University of Reading

Mitigating the urban heat island effect with an intensive green roof during summer in Reading, UK

by

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Abstract

The micrometeorological differences between a conventional roof and an intensive green roof located 254 m from each other and at similar elevation were investigated. This took place over a 3 month period during the summer of 2009 in the centre of Reading, South East England. Reading is a medium-sized town with a population of 143,000 and an average urban heat island of 1.6°C. The objective was to determine how effective intensive green roofs are in mitigating the urban heat island effect. Automatic weather stations were installed on each roof and statistical analysis of urban heat island characteristics was conducted with regard to different meteorological and surface controls over the formation of the urban heat island. The main results of the study concluded that it is possible to mitigate the urban heat island using intensive green roofs. The average differences in air temperature between the two roofs were found to be 0.2°C and the absolute maximum air temperature difference was 4.3°C. However, during a six day heat wave in June and July there was no difference in air temperature. Infrared images were taken of both roofs and the surface temperatures were compared. It was found on an overcast day that there was approximately a 4°C difference in surface temperature. Finally, the total roof area in the centre of Reading which could be retrofitted to green roof space without any additional structural support was also estimated to be 20,250 m^2 using ArcMap 9.2 and aerial photographs on Google Earth.

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1. Introduction

1.1. Rationale

Urbanization has reached a point where over half of the earth's population now lives in urban areas even though cities occupy just 2% of our planet's surface (UN-HABITAT 2007; UN-HABITAT, 2008). By the year 2050 it is estimated by the United Nations (UN, 2007) that the population will increase by 2.5 billion from 6.7 to 9.2 billion with nearly all the growth concentrated in urban areas in developing countries. In the UK around 90% of the population now lives in an urban environment with the majority at least three to four generations removed from rural living (Ingleby, 2002). With the government target of delivering an additional 2 million homes by 2016 and 3 million homes by 2020 this trend of urbanization looks set to continue (Department for Communities and Local Government, 2007). Such concentrations of people and activity are exerting increasing stress on the natural and built environment (Roth, 2009). This rapid urbanization in the world has caused changes in the surface and has altered the radioactive, thermal, moisture and aerodynamic properties of the urban environment (Kolokotroni and Giridharan, 2008). As a consequence the climate in urban areas has been altered so that it has a higher mean air temperature than the surrounding rural areas. This difference in temperature is a well documented human induced climate modification called the urban heat island (UHI) (Figure 1.1). Luke Howard was the first known to provide documentation of this phenomenon in *The Climate of London, Deduced from Meteorological Observations, Made in the Metropolis and at Various Places around It* (Howard, 1833). Following this, other notable work in the UK came from Chandler (1965) and Landsberg (1981). Urban temperatures can be up to 5°C warmer then the surrounding countryside but this difference can reach 12°C under favourable meteorological conditions which are usually represented by calm and clear anticyclonic weather (Roth, 2009).

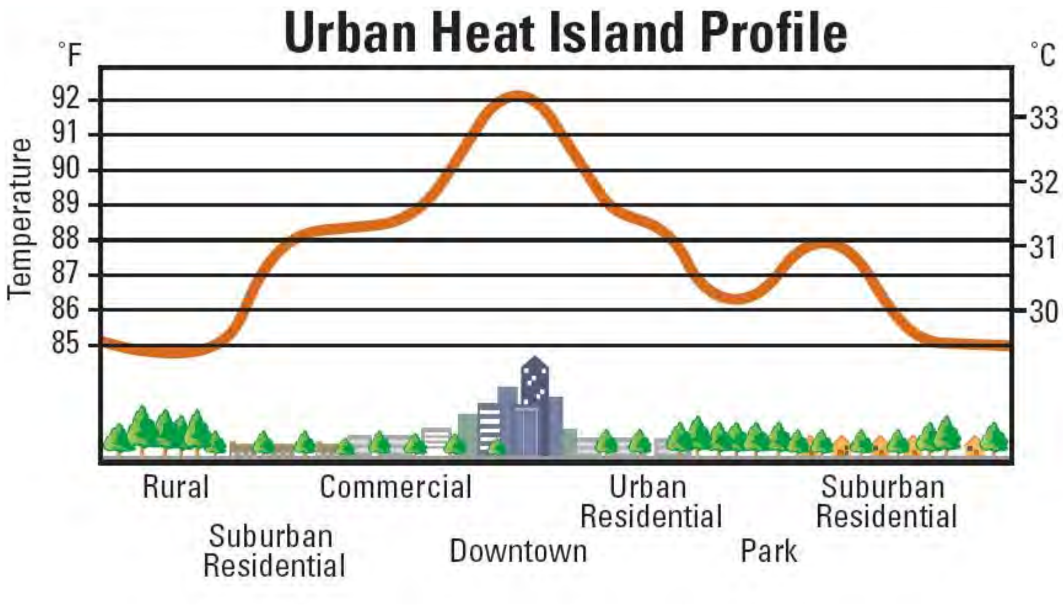

Figure 1.1: Variations in atmospheric temperatures (after GLA, 2006)

There are many environmental and socio-economic consequences to heat island development in urban areas and these are expected to intensify due to global warming (Corburn, 2007). Increased daytime temperatures and reduced night time cooling affect human health and comfort with increased chance of respiratory difficulties, exhaustion, heat cramps, physiological disruption, heat stroke, organ damage and heat related mortality (GLA, 2006; EPA, 2008a). During extreme weather events such as heat waves the risks are even greater (Figure 1.2). Figures produced by Johnson (2004) show that during the July and August 2003 heat wave in England and Wales there were around 2,045 (16%) excess deaths from the 4th to the 13th of August. Those most at risk in the population are the elderly over 75 and people with existing health conditions (Johnson, 2004; EPA, 2008a). The greatest increase in mortality occurred in London where deaths in all ages increased by 42%, of which 59% were over the 75 age group (Johnson, 2004).

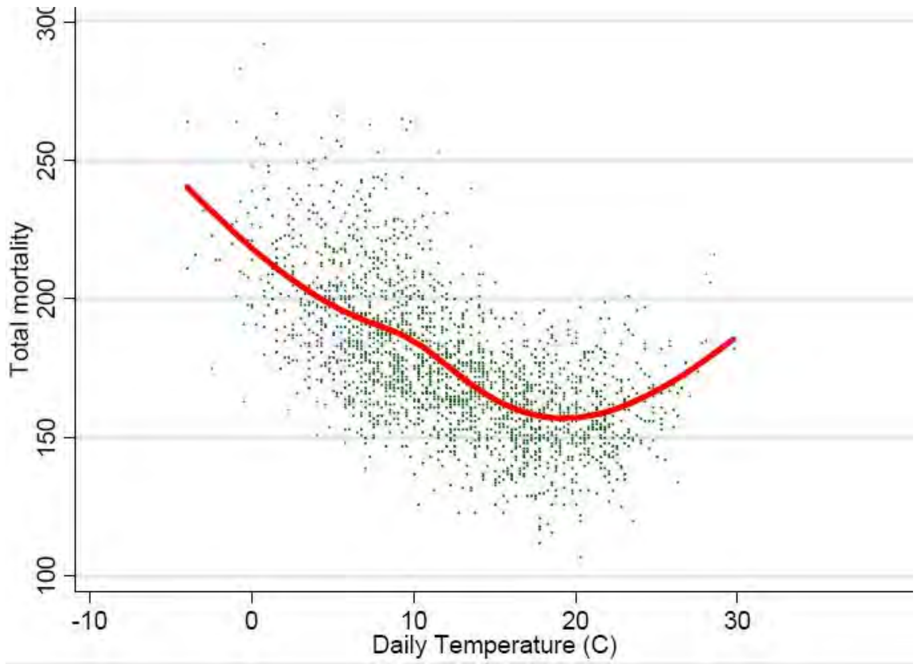

Figure 1.2: Association between daily average temperatures recorded at Heathrow airport and total mortality in London (after GLA, 2006)

High temperatures in cities can also lead to an increase in energy demand for cooling buildings. This in turn puts added pressure on the electricity grid during peak times and increases CO_2 emissions contributing to climate change (GLA, 2006; EPA, 2008a). The Environment Protection Agency (EPA, 2008a) found that in the US for every 0.6°C increase in summertime temperature there was an increase of 1.5 to 2% peak urban electricity demand. Figure 1.3 shows an increase in energy load once temperatures exceed 20 to 25°C.

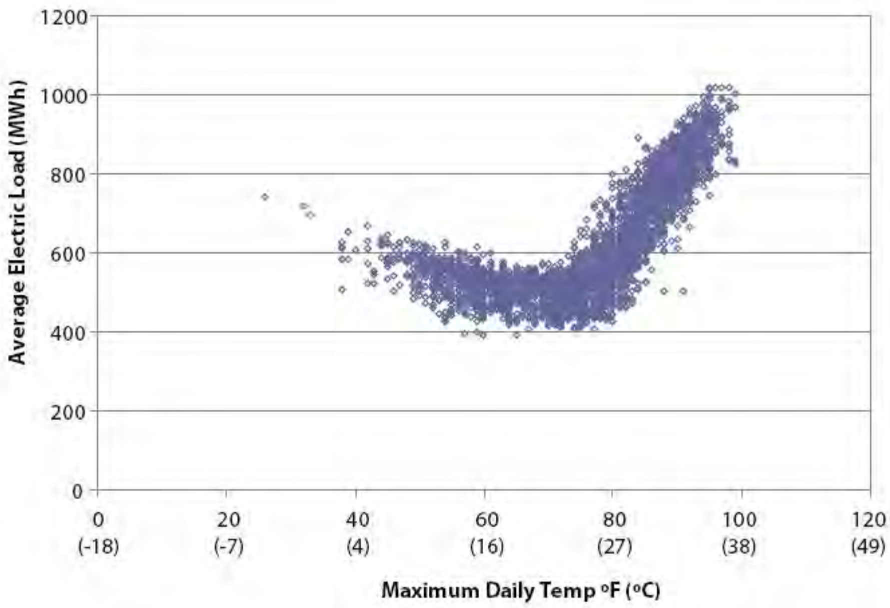

Figure 1.3: Increasing energy demand with temperature increases from New Orleans (after EPA, 2008a)

Increased air conditioning also elevates the rate of anthropogenic heat produced leading to possible further increase in air temperature (GLA, 2006). Weather conditions typical of heat islands also produce high levels of air pollution. Due to the high temperatures, the chemical reactions that produce ozone and smog are accelerated and because of the low wind speed the heat and pollution remain trapped in the city (GLA, 2006). High temperatures may also lead to increasing water usage which could put strain on water supply and dry the soil (GLA, 2006). Other effects of heat islands may include earlier flowering times causing discomfort to allergy sufferers and higher reproduction rates of insect pests (GLA, 2006).

Urban heat islands develop when naturally vegetated surfaces which trap moisture and reduce heat due to evapotranspiration are replaced with non-reflective, water-resistant impervious surfaces that absorb a high percentage of incoming solar radiation (Landsberg, 1981; Taha, 1997). There are a number of UHI mitigation strategies but the two which are commonly researched and employed are increasing the surface reflectivity (albedo) and increasing the vegetation density in urban areas (Solecki et al., 2005; GLA, 2006; Rosenzweig et al., 2006; Rizwan et al., 2008). This can be achieved in several ways, including planting trees and vegetation, better roof designs such as cool roofs, green roofs, reflective roofs and cool pavements (Solecki et al. 2005; GLA, 2006; Rosenzweig et al., 2006; Rizwan et al., 2008). Examples of other strategies include reducing anthropogenic heat release and optimising the sky view factor in new developments (GLA, 2006; Rizwan et al., 2008). The focus of this dissertation will be on mitigating the urban heat island by means of green roofs, and in particular with intensive green roofs. This dissertation will investigate the thermal benefits of intensive green roofs in a medium-size urban area in South East England.

1.2. Objectives and research questions

The key objective of this dissertation will be to quantify and characterize the meliorating thermal properties of intensive green roofs in central Reading. It will aid mitigation of the urban heat island and contribute to the adaptation to climatic warming. The following objectives will be accomplished:

1. Investigate the potential of intensive green roofs to mitigate the effects of the UHI in the Reading town centre.

2. Estimate the total roof surface area which could be used for green roofs in the centre of Reading by analysing aerial photographs.

The following research questions will be addressed:

1. Are there differences in air temperature between the conventional roof and the intensive green roof?
2. At what times during the day are there the greatest differences in air temperature between the conventional roof and the intensive green roof?
3. Will the intensive green roof provide substantial refuge from high temperatures during a heat wave?
4. Which observed controls play a role in the difference in air temperature between the conventional roof and the intensive green roof?
5. How much area would be suitable for green roofs in the centre of Reading?

This dissertation could serve as a resource for policy and decision makers, urban and town planners, developers, building and urban designers, engineers, architects, public health care professionals, geographers, urban climatologists, climate change scientists and anyone interested in sustainable urban living.

1.3. Study area

Reading is a town in the South East of England in the county of Berkshire. It is a unitary authority and located on the confluence of the River Thames and River Kennet some 65 km west of London. The Borough of Reading as defined by The Office for National Statistics in 2001 has a population of 143,096 people and an area of 40.4 km^2 (Neighbourhood Statistics, 2001). Reading's urban area or Greater Reading has a population of 232,662 people in an area of 55.4 km^2 (Neighbourhood Statistics, 2001). It has a population density of 35.4 persons per hectare (Neighbourhood Statistics, 2001). Greater Reading now includes areas administered by Wokingham and West Berkshire District Councils (Punter, 1999). Reading is a typical middle sized urban area in the South East of England which has grown from a large market town into a major regional centre of commerce and industry (Punter, 1999). The town has two universities and has strong links to the information technology and insurance sector.

2. Literature review

2.1. Urbanization and the urban heat island

2.1.1. Urbanization and climate

Cities produce a distinct microclimate. As detailed in this literature review, urbanization has an effect on temperatures in cities. But as well as a temperature increase, urban areas also have an effect on other climatological parameters. Incoming solar radiation is reduced because of scattering and absorption (Santamouris, 2001). In comparison to surrounding rural areas the sunshine duration in industrial cities is reduced by 10 to 20% and similar losses in energy received are observed (Santamouris, 2001). Wind speed in the canopy layer is generally decreased but can sometimes be increased. It may also be altered due to the specific roughness of a city, channelling effect through canyons and also the heat island effect (Santamouris, 2001). Cities will also affect the climate downwind when a heat plume produced by the city drifts over to the rural area as illustrated by Figure 2.1.

2.1.2. Urbanization and the loss of green space in Reading

Reading together with many towns in the UK has experienced expansion in the past 50 years. During this process of urban development trees are cut, natural vegetation cover is largely replaced by paved surfaces and urbanisation takes place. Table 2.1 presents urban development and public green space and waters in the borough between 1960 and 2003. As can be seen, urban development has nearly doubled and in comparison public green space and waters has nearly been halved. This loss of public green space and waters will have an effect on the urban heat island in Reading. If a target is set of reaching the 1960 level of public green space and waters, an additional 5.87 km^2 would be needed. Green roofs can contribute to green space in the urban centre where it is most needed in mitigating the urban heat island.

Table 2.1: Urban development and public sector areas with large green area and waters in Reading between 1960 and 2003 (after Lee, 2008)

	1960		1975		1990		2003	
	km^2	%	km^2	%	km^2	%	km^2	%
Urban development	38.25	100	55.00	143.79	65.75	119.55	71.50	186.93
Public sector areas with large green area (i.e. parks, large plying fields) and waters (i.e. rivers, lakes, ponds)	6.75	17.65	10.50	19.09	7.50	11.41	6.75	9.44

2.1.3. The urban heat island

The urban heat island can be distinguished in three types: (1) the canopy-layer heat island (2) the boundary-layer heat island and (3) the surface heat island (Oke, 1982). The first two are divided by two distinct layers (Figure 2.1). The urban canopy layer (UCL) is measured between the ground and up to the mean roof level like a vegetative canopy layer (Oke, 1982). This layer includes the roughness elements and is where the engineered environment has the most pronounced effect (Golden, 2004). This layer is also controlled by microscale, site-specific characteristics (Golden, 2004). The boundary layer (UBL) is situated above the UCL with the lower boundary layer being influenced by the presence of the city beneath and mesoscale phenomena (Oke, 1982). It is also affected by processes operating at larger spatial and temporal scales (Oke, 1982). The surface heat island occurs on hot, sunny days and is caused by the temperature of exposed urban surfaces becoming higher than that of the air temperature. On average the difference between urban and rural surface daytime temperatures is 10 to 15°C (EPA, 2008b). This is usually characterised by use of airborne or satellite thermal infrared remote sensing (Voogt and Oke, 2003). The focus of this dissertation will be on the canopy-layer heat island.

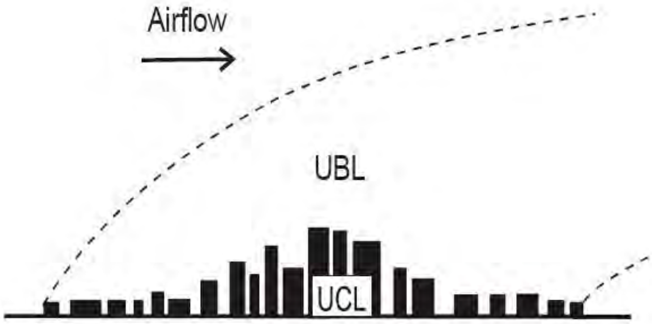

Figure 2.1: A vertically exaggerated cross-section of the urban atmosphere and its two main layers (after Mills, 2004)

According to Landsberg (1981) every town and city is subject to the UHI. Studies which characterise the urban heat island effect typically do this by recording temperatures from a rural or suburban location and of an urban location and analysing the differences. Table 2.2 presents a review of urban heat island intensities in cities around the world.

Table 2.2: Examples of average UHI (Δt_{u-r}) in cities around the world

City	Population	UHI (Δt_{u-r})	Reference
Mexico City, Mexico	8,800,000	5°C (dry season) 1-3°C (wet season)	Jauregui (1997)
New York, US	8,400,000	4ºC (summer, nocturnal)	Rosenzweig et al. (2006)
Melbourne, Australia	3,900,000	1.1 (annual) 1.3(summer) 1.2 (spring) 1.0 (autumn) 1.0 (winter)	Morris et al. (2001)
Lisbon, Portugal	565,000	2.5 ºC (nocturnal)	Alcoforado and Andrade (2006)
Granada, Spain	238,000	3.7 ºC (annual)	Montávez et al. (2000)
Debrecen, Hungary	220,000	2.3ºC	Szegedi and Kircsi (2003)

2.1.4. Controls over the urban heat island

Controls over the urban heat island have been extensively studied by Oke (1987). Urban heat islands are generated by factors which can be categorized as controllable and uncontrollable

(Rizwan et al., 2008) (Figure 2.2). It is not possible to say which of these controls is the most important in UHI formation as each city is unique and the controls will differ in contribution in each case. Figure 2.3 compares the energy balance of a typical non-urban area to a typical urban area.

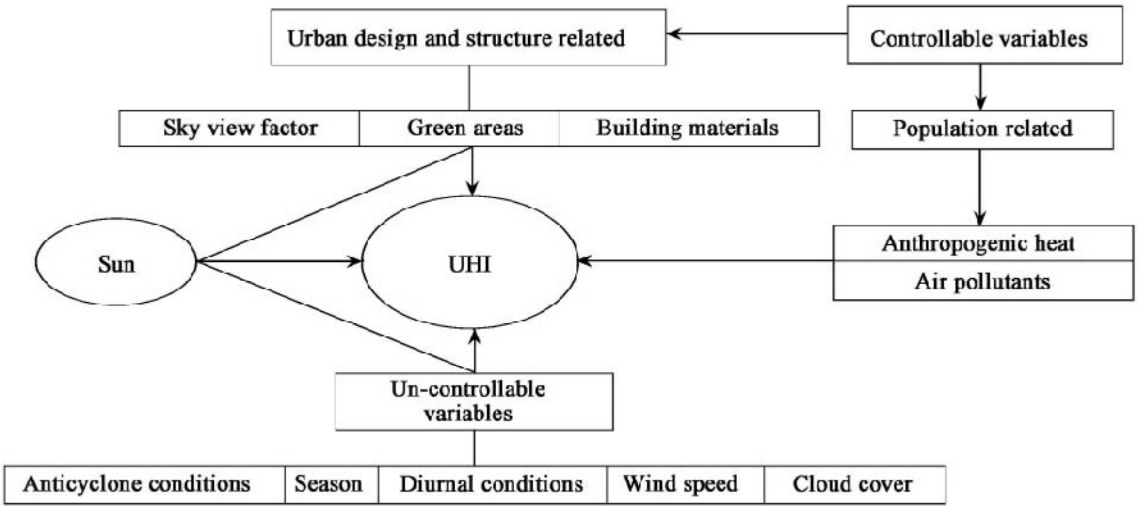

Figure 2.2: Generation of Urban Heat Island (after Rizwan et al., 2008)

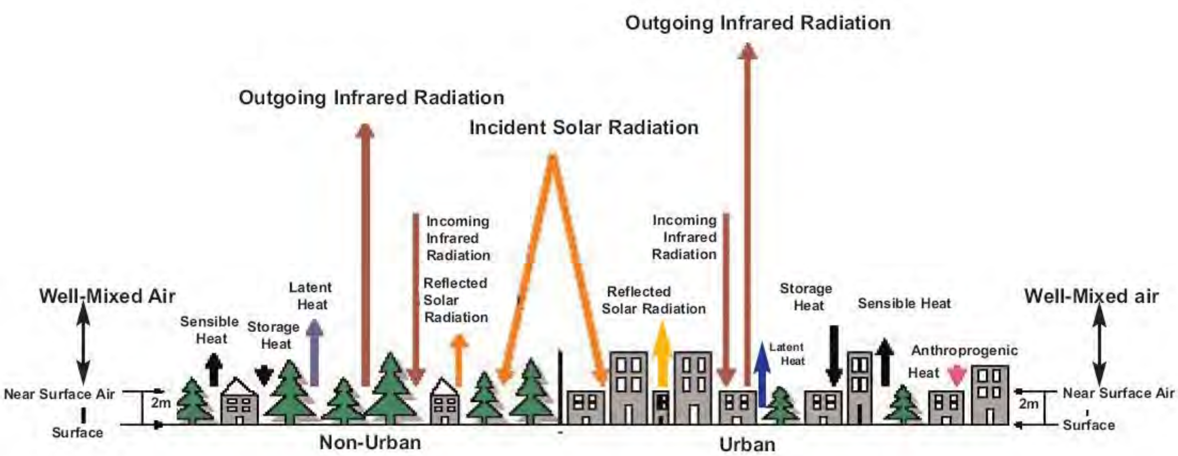

Figure 2.3: Typical non-urban energy balance as compared to a typical urban energy balance. Longer arrows denote a greater heat flux (e.g latent heat flux is larger in non-urban areas than in urban areas; sensible heat flux is larger in urban areas than in non-urban areas) (after Rosenzweig et al., 2006)

2.1.4.1. Urban geometry

Urban structures absorb solar radiation or short-wave radiation flux and store heat. After the sun sets and the environment starts to cool this stored energy is re-radiated as heat or long-wave radiation flux during the night (Rizwan et al., 2008). The amount and proportion of the absorbed solar radiation depends on the nature of the underlying surface, i.e. its colour and geometry. The complex geometry of urban building structures predetermines multiple reflection and absorption of solar radiation resulting in lower albedo values in comparison with the rural environments (Rizwan et al., 2008). Albedo (α) is the hemispherically and wavelength-integrated reflectivity of a surface (Taha, 1997). Typical urban albedos range between 0.10 and 0.20 (Taha, 1997) (Figure 2.4). High albedo building materials reduce the amount of solar radiation absorbed through the building envelope and urban structure and keep their surface cooler (Taha, 1997). These building materials with albedo values of up to 0.90 may include high reflective roofs or pavements lightened by using lighter-coloured aggregate in asphalt (Rosenzweig et al., 2006). A town with white facades and light coloured roofs, Figure 2.5 for example, will have a higher albedo and will thus reduce heat that is re-radiated from the buildings.

