victorian centre for climate change adaptation research

Technical Report

Airborne Thermal Remote Sensing for Analysis of the Urban Heat Island

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This report was funded by the Victorian Centre for Climate Change Adaptation Research as part of the project: Responding to the urban heat island: optimising the implementation of green infrastructure

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Responding to the urban heat island project overview

The responding to the urban heat island project aims to assess the effectiveness of different green infrastructure systems for urban cooling and develop decision-making guidance for urban land managers to optimise the selection and implementation of green infrastructure options. The inter-disciplinary and inter-institutional project team includes researchers from Melbourne, Monash and RMIT universities. This technical report is one of a number of project outputs that includes a literature review, discussion paper, policy brief and a green infrastructure implementation guide.

The project team comprises:
Professor Jason Beringer, Dr Shobhit Chandra, Dr Andrew Coutts, Assoc. Prof. Tim Fletcher and Professor Nigel Tapper (Monash University), Professor Darryn McEvoy (RMIT University), and Dr Dominique Hes and Dr Nicholas Williams (University of Melbourne).

Visit the VCCCAR website for more information about the Responding to the urban heat island project : www.vcccar.org.au

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Executive Summary

Vegetation or 'green infrastructure' is commonly promoted as a key approach for urban heat island mitigation, and research has revealed its capacity to support urban cooling. However, little guidance is available on the most effective type and location of green infrastructure to maximise urban cooling to help inform investment in urban greening. Urban planners and designers are turning to tools to help inform investment decisions on green infrastructure for urban heat mitigation.

This report focuses on the collection and use of airborne thermal remote sensing of the urban land surface as a tool for informing policy development and on-ground implementation of urban heat island mitigation strategies. It reviews previous studies to investigate approaches of collecting and using airborne thermal imagery to analyse drivers of high urban surface heating, and hence the urban heat island. This report aims to be a resource for urban policy makers who may consider the use of airborne thermal remote sensing, or other remote sensing products, in informing policy development for urban heat mitigation. It aims to demonstrate both the capability of airborne thermal imagery, how it is used in urban heat island analysis, and to develop guidance on how best to acquire, process, analyse and interpret airborne thermal imagery.

Airborne thermal remote sensing is an attractive option for identifying areas of high surface heat exposure, providing an idea of priority areas for green infrastructure implementation. Airborne thermal remote sensing gives an excellent spatial picture of the urban landscape for a snapshot in time, allowing a comparative analysis of areas of high surface temperatures. The advantage of airborne thermal remote sensing is the ability to observe high resolution (1-5 m) surface temperatures, allowing the identification and analysis of individual landscape elements. In contrast with satellite remote sensing, airborne thermal mapping allows for flexibility in prescribing the flight times. Previous research has demonstrated the capacity to relate surface temperatures to different land surface types and features, and have demonstrated that vegetation cover and urban geometries are important controls of surface temperatures.

A literature review of airborne thermal mapping for urban heat island analysis has highlighted some important themes that should be considered. Firstly, there are limitations to airborne thermal mapping, one being that it provides information on the surface urban heat island, rather than the urban canopy layer urban heat island which is most commonly referred to, and is most relevant to human thermal comfort. The airborne thermal analysis provides a bird's eye view of the surface, and hence leads to a sampling bias, as some three dimensional surfaces (e.g. walls) are neglected. The review also revealed that to make the most of airborne thermal remote sensing data, other auxiliary data can be accessed to assist in processing, analysing and interpreting the imagery. This includes aerial photography, land surface classifications, vegetation indices, LiDAR data and satellite thermal remote sensing products. Ground validation for verification of airborne thermal imagery is strongly recommended. Also, ground based air-temperature observations, through mobile transects, are routinely conducted to complement airborne thermal remote sensing, to both observe correlations between surface and air temperatures (or lack thereof), and to further understand the role of surface features in urban heat island development. Finally, it is critical that all details of the thermal capture are known to ensure accuracy in data processing.

Probably of most importance in using airborne thermal remote sensing for urban heat island analysis is an appreciation of what the data truly provides, and care is needed in interpretation given the special and specific nature of the data, as well as an appreciation of scales and surface processes influencing urban climates.

1. The Urban Heat Island

Humans have always changed the environments that they live in. The growing expanse of cities and towns has now reached a stage where over 50% of the global population live in urban areas, and this proportion continues to grow (PRB, 2009). While residing in these urban centres offers numerous opportunities, there is inevitably a change in the natural environment as a result of urbanisation. One such environmental change is in the urban climate and in particular, the formation of the Urban Heat Island. The Urban Heat Island (UHI) is a phenomenon where urban areas show higher temperatures than the surrounding rural landscapes, particularly at night (Figure 1). The replacement of natural surface with hard, impervious infrastructure and materials modifies radiative and energy exchanges at the land surface, leading to the formation of distinct urban climates. These impervious urban surfaces have high heat capacities, and therefore retain large amounts of thermal energy compared to rural areas. This heat is then slowly released at night while rural areas cool rapidly, producing urban – rural temperature contrast known as the urban heat 'island'. Heat released from human activities (e.g. waste heat from cars or buildings) also supports additional warmth in urban areas.

In Victoria, the UHI is evident in Melbourne, as well as across the state's rural cities and towns. Torok et al. (2001) conducted automobile transects across Melbourne and towns in rural Victoria under conditions for optimal UHI genesis. In Melbourne, a transect across the city at 9pm on the 25th August 1992 revealed a maximum observed UHI intensity of 7.1°C between the CBD and rural areas, with smaller peaks in the in industrial areas and the medium density terrace housing in the inner northern suburbs (Torok et al., 2001). Smaller, but significant UHIs were observed in Hamilton, Camperdown and Cobden, and Colac. At Hamilton, a maximum observed UHI intensity of 5.4°C on the evening of 24th January 1994 between the town centre (over concrete) and the rural outskirts (Torok et al., 2001). The UHI intensity is given by the temperature *difference* between urban and rural areas – the largest contrasts of which are seen at night, when rural areas cool rapidly, while urban areas remain warm. Urban-rural contrasts are most evident under clear and calm conditions, as clear skies permit maximum long-wave cooling from the surface, and calm conditions mean heat is not dispersed from urban areas. When UHI intensities are presented, it is commonly under these optimal conditions to demonstrate maximum contrasts.

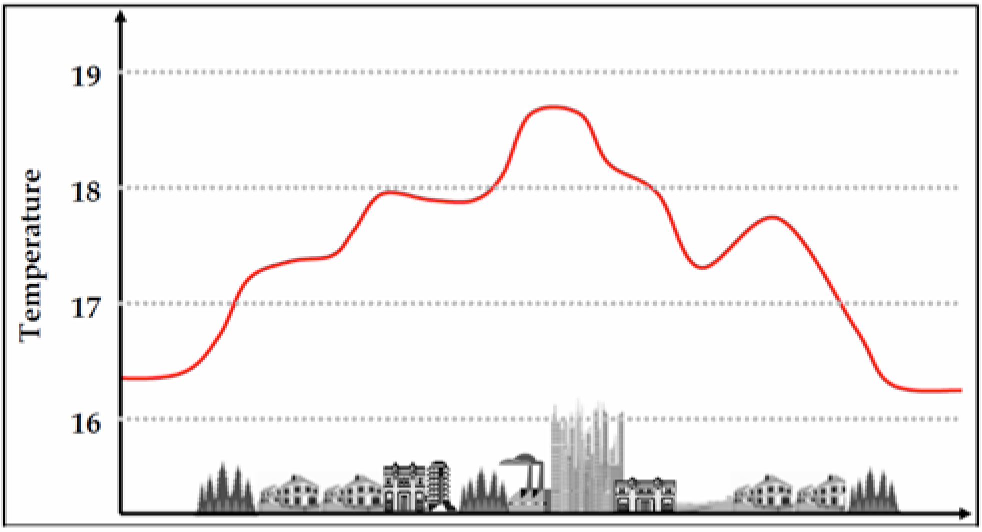

Figure 1: A generalised description of the urban canopy layer UHI at night.

In the context of climate change, elevated urban temperatures can stretch the adaptive capacity of urban populations to respond to extreme heat. As a result of global warming, mean temperatures across the state of Victoria are projected to increase, but extreme temperatures (heat waves) are also projected to change, with heat waves becoming more frequent, more intense, and longer lasting (CSIRO and BOM, 2007). Increases in temperature from the UHI, in combination with heat waves can lead to many heat related illnesses and mortality. For example, between 35,000 and 50,000 people died due to heat related illnesses in Europe during the heat wave of summer 2003 (Mirzaei and Haghighat, 2010; Harlan et al., 2006). In Victoria, a heat wave in January 2009 was linked to 374 excess deaths (DHS, 2009). Urban residents must adapt to the compounding effects of elevated temperatures from both the UHI and climate change.

The UHI is primarily driven by urban development, rather than climate change, but they can compound upon each other, particularly through energy use. The UHI is the result of complex interactions between the land surface and the atmosphere, so the design of cities has a direct and significant influence on the UHI (Stone, 2005). Key drivers of the UHI include (Oke, 1982):

- Vegetation removal which reduces shading and evapotranspiration;
- High stormwater runoff from impervious surfaces which reduces soil moisture and evapotranspiration;
- Urban materials with high heat capacity which retain heat and slowly release this at night;
- Low albedo urban materials that absorb large amounts of solar radiation;
- Complex urban geometries that absorb and trap heat;
- Waste heat production from urban activities.

