A thesis submitted to the Department of Environmental Sciences and Policy of Central European University in part fulfilment of the Degree of Master of Science

The Cost of Urban Heat Islands: Quantifying year round energy use due to UHI

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May, 2012

Budapest

Erasmus Mundus Masters Course in Environmental Sciences, Policy and Management

MESPOM

This thesis is submitted in fulfillment of the Master of Science degree awarded as a result of successful completion of the Erasmus Mundus Masters course in Environmental Sciences, Policy and Management (MESPOM) jointly operated by the University of the Aegean (Greece), Central European University (Hungary), Lund University (Sweden) and the University of Manchester (United Kingdom).

Supported by the European Commission's Erasmus Mundus Programme

Author's declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:

Ian Ross for the degree of Master of Science and entitled: The Cost of Urban Heat Islands: Quantifying year round energy use due to UHI

Month and Year of submission: May, 2012.

Abstract:

Despite the phenomena of urban heat islands (UHI) being extensively researched, there still remains a disproportionately little amount of research on the total impact that heat islands have on energy consumption throughout the entire year. Decision makers therefore may not fully know the total necessity or potential value of mitigating UHI in various cities. This paper seeks to remedy this problem by conducting a literature review on the relationship of urban heat islands and energy consumption. Furthermore, nine cities were chosen as case studies to compare urban and rural air temperature measuring stations. The study compared monthly mean temperatures with cooling degree days and heating degree days for the same 36 month period. The results show that urban heat islands do effect energy consumption in all case study cities. UHI is shown to save energy due to reduced heating demand in cooler climates and increase energy demand in hotter climates due to increased cooling demands. Strategies for predicting UHI intensity and mitigating the problem are also discussed.

Keywords: <urban heat islands, climate change, urban environment, energy consumption.

Acknowledgements: Many thanks are given to Dr. Diana Urge Vorsatz and Dr. Maja Staniec, who acted as advisors for this paper. Special thanks are given to Dr. Baranka Györgyi and Peter Bob who were instrumental advisors in the success of this paper.

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List of Abbreviations

UHI	Urban Heat Island
UHII:	UHI intensity: The difference in temperature between urban and rural locations at a given time
HVAC	Heating, ventilation and air conditioning
HDD's	Heating Degree Days
CDD's	Cooling Degree days

Executive Summary

1. Introduction

1.1 Context of the paper

This paper is a master's thesis for the MESPOM program in environmental science, policy, and management. This is a research paper intended for policy makers and researchers who are interested in estimating the overall energy costs of urban heat islands so to gauge their importance in preparing for the threat of climate change.

1.2 Importance of the problem

As the world population increases and cities expand, it is of great importance to design comfortable cities that provide for the needs of the current population without jeopardizing the security of future generations. In the context of climate change, this means limiting energy use that results in the release of Green House Gases. Energy producing power plants emit sulphur dioxide, carbon monoxide and nitrous oxide as well as increase the amount of suspended particulates in the air we breath (Santamouris *et* al 2001). The Fourth Assessment Report by the Intergovernmental Panel on Climate Change has stated that there is international scientific consensus on the occurrence of climate change and it's almost certain relationship to emissions resulting from anthropogenic activity. Air, surface, and sea temperatures have been rising at unusual rates since the industrial revolution and the linear warming trend for the 50 years from 1956 to 2005 is nearly twice the rate of the 100 years from 1906 to 2005 (IPCC 2007). This temperature increase has come with oceanic warming, increases in precipitation in many regions, decreases in arctic ice, rising sea levels, and increased occurrences of extreme weather events. Satellites show that sea-ice in the arctic has been decreasing at 2.7% per decade since 1978 (IPCC 2007). The release of carbon is also believed to be causing increases in ocean acidity. If the acidic level of the ocean continues to rise at the same rate, it threatens to inhibit the calcification of shell forming organisms (like coral), which could possibly be damaging to much of the oceanic food chain (IPCC 2007). As it then seems clear that reducing emissions is an important task, energy demanding sectors of our society must be examined and refined. The IPCC report also concluded that building efficiency has the greatest potential for Green House Gas reduction of any sector (IPCC 2007). Figure 1 highlights this potential as it compares to other sectors. In fact, Buildings account for 40% of energy use worldwide (Kolokotroni & Giridharan, 2008).

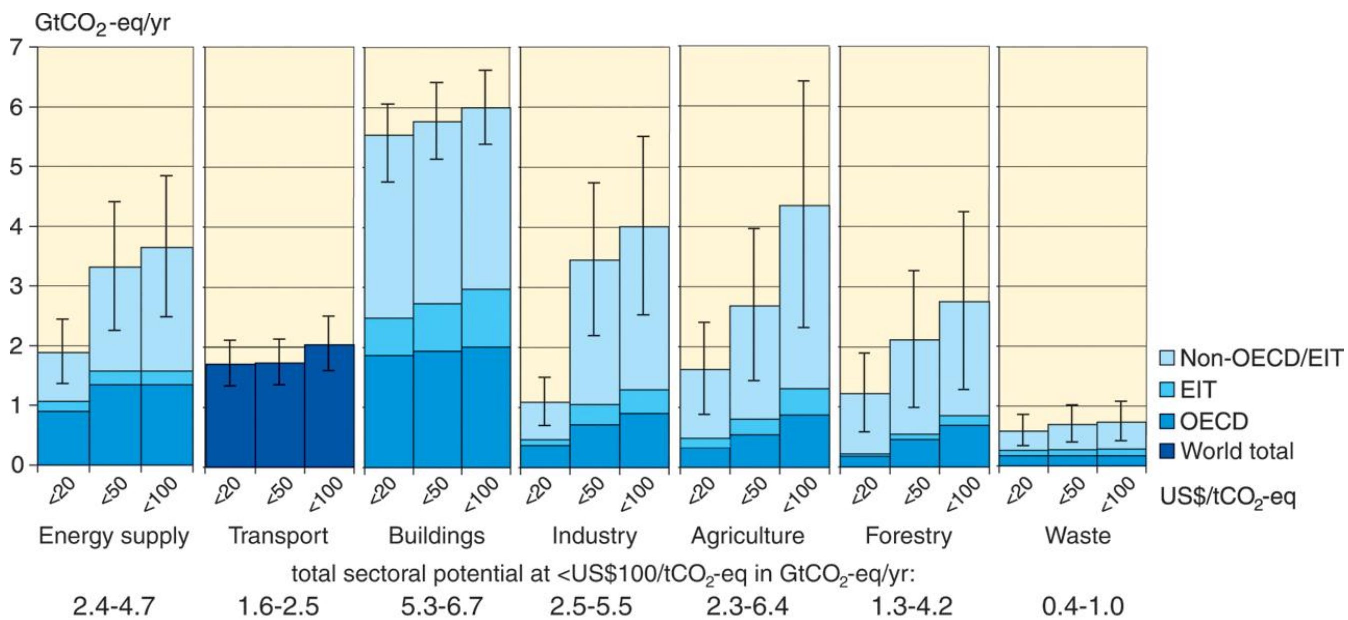

Figure 1: Estimated economic mitigation potential by sector and region using technologies and practices expected to be available in 2030. The potentials do not include change in life style. Taken from IPCC Fourth Assessment Report (2007)

The majority of building energy use is due to cooling and heating needs, which are directly influenced by outside temperatures (Santamouris et al 2001). Urban areas are of particular importance because they contain most of the world's buildings and people, and this number is rapidly growing. It is estimated that 80% of the world's population will be urban dwellers by the year 2100 (Santamouris *et al* 2001 B). As urban areas will indefinitely expand, attention must be given to the impact this will have on energy consumption and quality of life. Cities can create their own microclimate based on the characteristics of urban form, infrastructure, and population habits (Oke 1977). Oke (1977) divided the air space above a city into two categories, the urban “canopy” and the “Urban Air Dome”. The canopy is limited to the height of buildings in a given location while the urban air dome represents the portion of atmosphere that is affected by the presence of an urban area. Oke (1977) also stated that the climatic conditions within the canopy are directly related to the physical characteristics existing in that area, such as geometry and surface material. Urban surface and air temperatures are often higher than that experienced in surrounding rural areas. This phenomenon, known as the Urban Heat Island effect, is well documented but its impact on energy consumption is an area that is under researched by comparison. Higher temperatures would lead to higher energy use from air conditioning in the summer but could also lead to lower costs for heating in the winter. As cities begin to consider ways to manage their urban climates, it is necessary to understand the actual impact that UHI’s have on energy consumption.

1.3 Research Problem

Despite there being a large amount of UHI research, there exists a disproportionately little amount of research on the total impact that urban heat islands have on energy consumption throughout the entire year. Decision makers therefore may not fully know the total necessity or potential value of mitigating UHI in various cities.

1.4 Research Question

In order to address the above research problem this paper will seek to answer the following research question:

What is the energy consumption balance resulting from urban heat islands and how can it be predicted for a given city?

The main research question will be answered by addressing the following sub questions:

1. How are urban heat islands defined?
2. What is the most appropriate method for quantifying UHI as it relates to energy consumption?
3. What are the causes and impacts of UHI?
4. What has previous research discovered about the impact UHI has on energy consumption?
5. What is the potential of mitigation to reduce UHI related energy consumption?
6. What is the observed effect that UHI has on energy consumption?
7. How can the impact of UHI on energy consumption be quantified and predicted by policy makers?

2. Methodology

2.1 Research Framework

The format for this paper was decided upon after consultations from Dr. Diana Urge Vorsatz and Dr. Maja Staniec of 3CSEP, and Dr. Baranka Györgyi, of the Hungarian Meteorological Service.

To address the research questions the following methodology will be used:

1. Literature review: A literature will be conducted to define UHI and its causes and impacts, determine the most appropriate method for quantifying UHI for this study, examine previous research on UHI effects on energy consumption, and the ability of mitigation address these effects. Literature was chosen based on relevance to the topic and recommendation from consulting advisors.
2. Case Studies: To answer sub question 6, nine cities were chosen as case studies to examine the actual effect of urban heat islands on energy consumption. These cities were chosen because they are all either very large in population or very densely populated and they posses a wide variety of climates and infrastructure. To asses UHI intensity in the, rural and urban meteorological stations were chosen in each city. This is a similar method to a study done by the Hungarian Meteorological Service, which compared temperature data in an urban and rural location in Budapest for a seven-day period (Györgyi 2011). Comparing urban –rural measuring stations is a common method for assessing UHI in related literature

(Assimakopoulos *et al* 2006, Wen-Zer Lin et al 2005). Stations were chosen by examining satellite images of suitable stations to determine which best represented the desired urban and rural features discovered in the literature review. Urban stations were chosen based on their distance to the city centre and their proximity to large buildings and paved surfaces. Rural locations were chosen for being the nearest suitable measuring station to the city that was located in open areas and surrounded by as much vegetation as possible. Station data was compiled for the same 36 month period for every case, April 2009- March 2012. The period of 36 months was chosen so that variability throughout all seasons can be observed. The data compared was monthly mean air temperature, monthly maximum air temperature, Heating Degree Days calculated at a base of 15.5 ^{o}C, and Cooling Degree Days calculated at a base of 21.5 ^{o}C. Degree days are used here to describe energy consumption, a technique frequently used in large scale UHI studies where energy consumption data is not available (Ewing & Rong 2010, Taha 1997).

3. Regression Analysis: Regression will be used in an attempt to find methods for predicting UHI impacts on energy consumption.

2.1.2 Degree Days Explained

A common top down method for calculating energy consumption from heating and cooling is to translate temperature data into measurements of heating degree days and cooling degree days. Daily temperatures can be predicted from historical data by a probability or frequency function. This is expressed by a bell curve, specified by a mean temperature and standard deviation. The mean has the purpose of locating the position of the curve along the *t* (temperature) axis, while the standard deviation explains the scale, which is the width of the curve along the *t* axis. The standard deviation is expressed in the units of the *t* axis, degrees (Caskey 1954). Temperature can then be converted into cooling or heating degree days by subtracting a base temperature from the outside mean daily temperature (T). The base temperature is the turning point at which you start cooling (T_S) or heating (T_W). Heating degree days (HDD) and cooling degree days (CDD) can then be expressed as the following equations (Ihara *et al 2010*):

$$CDD = \Sigma(T-T_S) \text{ when } T>T_S$$

$$HDD = -\Sigma(T-T_W) \text{ when } T<T_W$$

Different base temperatures are often used, depending on the purpose of the calculation and the information available for the study. Energy professionals may use regression analysis to compare a buildings energy use with temperatures to find the base for that building, which will allow them to compare their energy efficiency for different years. Sometimes a standard temperature 65 ^oF (18.3 ^oC) will be used for both heating and cooling base for simplicity, however this is not very accurate in terms of energy consumption as there is likely to be temperatures where heating nor cooling is required to regulate the comfort of a building.

There is also a method called EUROSTAT that uses 15 ^oC HDD base and 18.3 ^oC as the CDD base (Budapest Meteorological Service). However, for this papers study, 15.5 ^oC and 21.5 ^oC were used as the heating and cooling bases respectively. These numbers were chosen based on Ihara e*t al* (2010) who conducted a study on the impact of air temperature on heating and cooling in urban Tokyo. They did regression analysis of energy consumption and temperature and determined that actual energy consumption were sensitive to these temperatures.

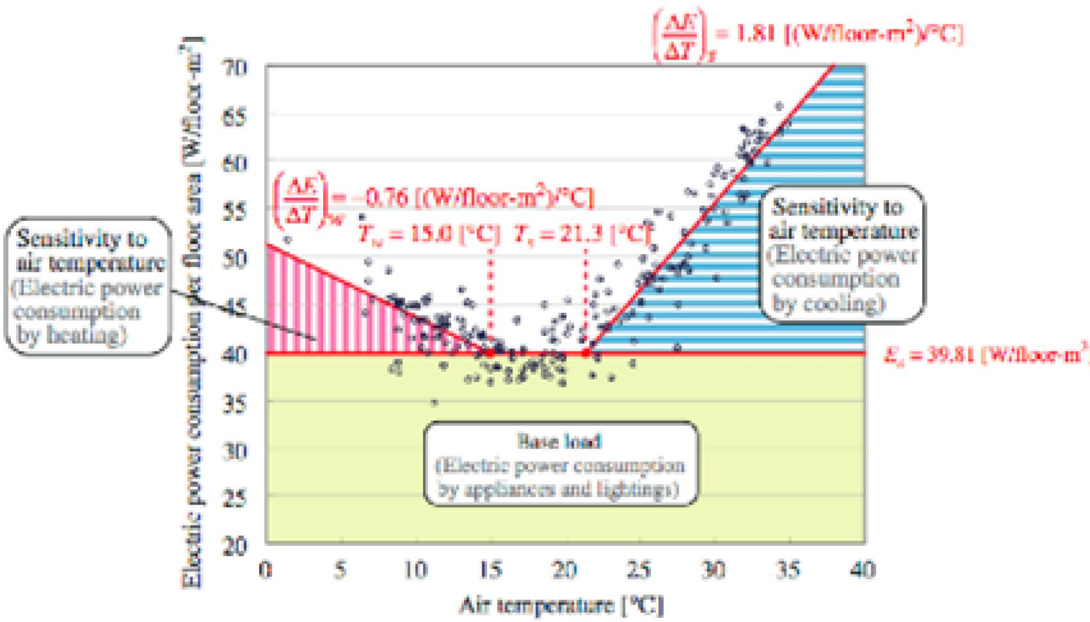

Fig. 2: Graph showing results of regression analysis between temperature and energy consumption of office building in downtown Tokyo business district. Source: Ihara *et al* (2010).

Obviously the base temperatures from Ihara's study will not be the accurate for all buildings but these bases give conservative estimates of energy demand so these will provide realistic data that does not exaggerate the results. The equation to describe the calculation method for daily -degree days used in this study is therefore (where T is the Daily mean Temperature):

HDD's = 15.5-T (when 15.5>T)

CDD's = 21.5-T (when 21.5<T)

Converting temperature into a degree-days scale can then be used to create a degree day frequency curve, which will help estimate the relationship between temperature and energy consumption. This is a useful technique when it is not possible to obtain specifics about the building stock of a city. The use of degree days to predict energy consumption can be somewhat misleading, due to the fact that degree days are based on 24 hour temperature records, while many buildings may only be heated and cooled during the times when they are being used by people. Despite this fact, degree days occurring in non-use times are not irrelevant in terms of energy consumption because the amount of energy required to bring the building to the desired temperature when it is inhabited will be somewhat dependent on the recent temperatures that the building was exposed to (degreedays.net).

Degree day calculations were obtained using degreedays.net which is a free website for energy professionals. Many of the temperature stations used by this website are also used to provide data for NASA's GIS Data page, and so they were deemed reliable. Satellite images were examined using Google earth and city population data was found on citypoulation.de.