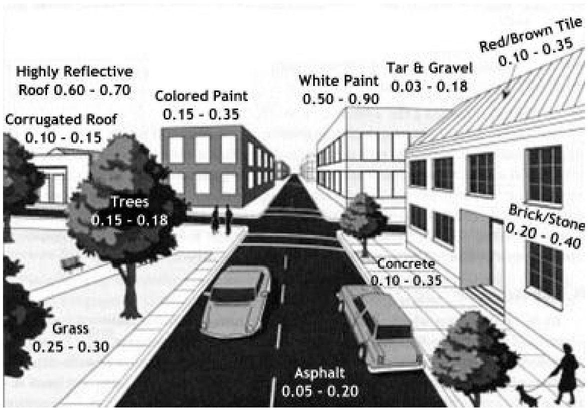

Figure 2.4: Albedo values for various urban surfaces (after Goodman, 1999)

Figure 2.5: Town with white facades and light coloured roofs

Street geometry and orientation also play an important role in determining the urban heat island. Urban geometry will influence the wind flow, radiation and water budget and the air humidity. The factors which play a role in the urban geometry are the canyon street's height-to-width ratio (H/W) and the sky view factor (ψ_s) (Grimmond et al., 2001). Sky view factor (SVF) can be defined as a measure of the degree to which the sky is obscured by the surroundings for a given point (Grimmond et al., 2001). High height-to-width ratios in urban areas will create street canyons leading to multiple reflection of short-wave radiation between the canyon surfaces (Figure 2.6). This will reduce the reflected radiant energy leaving the canyon and decrease the effective albedo causing surfaces to absorb additional solar radiation (Oke et al, 1991; Offerle et al, 2007).

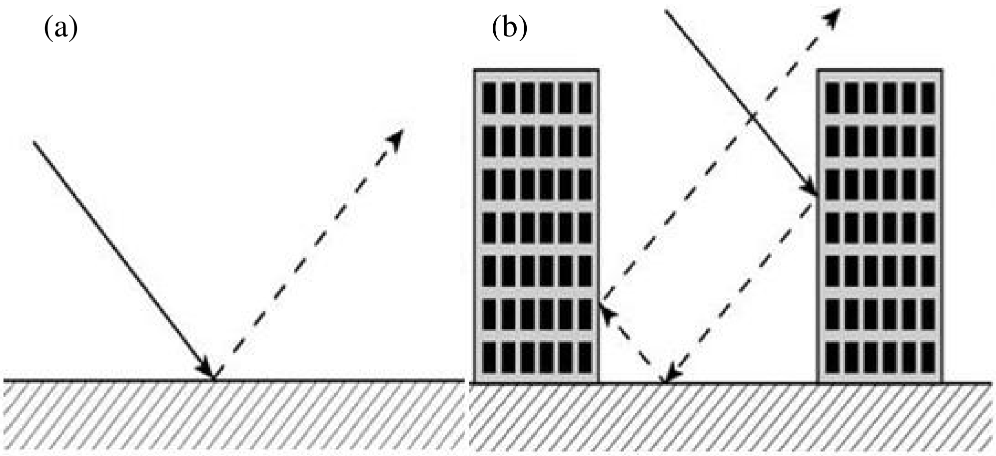

Figure 2.6: Schematic depiction of reflection of short-wave radiation in (a) rural setting and (b) urban setting

2.1.4.2. Vegetation

Another important factor in the creation of the heat island is the loss of vegetation in urban areas (Rizwan et al., 2008) (Figure 2.7). Vegetation and moisture will have a significant effect on the microclimate of the two sample sites. Any surface planted with vegetation has a different Bowen ratio[1] than a mineral surface since a large proportion of net radiation is converted into energy for evapotranspiration and photosynthesis (Wong and Yu, 2005). Less energy will be partitioned into the sensible heat fluxes and more into latent energy fluxes, consequently lowering the air temperature (McPherson, 1994) (Figure 2.8). This partitioning depends largely on the availability of atmospheric, surface, and soil moisture (McPherson, 1994). Urban parks or forests can also provide enough green space to create Park Cool Islands (PCI) within cities. These areas have a lower air and surface temperature and a study by Spronken-Smith and Oke (1999) has reported a cooling effect of 5 - 7°C cooler due to a park in Sacramento, CA. Jauregui (1991) also found that a large urban park in Mexico City can reduce ambient temperatures by 2 - 3°C compared to the surrounding built-up area. The PCI zone also reached outside the park to a distance about the same as the park width (Jauregui, 1991)

[1] Bowen ratio is the proportion of sensible heat to latent heat leaving a surface. It ranges from 0.1 for a moist surface to >10 for a dry surface (Wong and Yu, 2005).

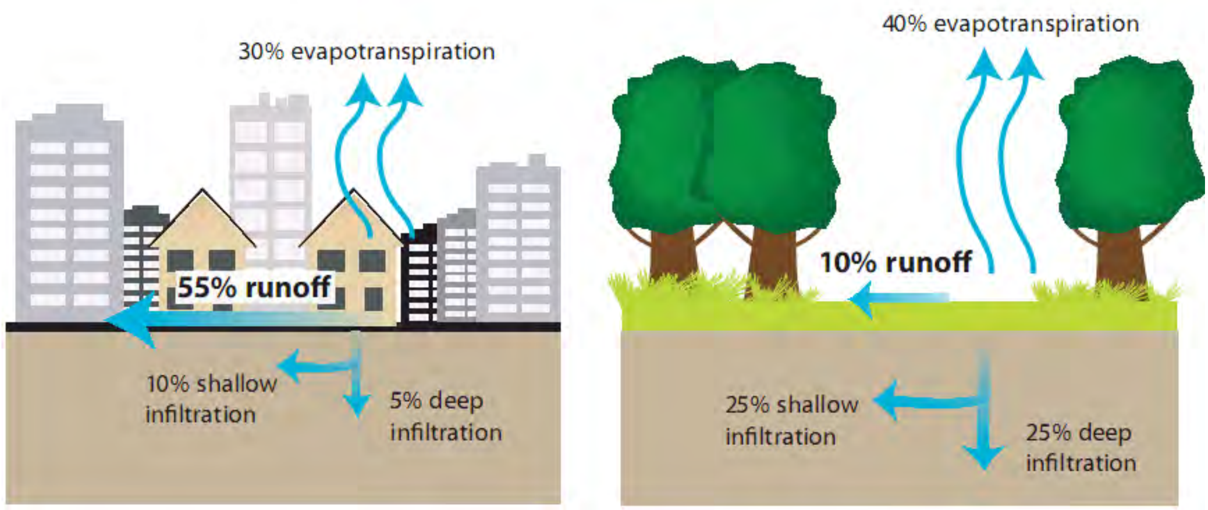

Figure 2.7: Impervious Surfaces and Reduced Evapotranspiration (after EPA, 2008a)

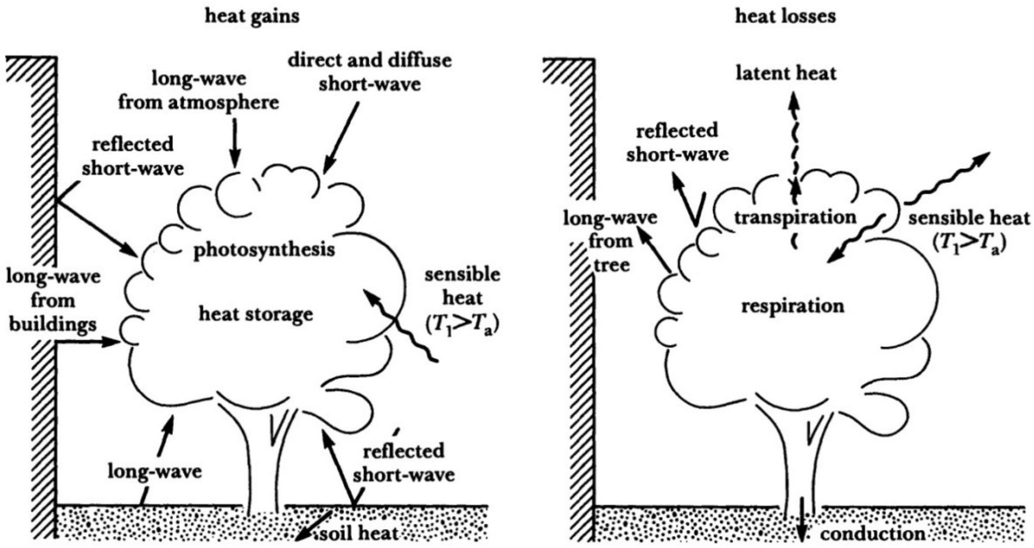

Figure 2.8: Scheme of the daytime energy exchanges between an isolated tree and its street canyon environment (after Oke, 1989)

2.1.4.3. Anthropogenic heat

Anthropogenic heat such as vehicles, air conditioning, power plants, and other heat sources can influence the magnitude of the urban heat island by affecting near surface air temperatures (Taha, 1997) (Figure 2.9). The effects of anthropogenic heat on the urban heat island are at its strongest during the winter due to high energy use and low amounts of short-wave radiation (Ichinose, 1999). Ichinose (1999) found in a study on the impact of anthropogenic heat on the urban climate in Tokyo that the anthropogenic heat flux in central Tokyo exceeded 400 W m^{-2} in daytime, and a maximum value of 1590 W m^{-2} in winter was noted. By comparison, on a clear or partly cloudy day at noon solar radiation at the surface ranges from about 700 to 1000 W m^{-2} (Taha, 1997). Ichinose (1999) also found that by reducing hot water supply and space cooling by 50 and 100% respectively, the near surface temperature would be reduced by 0.5°C at most.

Figure 2.9: An air conditioning unit while using a lot of energy for cooling indoor spaces, actually blows more heat outdoors than it cools indoor

2.1.4.4. Air pollutants

Air pollutants, in particular mineral and carbon aerosols, can contribute to the UHI by absorbing, re-radiating and inhibiting long-wave radiation at night (Rizwan et al., 2008). This forms a pseudo-greenhouse effect and inhibits urban areas from cooling down (Rizwan et al., 2008).

2.1.4.5. Population size

The use of population and city size as an indicator of the UHI has been studied by Oke (1973 and 1982). It was found that the two are positively correlated Oke (1973 and 1982) (Figure 2.10). Population and city size would have an effect on the number of buildings, vehicles and factories for example. However, Hung et al. (2006) has observed a maximum urban heat island intensity of 7°C in Manila with a population density of 15,617 (persons/km^2) and a maximum urban heat island intensity of 12°C with a population density of only 6,218 (persons/km^2) in Tokyo. Although cities with large population's tend to accommodate tall buildings and variables such as building design, density, sky view factor, material etc. play an important role in UHI formation, these variables are not always population dependent. As the

UHI is subject to a combination of these controls, it could be said that population could serve as an indicator of urban size and structure, but not necessarily increase the UHI effect.

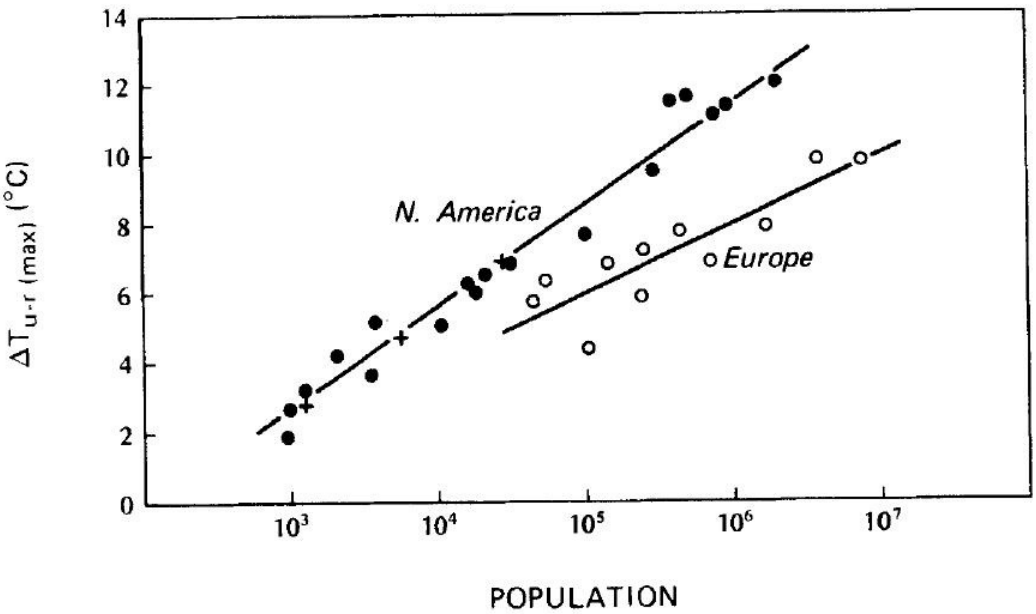

Figure 2.10: Relation between maximum heat island intensity ($\Delta T_{u\text{-}r(max)}$) and population (P) for European and North American cities (after Oke, 1982)

2.1.4.6. Time of day

The first uncontrollable factor is the time of day. The UHI is not a constant condition but shows fluctuations in strength during the day and is typically strongest during the night as can be seen from Figure 2.11. This higher than average minimum temperature rids the body of the chance of cooling down during the night and causes a risk to public health.

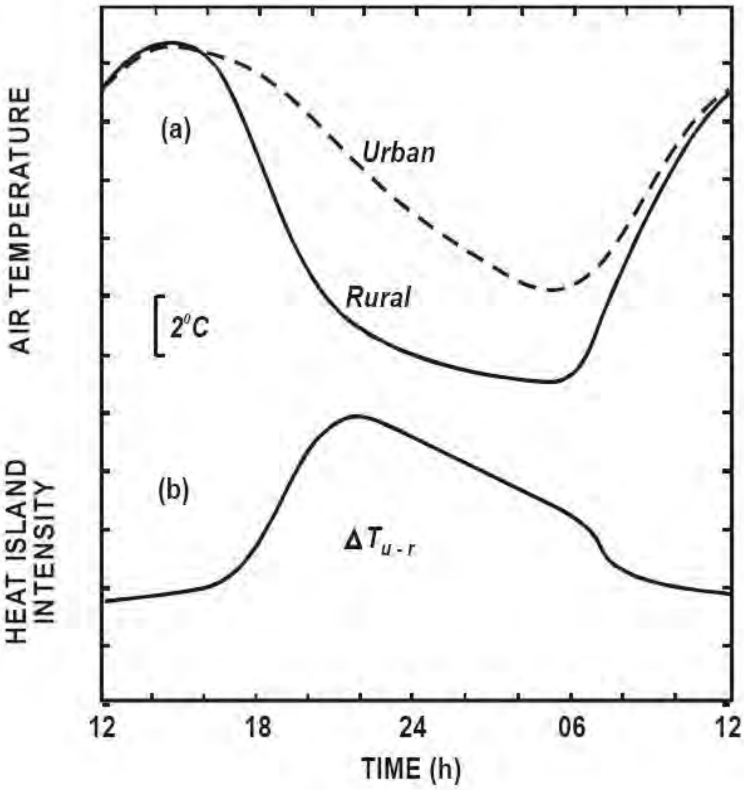

Figure 2.11: Diurnal urban heat island cycle with (a) the air temperature and (b) the heat island intensity (after Oke, 1987)

2.1.4.7. Synoptic conditions, wind speed and cloud cover

The other uncontrollable factors which have effect on the UHI are meteorological variables of which the most salient are wind speed and cloud cover (Oke, 1982; Morris et al., 2001). This is due to the role these variables play on the radiative and turbulent exchanges in and around the urban region (Morris et al., 2001). The intensity and occurrence of the UHI is reduced under windy and cloudy conditions when the air is well mixed and local temperature differences are eliminated (Oke, 1982). By contrast, low wind speeds and little or no cloud cover are associated with high intensities and occurrence of the UHI effect (Morris et al., 2001). These variables can be combined to a certain extent in a single variable of atmospheric stability (Oke, 1982). Low and thick strata clouds, which generate stronger downward long-wave radiation flux and are associated with windy conditions, are more effective in limiting the UHI than equal amounts of high, thin cirrus clouds (Oke, 1987). Morris et al. (2001) found in a study on the influences of cloud cover and wind speed on the nocturnal urban heat island of Melbourne that an increase in the amount of cloud cover and wind speed in excess of 2.0 m s^{-1} resulted in a statistically significant (95% confidence level) reduction in UHI magnitude. Also that cloud cover was more limiting than wind speed in UHI development for all seasons except summer (Morris et al., 2001).

The strongest heat islands develop under calm and clear weather typical of anticyclonic (high atmospheric pressure) conditions and least under windy and cloudy weather typical of cyclonic (depression or low pressure) conditions (Landsberg, 1981; Morris et al., 2001; Beranova and Huth, 2005). Anticyclonic weather conditions are most advantageous for heat island development because they provide undisturbed solar radiation and enhance the role of outgoing long-wave radiation in the nocturnal radiation budget (Szegedi and Kircsi, 2003). Beranova and Huth (2005) investigated the long term changes of the Prague urban heat island under different synoptic conditions between 1961 and 1990. It is concluded that the UHI increases in all seasons as well as annually but the trend under the anticyclonic conditions is larger than under the cyclonic conditions annually and in all seasons except for spring (Beranova and Huth, 2005). In Debrecen, Hungary, the effects of various synoptic conditions on the UHI were analysed by Szegedi and Kircsi (2003). Szegedi and Kircsi (2003) found that the most regular heat islands developed in cases when Hungary was situated between weak high and low pressure systems. The strongest heat islands formed again under anticyclonic conditions but their shape was usually deformed by the prevailing winds (Szegedi and Kircsi, 2003). Strong cyclone activity eliminated the formation of the UHI (Szegedi and Kircsi, 2003).

2.1.4.8. Season

In mid-latitude maritime areas there is a seasonal variation in the heat island and the greatest intensity of heat island events occurs in the warmer half of the year especially in the summer season due to more frequent anticyclonic weather, (Oke, 1982; Morris et al., 2001). Different studies found either autumn or spring to be the season second to summer in heat island intensity (Oke, 1982; Morris et al., 2001). Typically winter is the time of year which sees the least intense heat islands (Oke, 1982; Morris et al., 2001).

2.1.5. The urban heat island in Reading

The best characterisation and analysis of the UHI of the town of Reading has been undertaken by Lee (2008) for 2005-06. In this study Lee (2008) compared the temperature of a suburban site[2] and 15 other sites in Reading. Lee (2008) describes the urban parameters controlling the UHI in Reading to be the built-up ratio, the height/width ratio of buildings, the Normalized Difference Vegetation Index[3] (NDVI), distance from the town centre and population. Lee (2008) also found that the average heat island intensity averaged over summer was comparatively low measuring at 1.6°C. The maximum heat island intensity was in line with what would be expected for a town based on its size and population following Oke's (1973) regression model. For a population of 230,000 a maximum heat island intensity of 6°C was expected and the absolute maximum heat island intensity measured by Lee (2008) was 5.5°C. Lee (2008) also found that Reading's highest heat island intensities are measured during the day as indicated by air temperature sensors located in urban centre streets with comparatively heavy traffic. These coincide with the rush hour periods of 8:00 and 18:00 hours GMT. At these times the UHI could increase by a factor of 3 compared to other times in the day (Lee, 2008). This contradicts the assumption that UHI's are the most intense at night. However, these results are consistent with the fact that the temperature probes were installed at the side of the street, this would then lead to high temperatures when the most vehicles are on the road. Lee (2008) also found that the central business district which is characterised by the highest building density exhibits the largest temperature difference with the suburban site (Lee, 2008).

