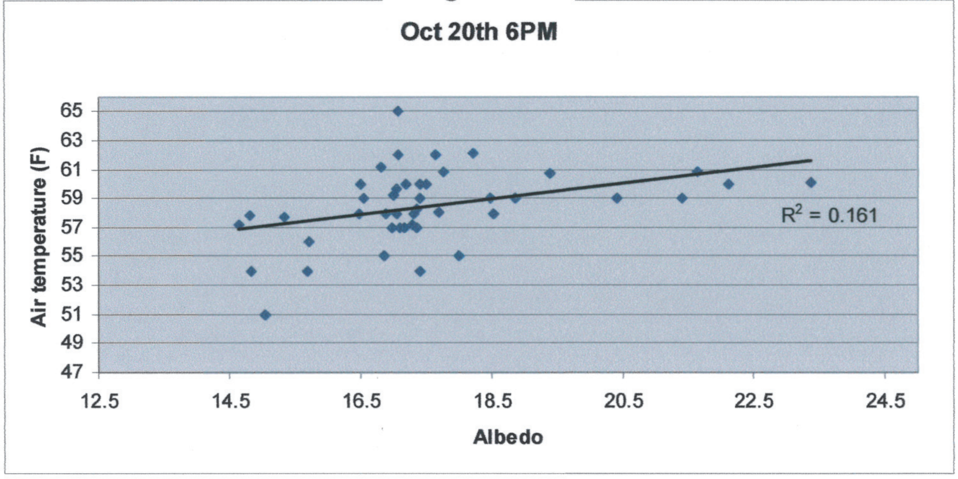


Figure 33

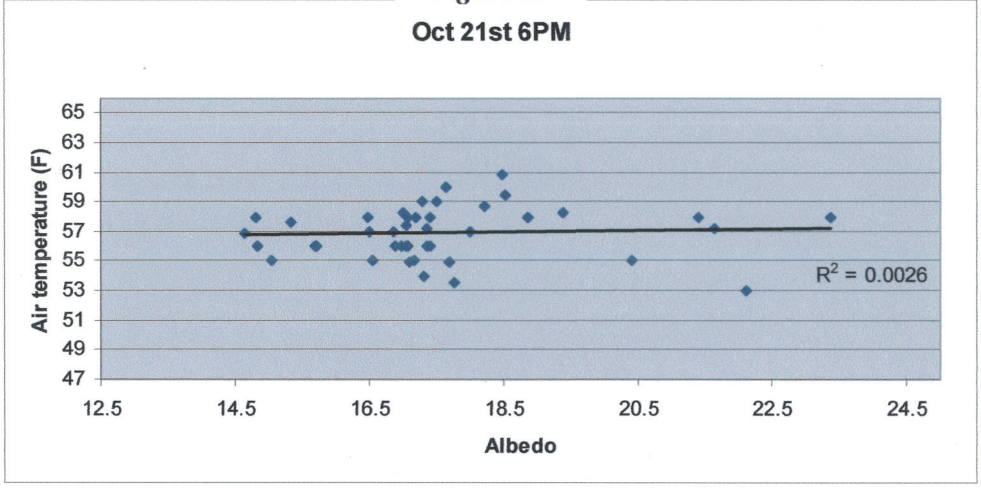


Figure 34

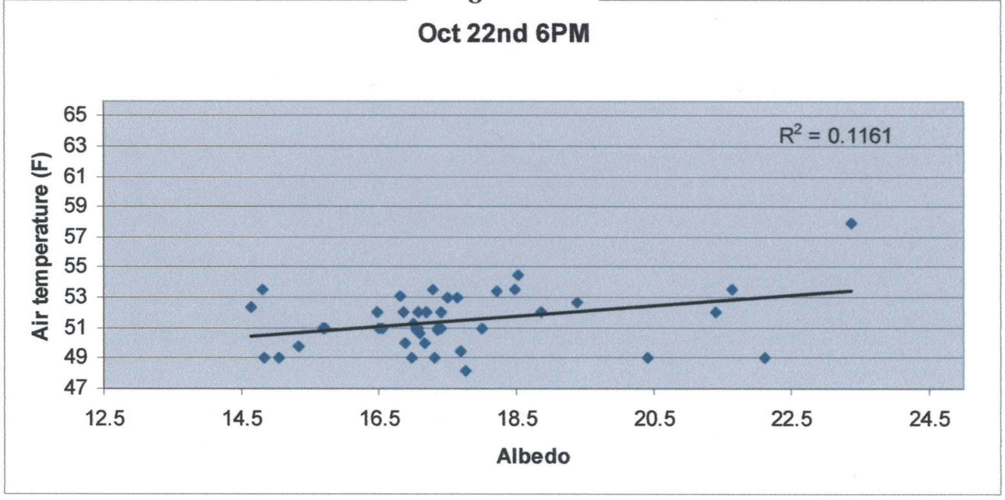
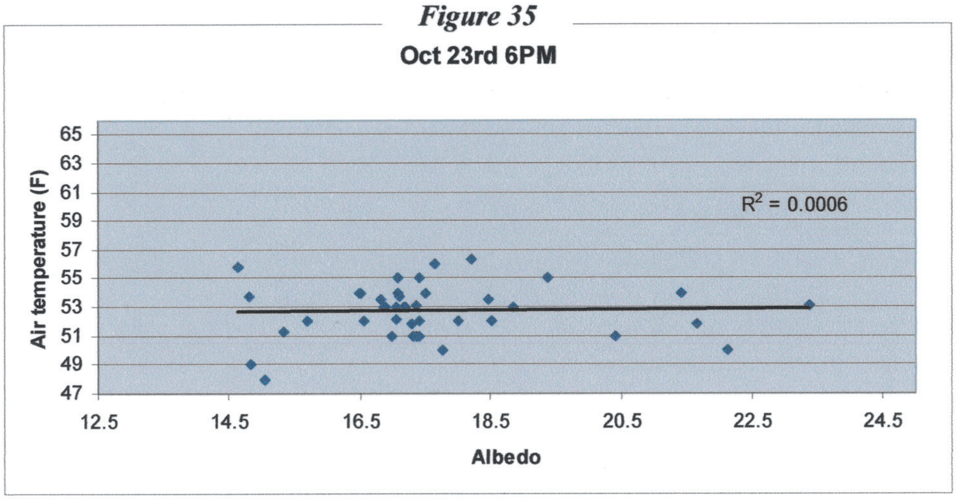
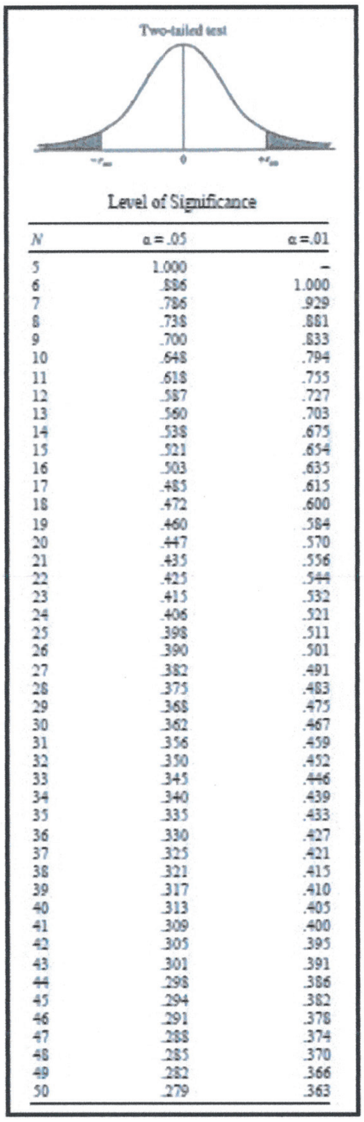


Figure 35



Oct 23rd 6PM

Table 8: *Critical Significance Levels for Spearman Rank Order Coefficients*



Level of Significance

N	α = .05	α = .01
5	1.000	–
6	.886	1.000
7	.786	.929
8	.738	.881
9	.700	.833
10	.648	.794
11	.618	.755
12	.587	.727
13	.560	.703
14	.538	.675
15	.521	.654
16	.503	.635
17	.485	.615
18	.472	.600
19	.460	.584
20	.447	.570
21	.435	.556
22	.425	.544
23	.415	.532
24	.406	.521
25	.398	.511
26	.390	.501
27	.382	.491
28	.375	.483
29	.368	.475
30	.362	.467
31	.356	.459
32	.350	.452
33	.345	.446
34	.340	.439
35	.335	.433
36	.330	.427
37	.325	.421
38	.321	.415
39	.317	.410
40	.313	.405
41	.309	.400
42	.305	.395
43	.301	.391
44	.298	.386
45	.294	.382
46	.291	.378
47	.288	.374
48	.285	.370
49	.282	.366
50	.279	.363

Source: "Critical Values of the Spearman Rank Order Correlation Coefficient: The Rs Tables. " Chart. 1972. PDF file.