2.1.3 Regression explained

In order to answer sub question 7 on developing a way to estimate UHI impacts on energy consumption, regression analysis was used on the 36-month temperature and degree-day data to determine if correlations between different UHI calculations could be identified. The initial method for this portion of the research was to perform regression between urban and rural differences in heating and cooling degree-days with urban and rural differences in mean monthly air temperature. However, upon attempting this regression it became obvious that there was far too little correlation between the two factors for this type of analysis to be useful. This is partly because differences in temperature will have no effect on degree-days if they are occurring at temperatures that have not surpassed the base for degree-day calculation. The alternative approach was then to perform regression between monthly mean temperatures and heating and cooling degree-days in the same location. This is an alternative way to view the relationship of urban-rural temperature differences and degree days because it describes how much degree days are altered by a one degree Celsius rise in monthly mean air temperature, which can then be compared with the mean temperature differences observed.

For this research the least squares method of regression analysis was used. This is a common method for determining the influence of one factor on another, and has previously been used in studies to determine the influence of temperature on energy consumption (Ihara et al 2010). The equation for the regression between mean temperature and degree days will be the following:

$$\text{HDD(or CDD)t} = \alpha+\beta(\text{mean temperature})$$

2.2 Limitations of the Research

There are a few limitations of this research that need to be mentioned. The literature review on this topic presents some difficulties because there is an extremely large amount of research on UHI and the relationship of energy demand to air temperature. This has made searching for the most appropriate information a large task and thus some relevant studies may have been excluded. The main limitation of the case studies was that measuring stations are often limited, especially in developing countries, and so many of the stations used were not optimal. Because stations with appropriate data were limited, not all stations are at the exact same height, and so data differences cannot be purely attributed to UHI. It was also surprisingly rare to find measuring stations in the densest area of the city and airports were often the only suitable option for use as a rural station. Despite airports being a common rural reference station in literature, airports generally have paved surfaces and buildings and so they are not perfect for use as rural stations. For these reasons UHI in terms of air temperature and its effects on degree-days are largely under represented in this study and the results are not as extreme as they could be if given better measuring stations. The use of regression is also limited in that mean monthly temperature may not be the best predictor of UHI. Limited availability of temperature data was also a hindrance for the regression study, as other factors (like average daily maximum temperature) may be better predictors of degree day differences but were unavailable.

3. Literature Review

Key Terms	*Description*
Surface Albedo	Ratio of outgoing to incoming radiation. Measured on a scale of zero black surface) to 1 (white surface).
Thermal Mass	Specific heat capacity
Green Density Ratio	Green area to environment area ratio
Aspect Ratio	Height to width ratio
Fabric Density	Vertical surface to environment area ratio
Plan Density Ratio	Foot print area to environment ratio
Sky View Factor	Relationship of visible area of sky to area covered by urban structures
Emissivity	The ability of a surface to emit energy by radiation.
Solar Irradiance	Power of electromagnetic radiation per unit area of surface

Table 1: List of Key terms

3.1 Description of Urban Heat Islands

3.1.1 Definition of UHI

One of the most well documented and studied phenomena's of an urban climate is the Urban Heat Island effect (UHI). The Urban Heat Island effect is the experience of higher near surface air temperatures occurring in densely populated urban areas than in surrounding rural areas.

3.1.2 Causes of UHI

Ambient air is primarily heated by the direct absorption of solar radiation, convection from hot surfaces, and the addition of waste heat by anthropogenic activities, such as exhaust from cars or the heating of buildings (Akbari 2007). Most of ambient air heating is coming from hot surfaces (Akbari 2007). The urban/rural temperature disparity is the result of replacing solar reflective and moisture absorbing vegetated space with dark built surfaces that absorb and retain the sun's energy (Lowry 1997). Paved surfaces also transport higher amounts of solar heat into the ground then soil. As solar energy is retained in the fabric of the many buildings and roads of a city, this energy is slowly released and often combined with waste heat emitted from other anthropogenic activities, such as energy use. The slow release of heat by urban fabrics continues into the night, when the UHI difference is generally greatest (Parker 2010). Tall buildings that limit the sky view can re-absorb escaping long wave radiation and create poor ventilation, inhibiting the escape of heat from a city. The geometry and placement of buildings also effects wind velocity, which can drastically change surface temperature (Priyadarsini 2012). Temperatures are usually highest near roads, both because of the pavements absorption of heat and the emitted of heat by vehicle combustion of fossil fuel (Siu Yu Lau *et al* 2011).

Moisture characteristics of an area also affect the urban climate temperature. In a rural landscape, much of the sun's energy is spent on evaporating water instead of heating the air. This is done through the process of evapotranspiration, where vegetation draws moisture from the ground to use for growth and regulating their temperature and then transpires the excess water, thereby cooling the surrounding air (Akbari et *al* 1992). Urban areas are generally lacking in vegetation and are largely covered by material that is impervious to water. This leads to increased run off that can upset the hydrological cycle and resulting in very little evapotranspiration occurring within the city (Grimmond 2007). This means there is not a lot of natural moisture within urban areas, reducing the amount of solar energy converted into latent heat and culminating in a further rise of temperature.

Local GHG emissions, aerosol release and dust also combine to create a micro greenhouse effect that traps heat within the city (Atkinson 2002). Incoming long wave radiation is believed to be enhanced in urban areas due to either the increased temperature or the presence of pollutants (Arnfield 2003). The majority of studies concluded that reduction of atmospheric pollutants will reduce solar irradiance, although a few more recent observations have reported a significant lack of irradiance in the polluted cities of Hong Kong and Mexico City (Arnfield 2003). It is also possible for urban city heat to be displaced downwind in rural or suburb areas, but the heat increase experienced by these areas will be less intense (Parker 2010).

3.1.3 Magnitude and Variability

The magnitude of the UHI effect varies greatly between cities, due to difference in urban form, local climate and inhabitant behaviour (Parker 2010). Cloudy weather limits the amount of radiation absorbed by urban structures and wind will alter the UHI intensity. Surface roughness can effect wind velocity, and therefore greatly alter urban air temperature (Arnfield 2003). UHI intensity would be expected to be highest in summer, however studies have shown this is not always true and there exists diverse seasonal variation in different cities (Arnfield 2003). In tropical regions winter and summer differences will likely be less influential for UHI intensity than dry and wet season changes (Arnfield, 2003). Cities located in arid regions and containing large amounts of irrigated green space can actually experience cooler temperatures then the surrounding countryside, actually making the city a "cool island" (Parker 2010). After sunrise, rural areas will generally warm faster than urban areas, which can also create this urban cool island effect (Shahmohamadi *et al* 2010). Lower city centre temperatures are most common in the middle of the day as the urban centre retains the heat at night, making this the time when UHI intensity is usually greatest (Shahmohamadi *et al* 2010). Figure 2 shows how urban heat island intensity varies throughout the day in Budapest, Hungary during a 7 day measuring period in August 2011. The graph shows that indeed urban-rural temperature differences are greatest at 21:00 P.M.

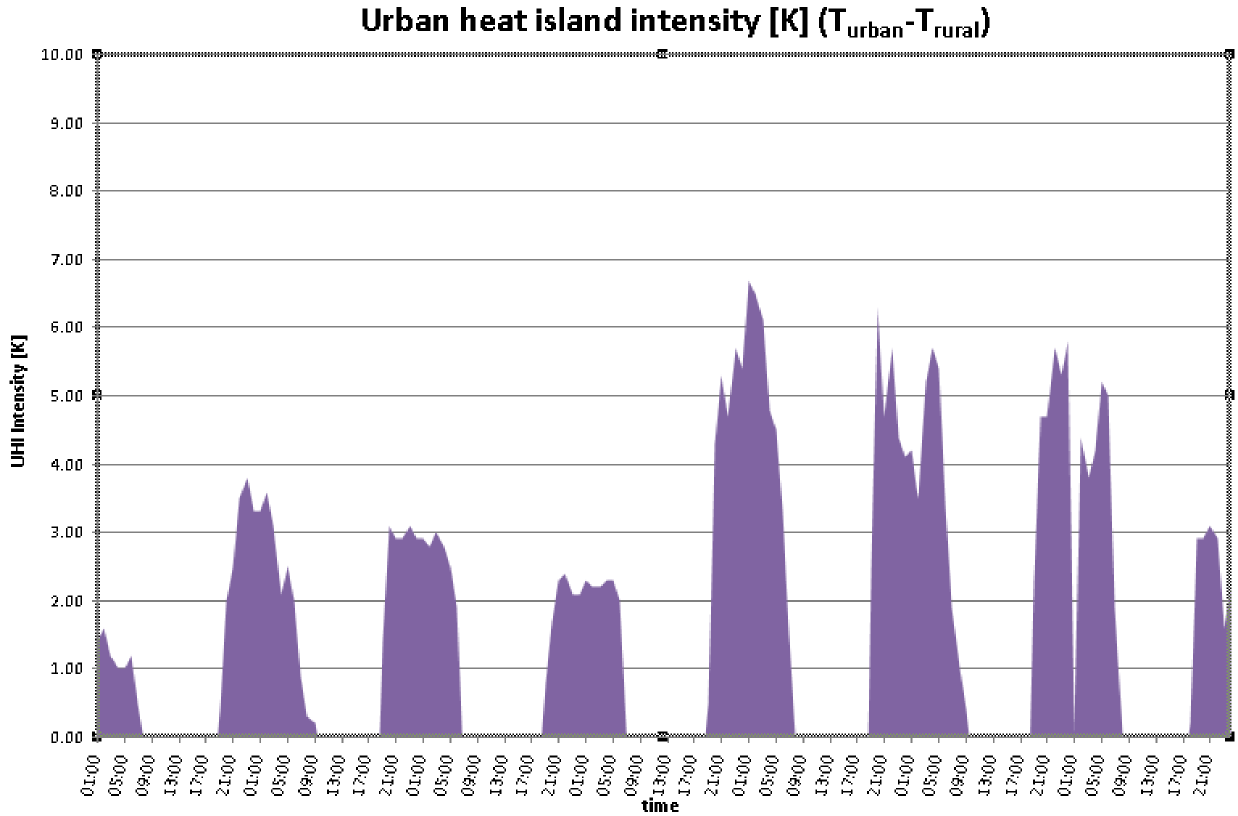

Fig. 3: Graph showing heat island intensity of an urban area in Budapest, Hungary over a seven day measuring period in August 2011. Data based on air temperature measuring stations. The graph was provided by Dr. Baranka Györgyi of the Hungarian Meteorological Service.

Despite the fact there is great daily and seasonal variation in UHII, there is an average higher temperature of 1–3 °C in urban centres than surrounding rural areas, and the difference can sometimes be 10°C or larger (Grimmond 2007). For example, some inner city areas of Copenhagen have been observed to have a temperature that is 12 °C higher than areas outside the city (MOC 2010). UHI intensity has been observed at 9 °C in Mexico City and 6 °C in Bombay (Akbari *et al* 1992). UHI intensity reached 9 °C in London during the 2003 august heat wave (Mavrogianni *et al* 2011). The mean UHI intensity for areas of central Athens is 6-12 °C (Assimakopoulos *et al* 2006).

While most of the studies mentioned in this paper focus on urban and rural temperature differences, it should be noted that temperatures could also vary greatly within a city. This was found by Petralli *et al* (2011), which used hierarchical clustering of thermal measuring stations to describe the urban climate of Florence, Italy over a five-year period. They used the HDD and CDD method for calculating energy consumption, but they added hourly temperature differences and then divided by 24 so as to obtain the most exact results possible. The base temp for HDD was 17 ^{o}C and 22 ^{o}C for CDD. Areas with high exposure to solar radiation and low presence of vegetation were clustered together due to higher mean temperatures. Examining where clusters were located on a map, in general, similar high thermal characteristics were observed in central locations. These areas consistently had lower HDD values and higher CDD values. However, the intra-urban heat demand showed differences of 19%, meaning that inner city variations could be comparable to urban –rural differences.

3.1.4 Growth of UHI

This is of great concern in sub tropic regions and arid regions, where UHI is usually the most intense. Northern Africa, the Middle East, and Western Asia have nocturnal heat islands that can be up to five times higher than mean world nocturnal UHI's. According to model scenarios, UHI will continue to increase in these already affected areas, in some cases by over 30% (McCarthy et al 2010). In fact, UHI intensity has been increasing in most cities. During the period of 1920 to 1960, many cities were actually cooler than there surrounding areas because there was more vegetation in urban centres. However, in the last 50 years heat islands have been increasing in intensity. Most cities in the U.S. experienced urban temperature increases of 2-4 ^{o}F from 1950-1990 (Akbari *et al* 1992). Tso (1994) studied the effects of a rising UHI observed in Singapore. The report estimated that urban temperatures had risen by 1^{o} C in recent history. They concluded that if this trend continued, in 50 years the added increase in building energy consumption for the whole island would be 33 GWh per year. UHI growth in select cities can be seen in figure 2 below.

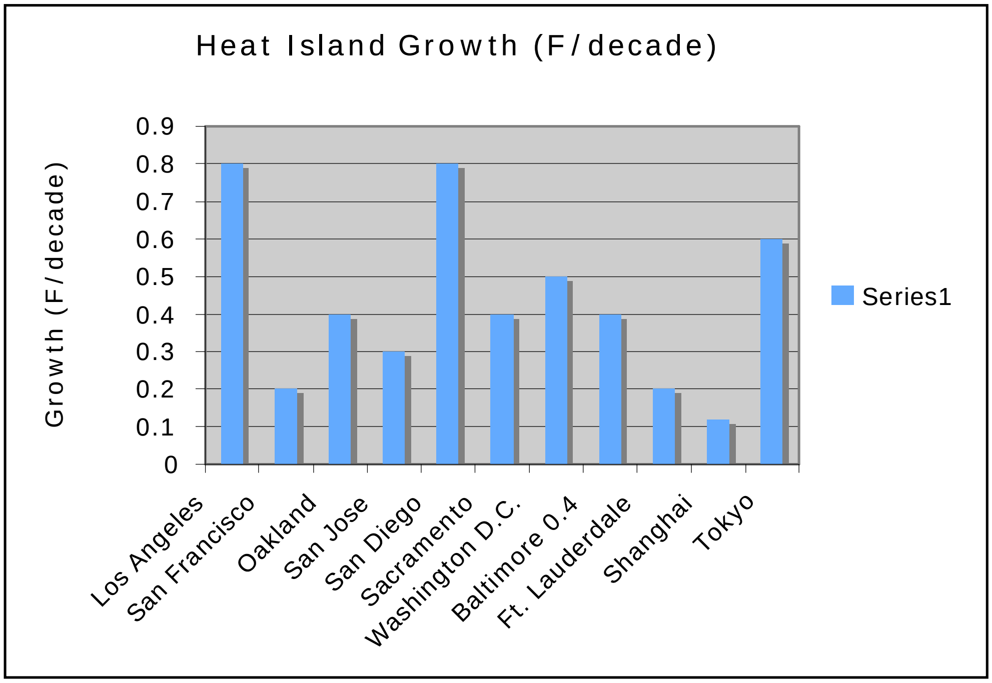

Figure 4. Heat Island growth per decade in °F. Based on data from different time frames 1910-1990. Data Source: Akbari et al 1992.

3.2 Measuring and defining the urban heat island

Heat islands can be measured and defined in different ways depending on the purpose of the study. There are two main methods for quantifying UHI that have been employed by the majority of UHI studies. The classic approach seeks to measure UHI of urban canopies by comparing air temperature (usually at about 2 meters from the ground) of urban and rural locations. Temperature data usually comes from measuring stations in the cities centre, or evenly placed throughout a grid of a city, which are then compared to rural locations (Kolokotroni et al 2009, Santamouris 2001). However, some studies measure the air temperature by making a traverse through a city with a mobile measuring unit attached to a vehicle (Schwarz et al 2011). Many of the studies that are concerned with UHI as it relates to energy consumption will use station data to determine the mean UHI intensity of an area, which is the average air temperature difference between the urban and rural locations (Kolokotroni et al 2009, Santamouris 2001). It may also be interesting for researchers to look at maximum UHI intensity (the largest air temperature difference observed) in order to analyse the potential impact an areas summer cooling load has on peak energy demand, or to asses the risk that the location poses on public health and safety. The second approach for quantifying UHI intensity is to conduct remote sensing using satellite GIS. This approach involves determining the emissivity of a surface and the resulting land surface temperature of that location. Remote sensing has a few advantages over station data, in that measurements are spatially defined, data is not limited by a lack of stations in a city, and the measurements are not influenced by changing weather patterns (Mavrogionni et al 2011, Schwarz et al 2011). This approach also looks at urban and rural temperature differences, but additionally it offers some other alternative ways to define UHI intensity. For example, urban land surface temperatures are sometimes compared to water or agricultural area temperatures. The "magnitude" of UHI can also be assessed, defined as the maximum temperature minus the mean (Schwarz et al 2003). Land Surface temperatures can also be interpreted as a Gaussian Bell, where the heat island can be measured as the height of the bell and the area it covers. Streutker (2002) developed this technique for assessing the heat island of Houston and determined that the magnitude of the UHI is was inversely correlated with antecedent rural temperatures, however the spatial distribution was independent of both the UHI magnitude and the rural temperature. Streutker's (2002) finding that the Gaussian magnitude of Houston's heat island decreased with increasing rural background temperatures is not entirely consistent with other studies which show increasing UHI during heat waves, and so background rural temperatures must not be dismissed as non-influential on urban heat island size (Schwarz et al 2003). Quantifying the total area of a city with temperatures higher than one standard deviation above the mean is another remote sensing approach, known as "hot island areas". Another remote sensing method is to define cities UHII by its "micro UHI" which is the percentage of a cities surface area that has higher temperatures then the largest temperature exhibited by local tree canopies (Schwarz et al 2003).