In a different study set in Reading, Melhuish and Pedder (1998) observed the UHI using a single thermometer carried on a bicycle. It was concluded that early-evening air temperatures near the centre of the town were on average 2.5°C above the lowest values observed around the outskirts during fair-weather conditions in summer. During light winds and anticyclonic weather, the maximum UHI intensity over Reading was observed to be greater than 5°C and in one case as large as 9°C.

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[2] The University of Reading campus which can be described as a suburban park.

[3] Normalized Difference Vegetation Index (NDVI) is an alternative measure of vegetation amount and condition. It is associated with vegetation canopy characteristics such as biomass, leaf area index and percentage vegetation cover (Rosenzweig et al., 2006).

2.2. Green roofs

A green roof is a vegetative layer grown on a rooftop (EPA, 2008b). Every green roof type makes a contribution to the urban environment (MoL, 2004). It can be as simple as a 5 cm covering of alpine like groundcover or a complex fully accessible park complete with shrubs and trees (EPA, 2008b). Green roofs can be built on a variety of buildings, including government facilities, industrial, offices, educational buildings, other commercial properties and residential homes (EPA, 2008b). They are ideally suited to steel frame and reinforced-concrete structures on which support platforms can be provided (Osmundson, 1999). Green roofs consist of four essential layers, starting from the concrete slab protecting the roof they are (1) the insulation layer (2) a waterproofing membrane (3) a layer of growing medium and (4) a vegetation layer (Osmundson, 1999; Oberndorfer, 2007). A green roof may be more expensive to construct then a conventional roof initially, but over its entire life span the green roof will work out more economical because of the longevity of the roof membrane and the energy saved (Oberndorfer, 2007). The modern green roof came to prominence at the turn of the 20^{th} century in Germany as an insulation measure, an energy saving measure, to mitigate the damaging physical effects of solar radiation on the roof structure and as a fire retardant structure (Oberndorfer, 2007). Subsequently in the 1970s, due to growing environmental concern especially in urban areas, urban ecologists began to see them as a way of enhancing urban biodiversity (Canada Mortgage and Housing Corporation, 2006; Oberndorfer, 2007). More recently, green roofs attracted attention of urban climatologists, urban planners and decision-makers as a method of mitigation of urban heat island and adaptation to the projected climatic warming. Green roofs can usually be divided into two groups: (1) extensive and (2) intensive (MoL, 2004).

2.2.1. Extensive green roofs

The concept of an extensive green roof is to design a rugged green roof generally suited for an alpine environment (EPA, 2008b). This type of green roof will need little maintenance or human intervention once it has been established (Oberndorfer, 2007; EPA, 2008b). They are mainly developed for aesthetic and ecological reasons, not for recreational reasons, and are aimed to be self-sustaining with low inputs of water and fertilisers (MoL, 2004). The plants are chosen for their stress tolerant characteristics (Oberndorfer, 2007). Plant selections typically include sedums, succulent, hardy plants, mosses, wild flowers and grasses (MoL, 2004; Oberndorfer, 2007; MoL, 2008). Because of the light weight of an extensive system, this method is suitable for large roofs and existing structures (MoL, 2004; EPA, 2008b). They require less additional structural support which will improve the cost-effectiveness when retrofitting an existing building (EPA, 2008b). This type of green roof has gained popularity in continental Europe but is so far uncommon in Britain (MoL, 2004). Examples in Britain include The Radisson Hotel & New Providence Wharf, London (Figure 2.12) and Bishops Square, London (Figure 2.13).

Figure 2.12: The Radisson Hotel & New Providence Wharf, London (after MoL, 2008)

Figure 2.13: Bishops Square, London (after MoL, 2008)

2.2.2. Intensive green roofs

Intensive green roofs are like conventional gardens and parks with almost no limit to the type of available plants, including large trees and shrubs (EPA, 2008b). They are usually also called ‘roof gardens’ and require intensive management (MoL, 2004). Intensive systems can act as substitutes for natural landscape in urban areas with all the amenities of gardens on the ground (Osmundson, 1999). They are principally designed to provide open space for people and for recreational use and amenity but they will also save the building owner or manager energy (MoL, 2004; Oberndorfer, 2007; EPA, 2008b). They will typically have a thick, nutrient rich, growing medium of 200 mm or more, lush growth of vegetation and require more water than an extensive green roof and therefore have an irrigation system (Oberndorfer, 2007). An intensive system will commonly require more structural support to accommodate for the weight of the additional growing medium and public use (EPA, 2008b). Notable examples in Britain include the roof garden above Jubilee Park, London (Figure 2.14) and Cannon Street Station, London (Figure 2.15).

Figure 2.14: Jubilee Park, London (after MoL, 2008)

Figure 2.15: Cannon Street Station, London (after MoL, 2008)

2.2.3. Benefits of green roofs

Green roofs have many benefits for the urban environment. The benefit which will be the main focus of this dissertation is the 'green roof effect'. However, additional benefits will come from a reduction in energy use and CO_2 emissions, they can reduce storm-water runoff and improve its management, they provide valuable habitat for urban biodiversity and they can reduce the levels of air pollution. Further benefits include, increasing the amenity and property value in urban areas, increasing the lifespan of a roof membrane, providing area for urban agriculture, and reducing sound pollution (see Ingleby, 2002; MoL, 2004; Banting et al., 2005; MoL, 2008).

2.2.4.1. The 'Green Roof Effect' on local climate

Green roofs have an effect on their surrounding climate for two main reasons (Niachou et al, 2001). They protect from solar radiation by the physical act of shading and they consume energy with the processes of evapotranspiration and photosynthesis (Niachou et al, 2001; MoL, 2008) (Figure 2.16). Green roofs have the same energy providers as conventional roofs but it is shading, evapotranspiration and photosynthesis that set it apart as a living system (MoL, 2008). By shading, the plants and growing medium block sunlight from reaching the underlying roof membrane and reduce the surface temperature below the plants (EPA, 2008b). Following this, these cooler surfaces reduce the sensible heat re-emitted into the atmosphere (EPA, 2008b). In the summertime, generally as much as 70 to 90% of the sun's energy is absorbed by leaves for photosynthesis and some of the rest is reflected back into the atmosphere (EPA, 2008b). Evapotranspiration occurs through the processes of evaporation and transpiration (EPA, 2008b). The movement of water absorbed through the roots and emitted through the leaves is called transpiration (EPA, 2008b). This process will be triggered by the rising of the sun which will then see the stomata opening and water vapour exiting the plant. Evaporation is a process where the surface of vegetation and the surrounding growing medium convert water from liquid to gas (EPA, 2008b). These processes cool the air by using heat to evaporate water (EPA, 2008b). There is some disagreement about which of these factors is the most salient. It is claimed by Niachou et al. (2001) that the main factor in passive cooling is protection from solar radiation or shading in other words. However a simulation suggests that the direct effect of shading is secondary to the indirect effect of evapotranspiration (Solecki, et al., 2005). Low green roof temperatures would in turn lead to less heat transferring into the air above the roof resulting in cooler air temperatures (Banting et al., 2005). Site-specific factors such as geographic location, solar exposure, roof composition, growing medium and moisture content all influence green roof temperature (EPA, 2008b). Plants also have a higher albedo than many standard roof surfaces which will enable the green roof to absorb less incoming solar energy and re-emit less heat (MoL, 2008).

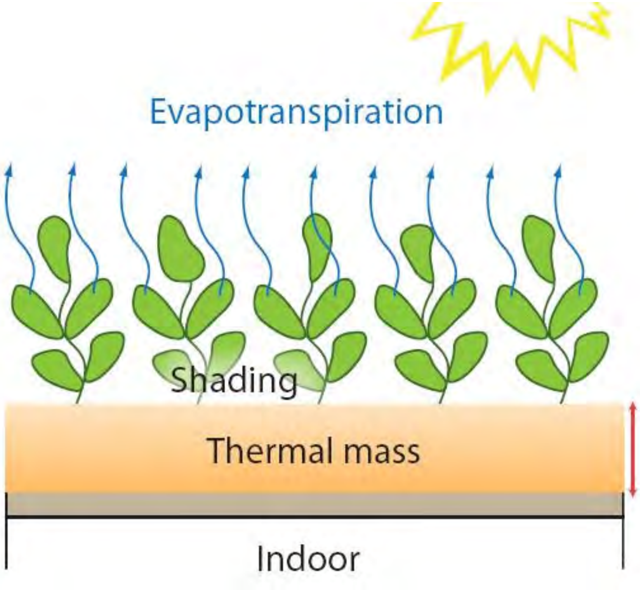

Figure 2.16: Evapotranspiration and shading on a green roof (after EPA, 2008b)

A similarity between green roofs and urban parks, which are well known to produce a cooling effect on local climate, invites a suggestion that green roofs can be used for the amelioration of urban climates. Studies of possible impacts of green roofs on urban heat island effect have already been conducted in a few major cities of the world, however, these studies were few and largely limited to the non-intensive green roofs. In a technical report by the Mayor of London (2008) it was estimated that 32% or 3.2 km^2 in central London could be converted to green roofs (MoL, 2008). Of this same area 80% would be extensive and 20% would be intensive (MoL, 2008). This would lead to an overall energy saving of 19,200 MWh per year or 8,256 CO_2e tonnes, the capacity to store 80,000 m^2 of rainwater at roof level, it would create 256 hectares of habitat and provide 64 hectares of green amenity space (MoL, 2008). This technical report does not quantify the thermal benefits of the estimated green roof space but if compared to other work there are strong indications that this amount of green roof space would have significant effect on the heat island. In New York City, heat island mitigation scenarios were tested in a climate model by Rosenzweig et al. (2006) and the New York City Regional Heat Island Initiative. They determined that vegetation had the greatest impact on surface temperature rather than urban geometry or albedo (Rosenzweig et al., 2006). It was also found that by providing 50% green roof cover with grass within the metropolitan area an average reduction of 0.1-0.8C° in surface temperature could be achieved (Rosenzweig et al., 2006). In Toronto, city-wide benefits were calculated based on the assumption that 50 km^2 could be available for extensive green roofs (Banting et al, 2005). It was concluded that this could reduce the local ambient air temperatures by 0.5-2C° depending on the time of year in the city (Banting et al., 2005). The extensive green roofs, however, offer little advantage by cooling local climate through shading. Intensive green roofs theoretically have greater potential for cooling by shading, however, studies documenting this effect have been very limited so far.

Few other previous studies have quantified the thermal benefits of green roofs in ways such as this dissertation; one was of an intensive green roof, the other of an extensive green roof. Wong et al. (2003) investigated the thermal benefits of a rooftop garden in the tropical environment of Singapore. This data is not directly applicable to a mid-latitude urban area such as Reading but it is one of the only research projects which have compared the microclimate of an intensive green roof to that of a conventional roof. Wong et al. (2003) found that the maximum surface temperature reduction measured under the vegetation was around 30°C. The cooling effect of plants was responsible for a maximum ambient air temperature reduction of 4.2°C (Wong et al., 2003). Niachou et al. (2001) used an infrared camera to compare the thermal properties of extensive green roofs in Athens. Niachou et al. (2001) found that there was no significant difference between the surface temperature of an insulated building with or without an extensive green roof. For this insulated building, the surface temperature of the extensive green roof ranged from 26°C for thick dark green vegetation to 40°C for the unshaded ground. However, for a non-insulated building the surface temperature of the extensive green roof ranged between 28 and 40°C compared to that without the extensive green roof ranging between 42 to 48°C. Therefore, the surface temperature reduction is in the 10°C order due to the extensive green roof. This study, however, did not address the impact of extensive green roofs on air temperature and the link between the air and surface temperatures is not always strong as shown by previous urban climate research (Roth et al., 1989).

Other studies investigate certain thermal aspects of green roofs such as the surface heat budget of lawn-grass green roofs (see Takebayashi and Moriyama, 2007), or evaluate the thermal reduction effect of green roofs (see Fang, 2008), or extensive green roofs as a passive cooling system used to improve indoor thermal comfort (see Palomo Del Barrio, 1998; Onmura et al, 2001; Theodosiou, 2003; Kumar and Kaushik, 2005). But there is a distinct lack of research to be found which quantify and characterize the meliorating thermal properties of intensive green roofs in mid-latitude urban areas.

2.2.4.2. Reduction in energy use and CO_2 emissions

Green roofs save energy used for heating and cooling buildings (EPA, 2008b). They do this with their substantial thermal mass and added insulation value (MoL, 2008). When wet, green roofs absorb and store large amounts of heat due to their thermal mass (EPA, 2008b). When dry, the green roof acts as an insulator and reduces the need for cooling energy by decreasing the flow of heat through the roof (EPA, 2008b). This means that in the winter, less heat is lost through the building thereby reducing heating needs and in the summer the roof surface and ambient air temperature are reduced, which in turn lowers the need for cooling (EPA, 2008b). Here again, the specific savings will depend on the roof characteristics, the local climate and the individual building (EPA, 2008b). It was simulated by Niachou et al. (2001) that during the whole year, heating and cooling needs in Athens were reduced with a green roof regardless whether the roof was insulated or not. The greatest savings occurred in a non-insulated roof with energy savings of 37 to 48%, for a moderately insulated roof this varied from 4 to 7% and finally for a well insulated roof almost 2%. By using an infrared thermometer it was determined that the indoor thermal comfort conditions with a green roof were improved by 2°C.

2.2.4.3. Enhanced storm-water management

Urban areas are typically characterised by hard, non porous surfaces which lead to high peak storm-water flows and overburdened facilities to manage the consequences (Oberndorfer, 2007; MoL, 2008). This has lead to a rise in urban flooding and combined sewage overflow into lakes, rivers and beaches (Oberndorfer, 2007; MoL, 2008). Apart from the consequences of urban flooding, urban runoff is high in pollutants such as petroleum residues and pesticides which can contaminate water supplies and damage aquatic habitats (Oberndorfer, 2007; MoL, 2008). Green roofs are ideally suited to tackle this problem because they make use of existing roof space and prevent runoff before it leaves the lot (Oberndorfer, 2007). They act like other natural vegetation and absorb water that would otherwise become runoff (EPA, 2008b). In addition, conventional storm-water management techniques such as reservoirs, wetlands and sand filters are very surface area intensive, which may not be suitable in dense urban areas (Oberndorfer, 2007). The effectiveness in retaining rainfall will depend primarily on the growing medium, the roof slope and the plant community (Oberndorfer, 2007; EPA, 2008b). Intensive green roofs with their thick growing medium will retain more rainfall than extensive green roofs (EPA, 2008b). Plants and growing medium from green roofs not only reduce and delay storm-water runoff but they also act as a filter which treats and binds contaminants in rainwater (EPA, 2008b; MoL, 2008).

2.2.4.4. Urban Biodiversity

Green roofs whether intensive or extensive provide valuable green links and stepping stones for animals such as invertebrates and birds (MoL, 2004; MoL, 2008). They will often be inhabited by various beetles, ants, bugs, flies, bees, spiders and leafhoppers (Oberndorfer, 2007). They may also be used by nesting birds and native avian communities (Oberndorfer, 2007). Those which supply an animal's four basic needs: food, cover, water and an area to breed will be the most attractive to urban wildlife (MoL, 2004). However, green roofs cannot be a direct substitute for habitat on the ground and certain elements may be inappropriate on a roof situation (MoL, 2004; MoL, 2008).

2.2.4.5. Reduction in air pollution

City air often contains high levels of pollutants which are harmful to human health such as $NO_{x,}$ Sulphur Dioxide (SO_2), Particulates e.g. PM_{10}, $PM_{2.5}$ and Ozone (O_3) (Figure 2.17). In cities this is caused by the density of human activity, including use of fossil fuels, the absence of natural biological controls and the presence of the urban heat island (Banting et al., 2005). As concerns increase about the magnitude and frequency of smog alerts and summer heat waves there is evidence emerging of the use of green roofs for air pollution control (Banting et al., 2005; Yang et al., 2008). Although many aspects remain unclear and more research is needed, some studies have reported substantial benefits from green roofs in air pollution control. Yang et al. (2008) reported a total of 1,675 kg of air pollutants being removed by 19.8 ha of green roofs in one year in Chicago using a dry deposition model. Of this total, O_3 accounted for 52%, NO_2 for 27%, PM_{10} for 14% and SO_2 for 7% (Yang et al., 2008). Yang et al. (2008) also reported that the pollutants removed would increase by 2,046.89 metric tons if all rooftops in Chicago were covered with intensive green roofs.

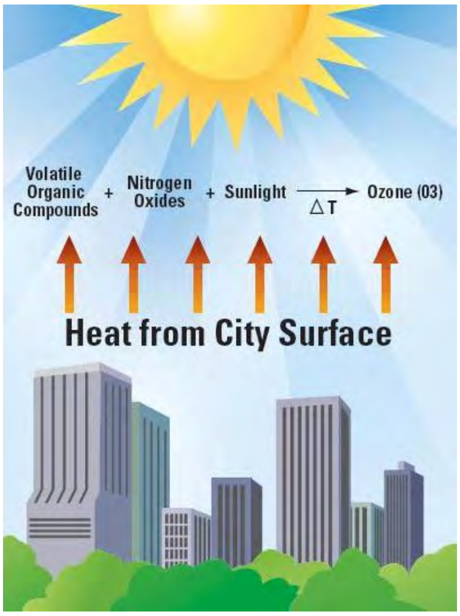

Figure 2.17: Ozone forms when precursor compounds react in the presence of sunlight and high temperatures (after EPA, 2003)

2.3. Urban heat island and green roof policy

2.3.1. Urban heat island policy

There is currently no national or local policy in place to mitigate the urban heat island effect in the UK. Nor are there any government incentives or strategies to tackle the problem. The only document produced from a government perspective which supports urban heat island mitigation is *London's Urban Heat Island: A Summary for Decision Makers* (GLA, 2006).

2.3.2. Green roof policy

At this moment in the UK, there is no national or local policy that encourages the design, implementation or requires the use of green roofs (Canada Mortgage and Housing Corporation, 2006). There are also no government incentives for green roofs (Canada Mortgage and Housing Corporation, 2006). However, there are national policies that support them. These include *Securing The Future – the UK Government's sustainable development strategy* and *Climate Change – the UK Programme* (HM Government, 2005; HM Government, 2006). The use of green roofs is also consistent with other planning policy statements and guidance documents such as *PPS1 - Delivering sustainable development, PPG2 - Green belts, PPS3 – Housing, PPS9 - Biodiversity and geological conservation,* *PPG17 - Planning for space, sport and recreation and PPS25 - Development and flood risk*. In a policy context for London, green roofs fit in with the London Plans *Policy 4A.3 - Sustainable design and construction, Policy 4A.9 - Adaptation to climate change, Policy 4A.11 - Living roofs and walls, Policy 4A.14 - Sustainable drainage* and *Policy 4A.17 - Water quality*[4].

In other cities leading the field in green roof implementation such as Munster, Basel, Chicago, Portland, Vancouver, Toronto and Tokyo a mixture of financial incentives, building regulations, planning policies and mandatory policy requirements are used (see Toronto City Planning, 2005 for examples). Barriers to wider implementation of green roofs and common misconceptions in the UK have been investigated by Ingleby (2002). These include a lack of a national and local policy framework that encourages the installation of green roofs, lack of a common standard for green roofs, maintenance, cost, structural issues, falsely perceived additional risk of leakage and damage to waterproofing, lack of expertise and skills and falsely perceived fire hazard risk (Ingleby, 2002).

2.4. Conclusions

The urban heat island effect has serious consequences for public health, energy use and air pollution and these are likely to be enhanced in the future warmer climate. Urban development in Reading has seen the town expand while public green space and water has been lost at the same time. Following this, an UHI has developed reaching an average value of 1.6°C and a maximum value of 5.5°C (Lee, 2008). Controls over the UHI have been described as urban geometry, the amount of vegetation, anthropogenic heat, air quality, population size, time of day, synoptic conditions, wind speed and cloud cover and the season. The extent and nature of vegetated areas have been confirmed as important factors in the formation and / or mitigation of urban heat islands. Green roofs are similar in their nature to urban green spaces and can be used as an urban heat island mitigation measure. Previous research has confirmed the benefits of extensive green roofs. However, there is a distinct lack of studies that can be identified with regards to the microclimatic effects of intensive green roofs in a mid-latitude urban area. These intensive green roofs which may have a greater potential for the reduction of the urban heat island effect, have not been sufficiently

[4] consolidated with Alterations since 2004

investigated. This specific gap will be addressed in this dissertation. This dissertation will provide evidence that the difference in air and surface temperature between a conventional roof and an intensive green roof is comparable to the cooling effect green areas such as urban parks and forests have in cities. Previous research in London, New York and Toronto has also been able to quantify estimates of wide scale green roof application. These methods will be used in this dissertation to be able to estimate the same in Reading.

3. Methods

The mitigation effect of intensive roof on urban heat island was assessed using meteorological measurements collected using two automatic weather stations installed on an intensive green and on a conventional roof in central Reading between the 4th of June to the 23rd of August 2009.