Elevated temperatures are a concern for those in the population that are vulnerable to extreme heat such as the elderly, those with pre-existing health conditions, and those of lower socio-economic status. Research has indicated that elevated night time temperatures are particularly important in influencing mortality rates, as higher temperatures at night limits relief from daily heat stress (Clarke and Bach, 1971). This means that the UHI, which is most pronounced at night, becomes especially relevant. In examining the heat wave of 1993 in Philadelphia, USA, Johnson and Wilson (2009) used geo-statistical methods to investigate relationships between mortality, vulnerability and the UHI. They suggest that the heat related mortality was concentrated in areas with higher UHI intensity levels, and the urban poor were particularly vulnerable (Johnson and Wilson, 2009). Given the projected increase in warm nights across Australia from global warming (Alexander and Arblaster, 2009) and continued urbanisation, mitigating the UHI and adapting to climate change is critical.

1.1 Responding to the UHI

Mitigating the UHI is a challenge for State and Local Governments, as well as the broader community. Currently, the common response to managing extreme heat and reducing mortality and morbidity is through the use of air conditioning (Davis et al., 2003), however, this comes at a cost – about one-sixth of all energy used in the United States for instance is for powering air-conditioners at a cost of $40 billion a year (Solecki et al., 2005; Rosenfeld et al., 1998). Other responses (during extreme heat events) include identifying vulnerable individuals, disseminating information, coordinating service providers, and preparing cooling centres. Few policy examples exist that focus on mitigating the UHI itself to reduce heat exposure. Relying on air-conditioning feeds back to additional urban warming (through waste heat production) and contributes to greenhouse gas emissions (when powered by electricity generated through fossil fuels). Air conditioning relies on centralised energy systems (which can fail) and in many instances, high heat exposure occurs outdoors (e.g. waiting for trains).

Urban heat islands in many different global locations have been studied (Saaroni et al., 2000; Hartz et al., 2006) and findings can be useful to develop policy and planning guidance to limit UHI intensities. The many drivers of the UHI present the opportunity for a variety of mitigation options (Table 1). Many of these mitigation approaches revolve around implementation of 'Green Infrastructure'. Green infrastructure is the implementation of natural ecosystems and vegetation into urban environments for climate and environmental benefits, while also providing a more aesthetically pleasing environment. Green infrastructure most commonly includes street trees, green roofs and green walls. Research has demonstrated the ability for green infrastructure to lower urban air temperatures (Rosenzweig et al., 2006), reduce surface temperatures (Wong et al., 2003), and reduce heat flow into buildings (Liu and Minor, 2005). Green infrastructure is a particularly attractive mitigation option because of the multiple benefits it can provide, including improvements in stormwater runoff quality (McPherson et al., 2005) and removing pollutants from the air (Yang et al., 2008).

While there is clear evidence from previous studies of the cooling and energy efficiency benefits of green infrastructure, there is little guidance available on how best to implement green infrastructure. Mitigation costs and limited resources require that implementation approaches are prioritised, as well as locations for implementation. State and Local Governments, community groups and individuals require information and tools to help make informed choices about implementation of mitigation approaches. In addition, each urban area is often quite unique with regards to its location, weather and climate, urban geometry, solar exposure, soil foundations, etc. which all influence a city's UHI at a range of scales. This means that it is important to study one's own city as the findings from previous studies may be slightly different (Oke, 1982) so implementation priorities may vary between urban areas.

Table 1: Urban heat island mitigation approaches (adapted from Coutts et al., 2010)

Mitigation Measure	How it Works
Increase Vegetation	Natural cooling system as it encourages evapotranspiration and energy is dissipated through latent heating instead of sensible heating.
Water Sensitive Urban Design	Increasing evaporation in the urban environment by retaining water.
Increased Albedo	Increasing the reflectivity of surfaces thereby limiting the heat transfer into buildings and heat storage.
High thermal emittance Surfaces	By covering roof materials with materials that reflect the near infrared can increase the albedo.
Outdoor Landscaping	Vegetation planted in specific locations can block or limit the solar radiation reaching buildings and reduce the heat storage.
Street Design	Widening streets as building heights increase allows a large sky view factor which helps with ventilation and cooling. Also the orientation of the city affects the exposure to incoming solar radiation.
Parkland and Open space	Provides cooling for areas downwind, with vegetation encouraging evapotranspiration.
Green Roofs	Reduce the heat transfer into the building while retaining water which encourages evapotranspiration. Green walls have similar effects.
Energy Efficiency	By using more efficient products, energy consumption can be reduced, minimising waste heat production.
Building Design	Insulation and double glazing can reduce the need for heating and air conditioning which can improve energy efficiency.
Mass Transport	Increasing the use of Public transport will reduce the number of vehicles that would contribute to CO_2 and anthropogenic heating

While broad policy actions may progressively limit the intensification of the UHI, urban managers may wish to target available resources to priority areas of more intense urban heating. Therefore, approaches are needed for rapidly and easily identifying areas of excessive urban heating across a large spatial area. One tool that can assist in understanding the UHI and provide data that can help decision making is thermal remote sensing. Thermal remote sensing has the capacity to support this demand by monitoring the surface UHI. While remote sensing does not provide direct observations of the urban canopy layer UHI (discussed later), it provides insight into the surface UHI, which is a primary driver of canopy layer climate. While not directly comparable, surface temperature has a large influence on the adjoining air temperature and the lower layer of the urban atmosphere (Weng, 2009). State and Local Governments, as well as industry are expanding their capacity for information urban planning and design through Geographical Information Systems (GIS), which opens up the capacity for use of data collected through remote sensing – such as airborne thermal remote sensing.

This report focuses on the application of thermal remote sensing of the urban land surface – in particular airborne thermal remote sensing – as a tool for informing policy development and on-ground implementation of urban heat mitigation strategies. This report reviews previous studies of airborne thermal remote sensing and its application to UHI studies to identify:

- Advantages and limitations of using airborne thermal imagery for UHI analysis;
- Key learning's from analysis of thermal imagery to further understand key drivers of the UHI;
- Methodologies applied in both the capture and analysis of airborne thermal imagery; and
- Additional data sources that can assist in the interpretation of airborne thermal imagery.

In addition, this report aims to be a resource for urban policy makers who may consider the use of airborne thermal remote sensing, or other remote sensing products, in informing policy development for UHI mitigation. It demonstrates the capacity and applicability of airborne thermal remote sensing for users to determine its suitability for use policy development.

1.2 Scale and types of urban heat islands

Before focussing on the use of airborne thermal imagery for UHI analysis, some background information is necessary to provide context into what information can be drawn from remotely sensed thermal data.

1.2.1 Importance of scale

Oke (2009) clearly shows that there are three scales for consideration in urban climate (Figure 2). The smallest scale is the micro-scale which refers to the climate of individual buildings, houses, trees and streets and the intervening spaces. Micro-scale climates are the result of the surface energy balance. The local scale (street to neighbourhood scale) focuses on the climate of neighbourhoods, which integrates microclimatic effects with similar combinations of urban features (Oke, 2004), and is a result of the surface energy balance, as well as the urban canopy layer energy balance. The final and largest scale is the meso-scale, where cities can have an influence on larger scale weather and climate at a scale of more the tens of kilometres (Oke, 2009). It is important that interpretations (from observations or models etc.) from different scales are not inappropriately mixed with those from other scales.

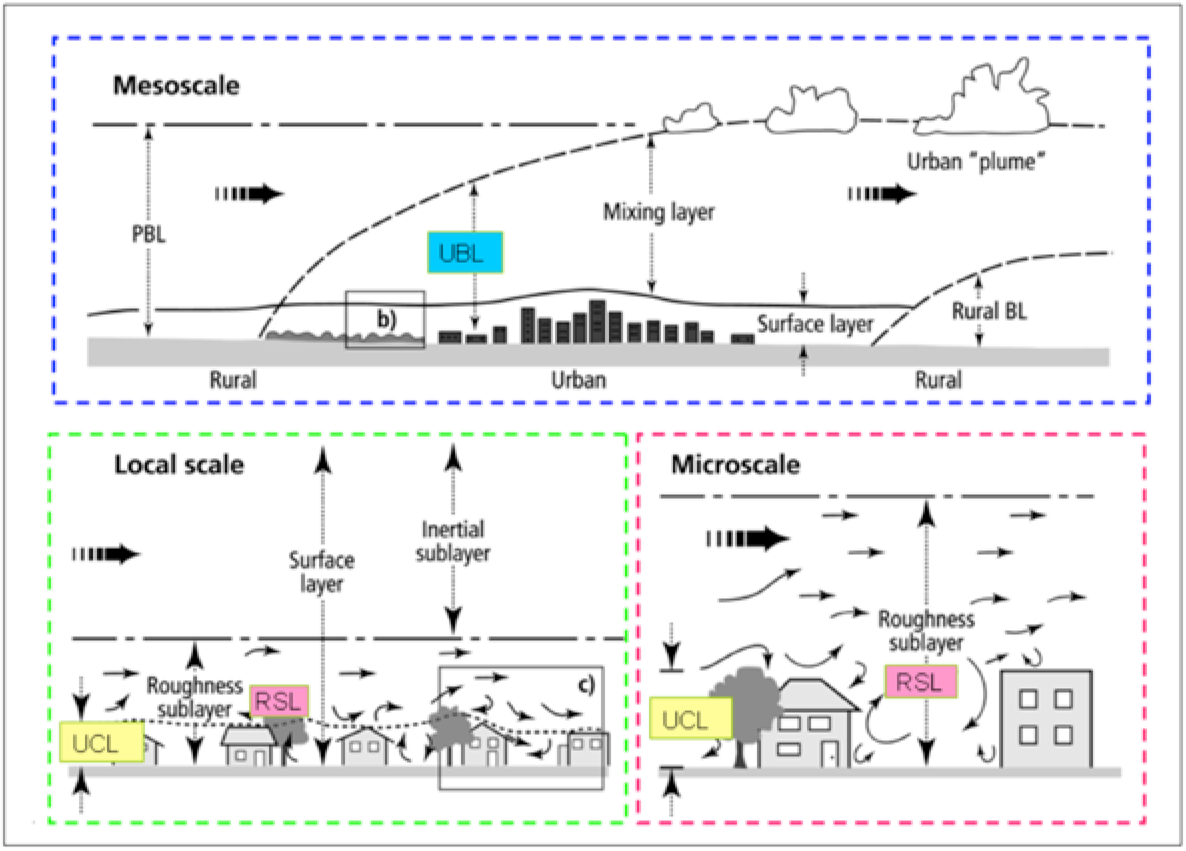

Figure 2: Image shows the different scales of UHIs. RSL is the Roughness Sub layer, UCL is the urban canopy layer, and UBL is the urban boundary layer (Oke, 2009).