Land surface temperature and air temperature are related but not the exact same. This is important to note when discussing UHI because the remote sensing indicators just mentioned have shown higher heat island intensity in the daytime, while air temperature data usually shows higher UHII at night (Schwarz et al 2003). Schwarz et al (2003) conducted all the different remote sensing methods mentioned for the same time period and locations and determined that there was surprisingly little correlation between many of the methods, especially between *core vs rural* land surface temperature and the other UHII measuring methods. They attributed some of this finding to the fact that their definition of urban and rural locations was based on administrative boundaries, which could actually vary greatly in terms of actual land use. This is one common method for determining locations for comparison, while other studies define urban areas by there estimated density, land use or their distance from the officially recognised centre of the city (Schwarz et al 2003).

The remote sensing techniques are mentioned here, not because they are used in the experimental research of this paper, but rather to show the different options available for quantifying UHI and their advantages. As mentioned earlier, land surface temperature is not influenced as much as air temperature by changing weather patterns. When analysing energy consumption, changes in air temperature due to wind speed are important because buildings energy consumption is largely influenced by the heat transferred between indoor and outdoor air through the walls and ventilation system (Ihara et al 2008).

3.3 Influence of key Factors in creating Urban Heat Islands

3.3.1 Population, density and infrastructure

Studies have shown that a 1% increase in the population size of a city will increase that city's total energy consumption by 2.2%. (Santamouris *et al* 2001). Studies have shown that the larger and denser a city is, the greater the urban to rural heat difference will likely be (Hogan and Ferrick 1998; Park 1986; Torok et al. 2001). Alternatively, it has also been shown that cities with larger populations consume less electricity and gasoline per capita then smaller cities, (Lariviere & Lafrance 1999).

The increased urban temperatures alone have little effect on global temperature measurements, but the total impact of UHI has major implications (Parker 2010). McCarthy *et al* (2010) analyzed $C0_2$ emissions, population growth, and temperature scenarios using the Hadley Centre Global Climate Model. They explained that average global anthropogenic waste heat is described as 0.03 Wm^{-2} but is usually ignored as a contributor to global climate temperatures. However, the model confirms that emissions and anthropogenic waste heat have a great influence over local temperatures. As automobiles are one of the largest waste heat sources, the availability of alternative public transport may also have a great influence over UHII.

As Cities that have older building stocks may have a low percentage of buildings with air conditioning, but as the city expands, new developments are more likely have air-conditioning (A.C.). A study done in Toronto highlighted this trend by showing that new building developments in Toronto were usually equipped with A.C. and caused to the city shift from having winter time peak energy to summer time peaks (Navigant C.C. 2009). However, a study in Quebec, Canada concluded

3.3.2 Urban Geometry

The openness of an area (its sky view factor) is one of the most influential factors of UHI intensity. Oke (1988) stated that under clear sky conditions and low wind, sky view is an accurate predictor of UHI intensity in a city. Oke did caution that urban geometry cannot predict all of the temperature variation within a city, as anthropogenic heat releases and other factors will affect the intensity greatly. Yamashita (1986) measured sky view factor (SVF) at a number of different locations and found that as SVF decreased, temperatures would increase at all locations. This study also mapped day and night time heat island intensity with SVF and showed there is a strong correlation between daytime temperature and minimum SVF. These studies have solidified SVF as a determining factor of UHI. Blankeenstein and Kutler (2004) examined the relationship of SVF and long wave radiation and concluded that there is a strong relationship between the two but there is also a week relationship between SVF and air temperature. The conclusion was not denying the relationship between the two factors but rather stating that there are far too many influential factors on air temperature for SVF to be a sole indicator to predict UHI. Yamashita (1992) later suggested sky view ratio, the ratio of wall height to street width, as a better indicator then SVF as it describes the wind velocity as well as long wave radiation. Despite this conclusion, most UHI studies still use SVF as one of the main parameters.

Other aspects of urban form are also extremely influential on UHI. Aspect ratio, “the ratio of wall height to building separation” is a major determinant of air-flow and solar radiation entrapment and thus has great effect on the incoming to outgoing urban energy balance. Surface roughness describes the geometry of a city and the textures it is comprised of. This is also one of the main determinants of air-flows, and can therefore influence the behaviour of heat, moisture and pollutant plumes. Altering geometry and roughness to increase wind speed is a way that heat islands can be mitigated. Studies done in China have shown that wind velocity can be increased, and temperature thereby lowered, by strategically placing three or four high-rise towers within an urban canyon (Wong et al, 2008).

3.2.3 Blue and Green Space

Green areas provide shade and solar reflectance as well as absorbing storm water runoff. Water bodies can also reduce runoff and act as heat sinks (Lowry 1997). The effects of this can be seen in the Lau *et al* (2011) study of Chinese urban areas that showed vegetation cover lowers temperature at base levels and an artificial pond could act as a heat sink. The ability of vegetated green space to moderate the rise of urban temperatures is one of the most observed and obvious limiting factors of UHI, and thus, a lack of vegetation in cities is considered as one of the main causes of this problem. Some trees can transpire up to 100 gallons per day, which produces a similar cooling effect to five air conditioners running for 20 hours (Akbari *et al* 1992). When comparing maps that show thermal temperatures and vegetated areas it is easy to see the magnitude of impact green space has on UHI. Figure 4 shows that temperatures are highest in developed areas and lowest in vegetated areas in Buffalo, New York.

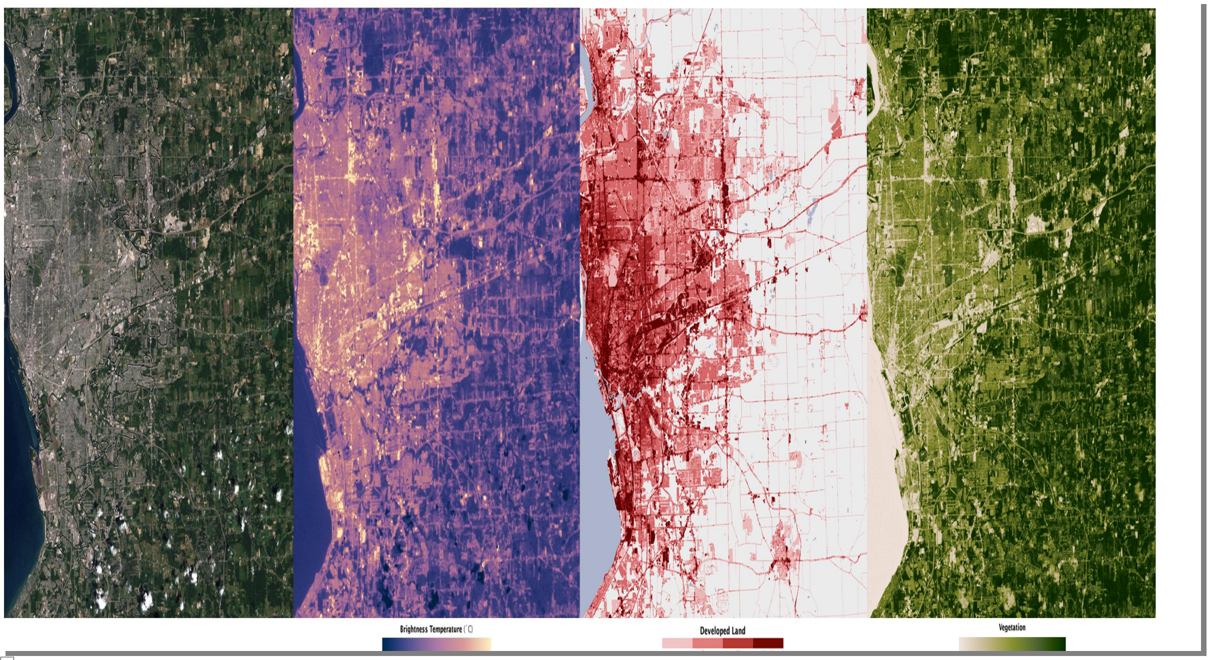

Fig. 5: Buffalo New York Heat Island map. Comparison of (from left to right) visible light, thermal heat, developed land and vegetation in Buffalo, New York (NASA website).

A study done in London comparing six different factors considered to be main determinants of UHI (surface albedo, thermal mass, green density ratio, aspect ratio, fabric density ration, plan density ratio) found surface albedo to be the most significant factor in predicting urban temperatures. A low surface albedo will absorb a lot of solar energy and trap the heat within the canopy. Thermal mass was the second most significant during clear sky periods, while aspect ratio is second in other periods. Green density ratio was consistently the third most important factor, but the author admitted that this measurement was not a good representation of green space and would expect this factor to be more significant if this category was given more accurate parameters (Kolokotroni & Girdharan 2008). This is likely, considering other studies that show vegetation cover to be more effective in lowering air temperature than changes in surface albedo (Rosenzweig *et al* 2001). The presence of vegetated areas and proximity to large water bodies are two of the most influential factors for minimizing UHI intensity.

Another modelling experiment concluded that surface resistance to evaporation and roughness length were most influential on UHI in the daytime and anthropogenic heat was most influential at night (Atkinson 2010).

3.4 Significant Impacts of UHI

3.4.1 Heat Related Deaths

UHI is of particular importance because it can pose serious health and safety risks. The severity of heat related threats was seen in 1995, after a five-day heat wave in Chicago, where maximum air temperatures reached 104 °F. In this period the number of deaths in the city increased 85%, which amounted to an excess of 700 deaths (Mgheehin & Mirabelli 2000). During heat waves, the UHI can increase heat related mortalities, as shown in a study of Shanghai records that reveals higher heat related death rates in urban areas than rural during heat waves (Tan *et al* 2010). Other studies have shown that people living in urban areas and without access to air conditioning are at greatest risk to heat illness deaths (Mgheehin & Mirabelli 2000). It is however possible that increased temperatures due to UHI will decrease the amount of deaths in winter related to exposure to cold.

3.4.2 Decreased Air Quality

Inner city air temperature can also affect the risk of harm from exposure to ozone and other air pollutants (Santamouris *et al* 2001). Increased urban temperatures are related to the formation of secondary pollutants, like ozone (William *et al* 2004). This is due to the fact that chemical reactions happen at an accelerated rate under warmer conditions. Surface Ozone is created by Nitrogen Oxide reacting with volatile organic compounds, under warm conditions. Furthermore, UHI effects the distribution of Ozone and other pollutants by increasing the size of a cities thermal internal boundary layer and the amount of convergence, causing these pollutants to accumulate and become more harmful. (Li-Wei & Wan-Li 2009). Akbari *et al* (2009) stated that the probability of smog increases 6% for every 1 ^{o}C increase above 22 ^{o}C.

3.4.3 Comfort

Along with these more severe impacts on health, general comfort of the population is of great concern. In addition to increased use of air conditioning, people will also travel to escape the heat of a city if it is unbearable, leading to further addition of GHG emissions. People's sleeping habits and general wellbeing can also be affected, causing less obvious but still significant detriments to society. Ihara *et al* (2009) conducted an environmental impact assessment of changes in Tokyo urban temperature based the LIME framework for end use life cycle impact assessment. The results of their assessment are summarized in the figure 5 below.

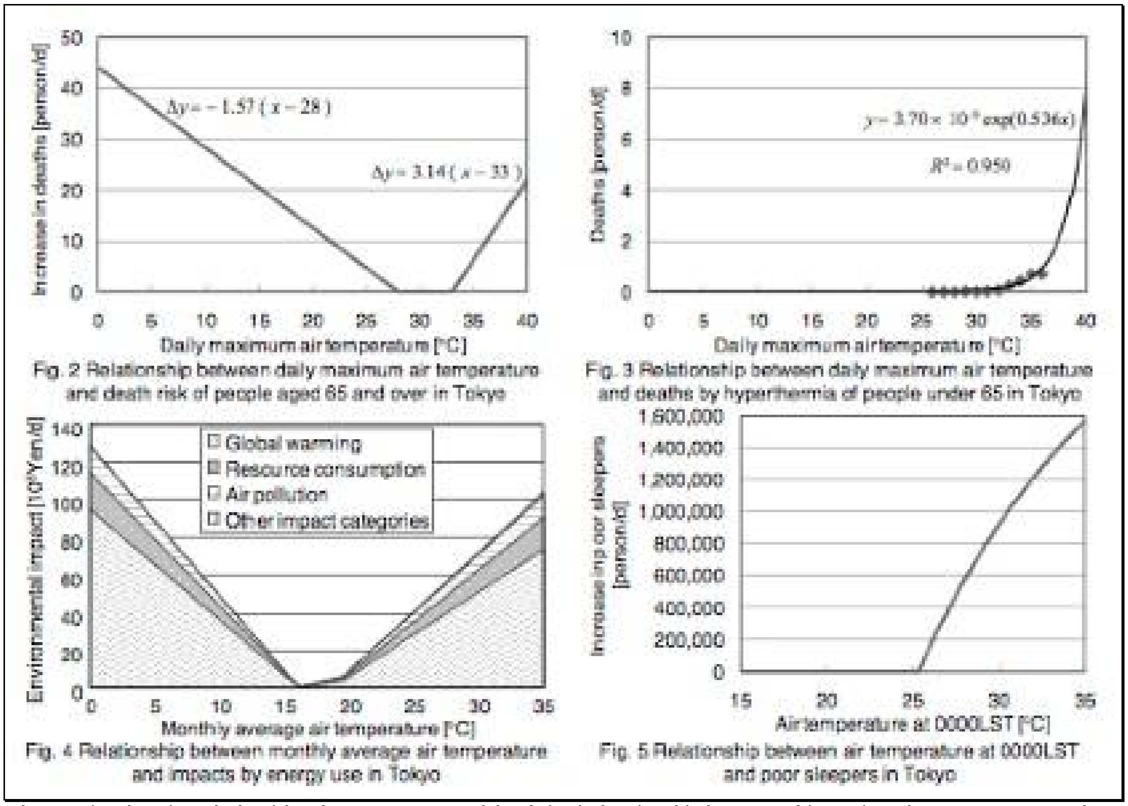

Fig. 6. Showing the relationship of temperature to risk of death for the elderly, rates of hyperthermia, energy consumption, and sleep disturbance in Tokyo, Japan. Ihara et al (2009)

The results shown above help to summarize the impact that urban climates can have on a society. The graphs clearly show the relationship of UHI to elderly death risk, hyperthermia death rates, energy consumption, and sleep disturbance.

3.4.4 Change in weather

`The UHI phenomenon can also affect the local weather of a city. Cenedesi and Monti (2003) discuss literature concerning the UHI effect on wind patterns, saying that numerous studies have shown that UHI can intensify the wind velocity of sea breezes, but that inland penetration of the sea breeze is delayed by UHI for a few hours, resulting in urban pollution remaining stagnant over the inland area until the sea breeze arrives. An interesting observation was documented in Taipei, Taiwan as sea breeze flows interact with the UHI of the city, causing an increase in thunderstorms over the area (Tsin-Chang Chen et al 2007). This increase in precipitation resulting from the thunderstorms is actually viewed as a positive effect in Taipei as it reduces the deficit of the water supply for the population. The exchange of sea air and polluted city air that occurs during the thunder storms actually serves to ventilate the urban environment; although, this may also lead to increased pollution of water systems down stream from the city (Tsin-Chang Chen et al 2007).

The increase of urban temperatures can have other positive effects as well. As the UHI can be distributed to surrounding areas and the higher temperatures could possibly extend the growing season for farmers in some areas.

3.5 The Relationship of UHI and Energy Consumption

The UHI/energy consumption research that does exist is often either a “top down” or “bottom up” approach. The top down method is based on comparing large scale observed temperature energy consumption statistics. The bottom up approach looks at consumption on the individual building level and then uses model simulation to asses what impact various urban climate characteristics would have on the reference building. Heiple *et al* (2008) compared top down and bottom up approaches on describing energy consumption in Houston, Texas, and concluded that they give very similar results on citywide energy consumption but the bottom up shows much more variation at grid cell resolution. This is partly due to the fact that top down approaches are based on monthly data, while bottom up is based on hourly data. The disadvantage of the bottom up method is that it can be costly and time consuming to develop the reference building model (Heiple et al, 2008).

3.5.1 Previous Studies on UHI and Energy

Energy demand for heating and cooling of office buildings has been growing substantially in most cities due to population growth but also increased consumption habits

(Santamouris. et al 2001). Energy consumption has often been closely linked to affluence and one study showed that a 1% increase in GNP will cause an almost identical rise in energy consumption (Jones 1992). However, the same study concluded that a 1% increase in population size will cause a 2.2 % rise in energy consumption. While it is obvious that there are many factors that affect energy consumption, urban temperature is of particular interest because of its relationship to climate change.