3.1. Sample sites

The two sample sites selected are in a non-residential commercial area in the centre of Reading which has shops, financial and professional services, restaurants and cafes, public houses, bars and nightclubs (Lee, 2008). Commercial areas in Reading exhibit the highest surface temperatures measured by Lee (2008) together with industrial areas during the day. At night, commercial together with industrial areas exhibited the highest surface temperatures (Lee, 2008). The NDVI of the commercial areas was calculated to be 0.02 (Lee, 2008). This NDVI is the second lowest only to that of industry areas in the borough and in this area some of the strongest UHI intensities have been noted.

The first sample site is the intensive green roof with over 120 species located on the second floor of the Reading International Solidarity Centre (RISC), 35-39 London Street, Reading which is 30 * 4 m (Figure 3.1). The coordinates are 51°27’02” N by 0°58’02” W and the roof is surrounded by low rise buildings on the north, south and west side of the green roof. To the east there is a car park. The nearest obstructions are the fencing around the roof garden, hedges and small trees. The closest vegetation apart from that of the green roof is approximately 20 m away. There is high moisture availability on the site seeing that there is lush vegetation and the garden has an irrigation system. There will be a substantial amount of anthropogenic heat originating from the office space, shop and restaurant below the roof garden which has sky windows which open into the roof garden. The underlying surface of the RISC automatic weather station (AWS) is *Echinacea purpurea* (Cone flower). At the time of installation in February there was very little growth. *Echinacea purpurea* is native to central United States and can grow up to a meter tall (Snyder and Lindquist, 2006; Aniśko, 2008). The AWS is located approximately a meter away from the northern edge of the roof garden and to the west of centre.

The second sample site is the conventional roof located on the fifth floor at Crown House, 10 Crown Street, Reading (Figure 3.2). Its coordinates are 51°27’10” N by 0°58’04” W and it is located on a corner with no neighbouring buildings surrounding the roof. The only near obstruction is the fifth story of Crown House which is next to the roof. The closest vegetation is approximately 20 m away. There will be anthropogenic heat originating from other buildings at lower levels and the street. There are no permeable surfaces and no vegetation on the Crown House roof so moisture availability is very low. The roof of Crown House and underlying surface of the AWS is a FDT Rhenofol CV Roofing Membrane with accessories in Light Gray. Rhenofol CV is a synthetic fibre reinforced roofing membrane product made of non-rigid polyvinyl chloride (PVC-P). Roofing membrane has become a common replacement for asphalt roof systems in Reading so selecting a membrane roof for this study is suitable. The AWS is located in the north western corner of the roof and approximately two meters away from the door accessing the roof and the fifth story of the building.

Figure 3.1: Reading International Solidarity Centre

Figure 3.2: Crown House

The two sites are in close proximity to each other as can be seen in an aerial photograph taken from Google Earth in Figure 3.3 and are 254 m apart. Both roofs are located in the urban canopy layer and there is a comparatively small difference in height between them seeing that one is on the second and the other on the fifth floor. Consent was given by the appropriate authorities from the sample sites to participate in the study.

Figure 3.3: Street layout of RISC and Crown House

3.2. Instruments

The automatic weather stations were first piloted on the University of Reading campus for at least a week in order to test that they are functioning correctly. HOBO automatic weather stations were used with a HOBO U Shuttle Data Transporter to download the recorded data. Each AWS has a 15 channel data logger and each is equipped with temperature and humidity probes, an anemometer, weather vane and two pyranometers. The rooftop garden AWS has in addition a soil moisture sensor, an atmospheric pressure sensor and a rain gauge. Further description of the instruments is given in Table 3.1. Cloud cover data was obtained separately from the meteorology department of the university. The cloud cover data was measured at

9:00 on the university campus. The HOBO AWS's are fully automated and can record data for a prolonged period of time without the need of attention. A limitation is their ability to measure precipitation. Rain can be blown horizontal by the wind and not be deposited in the rain gauge. Then on each sample site an AWS was installed. The AWS on the RISC site was installed on the 27th of March 2009 (Figure 3.4) and the Crown House AWS was installed on the 22nd of May 2009 (Figure 3.5).

Figure 3.4: AWS RISC

Figure 3.5: AWS Crown House

Table 3.1: Instrument description

Measurement	Product	Measurement Range	Accuracy
Temperature	Onset S-THB-M002	-40°C to 75°C	0.2°C over 0° to 50°C
RH	Onset S-THB-M002	0-100% RH at -40° to 75°C	+/- 2.5% from 10% to 90% RH (typical), to a maximum of +/- 3.5%
Wind Speed	Onset S-WCA-M003	0 to 44 m/s	± 0.5 m/s ± 3% 17 to 30 m/s ± 4% 30 to 44 m/s
Wind Direction	Onset S-WCA-M003	0 to 358 degrees, 2 degree dead band	± 5 degrees
Barometric Pressure	Onset S-BPA-CM10	660 mb to 1,070 mb	±3.0 mbar over full pressure range at 25°C; maximum error of ±5.0 mbar over -40° to 70°C
Solar Radiation Sensor (Silicon Pyranometer)	Onset S-LIB-M003	0 to 1280 W/m2	±10 W/m^2 or ±5%, whichever is greater in sunlight. Additional temperature induced error ±0.38 W/m^2/°C from 25°C

3.3. Data collection

The data was collected using the HOBO U Shuttle Data Transporter. The RISC AWS recorded data from 27th of March. The Crown House AWS recorded data in the same manner from the 3rd of June. The AWS's have been programmed to take sensor measurements every 2 seconds. These measurements are then averaged every hour to provide a reading on the hour, 24 hours per day. The data is then transferred to the accompanying HOBOwarePro software where it is then exported as a spreadsheet to MS Excel. A data set of each sample site from the 4th of June to the 23rd of August 2009 was created. Neither of the months June, July or August have complete data sets for the entire month due to technical difficulties with the AWS's. For June, data is missing between the 1st and 3rd of the month due to sensor problems with the Crown House AWS. For July, the data logger had to be removed and reinstalled due to a logger problem with both AWS's meaning that data is missing between the 16th and 31st of the month. And for August, data is missing between the 24rd and 31st of the month due to sensor problems with the Crown House AWS. This leaves 27 days in June, 15 days in July and 23 days in August making the total sample period 65 full days.

3.4. Statistical analysis used

The data was analysed using MS Excel Analysis ToolPak. Charts were created for visual comparison between the two sites. These charts would be comprised of either raw data or the mean of large plots of data. It was at this time that an anomaly was also noted in the RISC albedo measurements. Mainly between the hours of 8:00 and 11:00 albedos were calculated above 1. Since 1 is the maximum albedo which a material can poses, these measurements were removed from the results. This could be due to equipment failure or an obstruction to the incoming solar radiation sensor. The data was then analysed using various statistical methods such as linear regression, correlation and significance tested using the paired sample T-test. Linear regression and correlation were used to find relations between temperature and other meteorological variables (Wilson, 2005). The paired sample t-test was used to determine whether there is a significant difference between the means of the two samples (Wilson, 2005).

3.5. Thermal images

Thermal images were taken with a NEC infrared camera of the two roofs. These images serve to compare the surface temperature of the two roofs. They will also be used to quantify the amount of anthropogenic heat which can be found in the rooftop garden originating from the sky windows. The images were taken on the 9th of September between 16:00 and 17:00. The accuracy of the surface temperature measurements is not high but this is not considered a problem seeing that interest lies in the differences rather than absolute values.

3.6. Possible green roof space in Reading

Obtaining exact figures of how much roof space could be converted to green roof space in Reading is near impossible without individual site visits and surveying each buildings structural support. To start with the area between Queen's Road, Forbury Road, Vastern Road and Chaversham Road was selected as the sample area in Geographical Information System (GIS) software ArcMap 9.2 and Google Earth. After which all the flat roofs in the area were selected by means of visual analysis of aerial photographs on Google Earth. Following that, the flat roofs that could support a green roof were selected. This roof area had shingle ballast or paved finishing. These areas were then calculated using GIS. It is unlikely that the total roof area selected can be used for green roof space so it is assumed a further 75% would be available for greening. Following this, not every flat roof can support an intensive green roof without adding structural support so a ratio of 80% extensive and 20% intensive was used (MoL, 2008). The amount of potential rooftop garden space was then calculated as a percentage of the total roof area in the centre of Reading. In addition, the total building footprint (and therefore the total roof footprint) of the Borough of Reading was provided by the Reading Borough Council. It will however not be possible to multiply the results found for the centre of Reading to a Borough scale seeing that the proportion of flat roofs for the rest of the Borough is different to that of the centre.

4. Results and discussion

4.1. Introduction

In this chapter the results are presented from the AWS's, the infrared camera and the possible area which could be converted to green roof space. Several meteorological data which originated from the AWS's have been analyzed including air temperature, wind speed, cloud cover, incoming solar radiation, albedo, atmospheric pressure and relative humidity.

Information was obtained from the Met Office (2009) describing the summer of 2009 in the South East of England and Central South. The mean temperature for the summer of 2009 was 16.5°C which is 0.5°C above the 1971-2000 average. The mean temperature for June was 15.4°C, which is 1.0°C above the average, for July this was 16.8°C, which is 0.1°C below the average and for August it was 17.3°C, which is 0.6°C above the average. The mean maximum and minimum temperature for the summer in the region was above the average, with the maximum being 0.5°C above average at 21.3°C and the minimum being 0.6°C above average at 11.8°C. Between the 27th of June and 4th of July the region saw some exceptionally warm temperatures. This period saw the highest temperatures in three years but it also brought some very heavy and intense thunderstorms with hail. In the UK there is no formal definition of a heat wave but for the purpose of this dissertation the Heat Wave Duration Index used by the European Climate Assessment is used to define a heat wave (Frich; 2002; Hajat et al., 2002; Meehl, 2004).

> "Heat wave duration index: maximum period > 5 consecutive days with Tmax >5°C above the 1961–1990 daily Tmax normal"

The 1961–1990 daily Tmax for June is 19.1°C and for July 21.2°C. Following this definition, there was a heat wave measured by the AWS's for 6 days from the 27th of June to the 2nd of July. Rainfall during the summer in the region was 102% of the average with 161.9 mm of rain, but the three months had contrasting patterns. June and August were drier than average in the region but July saw 189% of the average rainfall with 85.6 mm compared to the 1971-2000. Sunshine in the region was 104% of the average with 635.5 hours recorded.

4.2. Relationship between air temperature and the urban heat island controls

4.2.1. Difference in air temperature between the sites

The results conclude that the air temperature of the intensive green roof is on average cooler than the conventional roof during the summer. The mean air temperature results for the entire sample period reveal that the mean air temperature for the Crown House site was 17.9°C and for the RISC site 17.7°C (Figure 4.3). The air temperature at RISC was 1.2°C above the average provided by the Met Office (2009) for the summer and 1.7°C above the 1971-2000 average for the region. The mean of the difference in air temperature is 0.2°C and T-test analysis has shown that although the difference between the samples is small, the means of the two populations are different at 3% confidence level. This 0.2°C difference in air temperature is less but still comparable to the 0.5-2C° reduction in ambient air temperatures calculated by Banting et al. (2005) in Toronto. It must also be taken into account that the intensive green roof in this study is only 120 m^2 compared to the 50 km^2 assumed by Banting et al. (2005). This reduction in air temperature is also comparable to the PCI results found by Spronken-Smith and Oke (1999) and Jauregui (1991) discussed in 2.1.4.2. The absolute maximum air temperature difference recorded was 4.3°C and occurred at 9:00 on the 2nd of August. This is a similar result to the 4.2°C found by (Wong et al., 2003) when an intensive green roof was compared to a conventional roof in Singapore. The mean air temperatures of the two sites are correlated with a Pearson correlation coefficient of 0.99.

4.2.1.1. Diurnal air temperature difference

As can be seen from Figure 4.1 the air temperature of the intensive green roof is below that of the conventional roof in the morning and early afternoon between 5:00 and 13:00. The factors behind this are evapotranspirational cooling and shading (Taha, 1997). The greatest reduction in air temperature occurs at 9:00 followed by 8:00 and 11:00. The mean of the difference in air temperature at 9:00 is 1.1°C. This is a somewhat different result to what has been found by the New York City Regional Heat Island Initiative which found that the greatest temperature reductions due to green roof cover with grass tended to occur in the early-to-mid-afternoon and often peaked around 15:00 (Rosenzweig et al., 2006).

During the other times of the day between 14:00 and 4:00 the air temperature of the intensive green roof is above that of the conventional roof with exception at 18:00 and 19:00. The difference in air temperature at night can be explained by the reduced sky view factor as a result of the taller vegetation which retains long-wave radiation under the canopy and acts to increase air temperature (Taha, 1997). The greatest addition in air temperature occurs at 16:00. The mean of the difference in air temperature at 16:00 is 0.4°C. A similar condition was also found by Taha (1998 cited in Taha, 1997, p.101) in which numerical simulations found that a 30% vegetative cover could provide a noontime temperature reduction of up to 6°C, in favourable conditions, and an addition to the night-time heat island of 2°C.

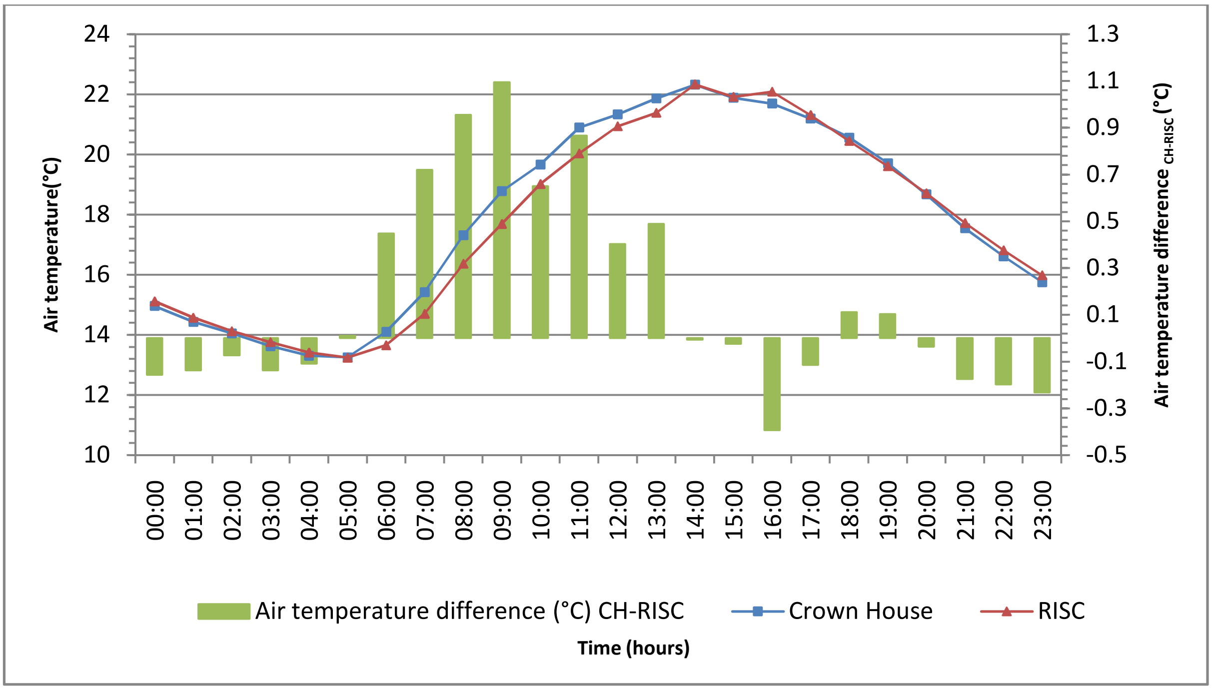

Figure 4.1: Mean diurnal air temperature and air temperature difference $_{CH-RISC}$

Averaged from 04-06-2009 to 23-08-2009

4.2.1.2. Daily maximum air temperature difference

From Figure 4.2 it can be seen that out of the 65 day sample period, 23 days saw a maximum air temperature differences between 1 and 2°C. The average wind speed for Crown House during these 23 days was 1.2 m s^{-1} and for RISC, 0.6 m s^{-1}. The average cloud cover was 6 oktas. The low wind speed provided conditions favouring the development of a heat island although it should be noted that the installation of AWS on roofs resulted in wind flow obstruction and, possibly, reduction of wind speed in comparison with those measured at fully exposed sites such as that of the meteorology department on the university campus. By contrast, cloud cover was high and, while this did not favour the development of heat island, it was characteristic of the regional climate (Met Office, 2009). In the 4-5°C interval two measurements were recorded. On these two days the average wind speed at Crown House was 0.9 m s^{-1} and for RISC, 0.4 m s^{-1}. The average cloud cover for the two days is 3 oktas. It should be noted from these results that the higher air temperature differences saw lower amounts of wind speed and cloud cover on the day. This confirms that these conditions enhance the microclimatic differences.

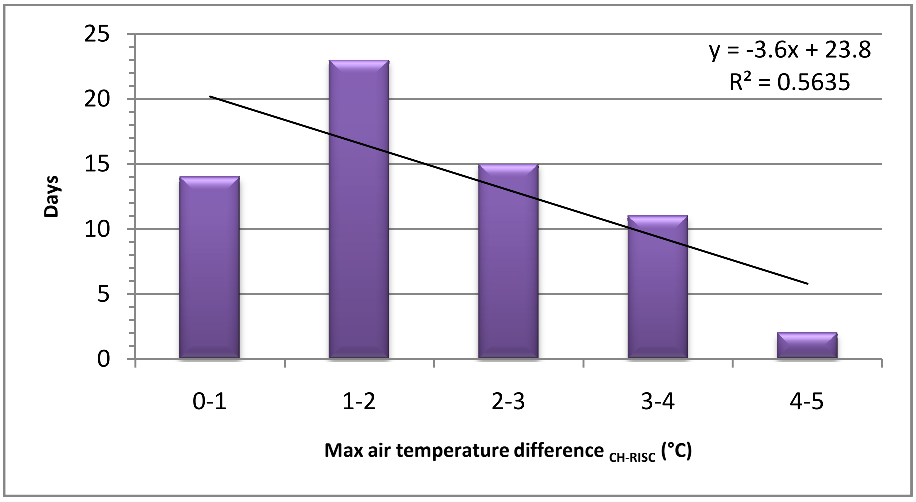

Figure 4.2: Max air temperature difference $_{CH\text{-}RISC}$ by amount of days

4.2.1.3. Monthly difference in air temperature

The difference in air temperature was the largest in July and August and the smallest in June. The means of the temperatures measured were all higher than the averages for the summer of 2009 and the 1971-2000 averages provided by the Met Office (2009) (Figure 4.3). For each of the three months diurnal calculations were made. During the month of June the mean air temperature for Crown House was 16.9°C and for RISC 16.8°C (Figure 4.4). This is over 1.4°C higher than the average for June 2009 and 2.4°C higher than to the 1971-2000 regional average. The mean of the difference was 0.1°C and there is evidence at a 10% significance level that the two population means are not equal. In July the mean air temperature at the Crown House site was 18.5°C and at the RISC site 18.3°C (Figure 4.5). This is over 1.5°C warmer than the average for July 2009 and 1.4°C higher compared to the 1971-2000 average in the region. The mean of the difference being 0.2°C and there is evidence at a 5% significance level that the two population means are not equal. In August the mean air temperature for Crown House was 18.6°C and for RISC 18.3°C (Figure 4.6). This is over

1.0°C warmer than the average for August 2009 and 1.6°C higher compared to the 1971-2000 average in the region. The mean of the difference was 0.2°C and there is evidence at a <0.01% significance level that the two population means are not equal.