1.2.2 Urban Heat Island types

There are actually a variety of UHI types that are observed across an urban area (Figure 3).
These are (Oke, 2009):

- **Subsurface UHI** – refers to the subsurface warmth under the city that results from conduction through surface soils and materials. The interaction of radiative energy with the ground and the ability of particular surfaces to reflect, absorb or emit energy are responsible for variability in the Subsurface UHI.
- **Surface UHI** – refers to the temperatures that extend over the full 3-dimensional urban surface interface of a city. Differentiating between energy exchanges between the roof top surfaces, walls, and ground surfaces is very important because the processes are very different. The Surface UHI is commonly largest during the day (Yuan and Bauer, 2007; Roth et al 1989). The dominant scale and source area influencing the temperatures of the Surface UHI is the micro-scale..
- **Urban canopy layer air UHI** (UCL air UHI) – refers to the air temperatures within the urban canopy layer (e.g. within streets and below roof-top level) using the height of the buildings at a boundary (Roth et al., 1989). The UCL air UHI is an expression of the surface energy balance which has affected the air volume within the urban canopy (Oke, 2009). The UCL air UHI is generally most pronounced at night.
- **Urban boundary layer air UHI** (UBL air UHI) – is another atmospheric heat island and refers to the combination of lots of local scale influences on the whole of the boundary layer (city scale) and can extend several hundred metres above the surface (Oke, 1987). It develops with mixing from the frictional drag of the atmosphere across surface of Earth and the rising air from heated surfaces. (Oke, 1987b). The UBL air UHI is also most pronounced at night.

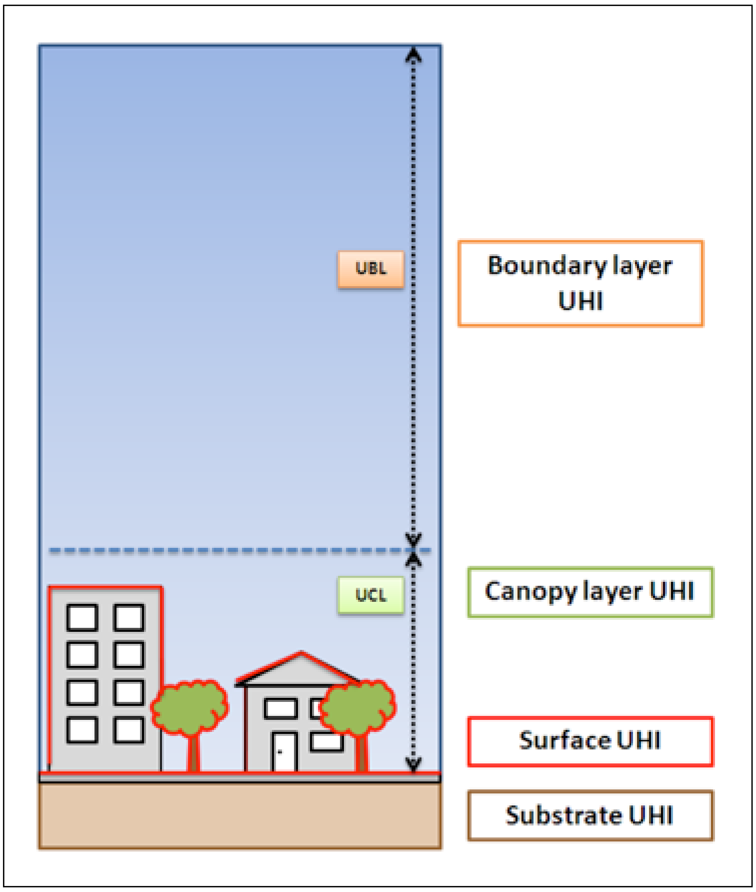

Figure 3: Types of urban heat islands (adapted from Oke, 2009)

Airborne thermal remote sensing can be used to observe aspects of the Surface UHI, which forms as a result of surface energy balances that occur over the entire 3-dimentional surface area. Surface temperature *'incorporates the effects of surface radiative and thermodynamic properties, including surface moisture, thermal admittance and surface emissivity, the radiative input at the surface from the sun and atmosphere, and the effects of the near-surface atmosphere and its relation to turbulent transfer from the surface'* (Voogt and Oke, 2003: pg 371) There are many different interactions that occur within the Surface UHI and it is important to distinguish the difference between roof surfaces, walls and ground surfaces. Airborne thermal remote sensing observes the plan view (i.e. bird's eye view) of the Surface UHI or rather upwelling thermal radiance (Voogt and Oke, 2003). In contrast, the UCL air UHI evolves through interactions between the land surface and the atmosphere. The UCL air UHI refers to all the energy interactions that happen within the urban canopy layer, within the streets and below roof top level. With the aim to improve the outdoor human thermal environment within the urban areas, this is probably the most important UHI. The UCL air UHI is the UHI that is felt most by pedestrians and urban dwellers. It is an expression of all the energy exchanges that affect the air volume within the canopy (Oke, 2009). As this UHI affects the air volume within the urban environment, it controls the external climate for buildings and vegetation, and has a direct link to human health, energy consumption, pollution and human comfort. In figures demonstrating the UHI (such as those produced from cross-city automobile transects), the UCL air UHI is the UHI type that is being presented (Figure 1).

The city wide urban heat island is the combined effect of local urban heating on the whole of the city boundary layer. This layer can extend several hundreds of meters above the city (Oke, 1987a) and also produce an urban plume of warm air in the boundary layer that can permeate downwind of the city.

1.3 Summary

Mitigating excess urban heat requires interventions to the way we plan and design our cities and towns. The UCL air UHI evident across a city or town (e.g. Figure 1) is what is commonly presented as the UHI. This discussion is has demonstrated that there are many types of UHIs. Given the UCL air UHI influence on the thermal experience of urban residents, this is the UHI type that local and state policy makers are most interested in mitigating.

Extreme heat events are a concern due to the potential health impacts and strain they can place on services and infrastructure. Urban development can exacerbate extreme heat events by supporting UHI effects, raising temperatures further, especially at night. In Melbourne, UHI intensities (urban – rural temperature contrasts) are largest under calm and clear conditions, during warm summer days under anti-cyclonic synoptic regimes (Morris and Simmonds, 2000). As such, maximum UHI intensities may or may not coincide with extreme heat events, but nevertheless, a level of additional warming from urban development can nudge temperatures higher, particularly at night. Furthermore, a high UHI intensity does not necessarily mean that it is hot. Some of the largest urban heat islands observed are in cold climates due to excessive anthropogenic heat release. As such, UHI intensities and their relations with extreme heat events is location specific. In Atlanta, Georgia, Zhou and Shepherd (2010) found that for the UHI intensity from selected stations was much higher during heat wave days than during non-heat wave summer days. UHI mitigation targets this additional warming from urban development, but may also provide a level of adaptation to extreme heat events.

A challenge for urban planners, policy makers and designers is the application of available resources for *UCL air UHI* mitigation. However, identifying high resolution hot-spots in the UCL air UHI across a large spatial area is difficult, and limited to observational approaches that do not lend themselves to a good spatial coverage, especially if interested in micro-scale variability. While not directly comparable to the UCL air UHI, thermal remote sensing can provide a useful tool for mapping the Surface UHI and identifying priority areas for surface heat mitigation. This report focuses on assessing the application of airborne thermal remote sensing as a tool for informing policy development and on-ground implementation of urban heat mitigation strategies.

2. Demonstrating the capability of airborne thermal mapping for UHI analysis

2.1 Remote sensing of the Surface UHI

The climate of a site is strongly driven by the nature of the urban surface, through modification of the urban surface energy balance. Even at the micro-scale, surface and air temperatures can vary by several degrees over very short distances (Oke, 2004). Because of the complexity of the urban landscape, this means that a whole variety of micro-climates are created throughout the urban landscape which over the area of the city, combine to form the UHI. In terms of mitigating excess urban heating and determining areas for implementation of green infrastructure, an understanding of the spatial variations in micro-climate are helpful.

One way to capture the spatial variability in urban heating is through thermal remote sensing. Satellite and airborne thermal remote sensing provides a mechanism for observing the surface temperature of an area. The use of satellite or airborne sensors allow a much larger and more uniform sampling method than traditional in-situ data (Streutker, 2002) for surface temperature measurements. Thermal remote sensing gives an excellent spatial picture of the urban landscape for a snapshot in time allowing a comparative analysis of areas of high surface temperatures. Examples of this include Aniello et al. (1995) who used a thermal satellite image of Dallas, Texas (USA) to compare the spatial distribution of urban heating by locating hot-spots from the thermal image and relating them to land use characteristics and tree cover.