The relationship between temperature and energy consumption has long been known and many studies have attempted to describe it. Ihara et al (2009) provides the following equation and explanation to describe this relationship:

$$E = E_0 + \underbrace{\left(\frac{\Delta E}{\Delta T}\right)_{\mathrm{w}} (T - T_{\mathrm{w}})}_{\text{when } T<T_{\mathrm{w}}} + \underbrace{\left(\frac{\Delta E}{\Delta T}\right)_{\mathrm{s}} (T - T_{\mathrm{s}})}_{\text{when } T>T_{\mathrm{s}}}$$

"Here, E (W/floor-m2) is the electric power consumption per total floor area of the building estimated from the air temperature T (^{o}C). E_O (W/floor-m2) is referred to as the base load of the electric power consumption, which indicates the electric power consumption for appliances and lightings. E_O is a constant. It is independent of the shift in the air temperature.Tw and Ts (1C) are defined as ''air temperature turning points'' for electric power consumption (ΔE/ΔT)w and (ΔE/ΔT)s ((W/floor-m2)/1C) represent the dependence of the electric power consumption to air temperature. The subscripts w and s indicate winter and summer conditions, respectively. In the business districts, if the temperature exceeds a threshold value, the electric power consumption for cooling increases during summer. Ts is the threshold temperature and (ΔE/ΔT)s is the rate of increase in the energy consumption for cooling when the air temperature rises by 1 1C." (Ihara et al 2009)

Fig. 7: Mathematical equation provided by Ihara et al (2009) for describing the relationship of energy consumption in buildings and outside air temperature

3.5.1.1 Lessons from the U.S

In the U.S. 45% of energy consumed in commercial buildings is by HVAC systems while 29% is for lighting and office equipment, and 15% is for water heating. In residential buildings these averages are 53% for HVAC, 29% for lighting and appliances, and 17% for water heating (Heiple et al 2008).

One study determined that for U.S. cities with populations larger than 100,000 people, every 1° F increase will cause a 1.5-2% increase in peak electricity load (Akbari *et al* 1992). In total, this means that UHI in U.S. cities accounts for 5-10% of peak electricity loads. This same study estimated that UHI could be costing more than $1 Billion per year in the United States, and accounting for 3-8% of urban electricity consumption in the country. Akbari (2007) states that air conditioning in the U.S. causes the emission 80 million metric tonnes of carbon per year. Furthermore, the influence of heat islands on energy consumption has been dramatically growing for the past 40 years and now accounts for 10% of electricity consumption for cooling (Akbari 2007). Parker *et al* (1994) estimated that UHI was costing Americans about 10 GW/h costing millions of dollars per hour during summer. Table 2 summarises more research from the U.S. on the relationship between UHI and energy consumption.

Table 2. Study	Method	Results	Comments
Matsuura (1995)	Model based on historical trends to estimate building type cooling loads in 7 U.S. Cities	1 ^{o}F increase in the annual mean temperature produced a 4 to 10 kWh decrease in mean daily energy loads in Casper, Duluth, Philadelphia, and Seattle. In Phoenix and Tampa an increase in 1 ^{o}F led to an increase of 12-14 kWh in net energy consumption.	Results were similar for office buildings and residential buildings UHI costs energy in warmer cities and saves in cooler cities Shadowing of buildings is highly influential
Ewing & Rong (2010)	Linking residential temperature models, housing type, housing size, and temperature models. Studying major U.S. cities based on census data	1% increase in the county sprawl index (meaning increase in density) meant the number of HDD's decreased by 0.21% while the number of CDD's increased by 0.48%.	Density increasing CDD's more than decreasing HDD's. in U.S.
Taha (1997)	Compared data from airports and city centres in 10 major U.S. cities to show the difference in HDD's and CDDs. Literature review on influence of albedo and vegetation. Model of anthropogenic heat and air temperature.	In 9 out of 10 cities the higher amount of CDD's in the city centre were less than the decrease of HDD's. This observed difference is greater in cities with northern locations. Vegetation and albedo were the most significant of all predictors of UHI. Anthropogenic heat can increase air temp. 2-3 ^{o}F in dense urban areas but has no significant influence on ambient temperatures in suburban areas.	UHI would appear to be saving on net energy consumption in the majority of U.S. studies.
Baker *et al* (2002)	Examined various UHI impacts in Phoenix AZ.	Urban warming has increased the number of CDD's from 1,560 to 2,130 since 1948 (a gain of 569) and decreased HDD's from 695 to 364 (a difference of 331).	Residents were now sleeping with A.C. on instead of with windows open.
Heiple *et al* (2008)	Model of temperature/ energy consumption using building stock profiles in Houston, TX. Building stock profiles based on other studies. GIS to determine number and height of buildings. Comparing model to observed energy consumption rates to show accuracy.	Buildings located in the city core showed much higher total energy consumption rates than rural and suburban areas. The downtown peak energy consumption was however slightly higher in January than in August.	Model was deemed accurate and showed more city scale variability then observed consumption rates. Important to account for natural gas as well as electricity. Building density was deemed more influential on inner city energy consumption variability then housing type.

3.5.1.2 Lessons from London

London, England has probably received more UHI attention in research then any other city. Luke Howard was the first person to describe the London UHI at the turn of the 19^{th} century. Howard observed a difference of -0.2 ^{o}C in the day and 2. ^{o}C at night in the city centre compared to surrounding rural areas (Kolokotroni *et al*, 2009). Since this discovery many researchers have monitored this phenomenon in its growth and impact. Much of the work in London has revolved around creating energy consumption building models based on temperature station data. Table 3 summarises more of the lessons learned from previous London research.

Table 3. Study	Method	Results	Comments
Kolokotroni & Giridharan (2008) The aim was to discover UHI impacts on net energy use now and under climate change scenarios.	Model developed by applying a referencing building to air temperature station data from locations throughout London. Model based on year 2000 results and expected climate for 2050 under IPCC climate change scenario. Different types of cooling considered.	In 2000 urban buildings have 5% less UHI total emissions impact compared to rural buildings. In 2050 consumption rates are even. However, If expected growth in the number of buildings with A.C. is accounted for then rural office energy use increases 300% and urban office use increases 500%.	The necessity of increases in the number of buildings with A.C. makes UHI a much bigger energy consumption threat under climate change scenarios then it is currently.
Kolokotroni *et al* (2009)	Model based on back propagation using air temperature data from 77 measurement points throughout London that recorded temperatures for 16 months in 1999 and 2000. The model was backed by site specific impute parameters that were based on physical characteristics of sites.	Model predictions were very consistent with observed data. Compared to Heathrow airport, the core of the city had 23% less HDD's, urban areas had 18% less, and suburbs had 9%. The core had 20% more CDD's.	Site specific physical characteristics appeared to have more influence on degree days in summer than in winter. Surface albedo, aspect ratio, and green density ratio were the most influential site specific factors on UHI. Generally, HDD's increased and CDD's decreased with distance from city centre but there was inner city variation.
Kolokotroni *et al* (2011)	Same model as Kolokotroni *et al* (2009) but results were converted into GHG emissions.	4% less emissions impact in urban location in 2000, and 4.5% more in 2050. Emissions are expected to increase 87% for rural offices and 141% for urban offices when accounting for expected addition of A.C. buildings.	Example of the self-propagating nature of climate change problem.

3.5.1.3 Lessons from Tokyo

Tokyo, Japan is another city of great interest in UHI research as it is one of the largest metropolises in the world and it has a humid subtropical climate. Watanabe *et al* (1991) mapped land temperature distribution and energy consumption rates of Tokyo during September of 1973. The map clearly showed that higher rates of energy consumption were experienced in the central and most dense areas of the city. Ojima (1991) showed that from 1965 to 1975 the cooling load for existing buildings in Tokyo had increased by 10-20% on average. Table 5 explains more of the research that has been done in Tokyo.

Table 4. Study	Method	Results	Comments
Saitoh *et al* (1996)	3D model based on historical trends to estimate current and future (2031) UHI energy impacts in Tokyo.	Observed maximum UHI = 8^{o}C Model maximum UHI= 5^{o}C Model showed anthropogenic heat adding 3^{o}C Tokyo urban temperature is expected to often reach 43 ^{o}C by 2031.	This study used a traverse of the city to collect temperature data, which may not be the most accurate method for data collection
Ihara *et al* (2010)	Regression analysis between air temperature and energy consumption rates in Tokyo city centre. (equation mentioned in methodology section).	When air temp <15°C electricity consumption increase: 76 W/Floor M$^{2.}$ Per 1 ^{o}C decrease. When air temp >21.3 ^{o}C, energy consumption rises by 1.81W/Floor-M^{2} per 1^{o}C rise.	Sensitivity temperatures inspired degree day bases for the study done in this thesis.
Hirano *et al* (2009)	Model based on temperature, land use and energy consumption. Energy consumption and temperature data was gathered from existing office buildings. Parameters were set based on land use and then changed to compare UHI and no UHI case.	In the residential sector the total energy use was decreased by 9000 TJ/year due to UHI 6% of cooling energy could be reduced by cutting off addition of waste heat from HVAC system into the urban canopy.	Accuracy of model: During the peak time of cooling, simulation estimated a temperature sensitivity of 6.07%/ 1 ^{o}C, compared to the actual building measurements of 5.66% per 1 ^{o}C rise HVAC waste heat identified as large temperature influence in

			summer.

3.5.1.4 Lessons from Athens

The results of these studies from the U.S., London, and Tokyo all show that UHI is influential on year round energy consumption and that the savings in decreased heating are usually more than the losses from increased cooling. These regions are all densely populated but have relatively moderate climates. For this reason Athens is another city that receives much UHI attention, as it has a warmer climate is notorious for its summer UHI intensity. Table 5 highlights two of the most relevant studies from Athens.

Table 5

Study	Method	Results	Comments
Santamoris *et al* (2001)	Temperature and consumption rates of one building applied to 20 stations in Athens	Maximum UHI often reached over 10°C. UHI can almost double the peak cooling demand, and can reduce the air conditioner efficiency by 25%. In winter the heating demand may be reduced by UHI by up to 30-50%.	The reference building already utilised significant energy savings measures.
Santamouris *et al* (2007) Aimed to show ecological footprint of UHI in Athens	Model of different building types based on temperature data from 1997 and 1998. Building categories based on 1000 observed buildings in Athens.	The energy cost of UHI was 33.2 kWh/m^2 for the year 1997 and 29 kWh/m^2 for the year 1998. Carbon Dioxide increase due to UHI was between 0,31 to 0,36 Million tons per year and the ecological footprint increase was 60,000 to 70,000 ha. This is up to 1.5-2 times the actual size of Athens.	This study did not account for heat savings in winter

3.5.1.5 Other Studies

Other areas of the world have been studied in terms of UHI and energy consumption, but this is still under researched in the developing world, where the impact of UHI is likely to be most detrimental. Table 6 summarises two more interesting lessons learned from other parts of the world.

Table 6

Study	Methods	Results	Comments
Souza *et al* (2009)	Cross examination of energy consumption and thermal environment of Bauro Brazil during summertime.	Mean temperature in the city during UHII peak was 4.5°C. Regions of the city that experienced temperatures above this average had energy consumption rates of 333 kWh/month, while areas experiencing lower temperatures had about 278 kWh/month.	The data was applied to a 3D map of the city, and overlap between UHI and high-energy consumption could easily be seen. The researchers deemed income to be the highest predictor of energy consumption.
Fung *et al* (2006)	Regression analysis to determine the dependence of electricity, coal and gas consumption on temperature using census data from 1990 to 2004.	1 °C increase in temperature would cause electricity consumption to rise by 9.2%, 3.0% and 2.4% in domestic, commercial and industrial sectors respectively, costing $1.6 billion HKD. However, the rise in temperature would have a reduction in demand for domestic gas of 2.4%, amounting to a savings of $ 77 Million H.K.D	Energy consumption in Hong Kong had gone up by 50% in this 15 year period due to population increases. Other studies show Hong Kong UHI to be 4°C in summertime. Interesting when compared to Memon *et al* (2009), who revealed that UHI intensity was highest in winter months at night-time in Hong Kong resulting in an estimated overall decrease in energy consumption for the entire year.

3.5.2 Thee Effect of Mitigation Strategies on Energy Consumption

Mitigation is important to discuss in this paper because the whole purpose of quantifying UHI energy impacts is to decide when and how to mitigate and understanding the potential of mitigation enhances ones grasp on the impact of UHI. When estimating the effectiveness of a UHI mitigation strategy, researchers will consider both the direct and indirect effects on energy consumption. Direct effects are the energy savings for the specific building that the change is made to. As mitigation strategies can often reduce the ambient temperatures of surrounding areas, these indirect impacts must also be considered in order to value the strategy at a correct level (Akbari & Konopacki 2003).

Mitigation techniques have been assessed all over the world at different scales, from buildings, to canopies, to entire cities. As discussed earlier, surface albedo, vegetation, and waste heat have been identified as having the most potential for altering UHI related energy consumption. Albedo alteration may include changing of roofs, side walls, sidewalks, or pavements. Albedo alterations can be as simple as painting a surface a lighter colour, can involve rebuilding the surface with high tech cool materials, or can be more complicated by building vegetation sustaining designs. Vegetation cover can reduce surrounding temperature more than albedo, making vegetated roofs a more effective solution than using reflective coating (as well as the absorption and insulation benefits that green roofs provide); however greatest overall reduction potentials for cities are likely to be through the use of light surfaces as there is the highest amount of space available for conversion and creating living surfaces can be much more expensive than other ways of increasing albedo (Rosenweig et al, 2005). Researchers are currently working on roofing shingles that will change colour from black to white as heat increases (Santamouris *(A)* 2001). Different ways of changing surface albedo are available and new options are likely to continue emerging.

New pavements are now available that dramatically increase the albedo of roads. Permeable pavements are also another option that can decrease storm water run off, thereby keeping more moisture within the city. Altering building design by use of passive cooling, natural ventilation, and regulating solar exposure to windows are all options for reducing cooling energy. Some studies have also looked at ways to minimise the waste heat from air conditioners by use of cooling towers or by displacing HVAC waste heat into the ground or sewage system instead of the surrounding atmosphere. Mitigation strategies may choose to focus on one type of alteration or a combination of many different things, generally according to what will give the quickest return on investment in terms of energy savings. While there are many options for addressing UHI and energy consumption, the majority of studies have focused on surface albedo (roofs, walls, and pavements), urban forestry, surface greening, and reduction of waste heat. This section describes some of the studies that have estimated the potential savings available from these strategies (Santamouris *(A)* 2001).

Rosenfeld *et al* (1995) describes findings from a study done by the Heat Island Project at the University of Berkley. Like other studies, this research concluded that increasing albedo and planting trees can counteract the heat island effect. For highly absorptive (low albedo) surfaces exposed to sunlight, the difference between the surface temperature and the air temperature can be as high as 50 ^{0}C, while a high-albedo surface such as white paint can reduce the difference to about 10 ^{o}C. The researchers measured the impact of implementing white roofs and shade trees on the energy use of six buildings in Sacramento, California. The study monitored buildings for periods with and without shade trees or high albedo walls and roof. The shade trees alone were estimated to lower the medium cooling load by 35%. The difference in increasing the albedo of a house from 0.18 to 0.73 caused the air conditioners to automatically switch on at an outdoor air temperature 2 ^{o}C higher than before and caused an energy savings of 40% (330 kWh/year). To estimate the city wide effects of albedo change, the researchers applied the Colorado State University Meso-scale Model to the Los Angeles Basin. The model identified 394 grid cells, covering an area of 10,000 $Km^{2,}$ where 20% of the land was artificial surface suitable for albedo modification. In the model the average albedo of this area was raised from 0.13 to 0.26. This was shown to reduce peak summertime temperatures between 2 and 4 ^{o}C which would result in a reduction of peak power consumption by 0.6 to 1.2 GW per hour, saving $100,000/h to $200,000/h assuming a cost of 16.5 cents/kWh. The researchers claim that this rise in albedo does not describe a mostly white city, but a more realistic design based on beige sloped roofs and weather treated asphalt. A city designed in the fashion of mostly white buildings, common in tropical areas, could raise the average albedo by 0.3, a significant increase compared to the rise of 0.13 described in the model.

Increasing the albedo of roofs is a very common technique observed in both site specific practical studies and large scale modelling simulations. Parker *et al* (1994) looked at the actual impact of albedo changes on residential buildings. They replaced the existing roofing materials of six Florida homes with material that changed the albedo from 0.08-0.31 to 0.61 0.73. This resulted in average cooling savings 9.2 kWh/ a day, an efficiency increase of 23%.