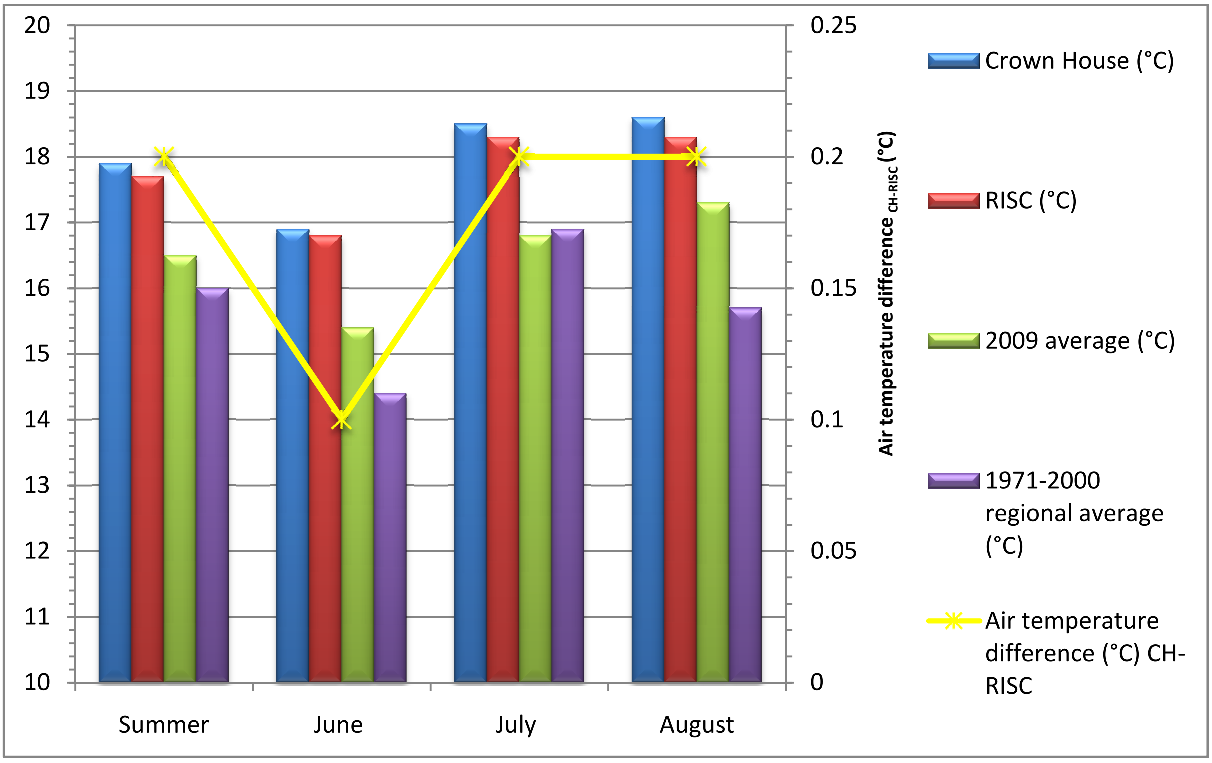

Figure 4.3: Mean air temperatures for Crown House and RISC, 2009 averages, 1971-2000 averages and air temperature differences $_{CH\text{-}RISC}$ for summer, June, July and August

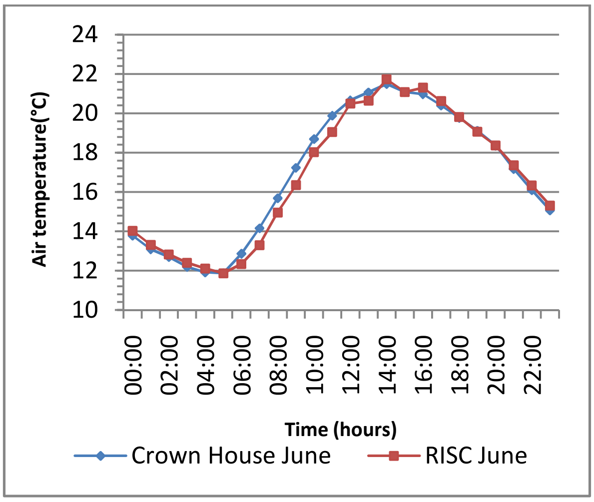

Figure 4.4: Mean diurnal air temperature June

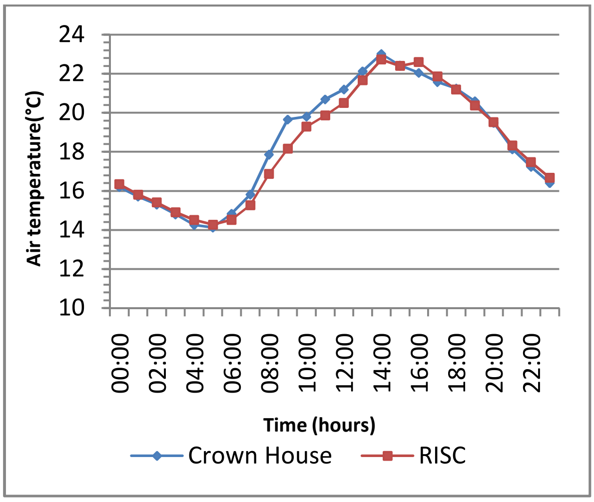

Figure 4.5: Mean diurnal air temperature July

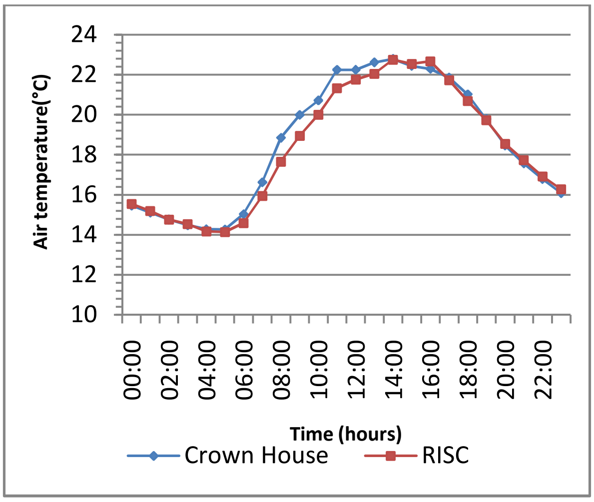

Figure 4.6: Mean diurnal air temperature August

4.2.1.4. Heat wave

During heat waves, heat island impacts tend to be further amplified (Rosenzweig et al., 2006). However this was not the case during the June-July heat wave. During this heat wave there was no statistically significant difference between the air temperatures of the two sites. The mean temperature for the 6 days was 23.2°C for both sites (Figure 4.7). Wind speed at Crown House and RISC were near to equal the average for the sample period and there is little relation between wind speed and air temperature difference during the heat wave (see 4.2.2.1 and 4.2.2.4). Cloud cover during the heat wave was 1 okta below average. These are very close to the sample period averages for wind speed and cloud cover, thus nothing abnormal to be noted. However relative humidity was 10% below average for both sites. But as discussed in 4.2.8, typically high temperatures tend to be coupled with low relative humidity and vice versa (Theodosiou, 2003; Wong and Yu, 2005). This low relative humidity should have stimulated the vegetation to increase evapotranspiration and thereby reduce the temperature of the site but this was not the case. Further research on the effects of heat waves on an intensive green roof would be needed to reach a definite conclusion.

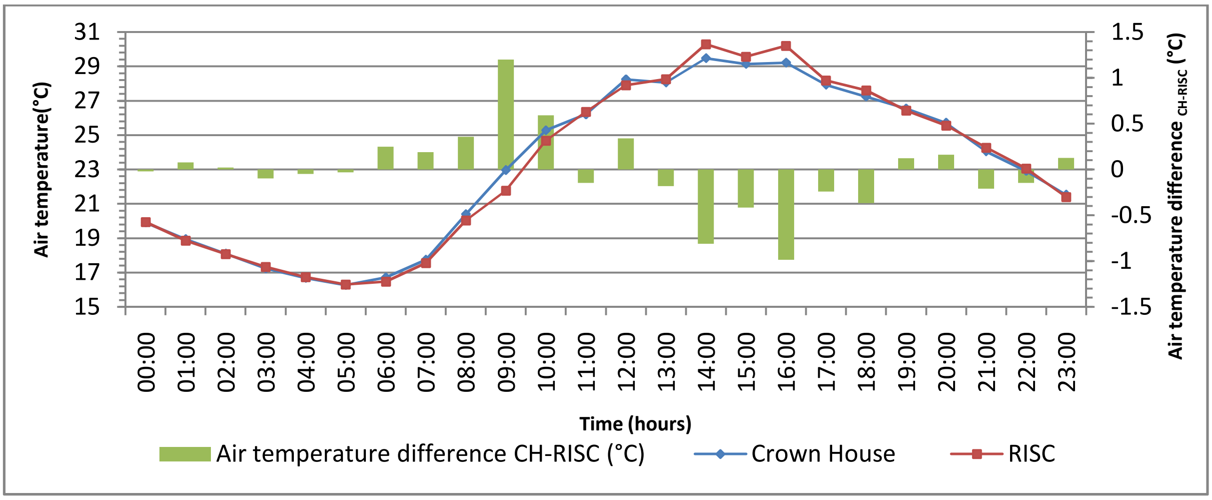

Figure 4.7: Mean diurnal air temperature and air temperature difference $_{CH-RISC}$ during the heat wave

4.2.2. Wind speed

4.2.2.1. Wind speed characteristics of both sites

The wind speed of the two sites was characterised for the entire sample period and for the heat wave in (Figure 4.8). The strength of the wind speed at the two sample sites although both considerably low, vary significantly. As can be seen in Figure 4.8 the wind speed at Crown House for the sample period was more than twice that of RISC. The mean wind speed at Crown House is 1.2 m s^{-1} and at RISC, 0.5 m s^{-1}. This is a 42% difference in mean wind speed between the two sites. The maximum recorded wind speed at Crown House was 3.7 m s^{-1} and for RISC 2.8 m s^{-1}. Another characteristic of the two sites is an increasing wind speed starting at approximately 6:00 and reaching its peak by approximately 15:00 at Crown House and 17:00 at RISC, the wind speed then decreases to a minimum at 4:00. This corresponds with the diurnal cycle of wind speed. During the heat wave, the wind speed at Crown House was equal to the sample period average and for RISC the difference was below the accuracy of the sensor.

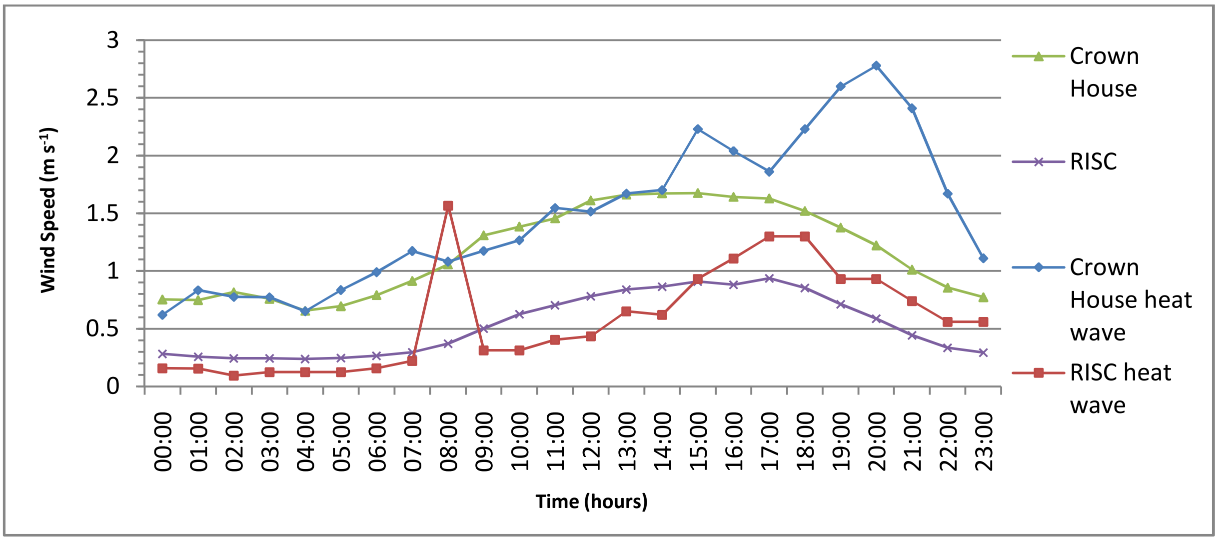

Figure 4.8: Mean diurnal wind speed for the sample period and heat wave

4.2.2.2. Difference in air temperature by wind speed

As it has already been shown, low wind speeds induce the formation of heat islands. A mean was taken of all the differences in air temperatures for different categories of wind speed with an interval of 1 m s^{-1} (Figure 4.9). The highest air temperature difference was between the wind speeds of 0 and 1 m s^{-1}. Between these near stagnant wind speeds the mean air temperature difference was 0.2°C. The results show that in the 2 - 3 m s^{-1} group, the RISC site has a mean air temperature 0.3°C higher than Crown House. Figure 4.9 does also show that as wind speed increases, the difference in air temperature decreases and that the greatest differences in air temperature are noted under calm wind conditions. These results show that wind speed is a control over the difference in air temperature between the two sites. This is in accordance with what has been stated in 2.1.4.7 and also makes the intensive green roof comparable to a rural or suburban area located in the town centre.

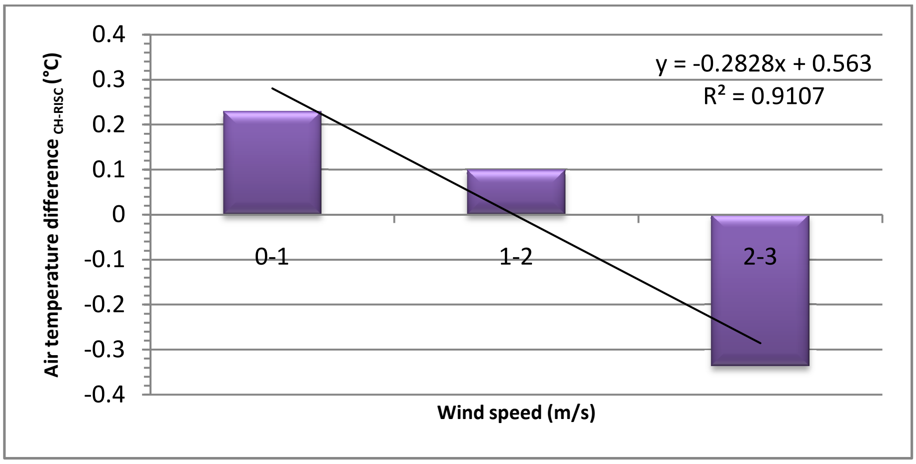

Figure 4.9: Air temperature difference $_{CH\text{-}RISC}$ by wind speed

Averaged from 04-06-2009 to 23-08-2009

4.2.2.3. Difference in air temperature during a low wind speed event

A period of low wind speed below 2.0 m s^{-1} was chosen from the 10^{th} of June to the 14^{th} of June (Figure 4.10). The mean air temperature for Crown House was 16.4°C and for RISC was 16.0°C. There was a substantial mean difference of 0.4°C and T-test analysis was applied to the two samples of air temperatures showing that there is evidence at a <0.01% significant level that the two population means are not equal. This difference in air temperature is twice as high as the average difference of 0.2°C for the sample period. Here again the largest differences in air temperature occur during the morning and early afternoon with 1.3°C difference at 8:00. This is more than six times the sample period average difference. In addition, the roof garden remained cooler than the conventional roof for longer, until 20:00. This would again show that low wind speeds result in high air temperature differences between the two sites.

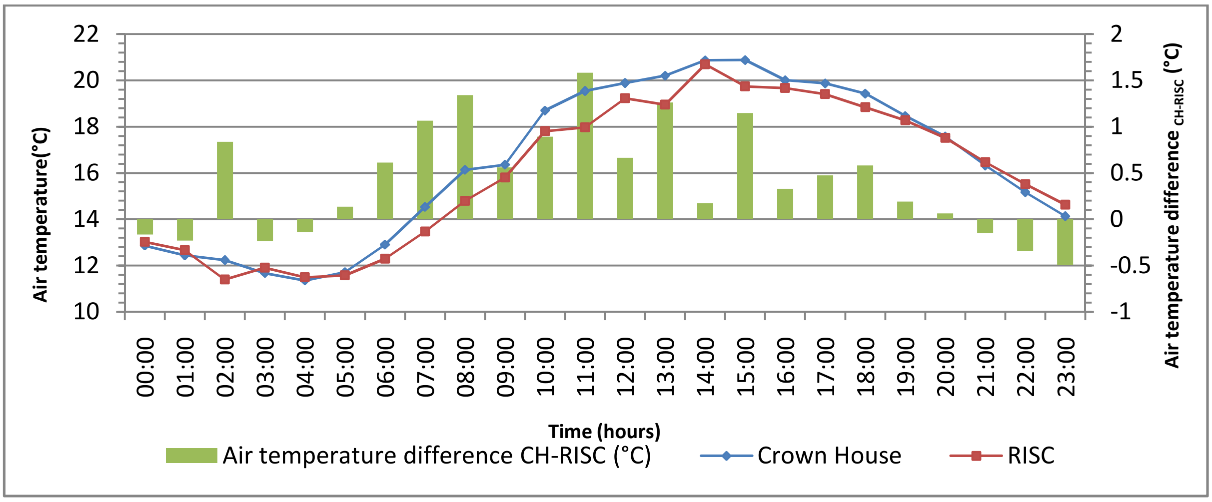

Figure 4.10: Mean diurnal air temperature and air temperature difference $_{CH-RISC}$ during wind speed below 2.0 m s-1 averaged from 10-06-2009 to 14-06-2009

4.2.2.4. Relation between difference in air temperature and wind speed during the June-July heat wave

A regression analysis was conducted for the air temperature difference and the average wind speed for both sites during the June-July heat wave (Figure 4.11). The results of the regression are presented in Table 4.1. As can be seen, the average wind speed accounted for 12% of the variation during the June-July heat wave. There is not a strong relation between difference in air temperature and wind speed during the June-July heat wave.

Table 4.1: Correlation coefficient and regression equation of air temperature difference and average wind speed of both sites during the June-July heat wave

Control (x)	Regression model	r	R^2	Sig.
Average wind speed both sites	$\Delta T_{CH-RISC} = -1.0301 * x + 0.7883$	0.35	0.12	<0.01

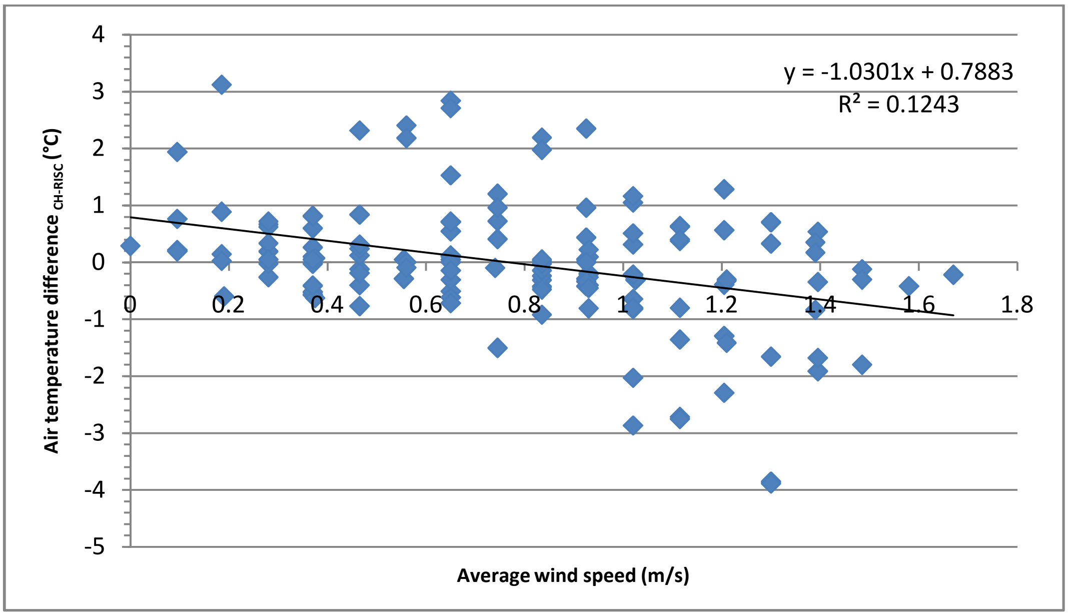

Figure 4.11: Air temperature difference and mean wind speed both sites during the June-July heat wave

4.2.3. Cloud cover

A mean was taken of all the differences in air temperatures for different cloud covers at 9:00 with an interval of 1 okta (Figure 4.12). This is also the time when the difference in air temperature is at its highest. The average cloud cover at 9:00 was 5 oktas. There were three measurements taken of 1 okta cloud cover and during this time the mean air temperature difference was 4.3°C. There were twelve measurements taken of the maximum cloud cover of 8 oktas, during this time the mean air temperature difference was 0.1°C. The 0 okta interval measures a particularly low difference in air temperature but this can be partly explained by the fact that there was only one measurement of 0 okta. When following the trend line in Figure 4.12 it could be concluded that as the amount of cloud cover increases, the air temperature difference between the two sites decreases and this would be in accordance with what has been stated in 2.1.4.7. However the strong variation between 0 and 1 okta, 3 and 4 oktas and the seemingly little difference between 1 and 4 oktas would call into question the reliability of these results.

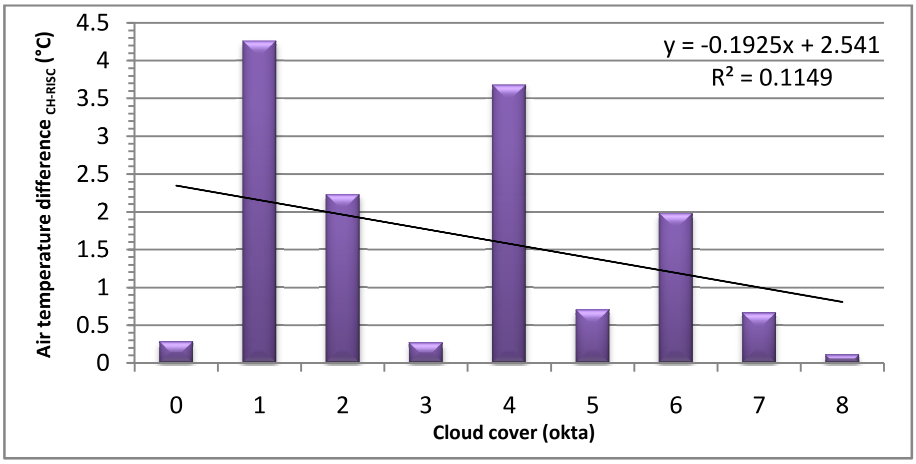

Figure 4.12: Air temperature difference $_{CH\text{-}RISC}$ by cloud cover at 9:00

Averaged from 04-06-2009 to 17-08-2009

4.2.4. Incoming solar radiation and shading

The amount of incoming solar radiation is controlled by the azimuth (Ω) and zenith (Z) angles of the sun with a maximum at local solar noon, these are relative to the horizon (Oke, 1987). As can be seen in Figure 4.13, the incoming solar radiation at RISC is considerably smaller than at Crown House. Between daylight hours of 4:00 and 21:00 the average incoming solar radiation at Crown House was 304 W/m² and the average at RISC was 182 W/m². What has been shown here by the difference in incoming radiation is that a fully grown roof garden can provide substantial shading from solar energy during the day. This shading provided by the vegetation around the RISC AWS illustrated by Figures 3.3 and 3.4 plays a key factor in the amount of incoming solar radiation received at RISC and will act to reduce energy absorption and surface temperature thus cooling the site. Between 5:00 and 14:00 the incoming solar radiation of Crown House is twice that of RISC. It should be noted, however, that these taller plants also act to reduce the sky view factor retaining long-wave radiation under the canopy and this will act to increase air temperatures at night (Taha, 1997). The strong fall in incoming solar radiation noted at Crown House between 14:00 and 16:00 is due to the position of the AWS being in the shade of the fifth floor at that time (see Figure 3.3 and 3.5).