The surface temperature (and hence the Surface UHI) is driven by many detailed and complex interactions. The surface temperatures that are recorded are influenced by the complete three dimensional urban landscapes so can be affected by the urban canyon geometry and building density. For instance, higher building densities can prevent solar radiation reaching street canyon floors due to shading, resulting in cooler ground surfaces. The canyon geometry can also limit the ability of long wave radiation to be transmitted from the surface to the sky at night, meaning surfaces temperatures remain warm.

Building materials also affect the surface temperature, as different urban materials have different absorption and thermal properties. Surface temperatures can be further influenced by factors such as surface albedo, emissivity and anthropogenic activities, while surface temperatures of natural surfaces vary with changing moisture conditions and thermal admittance. Within urban canyons, reflected solar energy can become re-absorbed by other urban surfaces. A summary of the major affects of surface temperature is presented in Figure 4.

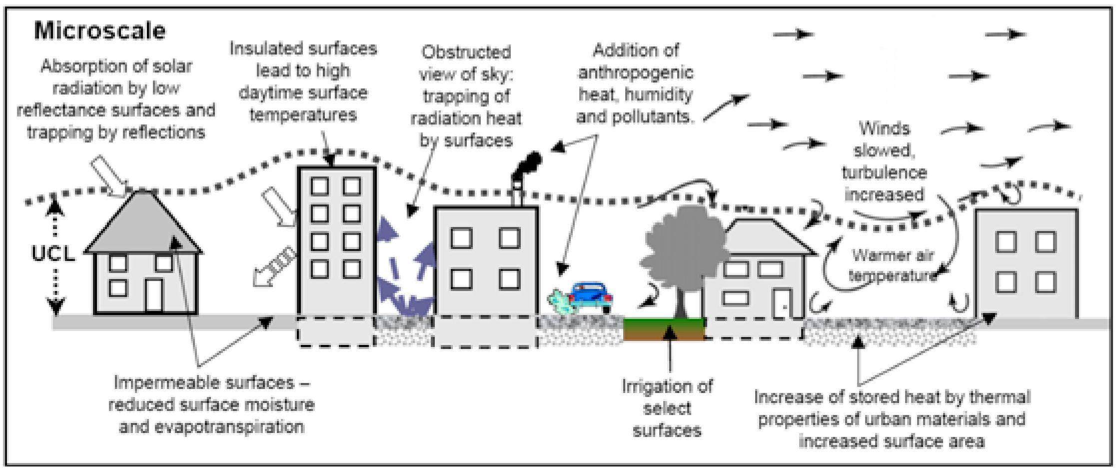

Figure 4: Image summaries the main influences on the surface temperature that is detected by remote sensing

(Voogt http://www.epa.gov/heatisld/resources/pdf/EPA_How_to_measure_a_UHI.pdf)

Hung (2006) states that urban thermal remote sensing can be broken down into three different study areas. These are: to examine the spatial structure of the urban thermal patterns and relate these to surface characteristics; examine the surface energy balance using thermal data and urban climate models; or study relationship of the combination of atmospheric and surface heat islands using ground and remote sensing data (Hung, 2006).

It is important to note that actual surface temperatures are not recorded by the airborne and satellite sensors – instead Planck's law is used (the electromagnetic radiation that is emitted from a black body at an absolute temperature) to create surface brightness temperatures (Weng, 2009; Weng et al., 2004; Streutker, 2002; Streutker, 2003; Dousset and Gourmelon, 2003) and these can differ in temperature from actual land surface temperature by 1-5 degrees Kelvin for some satellites (Hung, 2006). The measurements obtained from remotely sensed data are indirect and need to have factors like atmosphere effects, surface reflectance and emission considered and corrected, unlike when gathering on the ground in situ data (Voogt and Oke, 2003). Many different studies have utilised the spatial advantage that remotely sensed thermal data can provide to measure many different affects and different magnitudes of urban heating. When combined with other remote sensing derived products such as land use/land cover classifications, and vegetation indices (e.g. Normalised Difference Vegetation Index [NDVI]), information can begin to be drawn out about the influence of surface features on surface temperatures, and what is driving the development of micro- to local- scale urban heating. The advantage of airborne thermal remote sensing is the ability to observe high resolution (1-5 m) surface temperatures, and individual landscape elements can be identified.

2.2 Satellite and airborne thermal remote sensing

While a main limitation of using thermal remote sensing in UHI analysis is it's restriction to surface temperatures, there are many advantages that make it an enticing approach. The single biggest advantage of using airborne or satellite remote sensing is that surface temperatures over a large area can be monitored almost simultaneously. Temperature patterns are clear and it is a much more efficient way of large scale temperature mapping. The use of these remote sensing techniques also allows the surface temperature information to be related to the land uses and hence inform urban landscape design and policy.

One of the main advantages of using an airborne thermal remote sensing (from aircraft) over satellite remote sensing, is the level of detail that can be achieved. By being closer to the ground, the resolution of the captured data from the thermal camera can be much better than that of a satellite, and allows for the study of micro-scale variations in surface temperature such as those interactions occurring Figure 4. It means that specific areas can be targeted and a better resolution can be gathered for pre-defined areas of interest. Satellite remote sensing is more applicable to observing local scale variations in surface temperature, and is commonly used in city-wide UHI mapping (Bluesky).

Another advantage is that with airborne thermal imagery there is a much higher level of control as to when the image is taken and therefore climate influences can be countered for. The use of appropriate satellite data depends on the individual sensors, and their spectral and temporal resolution. To study the UHI, measurements need to be taken at particular times of the day and night. There is no control from the ground as to when a particular area will be captured by the satellite with the appropriate bands and spectral resolution. This means that the optimum time for capturing the surface temperature might not be possible with the satellite. With the use of airborne imagery, a specific day can be selected and changed as needed to make sure that the image is representative of what is required. It gives the user a much greater control over time of flight as well and also means that the ground measurements can be directly related to the thermal image.

Previous studies have highlighted the need to carefully select data collection periods so it is cloud free (Dousset and Gourmelon, 2003; Hung, 2006; Streutker, 2002).

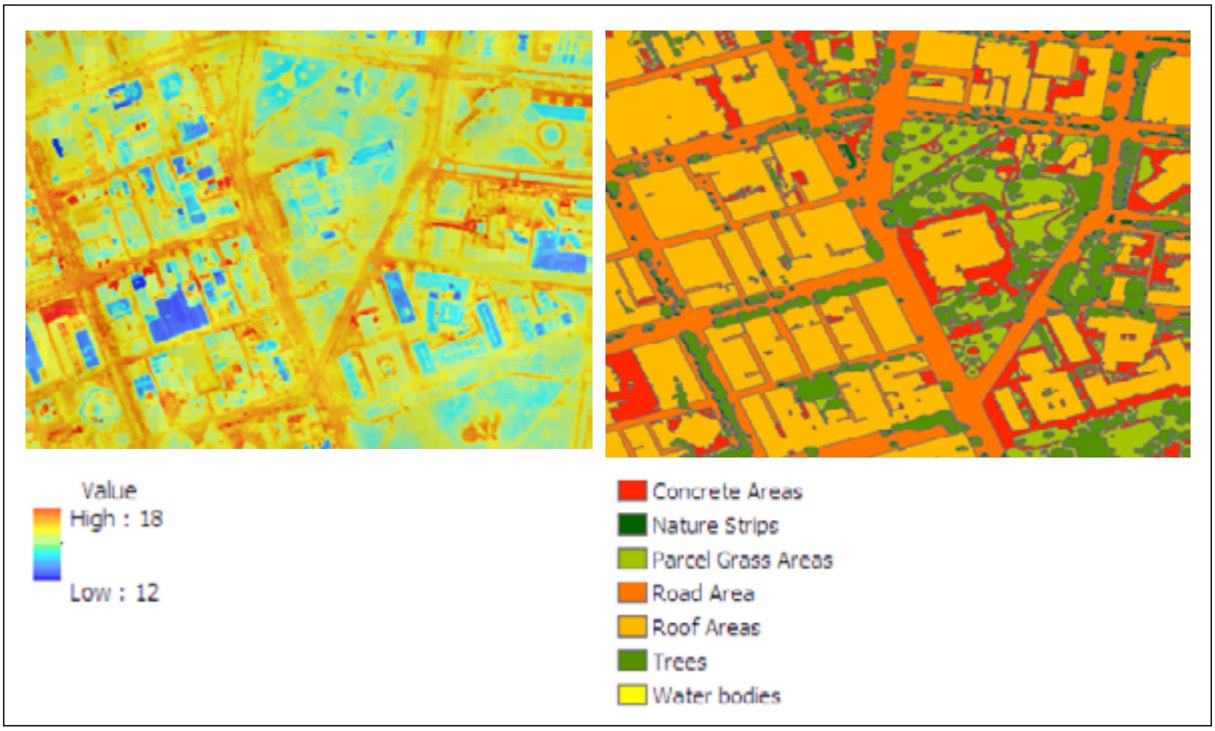

Figure 5: A thermal image (un-corrected) of central Melbourne at night in October 2010 in comparison to a simple land surface classification. Thermal signatures of different land surface types are clearly visible (data c/o City of Melbourne 2010)

2.3 Airborne thermal mapping for UHI analysis

Airborne thermal remote sensing has been utilised in a number of studies around the world for assessment of the UHI and its main drivers. These studies commonly combine thermal remote sensing with on the ground measurements, land use information and urban geometry information to calculate the different magnitudes and spatial extents of Surface UHI. As each study area is unique with regards to its layout, weather and climate conditions, there is value in examining each urban environment to estimate the extent of the UHI and which mitigation strategies would be appropriate for implementation to reduce the effects of increasing urban heat island magnitude.