Konopaki et al (1997) approximated the direct energy savings potential for citywide adoption of high albedo roofs in 11 metropolitan areas of the U.S. The study identified four types of building construction that were accounting for 90% of building energy use, these being pre 1980 residential buildings, post 1980 residential buildings, office buildings and retail stores. City wide albedo increases were estimated to have the potential to reduce energy costs by a range of $3 million U.S. dollars in colder cities to $37 million in hotter cities. These results were extrapolated to the entire U.S. and potential savings including heating penalties were estimated to be around $750 million U.S. dollars per year (assuming energy prices of 8 cents/kWh) (Akbari et al, 1999)

Taha *et al* 1996 created a meso-scale model of ten different regions in the U.S. to show what the energy use impacts of altering albedo and vegetation cover would have. Similar modelling experiments done by the researchers in the past had shown that albedo increases could result in 30% energy savings and reduce ozone formation by 20% in the summertime. The regions selected for the experiment were meant to represent a variety of climates and urban typologies (Southern Arizona, Southern California, Connecticut, District of Columbia, Delaware, Southern Florida, Central Georgia, New Jersey, Maryland, Eastern Pennsylvania, Downtown New York city, Southern and Eastern Texas and Northern Virginia). The model was based on measurements from January, March, May and July to have representation from all seasons. The study showed that Atlanta, Chicago, Los Angeles, New York, Washington D.C. and Philadelphia all experienced UHI intensities of 2 ^{o}C at 2 P.M. UHI intensity was slightly less in Dallas and Houston (1.5 ^{o}C), and even lower in Phoenix (1^{o}C) and Miami (less than 0.5 ^{o}C). The electricity savings resulting from albedo and vegetation increases of 0.15 were calculated for both residential and commercial buildings and then increased costs of winter gas heating were subtracted from this. The simulated electricity savings were $10-35 per 100 m^2 of roof area.

Akbari and Konopaki (2005) wanted to show the potential of different UHI mitigation strategies to reduce building energy consumption in every major U.S. city. They were interested in comparing shade trees, reflective pavements, and solar reflective roofs. This work stemmed from an initiative started in 1997 by the U.S. EPA to quantify the impact of UHI and the economic and social benefits of various mitigation strategies. The initial study had featured detailed observations of five U.S. cities (Baton Rouge LA, Chicago IL, Houston TX, Sacramento CA, and Salt Lake City UT) and the follow up study was meant to expand upon this data statistically in order to have a standardised method for assessing mitigation strategies for any U.S. city. This analysis includes three different building types that were determined to have the largest opportunities for energy use reductions; these being office, residential, and commercial buildings. The researchers grouped cities according to their cooling degree and heating degree days to simulate energy needs for the prototype buildings. They also simulated the effect of ambient temperatures on the buildings, and the ability to influence these factors with different intervention strategies. This allowed the study to measure both direct and indirect savings. When examining the data from the original five cities it is interesting to note that Chicago is an outlier in having both a low percentage of electric savings and a low percentage heating gas penalty. This confirms what the researchers had suspected, that colder climates will have a higher gas-heating penalty due to UHI mitigation but it will be a relatively small portion of their total heating demand. For the original five cities, indirect energy savings ranged from 11%-21%, excluding Chicago (1%). The indirect gas penalties ranged from 17%-25%. The most savings came from using a combination of mitigation strategies, with over 75% of the savings being direct building energy use caused by cool roofs and shade trees. The extrapolated results are summarised in table 7.

Estimated ranges of annual basecase (electricity use, gas use, peak demand, and carbon emissions) and savings from heat-island reduction measures across all climate regions

Prototype building	Electricity (kWh/1000 ft²)		Gas (Therm/1000 ft²)		Peak power (kW/1000 ft²)		Carbon (kgC/1000 ft²)	
	Basecase	Savings	Basecase	Penalties	Basecase	Savings	Basecase	Savings
Residential								
Pre-1980 gas-heated	1600–11000	400–1200	0–1000	0–50	3.1–4.0	0.4–0.6	1100–2200	60–220
Pre-1980 electrically-heated	8500–20000	100–1200			3.1–4.0	0.4–0.6	900–4800	60–220
1980⁺ gas-heated	700–7000	150–700	0–500	0–20	1.7–3.3	0.2–0.4	400–1200	30–100
1980⁺ electrically-heated	5000–9000	50–600			1.7–3.3	0.2–0.4	400–2300	30–100
Office								
Pre-1980 gas-heated	7000–18700	1200–1400	0–500	0–20	6.3–8.4	0.5–1.0	1800–3100	200–260
Pre-1980 electrically-heated	12600–18700	1100–1300			6.3–8.4	0.5–1.0	2000–2100	190–260
1980⁺ gas-heated	3500–10800	500–600	0–300	0–10	3.5–4.6	0.2–0.5	800–1800	70–120
1980⁺ electrically-heated	5700–10800	300–600			3.5–4.6	0.2–0.5	900–1800	50–100
Retail Store								
Pre-1980 gas-heated	8200–15700	1400–1500	0–200	0–10	4.5–5.7	0.4–0.7	1400–2900	210–290
Pre-1980 electrically-heated	10700–17200	1300–1700			4.1–5.7	0.4–0.7	1800–2900	200–290
1980⁺ gas-heated	3100–8900	500–700	0–60	0–6	2.2–2.8	0.2–0.3	520–1500	70–120
1980⁺ electrically-heated	4000–8900	300–700			2.2–2.8	0.2–0.3	650–1500	50–120

Table 8. Results of Akbari and Konopaki (2005) study on energy savings potential of mitigation efforts on different building types and locations.

Taha (2000) conducted a modelling simulation on the effect of mitigation techniques on peak energy use in California. They found that savings between 5-10% on peak utility can be achieved by adopting cool community strategies that involve albedo and vegetation increases. This study also highlights an important point that mitigation strategies will not have the same effect on different locations, as the evapotranspiration benefits from vegetation will not be nearly as dramatic in humid climates as in arid climates. These potential savings are consistent with other studies form the U.S. that claim cooling related to UHI is responsible for 5-10% of peak energy demand is the summer (Navigant 2009).

Studies done in New York showed curb side planting of trees can have the greatest potential for vegetation based temperature reductions (Rosenzweig *et al* 2001). Kerr and Yao (2004) did a study on New York's potential to mitigate its UHI and the benefits that this would incur. They state that for every 1 °F increase in urban temperatures after 68°F, citywide energy consumption increases by 3,300 MWh/degree/day. They estimated that cool roofs have the potential to reduce the New York UHI by 1 °F. As they assume that most roofs will need to be replaced at least once in the course of their lifetime, if every roof in New York was replaced by a cool roof (high albedo), at $.68 cents per Sq. foot additional cost from regular roofing, the city would save an estimated $105 million U.S. dollars per year ($23 million direct savings and $82 million indirect.). While this estimate concluded four times larger indirect savings then direct savings, Konapaki and Akabari (2002) found contradictory results. They conducted a modelling experiment funded by the US EPA that showed cool roofs would contribute to 75-85% direct savings of total UHI mitigation and 15-21% indirect in U.S. cities. Kerr and Yao estimate (2004) that the transition to green roofs on every roof in New York would achieve even higher results than with cool roofs. Green roofs have the potential to lower urban temperatures by 1.2 ^{o}F, which amount to energy savings of $149.4 million dollars/year but would cost 4.72 billion in initial construction. When compared to the results and payback period of doubling the amount of trees in New York (500,000 doubled to 100,000). This would also reduce urban temperatures by 1.2 ^{o}F but would cost $625 million and save $98.4 million annually in energy consumption, giving it a payback period a little more than 6 years. Because of these results, cool roofs and street trees were seen as better options then green roofs for mitigating New York UHI in terms of energy consumption. However, this did not take into account other benefits that green roofs provide, such as storm water absorption and aesthetic value.

Kikegawa *et al* (2006) conducted a study on the impact that UHI mitigation strategies would have on areas of Tokyo with various density characteristics. The researchers combined a one dimensional urban canopy model with a meteorological model and a building energy analysis model. Combining the urban canopy model with the building analysis model allowed the simulation to show the impact of outside temperature on buildings energy consumption while simultaneously measuring the impact that the waste heat from air conditioning units was having on the canopy temperature. This study had a hypothesis that sky view factor (SVF) was a sufficient predictor of UHI intensity and could therefore be used for planners to know where it is most important to mitigate and what strategies will work best. The 23 wards of Tokyo were divided up into 1,919 districts using a horizontal grid system. Each district was classified according to its sky view factor. A few of these districts that were deemed most representative of the city were then put into the model using summer time data from both office and residential buildings. The simulation was done for different countermeasures which were: increasing building surface albedo, sidewall greening, cutting off air conditioning waste heat (by releasing it into places other than canopy atmosphere), increasing building insulation, and reducing indoor waste heat (reducing electricity use). The results were that for districts with SVF of less than 0.8 (1.0 would be the SVF of an area with no buildings), side wall greening (humidification) was the most effective mitigation strategy in residential areas and reducing air conditioner waste heat was the most affective in office areas. However, areas with SVF's of greater than 0.8 would be more affected by surface greening. The simulation showed that side wall greening of residential canopies could reduce the daily average surface temperature by 0.7 ^{o}C, resulting in a cooling demand reduction of 20%. Cutting off air conditioning waste heat in office canopies would result in an average surface temperature reduction of 0.5 ^{o}C, which would result in energy savings of up to 5%. In both office and residential areas, these mitigation strategies were shown to get more effective as SVF decreased; indicating that the hypothesis was confirmed and SVF can be used as an effective indicator for UHI mitigation planning. While this study only focused on summertime cooling load reductions, the researchers planned on doing a year round impact study with the same methods in future research.

Ihara *et al* (2008) modelled the impact of various UHI mitigation strategies on year-long energy consumption for an office building in Tokyo. Their methodology consisted of combining a one dimensional meteorological canopy model with a building energy use model. The building was a model simulation based on newly built and mid sized characteristics. This study found that installation of humidification and albedo increasing techniques could reduce the amount of time that outside air temperatures reached 30 ^{o}C by 60 hours. Furthermore, the introduction of humidification techniques and heat sinks can reduce total year long energy consumption by 3% and 1% respectively.

Hsieh et al (2011) focused on how effective the reduction of HVAC waste heat can be for mitigating UHI and reducing energy consumption. The study was done in Taipei, Taiwan, where heat island intensity has been measured at 4.9 ^{o}C in the summertime. Previous studies had already shown that waste heat from air conditioning units was a significant contributor to UHI and thus cooling demand in Taipei and that cooling demand in the city were greatest at night. The study used a building energy model based on weather data and individual air conditioning use schedules to simulate outside temperatures and building energy use. Three countermeasure cases were assessed, based on different cooling systems and there placement. Case 1 had a split type air conditioner installed on every floor, so that 2-3 rooms are sharing the same unit. This means there are generally 8 units per floor, opposed to the base case where there are 16. Case 2 involves having one split type unit for each family, with the exterior unit on each floor. In case 3 a cooling tower is installed on the roof. The simulation showed that ambient urban canopy temperatures were not greatly decreased in case 1 (-0.45 ^{o}C) but the energy consumption was slightly decreased. Case 2 observed slightly more of an energy demand decrease and the cooling tower introduction of case three was seen to significantly reduce temperatures within the urban canopy (1.06 ^{o}C) but did not result in additional total energy savings because of additional electricity requirements.

3.5.2.1 Implementing Mitigation Strategies

It is equally important to understand these factors in the larger context of sustainable development. The importance of this holistic view is evident when discussing the impact of city density on overall energy consumption. Increasing the concentration of people in city centres is on one hand beneficial because it reduces habitat destruction by decreasing urban sprawl and it reduces emissions from pedestrian travel (Hamin and Gurran 2009). , On the other hand, increasing density increases the formation of UHI. Oke (1982) showed that population density can be one of the most influential predictors of UHI intensity.

Addressing urban heat islands fits into the larger problem of adapting cities to mitigate and cope with the threat of climate change. Improving transportation systems, increasing urban vegetation, utilizing high albedo coatings and building materials, and improving the efficiency of buildings are all steps in the right direction for reducing UHII and ultimately GHG emissions. However, developing low GHG emitting and comfortable cities is only a small portion of the developmental needs that must be addressed in order to prepare for climate change, as sanitation, nutrition, and economic development are also interrelated issues that are likely to define the future prosperity of humanity. Oxfam estimates that proper development investments related to climate proofing cities realistically require funding of $50 Billion U.S. dollars annually in developing countries alone (Ayers, 2009). Furthermore, this required amount will continue to grow the longer it takes for international emission reduction agreements take to be reached. The UHI adaptation strategies mentioned offer opportunities for economic growth by creating jobs and new markets, however the market alone cannot hope to solve the development crises, especially considering the fact that most of the areas in greatest need of investment exist in low income countries. International funding for climate adaptation development generally comes from either the United Nations Framework Convention on Climate Change (UNFCCC), which has assigned climate change funds, or from official development assistance (ODA) provided by other countries. These sources are not currently adequate because of an overall lack of funding, Lag in receiving committed ODA money because of claims that there is not adequate mechanisms to insure that money is distributed properly, a lack of trust of fund management, and a lack of guidance for the use of funds to developing countries (Ayers 2009). Fixing these funding issues is too large of an issue to go in to detail here, but it may involve a combination of various solutions including country owned multi donor trust funds, mainstreaming climate vulnerability assessment into The Word Bank's decision making, and local NGO's being more involved in overseeing funding distribution (Ayers 2009). It is that adaptation and mitigation to address both UHI and climate change is extremely necessary and it will likely take a massive combined effort by all stakeholders, including nation states, multinational corporations, NGO's and the general population.

3.5 Literature review conclusions

In an effort to define and describe the Urban Heat Island Effect (sub question #1) it has been concluded through a literature review that urban and rural temperature differences do exist in many large cities but that temperatures can vary as much within a city as they do between urban and rural areas. On average, UHII will equal 1-3 ^{o}C but we have seen in the literature and through observations that UHII can be higher than 10 ^{o}C. Studies show that the intensity of heat islands has been increasing in most cities at rates disproportionate to rates of climate change.

To answer sub question #2, heat islands have a large impact on various aspects, such as human health and comfort, weather patterns, and air quality. It has been shown that UHI's have a direct effect on ozone production and accumulation, and therefore UHII must be considered a danger to public health

UHI intensity can be quantified by comparing air temperature measuring stations or by using remote sensing to asses land surface temperature. Remote sensing offers a wide variety of methods for quantifying UHI and is not limited by insufficient station data, however it does not take into account the influence of wind and so air temperature was deemed more appropriate for a top down approach of calculating UHI energy consumption.

UHI intensity is usually highest in the summer, creating a large demand for cooling during peak periods when energy costs are at their highest. The little literature that exists on year round impact on energy consumption has shown that UHI will often decrease total energy consumption due to reduced heating demand in cities with cooler climates.

The literature shows that station data can be very useful when put into models. These models have shown to be accurate predictors of UHI and are useful for predicting energy consumption under future climates. The studies that have employed modelling warn that climate change will likely shift the UHI energy balance seen in most moderate climates, making UHI a larger energy consumer in future scenarios.

Mitigation and adaptation strategies may involve changing the albedo of building surfaces, creating more shade and evapotranspiration by improving urban forestry, or addressing individual building elements such as cooling strategies and excess heat generation. On a city wide implementation level, urban forestry has shown to be the most effective at lowering temperatures and addressing issues of air quality, however simple albedo increases are shown to be the most cost effective and are likely to have the highest potential due to availability and funding limitations. On the individual building level, passive cooling strategies, green roofs, energy efficient lighting, manual comfort cooling, and HVAC heat displacement strategies can be wise investments for lowing energy costs and making properties more attractive for buyers and renters. Research that modelled individual mitigation strategies an combinations of strategies showed that the greatest energy savings potential is reached with a combination of all strategies.

4 Case Studies

4.1 New York City, U.S.

With a population of 8,214,426, New York City is one of the largest and most densely populated cities in the world. The climate is classified as Humid Continental Climate (Kottek et al 2008) with average air temperatures usually ranging from 0 ^{o}C in January to 27 ^{o}C in July. The mean near surface air temperature in New York has risen by 1.1 ^{o}C in the last century. NASA-GISS global climate model predicts that temperatures will continue to rise in the city by 2.0 ^{o}C to 2.5 ^{o}C by 2100 under a medium emissions scenario, and 3.0 ^{o}C to 3.5 ^{o}C by 2100 under a high emissions scenario (Kerr & Yao 2004). Previous studies have shown the mean UHI in New York to range from 1.2 to 4 ^{o}C (Kerr & Yao 2004).

This study compared urban and rural near surface air temperature data from April of 2009 to March 2011. The urban measuring station was located in the heart of Manhattan, known as the Upper East Side, while the rural station was located just outside the city in North Arlington (73.96W, 40.77N).

Fig. 8: Satellite image of North Arlington measuring station (right) compared to 3D satellite image of Upper East Side measuring station (Left). Yellow markers indicate measuring station. Taken using Google Earth. April 10, 2012.

During the 36 month period analysed, the average monthly temperature was 1.17 ^{o}C higher in Manhattan than it was in Arlington. However, the monthly maximum temperature was 0.7 ^{o}C lower on average in Arlington than in Manhattan. The fall and winter (Sept.-March) generally had a significantly higher difference between urban and rural temperatures then the summer (June- Aug.). The amount of cooling degree days between both sites was very close, with there only being 6 CDD's less in the urban area for the 36 month period (including months when there was more CDD's calculated for the rural site). There was however 642 less HDD's in the urban area over the research period, with an average of 17.83 less HDD's per month and the highest savings in one month being 108 HDD's. The urban centre had 0.34 less CDD's per month on average than the rural station. From these results one would conclude that UHI is currently reducing energy consumption due to less heating demand (see appendix for data on temperature and degree day comparisons).