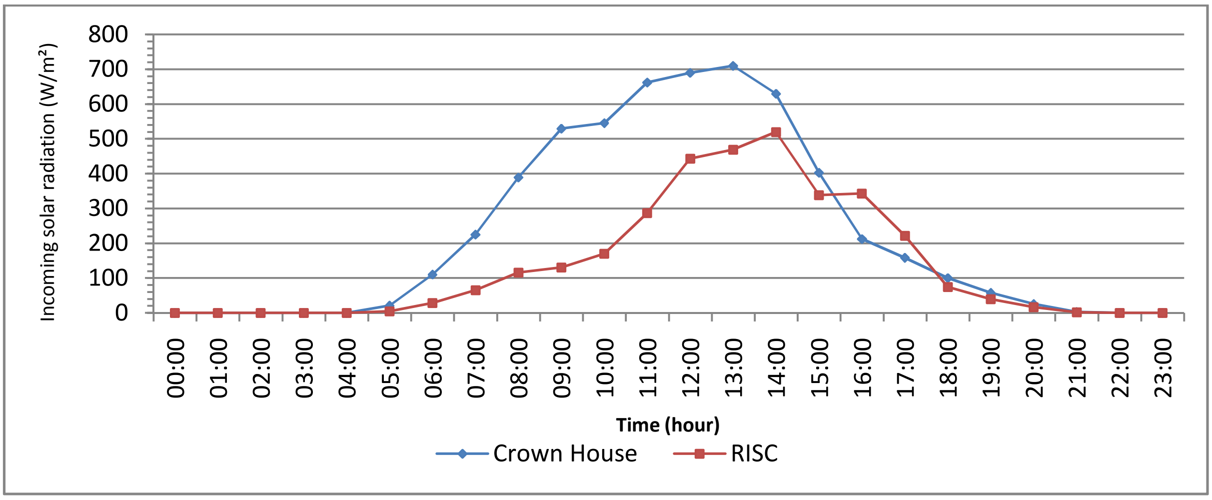

Figure 4.13: Mean diurnal incoming solar radiation

Averaged from 04-06-2009 to 23-08-2009

4.2.5. Albedo

4.2.5.1. Difference in albedo

The mean diurnal albedo for both sites was calculated for the sample period as shown in Figure 4.14. As can be seen, the albedo for RISC is more than three times that of Crown House. The mean albedo for Crown House between the hours of 4:00 and 19:00 was 0.10 and for the RISC site between the same hours, 0.31. This makes the albedo of the roofing membrane on Crown House comparable to the albedo of asphalt (see Figure 2.4). This increase in albedo will in turn lower surface temperatures on the roof due to a reduction in solar energy being absorbed and re-emitted. This in turn will act to decrease air temperatures above the roof (Oke, 1987; Taha, 1997). It gives evidence that an intensive green roof can effectively mitigate the UHI effect in an urban environment.

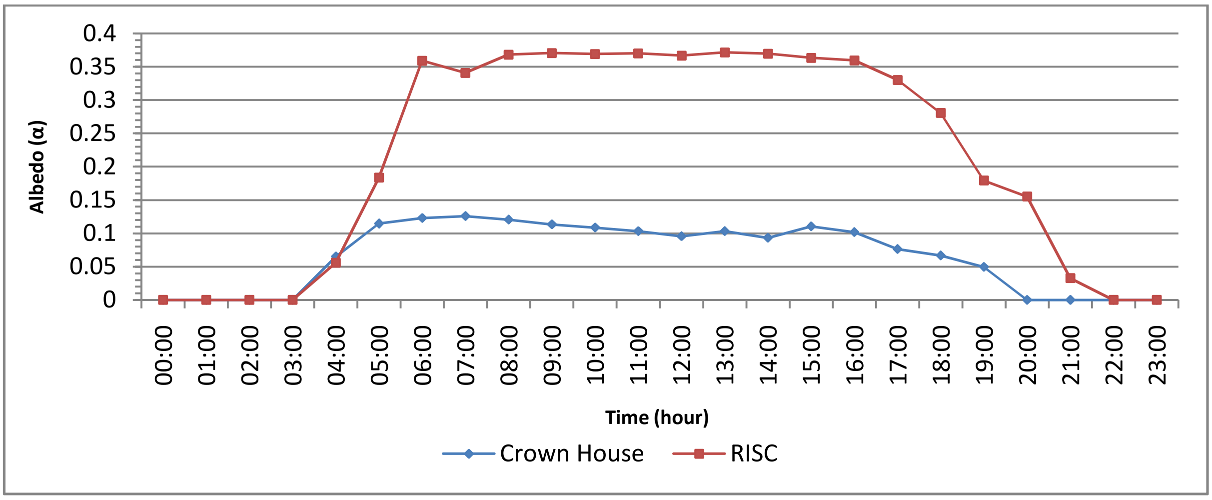

Figure 4.14: Mean diurnal albedo

Averaged from 04-06-2009 to 23-08-2009

4.2.5.2. Albedo of the vegetation cover

Measurements for the albedo at the RISC site at 12:00 were plotted from late March to September in Figure 4.15. The thick growth of the *Echinacea purpurea* and the effect this has on the albedo can be seen as it rises from a minimum of 0.13 on the 9th of April to a maximum of 0.42 on 30th of May. After which it decreases and by the 1st of September the albedo is 0.25. Figure 4.16 shows how the *Echinacea purpurea* has completely covered the sample site with vegetation.

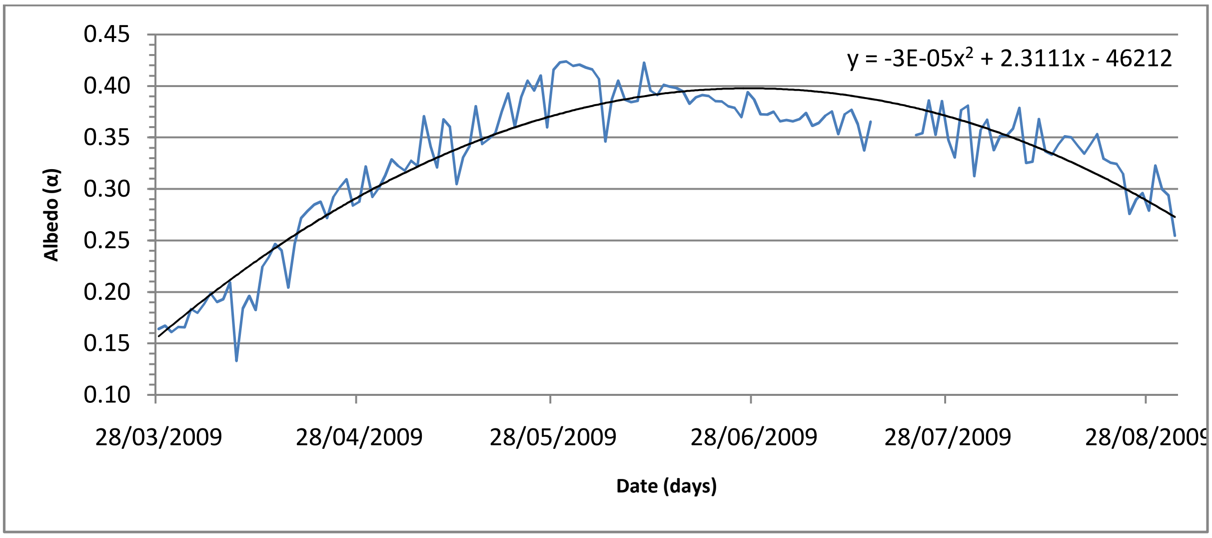

Figure 4.15: RISC Albedo at 12:00

Averaged from 28-03-2009 to 01-09-2009

Figure 4.16: RISC undergrowth taken on the 24th of August

4.2.6. Difference in surface temperature between the sites

Surface temperatures are depended on the surface energy balance. This is governed by properties such as (1) orientation and SVF, (2) albedo and reflectivity in the infrared (3) emissivity, (4) availability of surface moisture for evaporation, (5) ability to conduct and diffuse heat, and (6) roughness (Roth et al., 1989). These factors are strongly depended on the land-use and land cover features and the characteristics of the surfaces themselves (Roth et al., 1989). There is however no simple relationship between surface and air temperature and the two are not closely correlated (Roth et al., 1989).

On the day that the infrared images were taken the weather conditions were not optimal. It had been overcast most of the day up to when the images were taken and most of the Crown House roof was in the shade at that time. The differences in surface temperatures could have been much larger on a clear and sunny day but there are still clear differences to be seen in the images from the two sample sites. The surface temperatures measured in Figure 4.17 ranges from approximately 18 to 21°C. As can be seen from the visible image in Figure 4.18, the areas with low surface temperature in the garden are the vegetated areas.

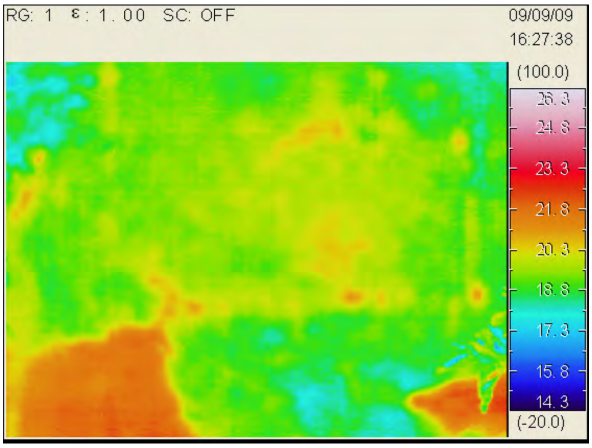

Figure 4.17: Intensive green roof - Infrared image 1

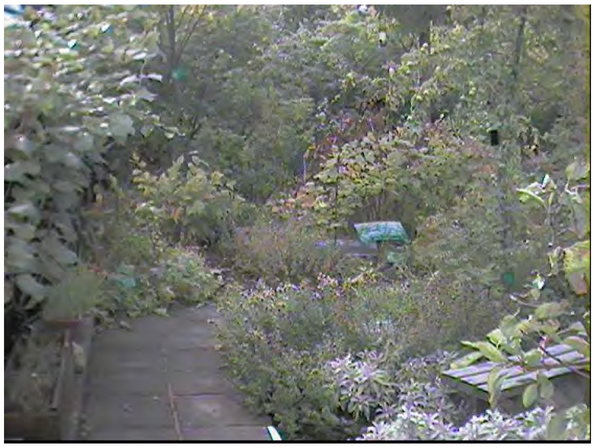

Figure 4.18: Intensive green roof - Visible image 1

In Figure 4.19 the difference between the surface temperature of the stone garden paving and vegetation can be seen. The stone paving in the centre of the image has created a much wider range of surface temperatures in this image ranging from approximately 19°C for the much cooler vegetation on both sides of the image to approximately 26°C in the centre of the image. This can be explained again by the stone surface possessing a lower albedo than the vegetation.

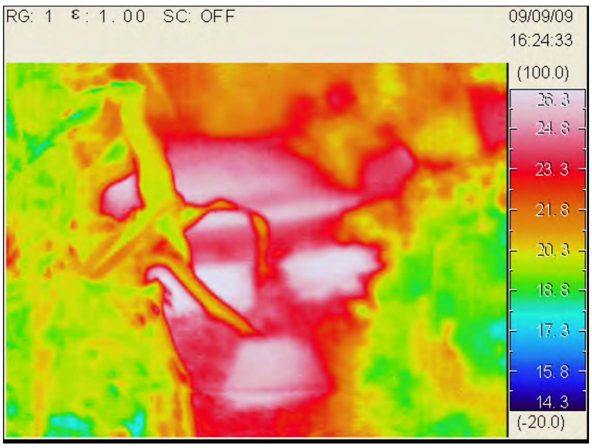

Figure 4.19: Intensive green roof - Infrared image 2

Figure 4.20: Intensive green roof - Visible image 2

Figure 4.21 and Figure 4.22 are images of the sky window which opens from the office space beneath the roof garden. There will be a substantial amount of anthropogenic heat escaping from the office space, shop and restaurant via these opened sky windows into the roof garden as can be seen from Figure 4.21. Another noteworthy point in these images is the reflection on the top and side of the window. This highly reflective synthetic material will have a high surface albedo. These factors have created a substantial range of surface temperature from approximately 16°C for the reflection on the top and side of the window to approximately 24°C for the opened sky window.

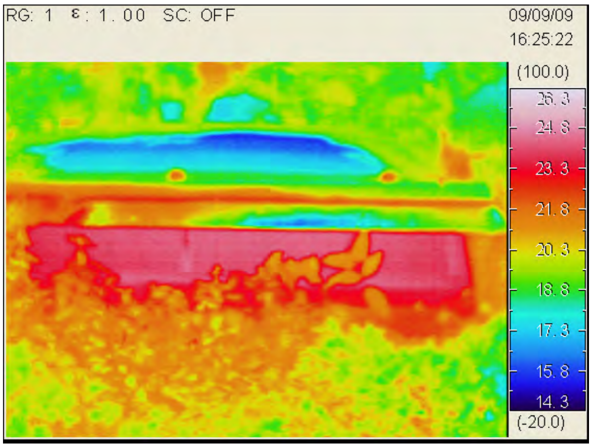

Figure 4.21: Intensive green roof - Infrared image 3

Figure 4.22: Intensive green roof - Visible image 3

Figure 4.23, Figure 4.24, Figure 4.25 and Figure 4.26 are infrared and visible images of the conventional roof. From Figures 4.23 and 4.25 it can be seen that the surface temperatures on the conventional roof range from approximately 22 to 26°C. Compared to the minimum range from the intensive green roof of 18°C to 21°C, this is a reduction in surface temperature of 4°C. This is less than the 10°C seen by Niachou et al. (2001) or the 30°C seen by Wong et al. (2003). However Niachou et al. (2001) and Wong et al. (2003) measured surface temperatures under the vegetation canopy and had this experiment taken place on a clear and sunny day, similar results may have been achieved.

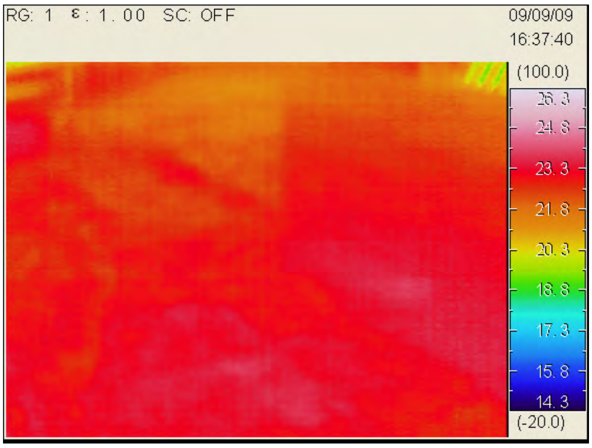

Figure 4.23: Conventional roof - Infrared image 1

Figure 4.24: Conventional roof - Visible image 1

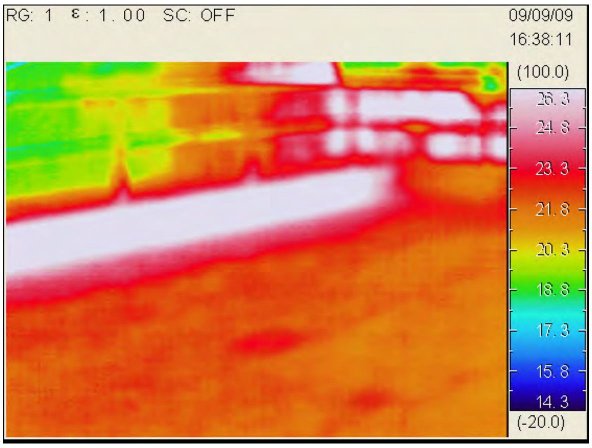

Figure 4.25: Conventional roof - Infrared image 2

Figure 4.26: Conventional roof - Visible image 2

4.2.7. Synoptic conditions

4.2.7.1. Anticyclonic conditions - High atmospheric pressure

A four day period of high atmospheric pressure above 1013.5 mbar was selected in order to investigate whether days with higher-than-average atmospheric pressure will result in stronger microclimatic differences. The mean air temperature for this period for Crown House was 17.3°C and for RISC 17.4°C (Figure 4.27). In this case there is no evidence that the two population means are not 0 ($p=0.30$). In addition this difference is below the accuracy of the temperature sensor thus the exact difference cannot be reported. From the synoptic chart in Figure 4.28 it can be seen that on the 23rd of June the South East of England was under an area of anticyclonic weather conditions which should be favourable for UHI development. The average wind speed during this period for Crown House was 1.4 m s^{-1} which is 0.2 m s^{-1} higher than the average for the sample period. At RISC the average was 0.5

m s^{-1} which equal to the average for the sample period. Cloud cover during this period was 4 oktas which is 1 okta lower than the average.

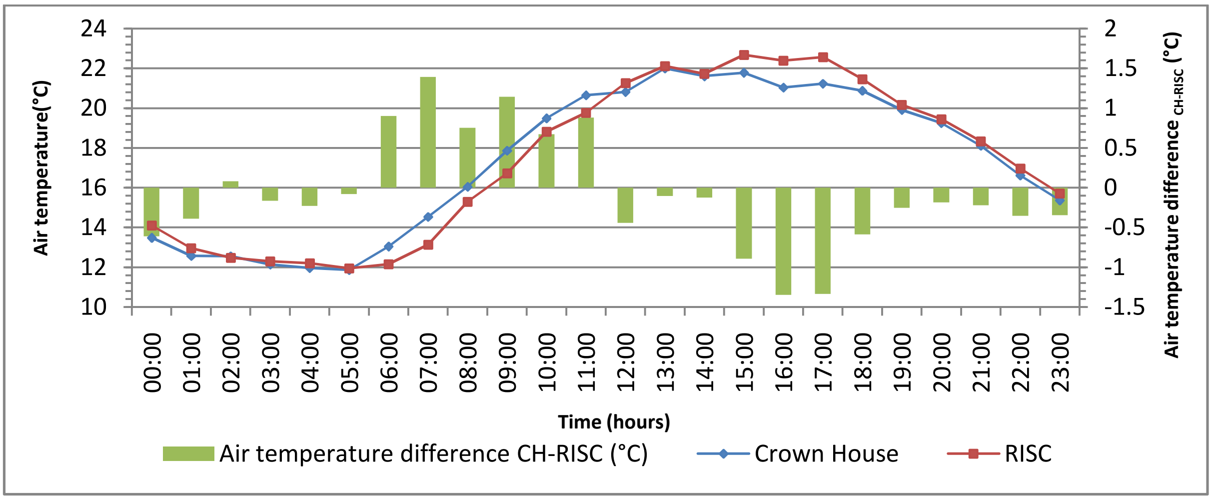

Figure 4.27: Mean air temperature and air temperature difference $_{CH-RISC}$ during high atmospheric pressure above 1013.5 mbar averaged from 20-06-2009 to 24-06-2009

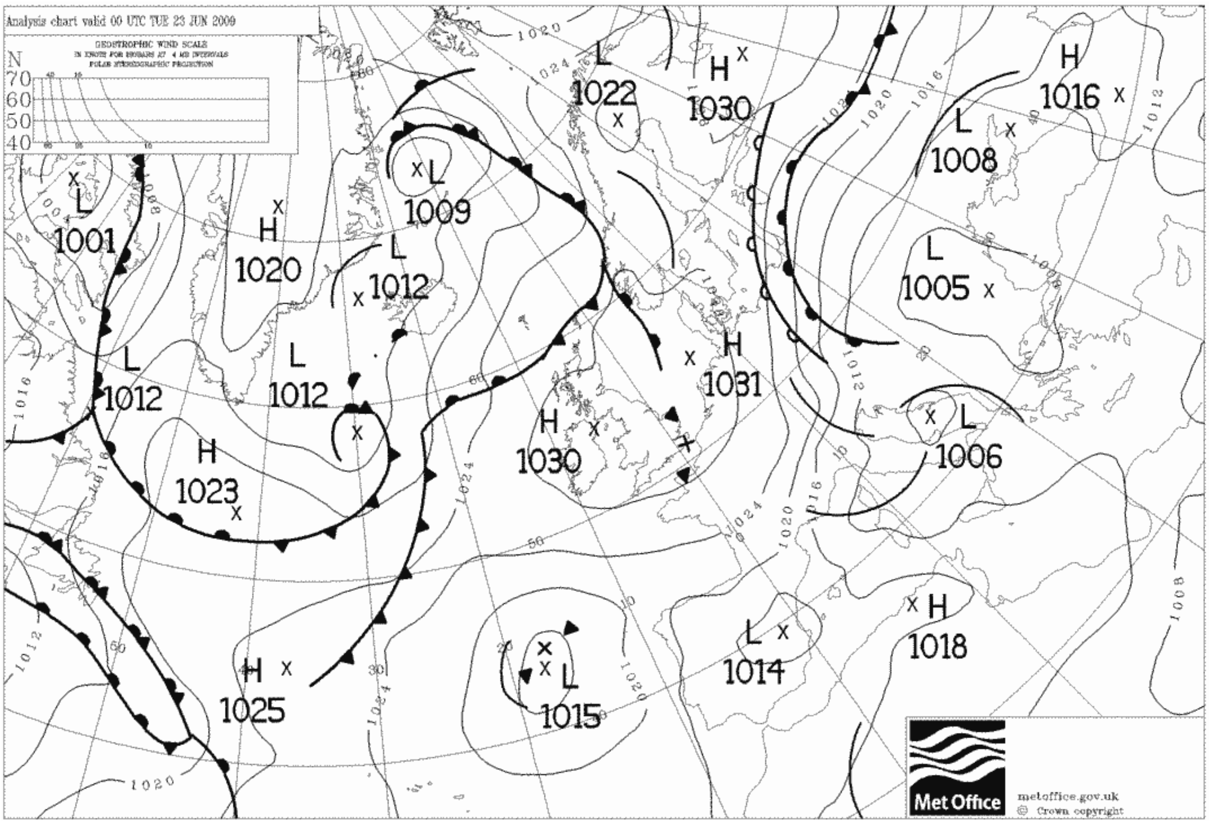

Figure 4.28: High atmospheric pressure above the South East of England on the 23th of June

4.2.7.2. Cyclonic conditions - Low atmospheric pressure

The mean for this period of low atmospheric pressure below 1000 mbar for Crown House is 12.2°C and for RISC 12.4°C (Figure 4.29). The mean of the difference tells us that the RISC site was 0.2°C warmer than Crown House and T-test analysis confirmed that the two means are significantly different at a <0.01% confidence level. The synoptic chart in Figure 4.30 shows that for the 7th of June the South East of England was under a depression with cyclonic weather conditions which should be unfavourable for UHI development. The average wind speed at Crown House for this period was 1.6 m s^{-1} which is 0.5 m s^{-1} higher than the average wind speed for the sample period. For RISC, the mean wind speed is 0.3 m s^{-1} which is 0.3 m s^{-1} higher than the average for the sample period. Unfortunately the meteorology department was unable to supply cloud cover data for the 7th and 8th of June but on the 5th and 6th as well as on the 9th and 10th of June 8 oktas cloud cover was measured.