Saaroni et al. (2000) studied the Surface UHI of Tel-Aviv in Israel using radiant surface temperatures which were collected by a thermal sensor installed on a helicopter. Using the observed surface radiant temperatures, they combined a number of on the ground and *in-situ* measurements including air temperatures – measured by automobile transects through the city and fixed location sensors on roof tops. Their main aim was to examine the relationships between the different levels of UHI in the canopy layer (roof, street and surface levels) (Saaroni et al. 2000). The imagery was taken during a night-time flight, as the effects of shadows are insignificant and the thermal characteristics for the entire city are more dependable. Data was captured at this time even though it is the UCL air UHI that is most pronounced than the surface heat island (Roth et al., 1989). The thermal image was used to study the thermal behaviour of various urban components and also to identify the main heat sources in the city. By using precise geo-referenced points, a direct comparison with air temperatures and selected land uses of different local areas could be studied.

Saaroni et al. (2000) found that while the inner city area had a higher air temperature than the city margins at night, it was cooler than the station that was based along the seashore (reversed during the day) due to the moderating effect of the ocean. To compare the surface temperature from the thermal flight with the air temperature measurements, two isotherm maps were created, one using the surface radiometric temperatures and one of the air temperatures for the same hours. The maps showed similarities in magnification of temperatures and spatial thermal distribution (Saaroni et al., 2000). There were some small differences between the two maps by these were explained by different atmospheric conditions. This was similar to other studies that show a positive correlation between surface radiometric temperatures and air temperatures in urban environments (Ben-Dor & Saaroni 1997; Voogt & Oke, 1997). The thermal images showed vegetated areas were cooler at night than other urban components and this was confirmed with the air temperatures taken along streets with street vegetation compared to those without (Saaroni et al., 2000). Finally, Saaroni et al. (2000) also found that the UCL air UHI was more evident at street level than at roof level, where it was speculated the cooling effect of the sea and the white roofs play an affect.

Bärring et al. (1985) used thermal imagery with ground and air temperature measurements to study the affect of the urban geometry in Malmö, Sweden. In this study they used airborne thermal imagery and related the relative temperatures to the sky view factor (amount of sky that is visible from the ground/sensor) and air temperatures from transects and three fixed stations. The study used the thermal image captured from the airborne thermal sensor to show that sky view factor and urban geometry have a large affect on the thermal patterns of city streets. The surface temperatures were strongly related to the urban geometry, whereas the air temperature was not as strongly correlated (Bärring et al., 1985).

Quattrochi and Ridd (1994) also used airborne thermal imagery to establish the varying thermal behaviour of materials within the micro scale urban environment with pixel resolution of 5m. They wanted to establish and separate different thermal responses by materials to create thermal 'building blocks' for more ecological building options based on the thermal responses in Salt Lake City, Utah (USA). There were two flights conducted, one at pre-dawn and one in early afternoon to correspond with the thermal min and max of materials.

As a way of calculating the different materials, Quattrochi and Ridd (1994) created a land use classification map using an aerial photo taken at the same time as the day flight. Using the thermal data from both flights a thermal response was calculated for each class type. By relating the thermal images to a land use classification map many different material characteristics could be studied. The thermal images showed the varying thermal responses of different land use types, and as a result showed the large thermal response differences between the different land cover types. The areas with vegetation were cooler than the urban environment; the ability of a surface to store or evaporate moisture also had a large impact on the magnitude and variability of the thermal response (Quattrochi and Ridd, 1994). They found that areas with little or no vegetation made a large difference in regards to the thermal energy upwelling that occured from the urban surfaces (Quattrochi and Ridd, 1994).

Using a similar method to establish 'building blocks' of thermal responses, Kottmeier et al. (2007) studied the urban heat island in Berlin, Germany. Using an airborne thermal transect across the city on two hot days, average thermal values were calculated for surfaces covered with vegetation, impervious surfaces and type of building structure to obtain surface temperature as a function of urban land use characteristics. The study used an existing land use classification map to relate surface temperatures to surface characteristics. Their aim was to determine which physical properties have a large effect on surface temperatures during different parts of the day (Kottmeier et al. 2007). With this information temperature maps were made for the whole urban landscape of Berlin. Using the surface temperature characteristics, Kottmeier et al. (2007) developed a city wide model by creating a land use map with three major classes that represent cultivated surfaces, bodies of water and remaining green spaces. This city wide model was also compared to a satellite image, with ground surface temperature measurements taken on the ground at the time of satellite overpass to validate the temperature comparisons. The surface temperature maps generated from the satellite image showed an agreement to the city wide map with an increase in surface temperatures towards the city centre (Kottmeier et al. 2007). Overall, Kottmeier et al. (2007) found that the formation of a surface heat island is less marked than in other large cities. Kottmeier et al. (2007) also note that block related characteristics is a suitable substitute for physical surface properties and this is useful as this information is often available for large cities. It was also shown that the surface temperatures are reduced with vegetation due to shading and that the shading from buildings (i.e. the urban geometry) is also important.

Most airborne thermal research is conducted with downward viewing sensors to limit the distortion from viewing angles that can affect analysis. An exception to this was the research done by Iino and Hoyano (1996) that used a downward and side viewing multi-spectral scanner (MSS). A simulation of surface temperature distributions of urban surfaces of various residential regions of Kawasaki was undertaken. The simulation was completed using an index based on sensible heat flux. The MSS were used to verify simulation results, to create an index for urban modelling. By looking at the sensible flux from the different urban surfaces, the thermal characteristics of each surface could be calculated and from that the heat island potential could be determined (Iino and Hoyano, 1996).

The key reason why this study used side viewing thermal imagery was to examine both the horizontal and vertical surfaces of buildings to calculate the surface heat flux. They created an index based on sensible heat flux and this was shown to be an effective index showing the various thermal characteristics of each type of region (Iino and Hoyano, 1996).

Urban surface temperature patterns are a major study area for investigating the UHI. Eliasson (1992) assessed urban temperature patterns in Gothenburg, Sweden. The study looked at the geometry of the urban area and compared it to observed surface temperatures collected from a helicopter. A thermal airborne scanner was used to generate the urban surface temperatures. The study aimed to utilise the thermal data to show the temperature variations between different surfaces within the urban environment. It also used sky view factors, a measurement of the urban geometry to show the effect of the geometry on surface temperatures (Eliasson, 1992). While the flight was undertaken, on the ground control points were measured along with vehicle transects through the city. Surface temperatures taken from the ground control points related well to the temperatures calculated from the flight (Eliasson, 1992). The research also showed that the surface temperature differences related to the difference in sky view factors (Figure 6). Using the infrared images a regression line; $T = 7.1 - 4.7(SVF)$ was calculated which was statistically significant at the 5% level with a determination coefficient of 0.64, while air temperatures relationships with sky view factor were not statistically significant.

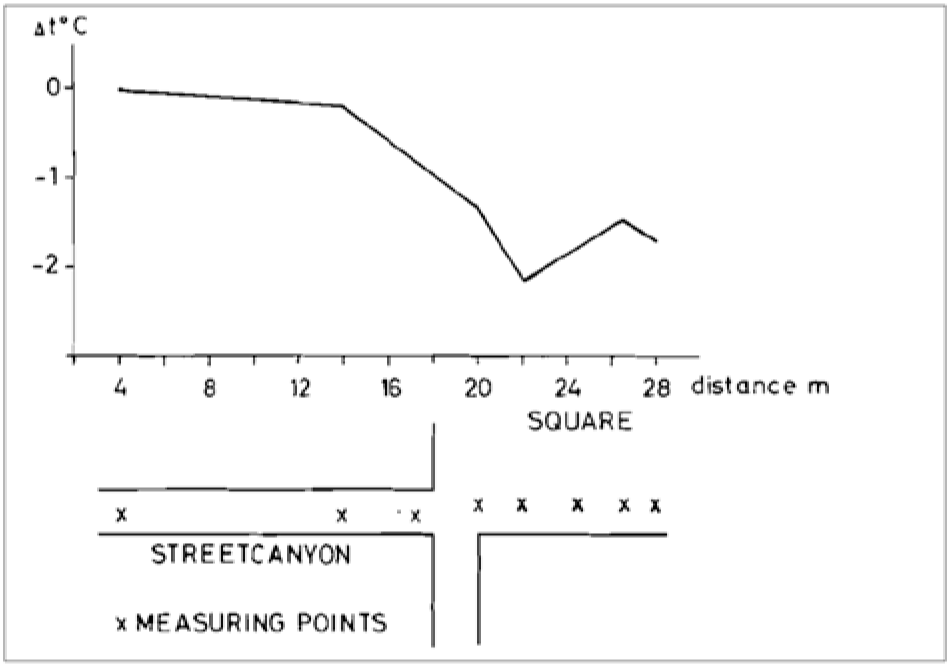

Figure 6: Profile of the difference in surface temperatures between a point in the middle of a street canyon and in a square – mean values for 20:00-21:00 hours on 18th November 1987 (Elisasson 1992).