4.1.2 Central Park compared to inner city

New York has a special point of interest in that there is a temperature station in Central Park, which is very close to the station in Manhattan. This allows for an examination of the effect that vegetation and open space can have on UHI within the city. There were 170 less HDD's at the Manhattan station then Central Park and 251 more CDD's for the 36 month period. This means that when compared to Central Park, the UHI in Manhattan is costing more in cooling than it is saving in heating. In, fact 19.7 % of the Manhattan station's CDD's can be attributed to UHI, and that is just compared to the park, which is still surrounded by the city.

4.2 Athens, Greece

Athens is one of the larger cities in Europe, with 10,787,690 inhabitants, and a Subtropical Mediterranean climate (Kottek et al 2008) (2011, citypopulation. de). As seen in other studies, the UHI intensity of Athens can sometimes reach 12 ^{o}C. (Assimakopoulos *et al* 2006). The city is of interest because it is one of the hottest cities in Europe, with temperatures recorded in this study sometimes reaching 41 ^{o}C. The comparison for this city was performed between two different airports, one within the city (23.94E, 37.94) and one out in an isolated area (23.73E, 37.89N). This unfortunately does not give the most extreme example of UHI impact because the city airport is not in the centre of the city. The locations were chosen because they had the best data available. This example is still interesting however because it compares similar land use types, therefore showing the impact of the urban air dome. The city airport had a mean temperature that was 3.24 ^{o}C hotter per month on average than the rural airport, with the maximum temperatures being 1.27 higher on average per month. The largest maximum temperature difference was 5.8 ^{o}C per month, occurring in May of 2011. The temperature difference was fairly constant throughout the year, with the biggest differences usually around summer. The city location had 508 less HDD's recorded for the 36 month period and 427 more CDD's. The difference per month was 14.11 in HDD savings and 11.86 in CDD losses. These results suggest that UHI is contributing 19% of the CDD's at the urban airport.

Fig. *9: Satellite image showing Athens urban measuring station (left) and rural station (right). Taken from Google Earth April 10, 2012.*

4.3. Rome, Italy

Rome is another one of Europe's historic coastal cities with a Mediterranean climate (Kottek et al 2008). Like Athens, the city has hot summers with humid and mild winters. The population is 2761,477 (2011, citypoulation.de). The urban measuring station in this comparison is slightly southeast of the city centre (12.50E, 41.86N), and the rural station is an airport that lies outside the city (12.24E, 41.80N).

Fig. 10. Satellite Image of Rome urban (left) and rural measuring stations (right). Taken from Google Earth 4/15/2012.

The urban station mean monthly temperature was only 0.24 ^{o}C higher on average than the rural location and actually had a lower average max temperature of -0.95. In this example the urban location had 12 more HDD's than the rural location and 492 more CDD's over the 36 month period. The highest difference of any month was 49 CDD's in August 2011, and the average CDD difference per month was 26.6. These results suggest that 31.25% of the CDD's recorded in the urban location for the study period are due to UHI.

4.4 Paris, France

As the capital of France, Paris is not one of the largest cities in Europe with a population of 2,234,105, but it is one of the densest cities in the world, with 20,741 people per K^2 (Citypoulation.de). Paris has a Western European Oceanic Climate that is characterised as being mild and fairly wet (Kottek et al 2008). Paris was also a good location for this particular study because it has a detailed temperature station at the very centre of the city (2.34E, 48.85N). The rural station used for comparison is an airport outside of the city (2.53E, 49.02).

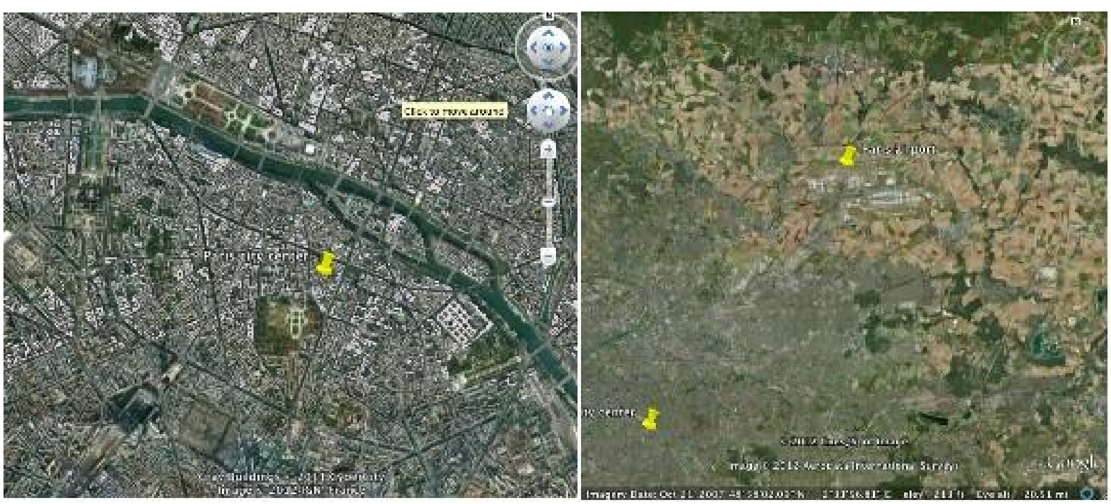

Fig. 11: Satellite image of urban Paris (right) and rural Paris (left). Taken with Google Earth. April 10, 2012.

The mean temperature was 2 ^{o}C higher on average per month in the city centre.

The urban location recorded 1,106 less HDD's in the study period and 96 more CDD's. The urban location had 30.72 less HDD's on average per month and only 2.67 more CDD's on average. These results suggest that 23.3% of the CDD's recorded in the city over the study period are resulting from UHI, however if not for UHI the city centres HDD's would be 24.6% higher.

4.5 Jakarta, Indonesia

As the capital city of Indonesia, Jakarta is the largest city in South East Asia with a population of 10,187,595 (2011, citypopulation.de). The city has a Tropical Monsoon Climate with distinctive wet and dry seasons (Kottek et al 2008). The urban measurement station is near the city centre at an observatory (106.84E, 6.19S). The rural measuring station is an airport just outside the city centre, so it may still be affected by the urban air dome (106.66E, 6.09S).

Fig. 12: Satellite image of urban Jakarta (left) and rural Jakarta (right). Taken with Google Earth April 10, 2012.

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This region has a very consistent climate in terms of air temperature, with an average urban air temperature of 28.66 ^{o}C in the city centre and 27.97 ^{o}C at the rural station. The highest temperature recorded in the city centre was 35 ^{o}C and 29^{o}C in the rural location. Because of the warm climate there were no HDD's recorded for either station. For the study period 1,073 more CDD's were recorded for the city centre, with an average of 29.80 CDD's per month. The highest difference for any month was 58 CDD's in July 2009, and the lowest was 8 CDD's in December 2011. It is concluded from these results that UHI in Jakarta is responsible for 13.67% of CDD's in the city for the total study period.

4.6 Manila, Philippines

Manila is the capital of The Philippines, and with a population of 1,652,171 inhabiting an area of only 38.25 km^2 it is the most densely populated city in the world (Tiango et al 2008). Manila is part of the larger Manila metro area which has a population of 9, 932,560 that inhabits 636 km ^{2}, making it the largest city in the Philippines. This region has a Tropical Savannah Climate which is very close to being a Tropical Monsoon Climate (Kottek et al 2008). It is located between Manila Bay and Laguna Lake, so it receives a sea breeze (cooler air coming in from the sea) in the day, but in the night the land becomes cooler than the water and so a land breeze pushes cooler air out to sea (Tiango et al 2008). This climate has a rainy season from June to November and a dry season from December to May. The range in mean temperature is 25.5 ^{o}C in January and 28.3 ^{o}C in May (Tiango et al 2008). Manila is an interesting city to analyse in terms of its heat island because it is known as having bad air pollution and many other environmental problems. The climate, density and poor environmental management make Manila a perfect example of a city that would be greatly impacted by the effects of an urban heat island. Tiango *et al* (2008) measured the UHI intensity in Manila at nigh time using land surface remote sensing techniques and found the maximum urban-rural difference to be highest at night with an intensity of 2.96 ^{o}C. The lowest night time UHI intensity they recorded was .87 ^{o}C. This is higher than what was recorded in this paper's study, with the urban location only having a mean temperature that was 0.25 ^{o}C higher on average per month than the rural location. The less extreme results observed in the present study are largely due to the fact that Tiango *et al* (2008) were measuring land surface temperature instead of air temperature, which is not influenced by wind speed. The urban station in the present study was located downtown near large buildings (34.48S, 120.58E) while the rural station was an airport at nearby Subic Bay (14.47, 120.16)

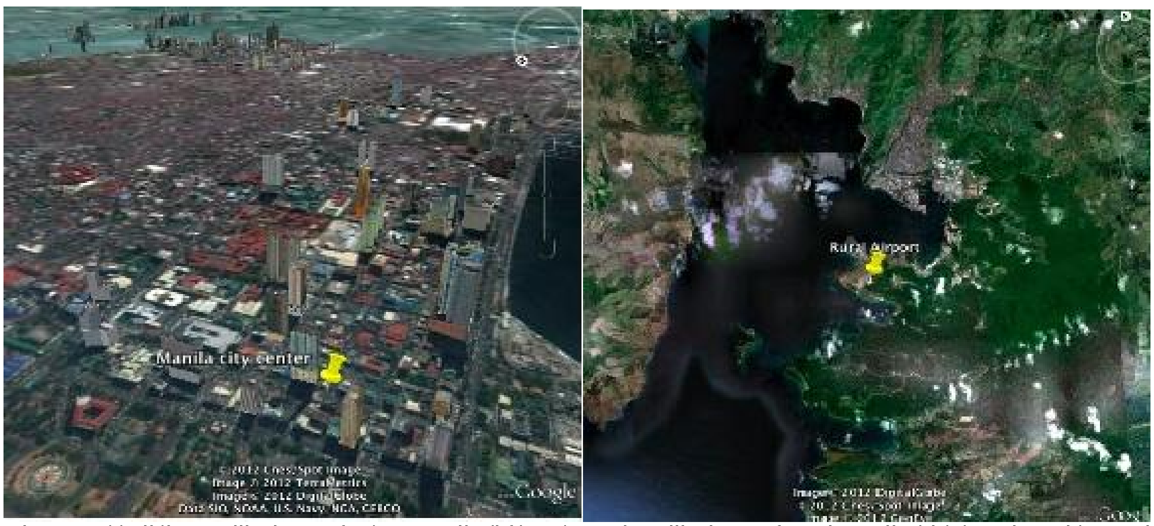


Fig. 13: 3d building satellite image of urban Manila (left) and actual satellite image of rural Manila (right). Taken with Google Earth. April 10, 2012.

The difference between the maximum air temperatures was 0.43 ^{o}C on average, with the highest difference being 9 ^{o}C in May 2011. During the course of the study period there were 1,079 more CDD's recorded in the urban location then at the rural station. The average difference per month between the city centre and rural station was 29.97 CDD's. There were no HDD's recorded at either station for this city. For the total study period the UHI accounted for 14.07 % of the recorded CDD's for the inner city of Manila.

4.7 Tokyo, Japan

Tokyo is the capital of Japan with 8 million people residing in its 23 wards and is considered the largest metropolitan area in the world (Kottek et al 2008). The city lies on the shore of the Pacific Ocean and is classified as having a Humid Subtropical Climate with hot and humid summers and mild winters with cold spells (Kottek et al 2008). As mentioned earlier UHI intensity in Tokyo has been recorded as high as 2.5 ^{o}C (Hirano et al 2009). For this study the urban measuring station was located just slightly inland (139.45E, 35.41N) while the rural station was an airport on the coast of the nearby island of Oshima (139.36E, 34.75N).

Fig. 14: 3d buildings satellite image of urban Tokyo (left) and actual satellite image of rural Oshima (right). Taken with Google Earth. April 10, 2012.

The urban location had a higher mean air temperature of 0.22 ^{o}C on average per month, but could reach a mean of 2 ^{o}C higher in July and August. The difference between maximum temperatures for the two locations was highest at 4 ^{o}C in March 2010, May 2011, and September 2011. This resulted in an urban- rural difference in CDD's of 598 for the study period. These results suggest that UHI is responsible for 34.6% of the CDD's experienced during the study period. The largest difference for one month was 77 CDD's in August 2010. Surprisingly there were 471 more HDD's in the urban location as well.

4.8 Dhaka, Bangladesh.

Dhaka is the capital city of Bangladesh and the one of the largest cities in Asia, with a population estimated well over 10 million (2010, citypopulation.de). Dhaka is considered a hot and humid Tropical Savannah Climate, with a yearly average humidity of 73.4% (2011) (Kottek et al 2008). Burkart *et a*l (2011) measured the UHI intensity of Dhaka to have a range of 0.3- 2.1 K, with the highest differences occurring in March and April. Interestingly, the UHI was not observed to be significantly greater at night in their study. The Burkart *et al* (2011) study was focused on assessing the heat related mortality rates for Dhaka, and found that people in urban centres of the city were indeed at greater risk of mortality during heat waves and they concluded that a 1 ^{o}C increase in urban temperature could lead to an increase of up to 15% in heat related deaths. For the present study there was not sufficient 36 month temperature data, as used in the previous cases, however NASA station data showed an average UHI intensity of 1.04 ^{o}C for the year 2000, when Dhaka city station was compared with the smaller city of Mymensingh which was used as the rural station by Burkart *et al* (2011).

Fig. 15: Satellite image of urban Dhaka (left) and rural Dhaka (right). Taken with Google Earth. April 10, 2012.

For the degree day calculation the urban station used here was an airport located within the city (90.38E, 23.78N) and the rural location was an isolated airport, located in Agartala, India (91.24E, 23,89N). For the entire study period there was 764 more CDD's recoded at the urban station than at the rural one, with a monthly average difference of 21.23 CDD's. These results would suggest that UHI is accounting for 12.5% of the experienced CDD's recorded in Dhaka. There was an HDD savings (presumably due to UHI) from December through May, which amounted to 191 less HDD's at the urban site for the 36 month period.

4.9 Taipei, Taiwan

Taipei is the capital of Taiwan (officially known as The Peoples Republic of China) and has an estimated population of 2,618,772. Taiwan is an island lying in the Pacific Ocean off the coat of China, with Japan to its North and the Philippines to its south, and Taipei is located on the northern tip of the island. Taiwan has a monsoon influenced Humid Subtropical Climate (Kottek et al 2008). The island of Taiwan is densely populated, with about 23 million people inhabiting 36,000 km^2. The island has been industrialising rapidly and as a result, the diurnal temperature range has risen by 1.1 °C since 1950 (Wen-Zer Lin et al 2005). Wen-Zer Lin *et al* (2005) used methods similar to this papers study to look at the UHI intensity in ten of the largest cities in Taiwan and found that Taipei exhibited a UHI intensity of only 1.60 °C which is small in proportion to its population compared to the other cities in Taiwan. This is also small compared to the Hsieh et al (2011) study mentioned earlier that showed a summer time UHI of 4.9 °C. In the present study the urban measuring station was not in the downtown but still had a very central location (121.52E, 25.03N) and the rural location was an airport just west of the city (121.23E, 25.098N).

Fig. 16: Satellite image of urban Taipei (left) and rural Taipei (right). Taken with Google Earth. April 10, 2012.

The station data showed the mean temperature for the urban location was 0.69 °C higher than the rural location on average with the biggest difference in monthly means being 2 °C. For one month the difference between maximum temperatures reached was 10 °C, but on average the monthly difference was .72 °C. For the entire study period there was 234 more CDD's recorded in the urban location with 6.5 CDD's more on average per month. The biggest difference in urban-rural CDD's for one month was 26 in July of 2011.

The urban station recorded 98 less HDD’s than the rural, with the largest difference being 18 CDD’s in March 2012. From these results one could conclude that 6% of the CDD’s recorded in the urban location were the result of UHI.

5. Predicting UHI Impact:

5.1 Regression Results

This section presents the summarised results and useful interpretation of the regression analysis of case study degree-day calculations with mean monthly temperatures and maximum monthly temperatures. Table 8 is showing the results for the regression between HDD's and monthly mean temperatures. Table 9 is showing the results of the regression between CDD's and monthly mean temperatures.

5.1.1 Mean monthly temperature regressed with degree days

City	Regressed	Beta	T-stat	F-stat	Adj. R2
New York	Urban HDD	-19.12	-16.43	0	0.88
	Rural HDD	-17.99	-18.32	0	0.91
Athens	Urban HDD	-8.09	-9.38	0	0.71
	Rural HDD	-10.46	-12.08	0	0.81
Rhome	Urban HDD	-11.66	-9.69	0	0.73
	Rural HDD	-10.63	-10.05	0	0.74
Paris	Urban HDD	-20.67	-23.50	0	0.94
	Rural HDD	-22.60	-29.94	0	0.96
Taipei	Urban HDD	17.37	17.95	0	0.90
	Rural HDD	16.98	17.23	0	0.89
Tokyo	Urban HDD	-13.30	-12.72	0	0.82
	Rural HDD	-13.47	-13.42	0	0.84

Table 8. Monthly HDD regressed with Monthly Mean temperature.