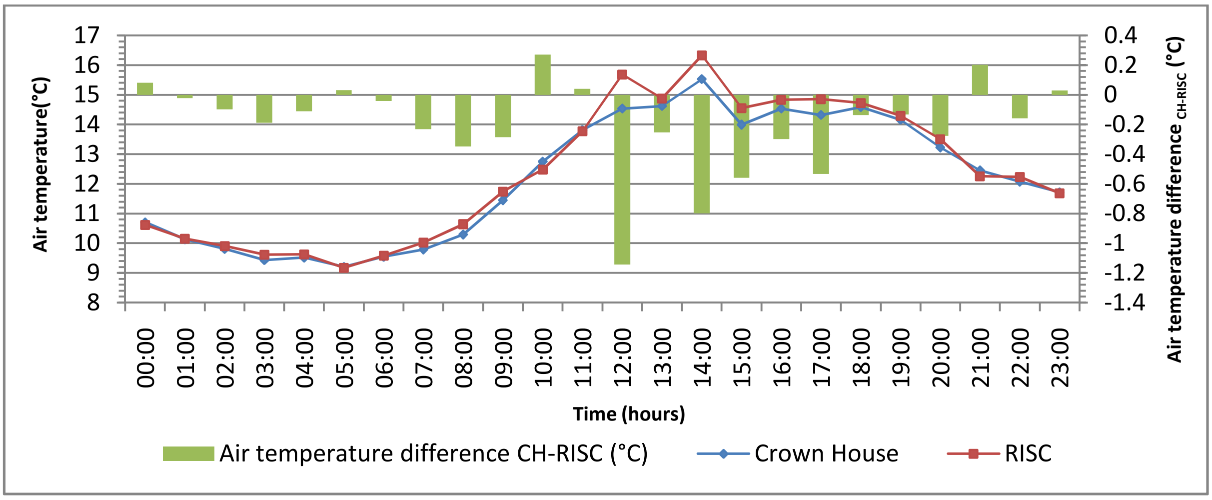

Figure 4.29: Mean air temperature and air temperature difference $_{CH-RISC}$ during low atmospheric pressure below 1000 mbar averaged from 07-06-2009 to 09-06-2009

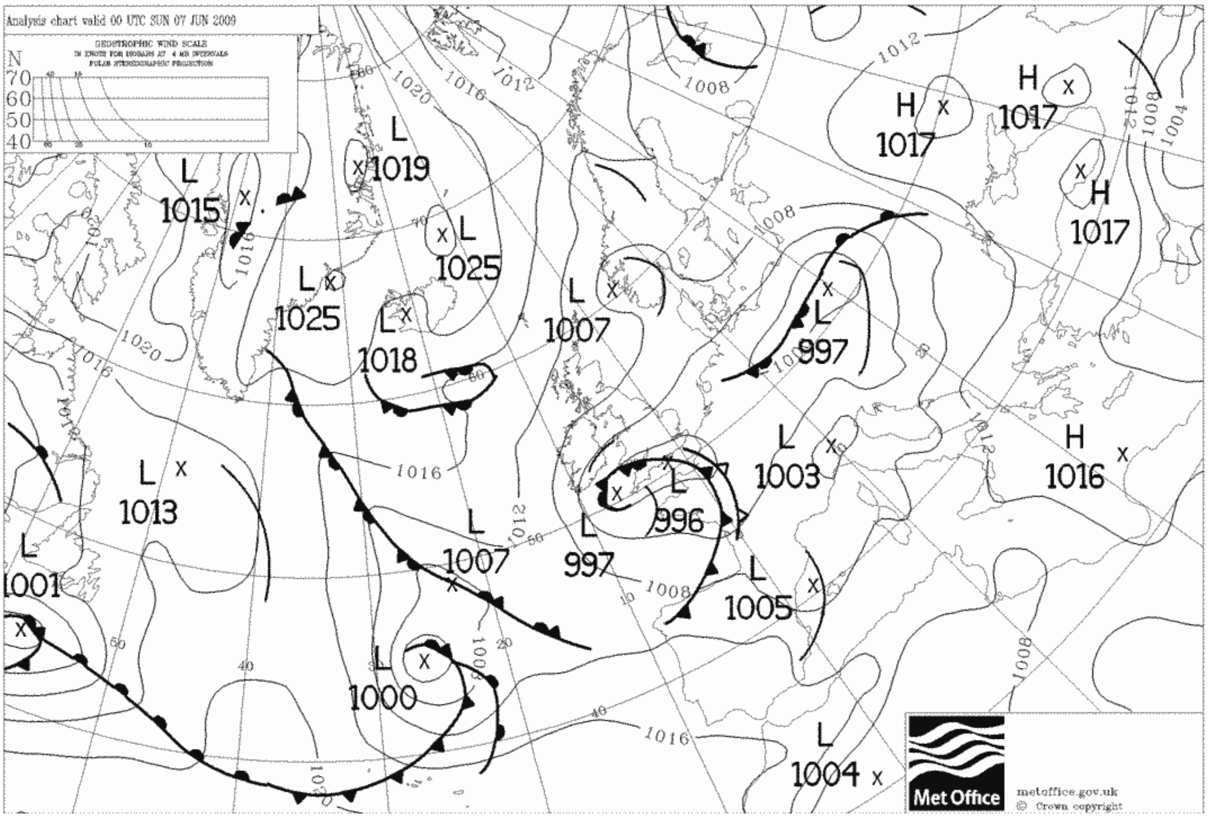

Figure 4.30: Low atmospheric pressure above the South East of England on the 7th of June

From these results it can be seen that under anticyclonic weather conditions, when UHI development would be expected, the weather was not calm and there was no statistically significant difference in air temperature. During cyclonic weather conditions, which are unfavourable for UHI development, the mean air temperature at RISC was 0.2°C higher than that at Crown House. There is a lack of consistency in the results for synoptic conditions. These two examples show that synoptic conditions did not play a major role on the difference in air temperature between the two sites, however, the assessment periods were very short and a longer-term assessment of the impact of synoptic conditions is required.

4.2.8. Relative humidity

Relatively humidity as a parameter in micrometeorological studies can prove to be unreliable due to its high diurnal variability (Shahgedanova et al., 1998). Typically locations with high temperatures tend to have low relative humidity and vice versa (Theodosiou, 2003; Wong and Yu, 2005). However it must also be noted that in humid environments, evapotranspiration is minimized and green roofs do not have much to offer compared to arid ones (Theodosiou, 2003). The result of this experiment showed that there is a small difference in relative humidity between the two sites and that the mean relative humidity for Crown House was 70% and for RISC, 71%. This give a 1% mean of the difference and there is evidence at a <0.01% significant level that the two means are not equal. This 1% mean difference however is less than the accuracy of the sensor so the difference should be discredited. The maximum difference occurs at 10:00 and is 3%. As can be seen from Figure 4.31, times when the relative humidity at the intensive green roof is higher than that of the conventional roof generally corresponds with the time when there is a reduction in air temperature due to the intensive green roof. However it is unclear whether the two are related or the higher levels of humidity at RISC are due to the reduction in air temperature or the reduction in air temperature is due to higher levels of humidity. In addition, it should not be forgotten that the intensive green roof is an irrigated garden and this could play a role in the results.

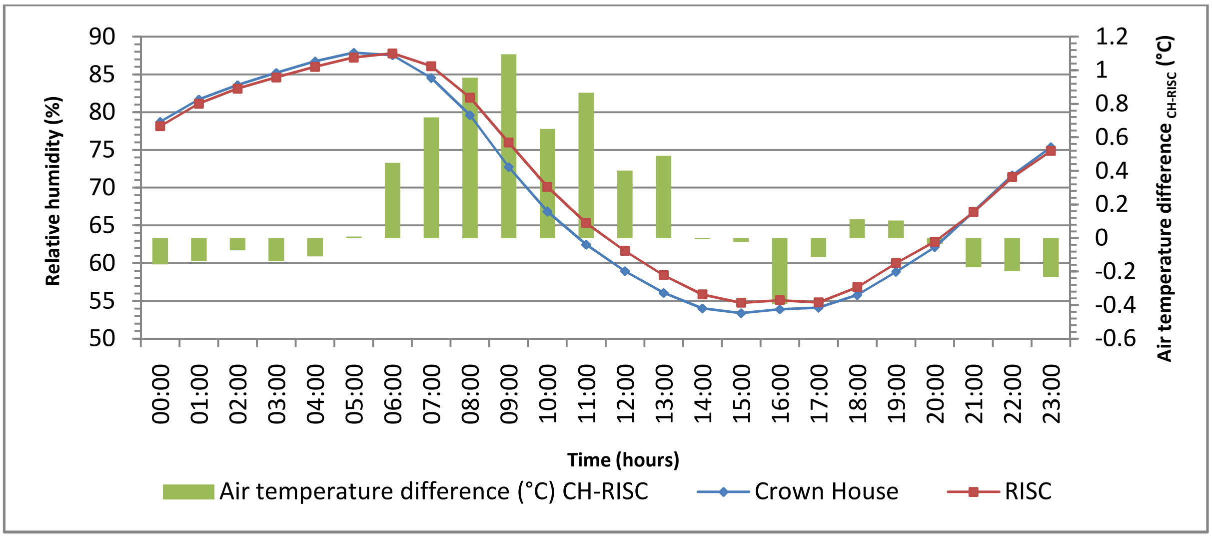

Figure 4.31: Mean diurnal relative humidity and air temperature difference $_{CH-RISC}$
Averaged from 04-06-2009 to 23-08-2009

4.3. Potential green roof space in the centre of Reading

The total building footprint of the Reading Borough provided by the Borough Council is 5,485,500 m^2 or approximately 13% of the total area of the Borough. Even if every roof in the borough would have a green roof this would still not equal the 5.87 km^2 of public green space and waters which has been lost since 1960 as seen in 2.1.2 (Lee, 2008). A large proportion of these roofs will not be suitable green roof space.

To calculate the potential green roof space in the centre of Reading first a sample area was selected (Figure 4.32). This area is a mixture of commercial and business area. As already stated in 3.1 the NDVI of the commercial areas is 0.02. The NDVI of business areas is 0.09 (Lee, 2008). The sample area in the centre of Reading was calculated to be 801,300 m^2, of this 126,400 m^2 is flat roof space or 16%. Following this, the flat roofs which could be used for green roof space without any structural support was estimated to be 27,000 m^2 or 0.03% of the sample area. Because it is unlikely that the total area selected can be used for green roof space, a further 75% of this or 20,250 m^2 was taken. This equals 0.025% of the sample area or the same area as 2.8 football pitches. Assuming that 80% of this area is extensive and 20% intensive this would provide 16,200 m^2 of extensive green roof space and 4,050 m^2 of intensive green roof space. The centre of Reading is made of a mixture of roof types. Flat roofs make up a large part of this area but it is not the type of flat roof which could be used for green roofs. As discussed in 3.6 it is roofing with shingle ballast or paved finishing that can be retrofitted without additional structural support. This is not the predominant flat roof type in the centre of Reading, rather the predominant flat roof type is a membrane roof such as the roofing used at Crown House which would need additional structural support.

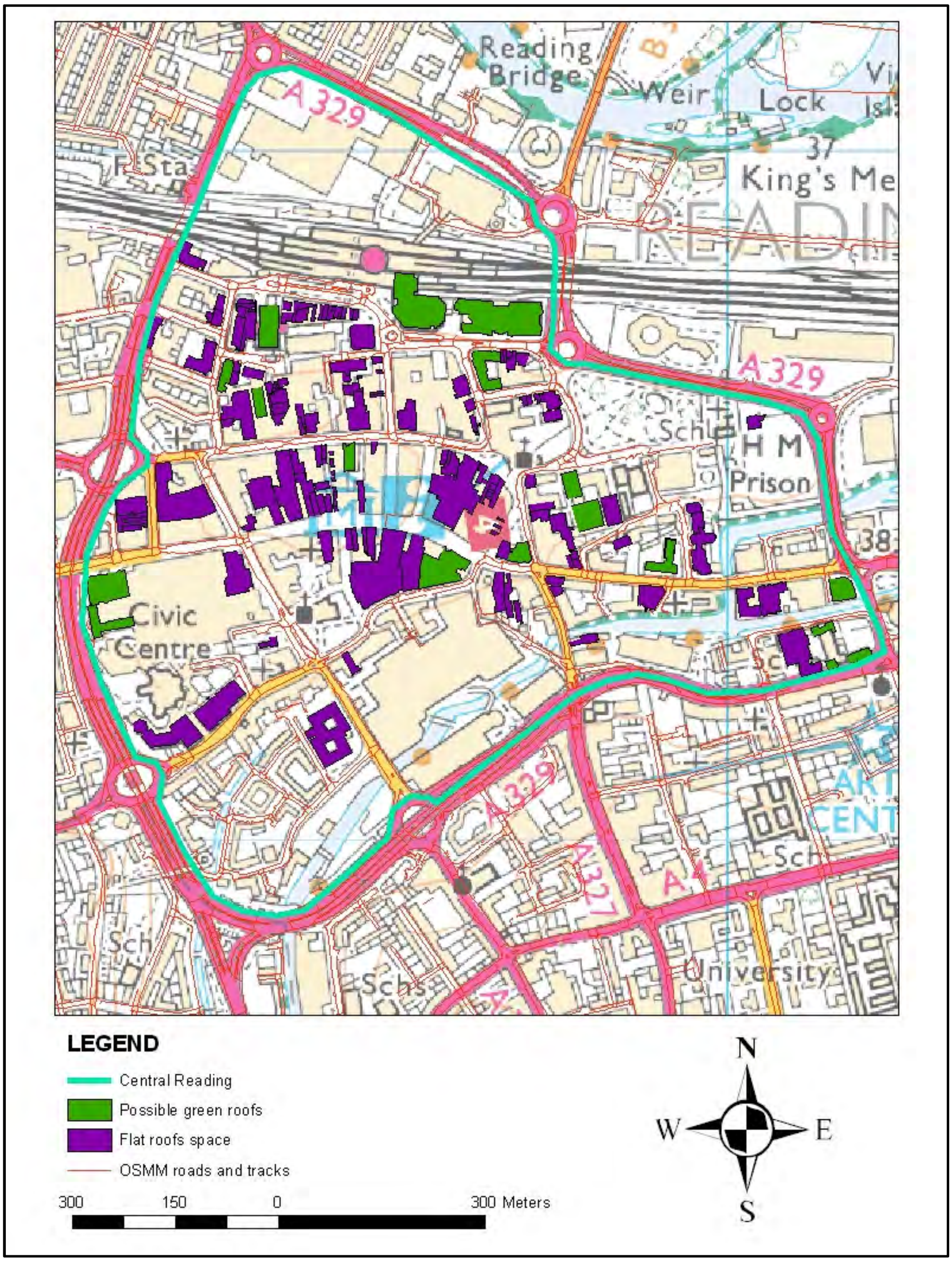

Figure 4.32: Potential green roof space in the centre of Reading

This area of 20,250 m^2 is only a very small fraction of the 5.87 km^2 which would be needed to regain the amount of public green space and waters which has been lost since 1960. And seeing that these roofs are privately owned, it would ultimately be up to the residents whether they would want to convert their roofs to green roofs. However, the sample area selected in this dissertation is only a fiftieth of the total area of the Borough. In addition, the amount of public green space and waters which has been lost in the sample area since 1960 would be needed to determine conclusive results. However the Borough Council could introduce policy and incentives which would reward residents who install green roofs and take action to mitigate the urban heat island. This could be put in place for future new developments and retrofitted structures. For example, a regulation which requires that all new and retrofit roofs achieve a minimum albedo of 25% has been introduced in Chicago effectively promoting / requiring a green roof (Toronto City Planning, 2005). In Germany, green roofs are promoted through a reduction in storm water drainage charge if a green roof is incorporated into the building such as is the case in Munster, Portland and Cologne (Toronto City Planning, 2005). Implementation of such measures in the UK can be beneficial for the more widespread installation of green roofs, mitigation of urban heat islands, and adaptation to climate change.

5. Conclusions

5.1. Answers to research questions

The key objective of this dissertation was to quantify and characterize the meliorating thermal properties of intensive green roofs in central Reading. Five research questions have been addressed and are listed below.

1. Are there differences in air temperature between the conventional roof and the intensive green roof?

The intensive green roof is on average 0.2°C cooler than the conventional roof during the summer. The absolute maximum air temperature difference recorded during the sample period was 4.3°C. Out of the 65 day sample period, 23 days saw a maximum air temperature difference between 1 and 2°C. The difference in air temperature was the largest in July and August and the smallest in June.

2. At what times during the day are there the greatest differences in air temperature between the conventional roof and the intensive green roof?

The air temperature of the intensive green roof is below that of the conventional roof in the morning and early afternoon between 5:00 and 13:00. This is due to evapotranspirational cooling and shading. The reduction in air temperature peaks at 9:00 when the intensive green roof is on average 1.1°C cooler than the conventional roof. During the other times of the day between 14:00 and 4:00 the air temperature of the intensive green roof is above that of the conventional roof with exception at 18:00 and 19:00. At night this is due to a reduction in the sky view factor as a result of the taller vegetation. The greatest addition in temperature occurs at 16:00 and is 0.4°C.

3. Will the intensive green roof provide substantial refuge from high temperatures during a heat wave?

The intensive green roof did not provide refuge from high temperatures during the heat wave. The mean air temperature of both sites during the heat wave was 23.2°C. During the heat wave there was little relation between wind speed and air temperature difference. In addition, during the heat wave relative humidity was reduced by 10% at both sites but this did not stimulate evapotranspiration. Additional research would be needed over a prolonged period of time in order to be more conclusive.

4. Which observed controls play a role in the difference in air temperature between the conventional roof and the intensive green roof?

- Wind speed: as wind speed increases, the difference in air temperature decreases and the greatest differences in air temperature are noted under calm wind conditions. Wind speed at the intensive green roof was half that of the conventional roof. Between wind speeds of 0 and 1.0 m s^{-1} the intensive green roof was on average 0.2°C cooler than the conventional roof. Between wind speeds of 2 and 3 m s^{-1} the intensive green roof was on average 0.3°C warmer than the conventional roof. During a low wind speed event, the average difference in air temperature was twice that of the average for the sample period.

- Cloud cover: it could be concluded that clear skies without clouds see the largest difference in air temperature. When 1 okta was measured, the mean air temperature difference was 4.3°C. When 8 oktas was measured, the mean air temperature difference was 0.1°C. However the strong variations between measurements call into question the reliability of the results.

- Incoming solar radiation and shading: between 4:00 and 21:00 the mean incoming solar radiation at Crown House was 304 W/m² and for RISC it was 180 W/m². The fully grown roof garden provides shading from solar energy during the day. This shading provided by vegetation will play a substantial role in cooling the air temperature beneath the vegetation and cooling the site.

- Albedo: the albedo for RISC is more than three times that of Crown House. The mean albedo between 4:00 and 19:00 for the conventional roof was 0.10 and for the intensive green roof, 0.31. The albedo of the vegetation cover peaked at the end of May. This increase in albedo will lower surface and air temperatures on the intensive green roof due to a reduction in solar energy being absorbed and re-emitted. It gives evidence that an intensive green roof can effectively mitigate the UHI effect.

- Surface temperature: On the day of measuring, the minimum surface temperature on the intensive green roof ranged between approximately 18°C to 21°C and for the conventional roof approximately 22 to 26°C. This gives a maximum reduction in surface temperature of 4°C.

- Synoptic conditions: during anticyclonic weather there was no difference in air temperature to be noted and during cyclonic weather the roof garden was warmer than the conventional roof. The two case studies showed that synoptic conditions did not play a major role on the difference in air temperature between the two sites, however, more comparisons may be required.