High spatial resolution is one of the major advantages with using airborne thermal sensors. This was used to good effect by Lo et al. (1997) who used day and night thermal imagery that was captured at a 5m resolution. These flights were used to detect the difference in thermal signatures of various land cover types between day and night and show contrasting fluctuations. Using this information, the relationship between the various land cover irradiance and amount of vegetation was studied. The study showed that the spatial layout of the urban environment is important for the development of heat islands and the knowledge of the importance of vegetation (NDVI in this study) could have in averting or alleviating the effect of urban heat islands (Lo et al., 1997).

Lo et al. (1997) also acquired a colour infrared photograph (a false colour composite where infrared is expressed as red, visible red as green and visible green as blue to create a colour image) was at the same time as the flights. On-ground measurements were also carried out to measure GPS control points and surface temperatures of different selected land cover types. Utilising the high spatial resolution from the sensor to capture the aerial photograph, a very accurate land use classification map was created. Using this map, the characteristics of the thermal signatures for each of the land covers could be calculated (Lo et al., 1997). Due to the difference in emissivities of the surfaces, the irradiance of each of the land cover surfaces was used in analysis, rather than surface temperature, as energy values do not need to be corrected for emissivity (Lo et al., 1997). By converting the land use classification map of the city into one of irradiance, a profile can be created on a city transect to show the peaks and troughs across the city. Using the difference in thermal signatures of land cover types at day and night means that the various contributions from each land use can be studied, and the spatial layout of potential heat islands can be mapped. Using the irradiance of each land use type and comparing it with the vegetation cover based on the NDVI of the area, Lo et al. (1997) showed that vegetation was effective at lowering the surrounding surface temperatures.

Thermal imagery can be used to concentrate on specific elements of the energy balance that can contribute to the UHI. Gustavsson and Bogren (1991) used infrared thermography (thermal photography) to study the variations in road temperatures so that potential risk of frost and slippery surfaces could be calculated. As other studies have shown (e.g. Bärring et al., 1985), road surfaces produce a large contribution to the urban energy balance. The dark impervious surfaces are large heat stores, and with the additional anthropogenic heating of cars, roads feature as a dominant surface influencing UHI generation. Thermography was more useful in this study as it captured the surface temperature of a larger area, whereas traditional methods of using temperature probes attached to the surface only gives a point measurement, and also it is difficult to get precise surface temperatures from these probes (Oke, 1987b).

In studies undertaken by Voogt and Oke (1997), Voogt and Oke (1998) and Voogt and Grimmond, 2000, a method of thermal imagery capture was completed using a thermal camera that was attached to a helicopter and captured angles at both the nadir (downward viewing) and also 45° off nadir. Voogt and Oke (1998) aimed to confirm the existence and magnitude of variations of the anisotropic effect on urban surfaces for a selection of land use areas. The anisotropic effect refers to the thermal radiance of a surface which is directionally dependent. They aimed to distinguish the difference in anisotropic effects on large scale surfaces and the individual components of the urban surface. The different directions of thermal image capture (nadir and off-nadir) meant that the directional variation of different surface temperatures (anisotropy) could be studied. The differences of these directional variations are due to the three dimensional environment with shade and sun angles having an effect. In most remote sensing thermal studies, there is a bias of data due to vertical surfaces not being accounted for or being under-sampled due to the nadir view angle of the sensors. Before the thermal imaging flight was flown, vehicles went through each study area to capture the thermal temporal pattern of vertical surfaces and then flight times were chosen to coincide with the maximum differences within the street canyons. On the ground grass targets were used as a calibration for the 45°off-nadir images (Voogt and Oke, 1998).

Voogt and Oke (1997) conducted a study to estimate the complete urban surface temperature of an area, taking all active energy transfer surfaces into account in a bid to restrict viewing bias. In this study a model for the complete surface temperature was created, using every active surface (e.g. roof, walls, and ground) as the UHI is a result of the interactions by surfaces and heat energy, to calculate the proper magnitude the entire active surface has to be calculated. Figure 7 present a description of the different definitions of the urban surface, and how airborne thermal remote sensing represents only the birds-eye view.

When the complete urban temperature model was calculated the results were then compared with the remotely sensed thermal temperatures to weigh up how much they agree with the complete model. The model was based on area-weighted temperature calculations using all the active surfaces (Voogt and Oke, 1997). There are two ways on combining the thermal data to calculate the complete urban model, the first is to use the off-nadir airborne data with on-the-ground traverse measurements, and the other is to combine the nadir and off-nadir airborne thermal images. Voogt and Oke (1997) close by stating that scales of observation need to be matched with those of analysis, and that when using remotely sensed data, regard must be given to 'the geometric nature of the surface being observed and the viewing conditions'.

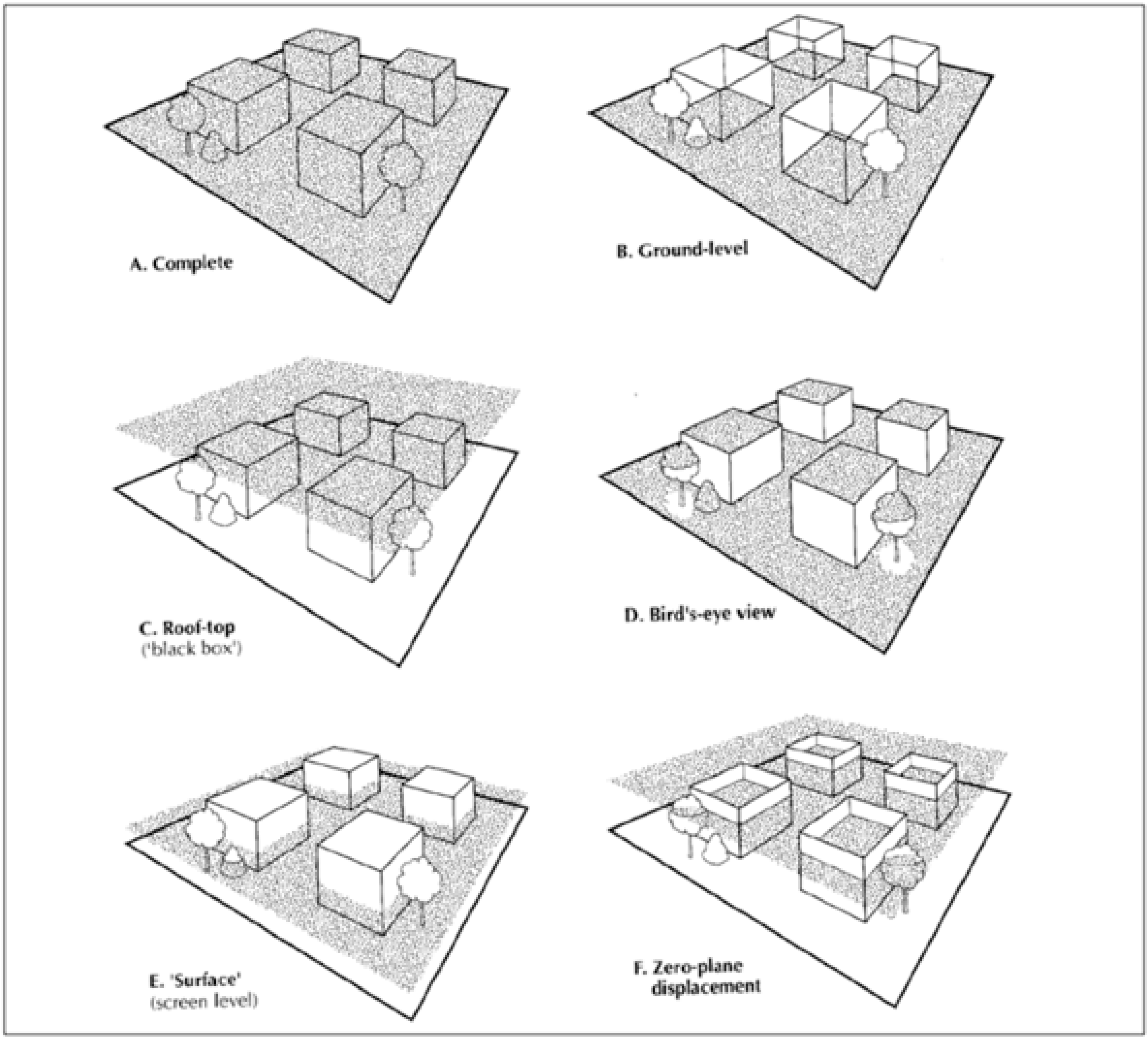

Figure 7: Different definitions of Urban surfaces (Voogt and Oke, 1997)

2.4 Satellite remote sensing for UHI analysis

There are also many studies that have used thermal satellite remote sensing to study various aspects of the UHI, and satellite remote sensing techniques are much more commonly drawn on than airborne thermal imagery due to the air of data access. For instance, Streutker (2002) and Streutker (2003) used remotely sensed thermal imagery to measure the UHI effect in Houston, Texas (USA) over a twelve year period. Using repeat satellite images, individual heat islands were observed for each scene and fitted to a Gaussian surface. To isolate the UHI, a land cover classification was used to create masks to separate the distinct urban and rural areas. By the repetition of the technique using the same thermal sensor the growth of the heat island could be measured. The thermal data was combined with statistical information and as a result showed that the surface UHI had increased in both magnitude and spatial scales with the increase in population. The studies showed that thermal images can be used to show both the magnitude and spatial extent of an urban heat island (Streutker, 2002; Streutker, 2003).