City	Regressed	Beta	T-stat	F-stat	Adj. R2
New York	Urban CDD	4.61	7.30	0	0.60
	Rural CDD	3.97	7.15	0	0.59
Athens	Urban CDD	11.16	11.68	0	0.79
	Rural CDD	9.63	11.92	0	0.81
Rhome	Urban CDD	8.08	9.91	0	0.74
	Rural CDD	5.70	9.99	0	0.74
Paris	Urban CDD	2.24	6.71	0	0.56
	Rural CDD	1.70	6.46	0	0.54
Taipei	Urban CDD	17.37	17.95	0	0.90
	Rural CDD	16.98	17.23	0	0.89
Tokyo	Urban CDD	7.72	8.90	0	0.69
	Rural CDD	6.01	7.67	0	0.62

Jakarta	Urban CDD	21.30	10.27	0	0.75
	Rural CDD	23.67	6.42	0	0.53
Manila	Urban CDD	30.51	13.31	0	0.83
	Rural CDD	26.03	8.28	0	0.66

Table 9 Monthly CDD's regressed with mean monthly temperature.

5.1.2 Maximum monthly temperature regressed with degree days

City	Regressed	Beta	T-stat	F-stat	Adj. R2
New York	Urban HDD	--18.46	--8.46	0	0.66
	Rural HDD	-17.86	-12.69	0	0.71
Athens	Urban HDD	--7.16	--8.92	0	0.69
	Rural HDD	--9.87	--11.19	0	0.78
Rhome	Urban HDD	-9.08	-10.87	0	0.76
	Rural HDD	--10.03	--9.40	0	0.71
Paris	Urban HDD	-15.38	--13.23	0	0.83
	Rural HDD	-16.90	--17.84	0	0.90
Taipei	Urban HDD	-2.85	-7.41	0	0.61
	Rural HDD	-3.41	-7.47	0	0.61
Tokyo	Urban HDD	--14.85	--11.98	0	0.80
	Rural HDD	-17.26	-12.17	0	0.81

Table 10: Monthly maximum temperature regressed with monthly HDD's.

City	Regressed	Beta	T-stat	F-stat	Adj. R2
New York	Urban CDD	4.80	6.97	0	0.53
	Rural CDD	4.31	6.39	0	0.905279
Athens	Urban CDD	9.55	9.56	0	0.72
	Rural CDD	8.85	9.88	0	0.73
Rhome	Urban CDD	5.98	9.11	0	.70
	Rural CDD	5.15	8.13	0	0.65
Paris	Urban CDD	1.65	5.84	0	0.49
	Rural CDD	1.24	5.75	0	.48
Taipei	Urban CDD	20.01	8.95	0	0.69
	Rural CDD	20.78	11.16	0	0.78
Tokyo	Urban CDD	7.93	6.85	0	0.57
	Rural CDD	8.87	7.26	0	0.60
Jakarta	Urban CDD	13.97	1.91	.24	..001
	Rural CDD	0.75	6.17	0.33	-0.001
Manila	Urban CDD	4.38	2.27	.03	.21
	Rural CDD	5.95	3.19	.003	0.01

Table 11: Monthly maximum temperatures regressed with monthly CDD's.

The results can be interpreted as follows: The Beta column refers to the Beta Coefficient which is describing here the amount that degree days are changing for every one degree Celsius rise in air temperature. Note that this is not an exact number but refers to the slope of the trend for the 36-month period. For example, in Paris city centre the Beta Coefficient for HDD's was -20.67, meaning that for every one-degree rise in temperature, HDD's will be reduced by roughly 21. In December of 2010 the difference in urban and rural monthly mean temperatures was 2.2 ^{0}C degrees, so by multiplying the Beta with the mean UHI we might expect that the rural location received 45 more HDD's than the urban location, and in fact there were 50 more HDD's recorded in the rural location for that month. You can see this is not an exact method of prediction but can give a reasonable estimation if you do not have urban and rural measuring station data to compare but do have temperature data for one station and some idea of what UHI you can expect for that size of city.

When performing regression we are testing to see how much correlation exists between two factors, therefore we are actually testing two hypothesise, for example: Null Hypothesis: There is no linear relationship between mean monthly temperature and HDD's, Hypothesis 1: there exists a linear relationship between mean monthly temperature and HDD's. The P- value is a way to summarise for comparison the amount of correlation between different relationships, with the P- value representing the probability of an event (the probability degree days will occur within this trend). The smaller the P- value, the larger level of confidence you have in rejecting the null hypothesis. In this case t-stats are used to describe the P-Value, where the larger the t-stat is the smaller the P-value. With a 95% level of confidence you would have a t-stat of 2.04. The regression shows that for every almost case both mean monthly temperature and monthly maximum temperature have t-stats higher than 2.04, so we see the relationship between these factors and degree days is strong. However, the mean monthly temperature t-stats are higher then monthly maximum temperature t-stats, so there is more correlation with degree days and mean temperatures than maximum temperatures. F-stat is another measure of significance where the lower the stat the better, so a .05 would indicate the entire model is significant at 5%. The adjusted R2 calculation is describing the overall regression fit, meaning it is describing what percentage of the degree days are described by the model. One might expect this to be 100% because degree days are directly calculated by Mean temperature, however this is not the case because often the degree day calculations are not in correlation with the temperatures because the base temperature has not been surpassed.

5.2 Predicting Maximum UHI

As mentioned earlier, population is an excellent way to predict maximum the UHI intensity of a city. Oke (1982) describes the relationship of UHI intensity in a city to its population size, stating that an increasing urban infrastructure (transport, buildings, utilities) required tosustain growing populations will in turn trap more heat within the city centre. Oke proved this by correlating measured UHI intensities ($\Delta T_{U\text{-}R}$) in cities with their population (P) densities to show that the size of a city has a direct impact on UHI intensity, so ($\Delta T_{U\text{-}R}$) is proportional to LOG P. The ideal conditions for UHI development were shown to be clear skies and calm winds and so these conditions could be considered to describe the maximum UHI intensity ($\Delta T_{U\text{-}R}$ *(max)*). It was shown that expected maximum UHI ($\Delta T_{U\text{-}R}$ *(max)*) would be 8 K in European cities and 12 K in American cities, likely due to trend of U.S. cities to contain tall sky-scrapers and denser areas (Shahmmohohamadi et al 2010). Based on these findings Oke (1987) developed an equation for calculating expected UHI intensity in a city:

$$\Delta T_{U\text{-}R} = P^{0.25} / (4U)^{0.5}$$

Where $\Delta T_{U\text{-}R}$ is the UHI intensity in K, P is the population size and U is the non-urban regional wind speed (m/s) at 10 m.

5.2.1 Using Oke's equation with Beta Coefficient

The Beta Coefficient obtained from the regression analysis can be thought of as an indicator for how sensitive a locations energy consumption is to a change in the mean or maximum temperature. In an effort to estimate UHI energy impact for mitigation prioritisation, Oke's equation was used to predict maximum UHII for each city based on their population and yearly average rural wind speed (obtained from the rural measur5ing sites). This was then multiplied by the urban Beta Coefficient for HDD's and CDD's from the regression analysis of monthly mean temperature and degree days. This does not give an actual calculation for what the energy consumption will be, as max UHI will not raise mean monthly temperature to the same level, but this does allow for a simple comparison of cities that accounts for both their UHII potential and climatic conditions. Table 12 summarises this comparison:

City	Oke's Max UHI	Case Max UHI	HDD Potential	CDD Potential	UHI threat
Athens	9.06	5.8	-73	100	27
Tokyo	6.26	5	83	48	-35
Manila	5.97	9	0	182	182
Jakarta	9.9	6	0	228	228
Rome	7.82	5.7	-91	63	-28
Paris	9.32	9.3	-192	21	-171
New York	9.46	4	-170	44	-126
Taipei	5.82	4	-98	101	3

Table 12: Shows results of UHII estimation using Oke's equation (left), observed maximum UHI, Oke's UHII multiplied by Urban HDD/ mean temp Beta Coefficient, Oke's UHII multiplied by Urban CDD/ mean temp Beta Coefficient, and the Hdd potential +CDD potential.

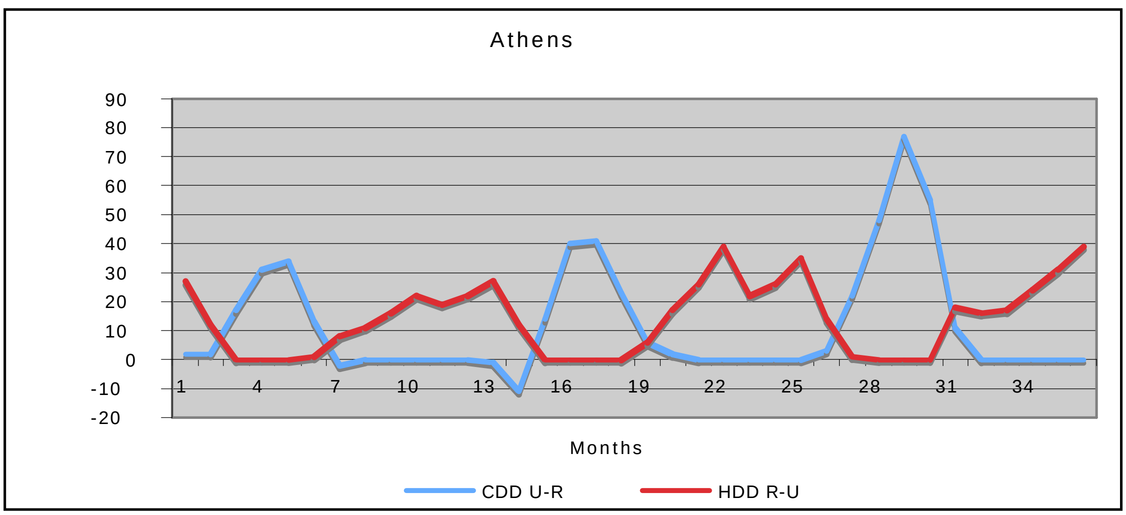
This experiment estimates that mitigation priority should go: Jakarta, Manila, Athens, Taipei, Rome, Tokyo, New York, and Paris. These conclusions are not exactly the same as one would get from looking at the observed data, but the order is very similar and experiment conclusions are mostly logical when considering the literature. It should also be noted that this experiment does not work when using the maximum temperature Beta Coefficients as maximum does not appear to have as much influence on the degree days in hotter climates as in moderate climates (judging from t-stats).

To compare air temperature and degree day records, 9 cities with a variety of climates and infrastructures were chosen as case studies. Albedo, the presence of vegetation, and sky view factor have been identified in the literature as the most influential factors in determining UHI and so this paper's study chose its urban and rural measuring stations based on estimations of the influential factors found in the literature. The results of the station data analysis are summarised in table 4. In most cases the degree day calculations were consistent with what was expected based on climates, in that cities with higher temperatures had greater UHI related cooling demands and cities with lower temperatures had heating demands reduced by UHI more than cooling demands increased. This was not always the case however, and this may be attributed to the fact that measuring stations were not always in the ideal conditions to represent their land use categories.

City	Urban Mean Temp (C)	Urban Mean Max. temp (C)	Avg. Mean UHI (C)	Total CDD diff. (u-r)	Total HDD diff. (r-u)
Jakarta	28.67	34.14	1.72	1,073	0
Manila	28.22	34.22	.25	1,079	0
Taipei	23.35	32.72	.69	234	98
Athens	20.24	28.03	3.24	427	508
Rome	17.21	26.04	.24	492	-29
Tokyo	16.22	25.94	.13	598	-471
New York	13.95	27.19	1.17	6	642
Paris	13.18	24.37	1.45	96	1106
Dhaka	NA	NA	1.04	764	191

Table 13: Summary of temperature and degree day data. Full data can be found in the appendix

In some cases the relationship between urban and rural temperature and degree day calculations were the opposite of what was expected, highlighting the complexity and variability of UHI. The case study data shows no correlation between maximum temperatures and maximum UHI, nor can UHI statistically predict degree day differences. Comparing graphs of Athens and Paris degree day differences summarises how UHI can affect different cities in Europe. When looking at figure 17 one can easily see that the energy consumption balance due to UHI is mostly even in Athens, where it is saving energy in Paris.



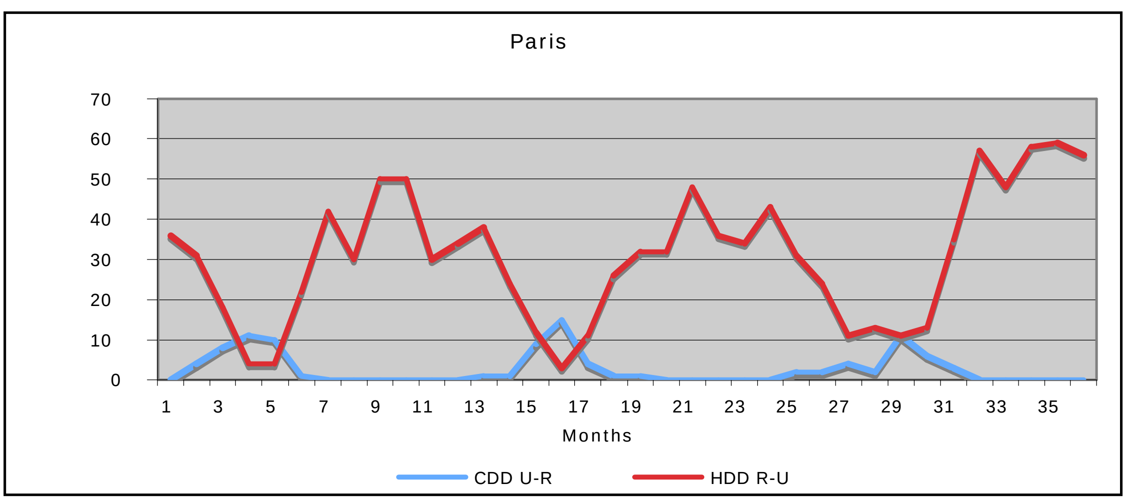


Fig .17 Comparison of graphs showing UHI energy balance (HDD savings and CDD losses) in Athens and Paris case studies. X axis is monthsin study period, starting with April 2009, and y axis is degree day differences.

To discover ways for predicting UHI impact on energy consumption (sub question 7), regression analysis was performed between degree days and mean and maximum monthly temperatures. It was found that degree days could be approximated reasonably well by this method in the event there is not numerous measuring stations available for comparison. This can be useful, as it was found during the course of this study that many of the cities in the developing world only have one temperature measuring station, usually being the local airport. Furthermore, multiplying Oke's equation with mean temperature/degree day Beta Coefficients can also be useful in prioritising cities for mitigation necessity, however this is just an approximation and not an exact method.

6. Conclusions

It can be seen from both the literature and the case studies that UHI exist in most major cities and it has a significant effect on energy consumption. While many cities may save as much on reduced heating costs due to UHI than they lose on cooling costs, it is clear that the combination of impacts that UHI imposes offers a significant problem in light of the expected continuation of climate change. The literature has provided predictors for regions where UHI will have the greatest impact on energy use, such as population, climate, density, building stock, infrastructure, and income. For the most part, the case studies used have confirmed these predictions and therefore regions with high UHI vulnerability are often obvious. Mitigation has the potential to greatly reduce all of the impacts of UHI, but choosing the best option will differ on a case by case basis. Urban forestry has shown to be the most effective strategy but also may be the most costly, while albedo increases may have the cheapest and greatest overall potential for impact. The literature has shown that UHI is expected to become much more of an energy burden as temperatures continue to rise.

Significant differences in temperature and degree days were found in all 9 cities examined. The regression analysis performed in this study showed that urban-rural differences in mean temperature and monthly maximum temperature do not correlate with differences in degree days. The study did show that monthly mean temperature does correlate with monthly degree days, as do monthly maximum temperatures, and these can be used to roughly approximate degree day differences if only one station is available with data and the average UHI for that city is known.

Station data can be useful in estimating UHI effects on energy consumption; however limited data greatly limits this approach. The method of combining regression analysis results with Oke's equation for estimating maximum UHI can be useful in prioritising mitigation but it is far from exact and therefore remote sensing techniques may offer more accuracy.

7.1 Recommendations for further research

The methodology used in this study would be much more useful if better station data was available, so this may be an interesting study to try in the near future when more measuring stations are available. Mean monthly maximum temperature would also be interesting to regress with degree-days, however this is also currently difficult due to data availability. Another good approach would be to perform regression between UHI data based on land surface temperatures and actual energy consumption rates for various cities.