- Relative humidity: the 1% difference in relative humidity was below the accuracy of the sensor. However a maximum difference of 3% was noted at 10:00 showing that the relative humidity of the intensive green roof in higher than that of the conventional roof. There is not enough evidence to conclude that relative humidity played a role in the difference in temperature between the sites due to the comparatively small difference and the possibility that this could have been caused by the garden irrigation system.

5. How much area would be suitable for green roofs in the centre of Reading?

An estimated 20,250 m^2 or 2.8 football pitches could be used for green roof space in the centre of Reading without adding structural support to the buildings. This would provide 16,200 m^2 of extensive green roof space and 4,050 m^2 of intensive green roof space. This equals <1% of the selected sample area in the centre of Reading. This is mainly due to the large amount of membrane flat roof type in the centre of Reading.

5.2. Accomplished objectives and prospects for further research

Cities have a direct interest in mitigating the urban heat island. This would benefit the public health of residents, save energy, reduce CO_2 emissions, enhance storm-water management, benefit urban biodiversity and reduce air pollution. If not, the viability of some cities could become threatened. The summer of 2009 was 0.5°C warmer than the average for 1971-2000. If this trend is set to continue then the same measures described here to reduce the UHI will serve cities to become a more comfortable environment for their inhabitants in a warmer world with increased summertime temperatures and more frequent extreme conditions. Further research could take place on how intensive green roofs can mitigate and serve to adapt to future global climate change.

This dissertation has achieved the objective of proving that intensive green roofs can not only serve for recreational purposes but can also mitigate the urban heat island in a mid-latitude urban area. This was previously unproven in academic literature. This research fits in with other literature on the thermal effect of green roofs and urban green space in urban environments. Urban green space is widely recognized as beneficial to urban environments. This dissertation has shown that the same effect urban green space has on its surrounding microclimate has been produced by an intensive green roof on a smaller scale. Most important of all, this took place within the centre of an urban area, where UHI mitigation is at its most needed. The lower air temperatures in the morning and early afternoon can provide valuable time in which temperatures are reduced for groups in the population vulnerable to high temperatures. However, that the intensive green roof did not reduce the air temperature during a heat wave was unexpected. More data during heat waves would be needed to completely rule out the effectiveness of an intensive green roof during these extreme temperatures. It should also not be forgotten that just one roof was the subject of this dissertation. Additional research could take place to calculate the benefits multiple intensive green roofs would have over a larger surface area in Reading.

The second objective was achieved by estimating that 20,250 m^2 or 2.8 football pitches could be used for green roof space in the centre of Reading. This natural landscape could bring substantial benefits to the local area. National and local governments should be encouraged to introduce policy which can provide incentives for UHI mitigation and the instalment of green roofs when buildings are being retrofitted and new developments take place. These measures together with other strategies can help green cities and can retake once lost natural landscapes.

Appendices

Appendix A: Results of statistical analysis

Table A.1: Results for Figure 4.1 Mean air temperature

Descriptive Statistics for Temp Difference	
Mean	0.169172917
Standard Error	0.086316472
Median	-0.0153
Mode	#N/A
Standard Deviation	0.422862626
Sample Variance	0.1788128
Kurtosis	-0.390068925
Skewness	0.912405478
Range	1.48741
Minimum	-0.39308
Maximum	1.09433
Sum	4.06015
Count	24

t-Test: Paired Two Sample for Means

	Variable CH	Variable RISC
Mean	17.86986208	17.70068917
Variance	10.25974714	9.947259385
Observations	24	24
Pearson Correlation	0.991269486	
Hypothesized Mean Difference	0	
df	23	
t Stat	1.959914635	
P(T<=t) one-tail	0.031115796	
t Critical one-tail	1.713871517	
P(T<=t) two-tail	0.062231592	
t Critical two-tail	2.068657599	

Table A.2: Results for Figure 4.4 Mean air temperature June

Descriptive Statistics for Temp Difference		t-Test: Paired Two Sample for Means		
			Variable CH	Variable RISC
Mean	0.114266667	Mean	16.88822917	16.7739625
Standard Error	0.085096493	Variance	11.72815436	11.68165947
Median	-0.022	Observations	24	24
Mode	#N/A			
Standard Deviation	0.416885974	Pearson Correlation	0.992577981	
Sample Variance	0.173793915	Hypothesized Mean Difference	0	
Kurtosis	-0.805059154	df	23	
Skewness	0.886847404	t Stat	1.342789373	
Range	1.2128	P(T<=t) one-tail	0.096221483	
Minimum	-0.3176	t Critical one-tail	1.713871517	
Maximum	0.8952	P(T<=t) two-tail	0.192442966	
Sum	2.7424	t Critical two-tail	2.068657599	
Count	24			

Table A.3: Results for Figure 4.5 Mean air temperature July

Descriptive Statistics for Temp Difference		t-Test: Paired Two Sample for Means		
			Variable CH	Variable RISC
Mean	0.1665125	Mean	18.51499583	18.34848333
Standard Error	0.098913164	Variance	8.704630737	8.286692323
Median	-0.00305	Observations	24	24
Mode	#N/A			
Standard Deviation	0.48457356	Pearson Correlation	0.986478968	
Sample Variance	0.234811535	Hypothesized Mean Difference	0	
Kurtosis	1.041305745	df	23	
Skewness	1.090819752	t Stat	1.68342103	
Range	2.0518	P(T<=t) one-tail	0.052909982	
Minimum	-0.5535	t Critical one-tail	1.713871517	
Maximum	1.4983	P(T<=t) two-tail	0.105819964	
Sum	3.9963	t Critical two-tail	2.068657599	
Count	24			

Table A.4: Results for Figure 4.8 Mean air temperature August

Descriptive Statistics for Temp Difference	
Mean	0.2344
Standard Error	0.087147696
Median	0.08165
Mode	#N/A
Standard Deviation	0.426934774
Sample Variance	0.182273301
Kurtosis	-0.262288976
Skewness	0.860256195
Range	1.5586
Minimum	-0.3701
Maximum	1.1885
Sum	5.6256
Count	24

t-Test: Paired Two Sample for Means	Variable CH	Variable RISC
Mean	18.5710375	18.3366375
Variance	10.06200442	9.510489992
Observations	24	24
Pearson Correlation	0.991080811	
Hypothesized Mean Difference	0	
df	23	
t Stat	2.689686722	
P(T<=t) one-tail	0.00654067	
t Critical one-tail	1.713871517	
P(T<=t) two-tail	0.01308134	
t Critical two-tail	2.068657599	

Table A.5: Results for Figure 4.7 Mean air temperature heat wave

Descriptive Statistics for Temp Difference	
Mean	-0.011470833
Standard Error	0.088413214
Median	-0.0257
Mode	#N/A
Standard Deviation	0.43313452
Sample Variance	0.187605513
Kurtosis	2.467922056
Skewness	0.32401472
Range	2.1845
Minimum	-0.9845
Maximum	1.2
Sum	-0.2753
Count	24

t-Test: Paired Two Sample for Means	Variable CH	Variable RISC
Mean	23.19244583	23.20391667
Variance	21.50290745	23.18767587
Observations	24	24
Pearson Correlation	0.996510485	
Hypothesized Mean Difference	0	
df	23	
t Stat	-0.12974116	
P(T<=t) one-tail	0.4489496	
t Critical one-tail	1.713871517	
P(T<=t) two-tail	0.897899201	
t Critical two-tail	2.068657599	

Table A.6: Results for Figure 4.10 Mean air temperature with wind speed below 2.0 m s^{-1}

Descriptive Statistics for Temp Difference		t-Test: Paired Two Sample for Means		
			Variable CH	Variable RISC
Mean	0.423175	Mean	16.38438333	15.96120833
Standard Error	0.1201298	Variance	11.29348003	9.771129104
Median	0.4014	Observations	24	24
Mode	#N/A			
Standard Deviation	0.588513424	Pearson Correlation	0.986136505	
Sample Variance	0.34634805	Hypothesized Mean Difference	0	
Kurtosis	-0.933943367	df	23	
Skewness	0.305517342	t Stat	3.522648015	
Range	2.0778	P(T<=t) one-tail	0.000912225	
Minimum	-0.495	t Critical one-tail	1.713871517	
Maximum	1.5828	P(T<=t) two-tail	0.001824451	
Sum	10.1562	t Critical two-tail	2.068657599	
Count	24			

Table A.7: Results for Figure 4.11 Air temperature difference and mean wind speed both sites during the June-July heat wave

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.352537881
R Square	0.124282958
Adjusted R Square	0.118115936
Standard Error	1.046135335
Observations	144

ANOVA

	df	SS	MS	F	Significance F
Regression	1	22.05524395	22.05524395	20.15283377	1.46726E-05
Residual	142	155.4046779	1.09439914		
Total	143	177.4599218			

Table A.8: Results for Figure 4.27 Mean air temperature with high atmospheric pressure above 1013.5 mbar

Descriptive Statistics for Temp Difference	
Mean	-0.076325
Standard Error	0.145556242
Median	-0.2026
Mode	#N/A
Standard Deviation	0.713077043
Sample Variance	0.508478869
Kurtosis	-0.113617614
Skewness	0.364951296
Range	2.7414
Minimum	-1.3476
Maximum	1.3938
Sum	-1.8318
Count	24

t-Test: Paired Two Sample for Means	Variable CH	Variable RISC
Mean	17.27865	17.354975
Variance	13.81907639	15.76742322
Observations	24	24
Pearson Correlation	0.984951793	
Hypothesized Mean Difference	0	
df	23	
t Stat	-0.52436776	
P(T<=t) one-tail	0.302520093	
t Critical one-tail	1.713871517	
P(T<=t) two-tail	0.605040187	
t Critical two-tail	2.068657599	

Table A.9: Results for Figure 4.29 Mean air temperature with low atmospheric pressure below 1000 mbar

Descriptive Statistics for Temp Difference	
Mean	-0.206855417
Standard Error	0.063818605
Median	-0.14785
Mode	#N/A
Standard Deviation	0.312646036
Sample Variance	0.097747544
Kurtosis	2.57682231
Skewness	-1.325256697
Range	1.4145
Minimum	-1.1428
Maximum	0.2717
Sum	-4.96453
Count	24

t-Test: Paired Two Sample for Means	Variable CH	Variable RISC
Mean	12.17706667	12.38392208
Variance	4.456203592	5.169359397
Observations	24	24
Pearson Correlation	0.992573017	
Hypothesized Mean Difference	0	
df	23	
t Stat	-3.24130271	
P(T<=t) one-tail	0.001802105	
t Critical one-tail	1.713871517	
P(T<=t) two-tail	0.00360421	
t Critical two-tail	2.068657599	

Table A.10: Results for Figure 4.31 Mean relative humidity

Descriptive statistics difference in RH		t-Test: Paired Two Sample for Means		
			Variable CH	Variable RISC
Mean	-0.9273875	Mean	69.93163333	70.85902083
Standard Error	0.275497049	Variance	160.9589386	145.0847677
Median	-0.88255	Observations	24	24
Mode	#N/A			
Standard Deviation	1.349654392	Pearson Correlation	0.995387909	
Sample Variance	1.821566979	Hypothesized Mean Difference	0	
Kurtosis	-1.22991392	df	23	
Skewness	-0.339417549	t Stat	-3.36623388	
Range	3.9803	P(T<=t) one-tail	0.001333957	
Minimum	-3.2485	t Critical one-tail	1.713871517	
Maximum	0.7318	P(T<=t) two-tail	0.002667915	
Sum	-22.2573	t Critical two-tail	2.068657599	
Count	24			

Appendix B: Additional results

Daily mean air temperature difference

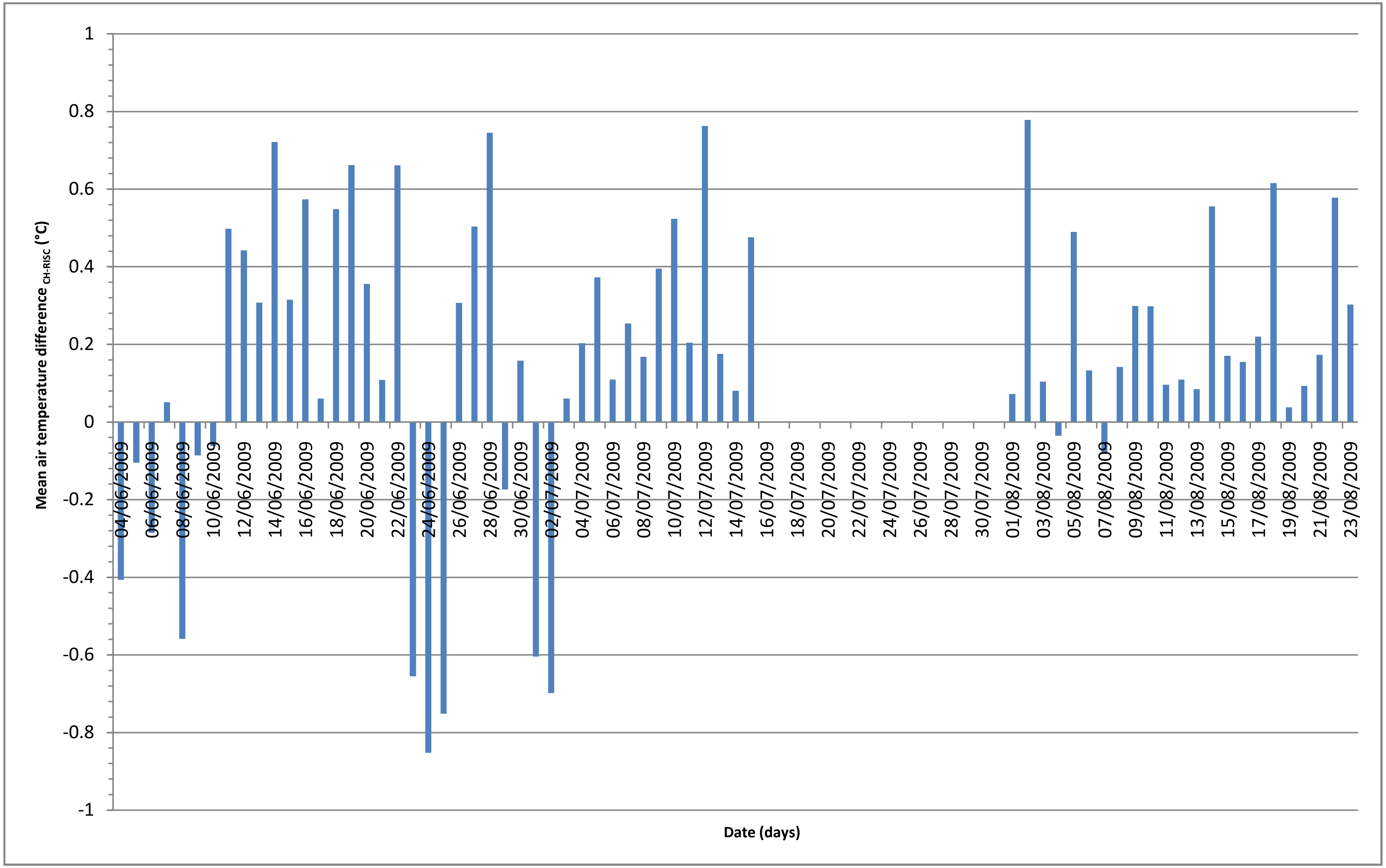

Figure B.1: Daily mean air temperature difference averaged from 04-06-2009 to 23-08-2009

Relationship between air temperature and wind speed

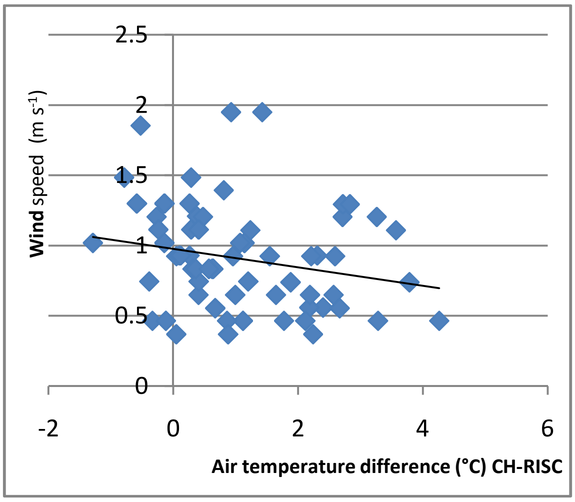

Figure B.2: Air temperature difference and mean wind speed from both sites regression at 9:00 averaged from 04-06-2009 to 23-08-2009

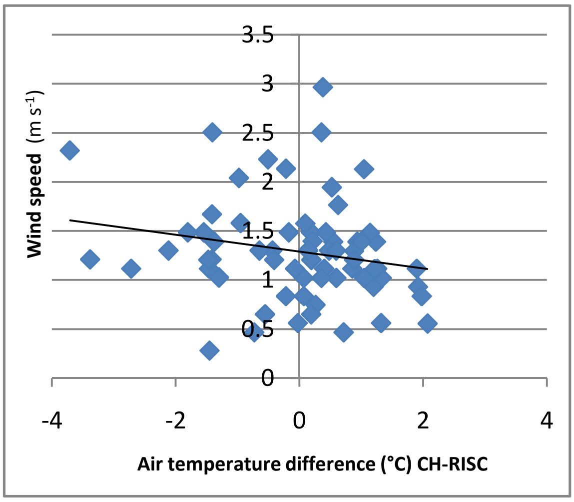

Figure B.3: Air temperature difference and mean wind speed from both sites regression at 15:00 averaged from 04-06-2009 to 23-08-2009

Table B.1: Results for Figure B.2 Air temperature difference and mean wind speed from both sites regression at 9:00 averaged from 04-06-2009 to 23-08-2009

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.215219309
R Square	0.046319351
Adjusted R Square	0.031418091
Standard Error	1.214131846
Observations	66

ANOVA

	df	SS	MS	F	Significance F
Regression	1	4.582169713	4.582169713	3.108418386	0.082662265
Residual	64	94.34343295	1.47411614		
Total	65	98.92560267			

Table B.2: Results for Figure B.3 Air temperature difference and mean wind speed from both sites regression at 15:00 averaged from 04-06-2009 to 23-08-2009

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.202404377
R Square	0.040967532
Adjusted R Square	0.026213186
Standard Error	1.205520906
Observations	67

ANOVA

	df	SS	MS	F	Significance F
Regression	1	4.035239688	4.035239688	2.776641714	0.10046089
Residual	65	94.46324258	1.453280655		
Total	66	98.49848227			

Relationship between air temperature and atmospheric pressure

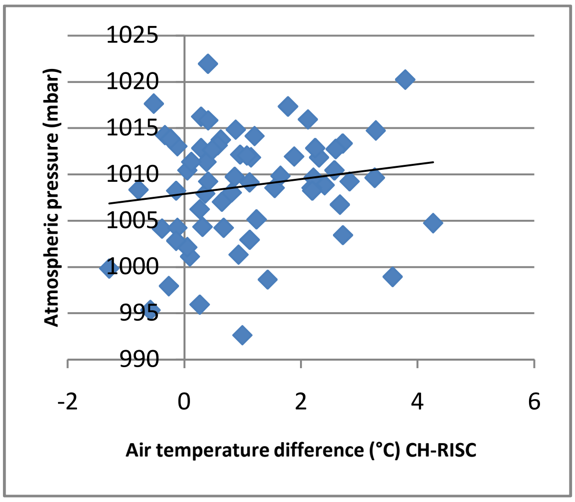

Figure B.4: Air temperature difference and atmospheric pressure regression at 9:00 averaged from 04-06-2009 to 23-08-2009

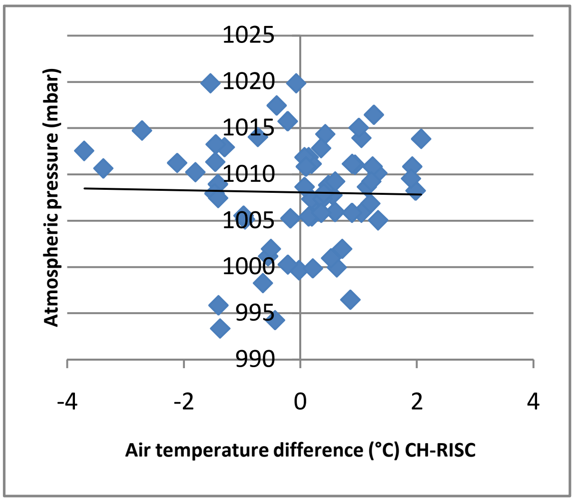

Figure B.5: Air temperature difference and atmospheric pressure regression at 15:00 averaged from 04-06-2009 to 23-08-2009

Table B.3: Results for Figure B.4 Air temperature difference and atmospheric pressure regression at 9:00 averaged from 04-06-2009 to 23-08-2009

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.16295457
R Square	0.026554192
Adjusted R Square	0.011344101
Standard Error	1.226648847
Observations	66

ANOVA

	df	SS	MS	F	Significance F
Regression	1	2.626889433	2.626889433	1.745827312	0.19110654
Residual	64	96.29871323	1.504667394		
Total	65	98.92560267			

Table B.4: Results for Figure B.5 Air temperature difference and atmospheric pressure regression at 15:00 averaged from 04-06-2009 to 23-08-2009

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.023885774
R Square	0.00057053
Adjusted R Square	-0.014805308
Standard Error	1.230648896
Observations	67

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.056196358	0.056196358	0.037105633	0.84785073
Residual	65	98.44228591	1.514496706		
Total	66	98.49848227			

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