Land classification was also used to study the UHI by Hartz et al. (2006) as part of a study to link satellite imagery with on-ground thermography. In this study in Phoenix, Arizona (USA), each land cover type was identified using a supervised classification image and was assigned temperature values taken from hand held thermography. This allowed an estimated neighbourhood mean surface temperature to be calculated (Hartz et al., 2006). The thermal image was also compared to transects and in situ measurements. The study showed that during day time, it was difficult to compare the surface temperature from a satellite and air temperatures taken from transects. It was suggested that the differences were due to the urban geometry and the wind breaks that it created. The thermal imagery was shown to be very good for estimating relative neighbourhood temperatures when combined with the neighbourhood surface temperatures from the classified map and hand held thermography at the time of the evening thermal image (Hartz et al., 2006). It also showed that the thermal image for the day time was less accurate when calculating actual urban canopy air temperatures (Hartz et al., 2006). When the thermal images were compared to transects, they showed that the transects did not give an accurate representation of the neighbourhoods' microclimates. It is claimed that using a selected area within the images to assess a larger neighbourhood would likely produce a more accurate result.

Dousset and Gourmelon (2003) also used land cover and satellite thermal imagery to derive the parameters of surface fluxes by temporal and spatial variations of surface temperature and relate this to the land use. Hung et al. (2006) used various scaled satellite images, with both thermal and visual bands was used to map and analyse spatial and temporal variations of the urban heat islands and then combine them with higher spatial data to study the relationship with vegetation and urban surface characteristics.

The combination of satellite and airborne thermal imagery has been done in a few studies to compliment the results of the studies (e.g. Kottmeier et al., 1997). Satellite image can provide a much larger area and can be used to give an estimate of results that are found from conducting an airborne thermal flight and place the surveyed area into the broader context of a city's Surface UHI. The combination of satellite data with airborne depends on the times of overpass of the satellite. If the satellite passes at a time when monitoring is needed then it can provide a very useful tool to combine with specially timed airborne thermal flights. Using a satellite image can provide a photography of the study area and so can provide a land use image to combine with the airborne thermal image taken.

2.5 Summary

Airborne thermal imagery is an extremely useful tool to capture and study micro-scale variations in urban surface temperature. It provides for an excellent spatial coverage of the surface UHI in high resolution (1-5 m) using a uniform sampling method, allowing the identification of thermal signatures of individual surface elements (roads, roofs, tree-tops, etc). A major advantage of using airborne thermal mapping is the control of flight times (compared to satellite data acquisition); this allows targeted monitoring of specific features that are to be studied.

The selection of studies presented here demonstrates the advantages of using airborne thermal data to map various aspects of the urban heat island and the enticing feature of mapping urban surface hot or cold spots. Analysis of airborne thermal imagery data using urban land surface classification has shown relationships between urban surface temperature and different surface types and urban geometries. During night-time conditions, areas of high vegetation cover tended to display lower surface temperatures (Kottmeier et al. 2007; Saaroni et al., 2000) while areas with a high sky view factor also tended to display higher surface temperatures (Eliasson, 1992; Barring et al., 1985).

Some common themes have emerged through this review of previous studies that need to be considered when undertaking airborne thermal mapping.

- **Limitations** – As emphasised at the beginning of this report, there are different types of UHIs, of which form as a result of unique processes across different scales of urban climate. Remote sensing provides a measure of the Surface UHI. Also, and Voogt and Oke (1997) describe, airborne thermal remote sensing provides a bird's eye view, rather than a picture of the complete three dimensional urban surface, and hence leads to a sampling bias. Also, airborne thermal imagery provides a measure of surface brightness temperature, which needs to be corrected for atmospheric effects, reflectance and emissivity to obtain accurate values of absolute surface temperature. An issue with all the thermal imagery, airborne and satellite, is the pixel size of the image results in some mixed surface types within each pixel, so the surface temperature value observed may not be pure. This limitation can be monitored with the use of auxiliary data. Finally, while the spatial coverage of airborne thermal mapping is excellent, the temporal resolution is poor, within images providing but a snapshot in time of surface temperatures at that particular moment, and surface temperature patterns can vary with things like thermal admittance and surface moisture and differences in near-surface atmospheric influences (Voogt and Oke, 2003).
- **Surface versus air temperature** – The urban canopy layer air temperature is usually referred to in UHI studies, which is a different UHI to the Surface UHI. Saaroni et al. (2000) showed using thermal airborne imagery that the surface temperatures can be linked to on the ground measured air temperatures. Comparing the thermal map with the air temperatures isotherm map for the collected it was showed that both maps show a similarity in spatial distribution and magnification of temperature variation. However, other studies have shown that surface temperature from a thermal image can be related to on the ground measurements this is not the same for air temperatures due to urban geometry (Eliasson, 1992) and factors like wind flow. Surface to air temperature correlations are strong under more stable atmospheric conditions, but surface to air temperature relations become decoupled under higher wind velocities (Stoll and Brazel, 1992). The UCL air UHI is also influenced by complete urban surface temperatures (Voogt and OKe, 1998), rather than just the surface temperatures captured through an airborne thermal image. Correlations between surface and air temperatures improve at night, when micro-scale advection is reduced (Unger et al., 2010).

- **Ground validation** – To ensure accurate results from the airborne thermal images, on the ground measurements are normally taken at the time of flight or satellite pass-over. Ground measurements are conducted to provide control measurements to confirm the thermal data and also to provide auxiliary data. Some studies have actually used ground validation points to transform the relative scale of the airborne thermal imagery to absolute temperatures (Unger et al., 2010). Ground validation measurements of surface temperature are often completed through transects and/or fixed stations.
- **Auxiliary data** – To get the maximum use out of the thermal imagery auxiliary data needs to be used and combined to get a complete picture of energy and thermal surface interactions. By using land cover maps, aerial photography, long term ground measurements and other information such as LiDAR data and remotely sensed vegetation indices, a more rigorous study can be conducted. Studies have also drawn on satellite data in combination with airborne thermal remote sensing data. Other auxiliary data that is more difficult to obtain includes high spatial resolution observations of air temperature, collected as a means of documenting the surface to air temperature correlations at the time of the airborne thermal flights. In order to assess the complete surface temperature, auxiliary remotely sensed data is required using either off-nadir airborne thermal imagery, or ground based thermography using transects. By using a three dimensional approach, more of the surfaces can be used in the estimation of the Surface UHI and important energy exchanges between all the important surfaces in the urban environment. Collection of auxiliary data depends on the research questions being asked.
- **Interpretation** – Roth (1989) emphasises the need for careful interpretation of remotely sensed data, and that it is essential for those interpreting the data to appreciate the special nature of the data.

Detailed analysis of airborne thermal remote sensing data for Australian cities has not been presented in any scientific literature, so information on surface characteristics influencing the Surface UHI is not available. While international studies indicate that vegetation tends to promote cooler surface temperatures and as such, is likely to provide a mitigating effect in UHI development, these studies do not tend to go on and attempt to use airborne thermal imagery in suggesting approaches for implementation of vegetation or 'green infrastructure'. Previous research has been limited to identifying land surface types and their thermal signatures. Further research is required to better understand the capacity for airborne thermal imagery to provide information on specific criteria for implementing Surface UHI mitigation strategies, including green infrastructure.

This review has demonstrated the capability of airborne thermal remote sensing to provide useful information in policy development and planning, *if* the data is collected correctly, complemented with other datasets, and interpreted carefully. With respect to the collection of the thermal imagery, Table 2 outlines the key methodological approaches used in the selected studies review earlier, and provides a good base for which to develop basic guidelines for the acquisition of airborne thermal imagery.

Table 2: Summary of some previous studies that used airborne thermal imagery

Study	Flight times	Ground validation	Complementary Air Temperature measurements	Image resolution	Use of other datasets
Saaroni et al.	0300 at 2000m in Winter	Six Fixed Roof Top Weather screens	Four Transects	±0.05°C 2m spatial resolution	
Quattrochi and Ridd	0500 and 1330 at 3500m in Summer	Temperature data from airport,		5 m pixel size	CIR Photo taken at same time as thermal flight
Bärring et al.	2100 in winter	Car transects as part of Temperature measurement program	Three fixed stations measuring air temperatures.	2 m pixel size	Temperature measurement program during the winter of 1983/1984. Three fixed stations
Kottmeier et al.	4 morning flights between 0647 and 0914 and 4 afternoon flights between 1509 and 141 at 350m, 700, 900m and then 350m per four flights	Surface temperatures measured on ground at satellite overpass time.		Spatial Resolution at ground is 1% of height.	Landsat 7 data Digital land use data
Eliasson	Between 1900 and 2100 hours at 600m in winter.	Reference surface temperatures taken at different points.	Reference air temperatures, humidity and wind were taken at different points. Vehicle measurement followed profiles through different urban environments.	2m Geometrical resolution	Sky view factor by two separate methods
Lo, Quattrochi and Luvall	Nine flights around 1100 hours at altitude of 5000m and six flights at 2500m. All flights repeated in evening after 2030	Ground data collection, GPS control points, measurement of surface temperatures		5 metre spatial resolution	CIR Photo
Gustavsson and Bogren	No Information on flight time or Season, but assuming winter. Flight at Altitude of 300m	Mobile transects for ground temperatures.	Mobile Transects for air temperature.	1 metre	

3. Guidelines for acquisition of the airborne thermal imagery

Drawing on the studies discussed above, this section presents an outline of the basic methodology for the collection of airborne thermal imagery, and how to maximise the information of thermal airborne imagery, satellite imagery and ground in-situ measurements. Acquiring and analysing airborne thermal imagery can assist in developing UHI mitigation measures such as identifying the best type, location and timing of implementation of green infrastructure in a bid to create more liveable, healthier and pleasant urban environments. By drawing on previous studies using airborne thermal imagery to analyse the Surface UHI a methodology can be created to ensure that accurate and appropriate results can be gathered and useful findings produced.