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Appendices

Degree Day Data

ATHENS

	23.94E, 37.94N		23.73E,37.89N			
	Athens Rura LGAV		Athens Urban LGAT		HDD Savings	CDD Losses
Month starting	HDD B 15.5	CDD B 21.5	HDD B 15.5	CDD B 21.5	UHI (R-U)	UHI (U-R)
4/1/09	71	0	44	2	27	2
5/1/09	17	42	5	44	12	2
6/1/09	0	111	0	128	0	17
7/1/09	0	192	0	223	0	31
8/1/09	0	162	0	196	0	34
9/1/09	1	46	0	59	1	13
10/1/09	13	19	5	17	8	-2
11/1/09	75	0	64	0	11	0
12/1/09	84	0	68	0	16	0
1/1/10	170	0	148	0	22	0
2/1/10	118	0	99	0	19	0
3/1/10	114	0	92	0	22	0
4/1/10	47	3	20	2	27	-1
5/1/10	14	50	2	39	12	-11
6/1/10	0	105	0	119	0	14
7/1/10	0	182	0	222	0	40
8/1/10	0	219	0	260	0	41
9/1/10	0	73	0	96	0	23
10/1/10	24	9	18	15	6	6
11/1/10	35	2	18	4	17	2
12/1/10	126	0	100	0	26	0
1/1/11	204	0	165	0	39	0
2/1/11	169	0	147	0	22	0
3/1/11	164	0	138	0	26	0
4/1/11	80	0	45	0	35	0
5/1/11	19	15	5	18	14	3
6/1/11	1	91	0	113	1	22
7/1/11	0	199	0	247	0	48
8/1/11	0	167	0	244	0	77
9/1/11	0	105	0	160	0	55
10/1/11	41	8	23	19	18	11
11/1/11	137	0	121	0	16	0
12/1/11	155	0	138	0	17	0
1/1/12	267	0	243	0	24	0
2/1/12	214	0	183	0	31	0
3/1/12	154	0	115	0	39	0
Toatal	2514	1800	2006	2227	508	427
Average/month					14.1111111	11.8611111

					1	1
	Rome					
	12.50E, 41.86N		12.24E, 41,80N			
	Urban Rome Appla Antica		Rural Rome Flumicino		UHI Savings	UHI Losses
Month starting	HDD B 15.5	CDD B 21.5	HDD B 15.5	CDD B 21.5	HDD (R-U)	CDD (U-R)
4/1/09	30	4	71	0	41	4
5/1/09	11	69	26	38	15	31
6/1/09	0	86	2	52	2	34
7/1/09	0	154	2	117	2	37
8/1/09	0	174	0	144	0	30
9/1/09	0	63	1	57	1	6
10/1/09	39	9	48	7	9	2
11/1/09	85	0	71	0	-14	0
12/1/09	175	0	168	0	-7	0
1/1/10	230	0	222	0	-8	0
2/1/10	175	0	167	0	-8	0
3/1/10	136	0	141	0	5	0
4/1/10	59	6	65	0	6	6
5/1/10	18	18	19	4	1	14
6/1/10	1	79	3	51	2	28
7/1/10	0	184	1	139	1	45
8/1/10	0	128	0	91	0	37
9/1/10	2	46	2	43	0	3
10/1/10	26	8	23	6	-3	2
11/1/10	95	0	58	0	-37	0
12/1/10	209	0	200	0	-9	0
1/1/11	207	0	187	0	-20	0
2/1/11	189	0	196	0	7	0
3/1/11	131	0	149	0	18	0
4/1/11	37	8	54	0	17	8
5/1/11	14	45	18	15	4	30
6/1/11	0	106	0	53	0	53
7/1/11	0	124	0	78	0	46
8/1/11	0	160	0	111	0	49
9/1/11	1	89	0	66	-1	23
10/1/11	24	12	24	10	0	2
11/1/11	110	0	89	0	-21	0
12/1/11	169	0	140	0	-29	0
1/1/12	229	0	210	0	-19	0
2/1/12	268	0	268	0	0	0
3/1/12	80	2	96	0	16	2
Toatal	2750	1574	2721	1082	-29	492
Average per month					-0.805555556	26.59459459

	2.53E, 49.02N		2.34E, 48.85N			
	Paris airport		Paris city centre		UHI savings	UHI losses
Month starting	HDD B 15.5	CDD B 21.5	HDD B 15.5	CDD B 21.5	HDD (R-U)	CDD (U-R)
4/1/09	105	0	69	0	36	0
5/1/09	63	5	32	9	31	4
6/1/09	32	17	14	25	18	8
7/1/09	5	31	1	42	4	11
8/1/09	4	52	0	62	4	10
9/1/09	31	7	9	8	22	1
10/1/09	118	1	76	1	42	0
11/1/09	162	0	132	0	30	0
12/1/09	362	0	312	0	50	0
1/1/10	462	0	412	0	50	0
2/1/10	328	0	298	0	30	0
3/1/10	254	0	220	0	34	0
4/1/10	148	2	110	3	38	1
5/1/10	118	7	94	8	24	1
6/1/10	26	26	14	35	12	9
7/1/10	3	54	0	69	3	15
8/1/10	15	17	4	21	11	4
9/1/10	50	3	24	4	26	1
10/1/10	144	1	112	2	32	1
11/1/10	258	0	226	0	32	0
12/1/10	474	0	426	0	48	0
1/1/11	342	0	306	0	36	0
2/1/11	262	0	228	0	34	0
3/1/11	212	0	169	0	43	0
4/1/11	78	6	47	8	31	2
5/1/11	51	9	27	11	24	2
6/1/11	24	21	13	25	11	4
7/1/11	20	9	7	11	13	2
8/1/11	14	23	3	34	11	11
9/1/11	18	20	5	26	13	6
10/1/11	93	5	58	8	35	3
11/1/11	187	0	130	0	57	0
12/1/11	258	0	210	0	48	0
1/1/12	289	0	231	0	58	0
2/1/12	401	0	342	0	59	0
3/1/12	186	0	130	0	56	0
Total	5597	316	4491	412	1106	96
Average per					30.7222222	2.66666666

month					2	7

	139.78E, 35.55N		139.45E, 35.41N			
	Tokyo (airport)		Tokyo inner city		UHI Savings	UHI Losses
Month starting	HDD B 15.5	CDD B. 21.5	15.5	CDD B 21..5	HDD (R-U)	CDD (U-R)
4/1/09	45	1	43	2	2	1
5/1/09	1	11	1	20	0	9
6/1/09	0	34	0	50	0	16
7/1/09	0	126	0	149	0	23
8/1/09	0	141	0	160	0	19
9/1/09	0	41	0	55	0	14
10/1/09	2	8	3	9	-1	1
11/1/09	76	1	84	1	-8	0
12/1/09	192	0	201	0	-9	0
1/1/10	258	0	265	0	-7	0
2/1/10	252	0	254	0	-2	0
3/1/10	205	0	207	0	-2	0
4/1/10	114	0	112	1	2	1
5/1/10	8	9	7	16	1	7
6/1/10	0	65	0	83	0	18
7/1/10	0	182	0	201	0	19
8/1/10	0	232	0	251	0	19
9/1/10	0	124	0	132	0	8
10/1/10	12	9	16	13	-4	4
11/1/10	66	0	74	0	-8	0
12/1/10	171	0	178	0	-7	0
1/1/11	312	0	324	0	-12	0
2/1/11	232	0	240	0	-8	0
3/1/11	232	0	233	0	-1	0
4/1/11	64	1	66	1	-2	0
5/1/11	6	7	6	10	0	3
6/1/11	1	54	1	66	0	12
7/1/11	0	169	0	183	0	14
8/1/11	0	183	0	186	0	3
9/1/11	0	120	0	123	0	3
10/1/11	3	12	4	16	-1	4
11/1/11	45	0	50	0	-5	0
12/1/11	240	0	249	0	-9	0
1/1/12	324	0	331	0	-7	0
2/1/12	292	0	291	0	1	0
3/1/12	213	0	209	0	4	0
Total	3366	1530	3449	1728	-83	198
Average per month					-2.30555555	5.5

						6	

	106.95E, 6.70S		106.84E, 6.19S			
	Rural Jakarta		Jakarta City (observatory)		UHI Sacings	UHI Losses
Month starting	HDD B 15.5	CDD B 21.5	HDD B. 15.5	CDD B 21.5	HDD (R-U)	CDD (U-R)
4/1/09	0	36	0	229	0	193
5/1/09	0	36	0	228	0	192
6/1/09	0	38	0	232	0	194
7/1/09	0	39	0	239	0	200
8/1/09	0	42	0	241	0	199
9/1/09	0	47	0	241	0	194
10/1/09	0	40	0	247	0	207
11/1/09	0	30	0	210	0	180
12/1/09	0	28	0	218	0	190
1/1/10	0	14	0	184	0	170
2/1/10	0	22	0	189	0	167
3/1/10	0	30	0	222	0	192
4/1/10	0	49	0	250	0	201
5/1/10	0	49	0	247	0	198
6/1/10	0	29	0	214	0	185
7/1/10	0	35	0	220	0	185
8/1/10	0	31	0	228	0	197
9/1/10	0	23	0	194	0	171
10/1/10	0	25	0	196	0	171
11/1/10	0	24	0	209	0	185
12/1/10	0	13	0	197	0	184
1/1/11	0	8	0	185	0	177
2/1/11	0	15	0	175	0	160
3/1/11	0	22	0	202	0	180
4/1/11	0	27	0	214	0	187
5/1/11	0	32	0	230	0	198
6/1/11	0	41	0	228	0	187
7/1/11	0	30	0	220	0	190
8/1/11	0	38	0	235	0	197
9/1/11	0	36	0	236	0	200
10/1/11	0	39	0	243	0	204
11/1/11	0	26	0	226	0	200
12/1/11	0	28	0	218	0	190
1/1/12	0	12	0	188	0	176
2/1/12	0	23	0	200	0	177
3/1/12	0	23	0	214	0	191
Total						6769
Average						188.027777

		8

Month starting	120.27E, 14.79N Sublic Bay Wther Station HDD 15.5	CDD B 21,5	120.98E, 14.58N Manila city center 15.5	CDD B. 21.5	HDD savings	CDD Losses
4/1/09	0	207	0	232	0	25
5/1/09	0	202	0	242	0	40
6/1/09	0	168	0	211	0	43
7/1/09	0	169	0	210	0	41
8/1/09	0	196	0	232	0	36
9/1/09	0	161	0	190	0	29
10/1/09	0	174	0	208	0	34
11/1/09	0	171	0	206	0	35
12/1/09	0	149	0	173	0	24
1/1/10	0	155	0	178	0	23
2/1/10	0	157	0	194	0	37
3/1/10	0	219	0	238	0	19
4/1/10	0	242	0	266	0	24
5/1/10	0	273	0	310	0	37
6/1/10	0	208	0	252	0	44
7/1/10	0	200	0	239	0	39
8/1/10	0	182	0	222	0	40
9/1/10	0	186	0	227	0	41
10/1/10	0	185	0	218	0	33
11/1/10	0	172	0	201	0	29
12/1/10	0	165	0	193	0	28
1/1/11	0	145	0	164	0	19
2/1/11	0	143	0	161	0	18
3/1/11	0	198	0	202	0	4
4/1/11	0	200	0	216	0	16
5/1/11	0	225	0	255	0	30
6/1/11	0	183	0	226	0	43
7/1/11	0	170	0	207	0	37
8/1/11	0	168	0	211	0	43
9/1/11	0	147	0	202	0	55
10/1/11	0	183	0	217	0	34
11/1/11	0	174	0	205	0	31
12/1/11	0	170	0	184	0	14
1/1/12	0	172	0	190	0	18
2/1/12	0	166	0	177	0	11
3/1/12	0	207	0	212	0	5
Total	0	6592	0	7671	0	1079

29.97222222

	73.96W, 40.77N		74.13W, 40.80N			
	Urban Upper ES		Rural N. Arlington		UHI savings	UHI Losses
Date	HDD B 15.5	CDD B 21.5	HDD B 15.5	CDD B 21.5	HDD R-U	CDD U-R
4/1/09	112	18	148	17	36	1
5/1/09	23	18	42	20	19	-2
6/1/09	3	27	7	33	4	-6
7/1/09	0	84	1	77	1	7
8/1/09	0	129	0	114	0	15
9/1/09	3	26	15	27	12	-1
10/1/09	76	1	116	3	40	-2
11/1/09	110	0	170	0	60	0
12/1/09	380	0	431	0	51	0
1/1/10	444	0	498	0	54	0
2/1/10	389	0	424	0	35	0
3/1/10	182	0	224	1	42	-1
4/1/10	73	10	99	12	26	-2
5/1/10	31	42	41	46	10	-4
6/1/10	0	106	2	103	2	3
7/1/10	0	189	0	187	0	2
8/1/10	0	124	1	114	1	10
9/1/10	0	55	7	60	7	-5
10/1/10	55	3	86	6	31	-3
11/1/10	172	0	228	0	56	0
12/1/10	445	0	485	0	40	0
1/1/11	482	0	549	0	67	0
2/1/11	344	0	396	0	52	0
3/1/11	289	0	325	1	36	-1
4/1/11	115	3	141	8	26	-5
5/1/11	22	26	107	30	85	-4
6/1/11	0	76	5	81	5	-5
7/1/11	0	177	0	186	0	-9
8/1/11	0	97	1	92	1	5
9/1/11	3	48	9	35	6	13
10/1/11	75	9	102	7	27	2
11/1/11	717	0	175	0	-542	0
12/1/11	210	0	318	0	108	0
1/1/12	320	0	418	0	98	0
2/1/12	243	0	328	0	85	0
3/1/12	136	2	197	4	61	-2
Total	5454	1270	6096	1264	642	6

	Central Park	Central Park	Upper ES	Upper ES	Heating savings	UHI losses
Month	HDD B 15.5	CDD B 21.5	HDD B 15.5	CDD B. 21.5	HDD (CP-ES)	CDD (ES-CP)
4/1/09	143	14	112	18	31	4
5/1/09	39	13	23	18	16	5
6/1/09	7	17	3	27	4	10
7/1/09	0	51	0	84	0	33
8/1/09	0	88	0	129	0	41
9/1/09	9	15	3	26	6	11
10/1/09	108	0	76	1	32	1
11/1/09	152	0	110	0	42	0
12/1/09	414	0	380	0	34	0
1/1/10	477	0	444	0	33	0
2/1/10	419	0	389	0	30	0
3/1/10	215	0	182	0	33	0
4/1/10	91	8	73	10	18	2
5/1/10	39	30	31	42	8	12
6/1/10	1	88	0	106	1	18
7/1/10	0	173	0	189	0	16
8/1/10	0	114	0	124	0	10
9/1/10	1	50	0	55	1	5
10/1/10	70	1	55	3	15	2
11/1/10	204	0	172	0	32	0
12/1/10	468	0	445	0	23	0
1/1/11	519	0	482	0	37	0
2/1/11	376	0	344	0	32	0
3/1/11	315	0	289	0	26	0
4/1/11	136	3	115	3	21	0
5/1/11	30	21	22	26	8	5
6/1/11	1	61	0	76	1	15
7/1/11	0	157	0	177	0	20
8/1/11	0	78	0	97	0	19
9/1/11	6	32	3	48	3	16
10/1/11	85	4	75	9	10	5
11/1/11	141	0	717	0	-576	0
12/1/11	280	0	210	0	70	0
1/1/12	379	0	320	0	59	0
2/1/12	312	0	243	0	69	0
3/1/12	187	1	136	2	51	1
Total	5624	1019	5454	1270	170	251

	91.24E, 23.89N Dhaka City airport		91.24E, 23.98N VEAT Rural		UHI (R-U)	UHI (Urban-Rural)
	HDD 15.5	CDD 21.5	HDD 15.5	CDD 21.5	HDD Savings	CDD losses
4/1/09	0	264	0	235	0	14
5/1/09	0	227	0	214	2	4
6/1/09	0	268	0	218	2	5
7/1/09	0	233	0	217	5	12
8/1/09	0	228	0	215	1	17
9/1/09	0	214	0	201	1	31
10/1/09	0	185	0	158	0	9
11/1/09	0	107	1	90	0	12
12/1/09	3	26	22	26	0	4
1/1/10	22	14	53	19	0	6
2/1/10	5	66	16	57	0	16
3/1/10	0	206	0	181	-3	7
4/1/10	0	261	0	221	-18	6
5/1/10	0	251	0	211	-19	6
6/1/10	0	227	0	196	-7	5
7/1/10	0	250	0	231	-4	15
8/1/10	0	245	0	225	-2	10
9/1/10	0	221	0	201	-3	23
10/1/10	0	214	0	186	0	19
11/1/10	0	133	0	89	0	11
12/1/10	6	35	26	30	0	0
1/1/11	18	15	61	14	0	-3
2/1/11	2	86	11	53	0	12
3/1/11	0	171	1	125	-1	7
4/1/11	0	201	0	177	-10	7
5/1/11	4	211	0	182	-14	6
6/1/11	0	231	0	212	-3	5
7/1/11	0	233	0	216	0	17
8/1/11	0	213	0	198	-3	26
9/1/11	0	226	0	207	0	19
10/1/11	0	217	2	181	-1	23
11/1/11	0	97	0	70	-1	9
12/1/11	13	41	21	31	0	14
1/1/12	7	18	38	16	0	9
2/1/12	2	77	21	57	0	23
3/1/12	0	177	0	165	#VALUE!	#VALUE!