In summary, the overall process for using a thermal image for UHI and mitigation studies is shown in Figure 8. The following section outlines each of the steps involved in both acquiring airborne thermal imagery, processing the thermal imagery and using auxiliary data to assist in analysis of the thermal imagery.

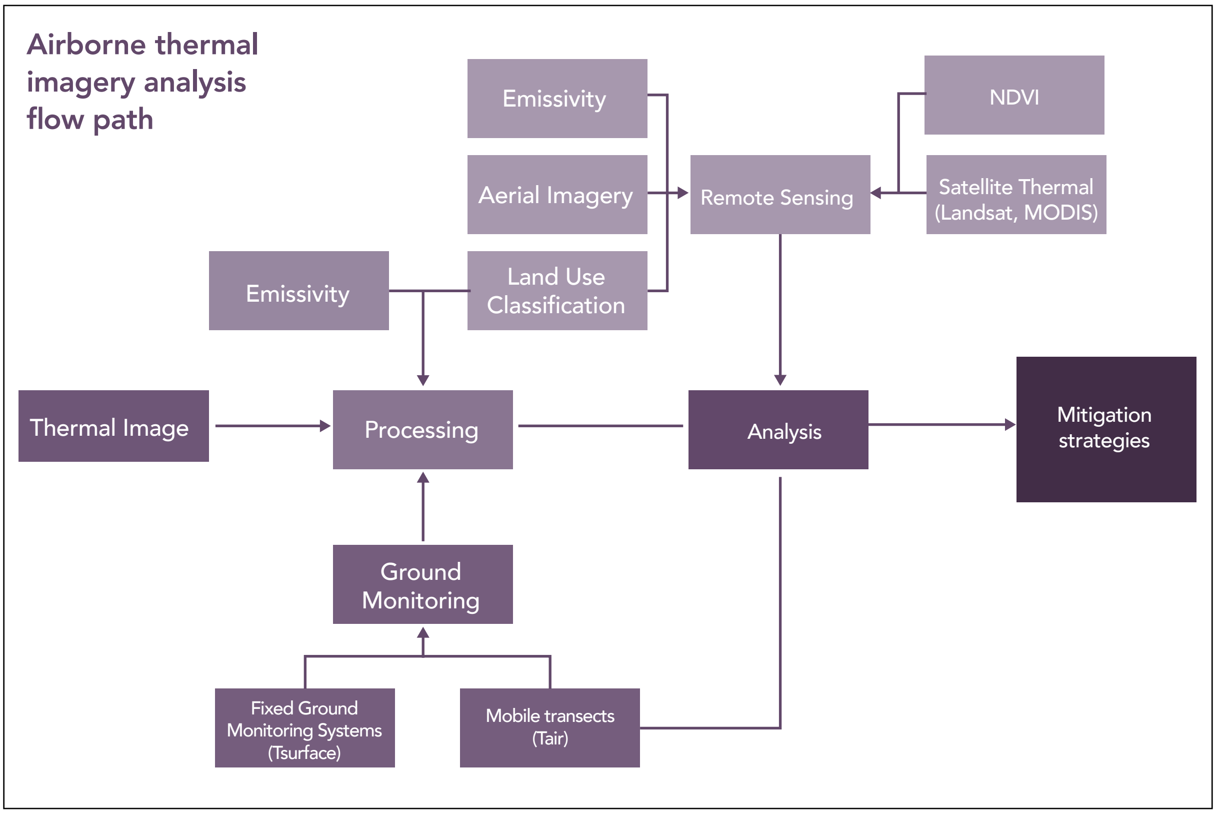

Figure 8: Flow chart of the process of processing and analysing airborne thermal imagery for informing UHI mitigation strategies.

3.1 Collection of the thermal image

3.1.1 Flight times

The Urban Canopy Layer air UHI is most pronounced at night, when urban areas remain due to high heat adsorption during the day, while rural area cool rapidly. These urban-rural temperature contrasts are most pronounced under clear skies and low wind velocities. UCL layer UHI are most pronounced in the early morning (Roth et al., 1989), just before sunrise, giving the land surface the maximum amount of time to cool. As such, previous studies commonly fly at pre-dawn; however others fly at earlier times of the night. This may be most practical in some cases, especially if simultaneous ground validation or auxiliary data collection is taking place. Night time flights are also beneficial because at this time, atmospheric stability is higher, and so surface to air temperature correlations are likely to be stronger. Night time flights also mean there are fewer effects of shadows and traffic flow, which contributes to the anthropogenic heat (Saaroni et al., 2000).

The Surface UHI however is commonly greatest during the day as observed from satellite remote sensing (Roth, 1989). As such, a daytime flight is also commonly undertaken. This can aid in interpreting any proceeding night time flight and can provide an indication of the diurnal temperature fluctuations of different surfaces. Day time flights should be undertaken around solar noon to capture the point of maximum urban surface warming, and to minimise shading effects.

3.1.2 Meteorological conditions

If UHI mitigation is the focus for the airborne thermal mapping, flights should occur under conditions that support optimal UHI genesis. Clear skies are crucial during the thermal image capture as clouds will obstruct the thermal sensor. Furthermore, cloudy skies will distort the land surface temperatures by shading some surfaces and not others, giving a false impression of relative surface temperature differences between surface types. Clear skies at night permit higher amounts of long-wave radiative cooling.

There should be little or no wind at time of flight to restrict surface cooling effects. Low wind speeds are important, as high turbulence can affect the aircraft and push the sensor off-nadir, reducing the accuracy of the thermal image. With increasing wind speeds and reduced atmospheric stability, any correlations between surface and air temperatures will be lost through micro-scale advection. This condition also supports optimal conditions for ground based ait temperature observations (outlined below).

Given the interest in using airborne thermal mapping as a tool in mitigating excess heat, flight times should target times of excessive urban warming, and periods that will demonstrate the largest contrasts in surface heating between surface types (urban versus natural surfaces) due to intense surface warming of urban materials. Ideally, the flights should be aimed to be undertaken during a period of 2-3 consecutive hot days.

The combination of these meteorological conditions tends to support optimal canopy layer UHI genesis. Meeting all of these meteorological conditions is a challenge, so some discretion and flexibility is needed in determining the choosing the best days to fly.

3.1.3 Camera Resolution

The camera and altitude of the flight are important to determine the resolution for the thermal data. The resolution of the thermal image is dependent on what type of analysis the user is after. Previous studies have shown that a resolution between 1m and 5m is sought after. The larger resolutions are used to show ‘hot’ spots and thermal patterns while the better 1m resolution is used to focus on smaller, individual elements.

3.2 Ground based monitoring

3.2.1 Ground validation of surface temperature

During the time of flight it is very important to have ground monitoring and validation points set up. Previous studies have used different approaches of either fixed point sources of surface temperature data or mobile transect measurements of surface temperature at the time of the flights. Surface temperatures are measured using an infrared temperatures sensor. The ground validations are used to demonstrate the accuracy of the thermal flight.

Fixed ground validation points are provided via climate stations that are established before the flight is flown, providing climate data over a period of time. The advantage of fixed stations over mobile transect is that they can provide a longer term measurement of the diurnal variation of different surfaces for use in analysis. Fixed stations can also provide a larger temporal resolution for different areas (Lo et al., 1997) rather than a snapshot in time like the thermal image. Fixed stations also ensure that validation data is collected at the precise time of the flight. In contrast, mobile transects are likely to provide a higher number of ground validation, but may risk misalignment in timing of the surface temperature measurement taken by the ground based station and the airborne thermal camera.

Ground validation points need to be selected over homogeneous areas that are a minimum of 5 m^2. This is so the area can be singled out on the thermal image and a direct comparison of the two data sets can be done. The fixed stations can be information from local climate stations (if surface temperature is recorded) or by stations set up by the investigator.

3.2.2 Canopy layer air temperature observations

Observational studies commonly conduct air temperature measurements to complement the airborne thermal imagery and to resolve any patterns between surface and air temperatures as Saaroni et al. (2000) have done. Air temperature transects provide a good spatial coverage of canopy layer air temperatures for the pre-defined areas of interest. Measurements are normally carried out by having sensors attached to vehicles and driven the throughout the pre-defined area of interest (Saaroni et al., 2000; Bärring et al., 1985). Systems usually consist of an air temperature sensor and a GPS.

Table 3: Summary of Flight Specifications

Flight time	**Nocturnal:** Pre-dawn, ideally between 0300 and 0500, however flights at midnight for instance are still extremely useful, and may be more practical for data collection **Daytime:** Solar maximum, between 1300 and 1500
Resolution	Aim for a resolution of between 1-5 metres. With an altitude of 5oooft a ground resolution of 1.5 metres
Ground validation	**Surface temperature:** Fixed ground monitoring stations using IR temperature sensors **Canopy layer air temperatures:** mobile transects through areas of interest using an air temperature sensor and a GPS.
Meteorological requirements	Preferably 2-3 consecutive days of warm-hot sunny periods. Clear skies and low wind speeds are critical

3.3 Auxiliary data

The study of the UHI can also be undertaken with lower resolution thermal data that can be captured from satellite data. The major differences in using satellite data instead of airborne is the pass-over time of the satellite might not be optimum for the study purposes and the ground resolution is less than with an airborne camera. Satellite remote sensing data can complement UHI analysis, and help to draw out information and generalisations from the thermal image about urban land use and design.

3.3.1 Satellite thermal data

A higher altitude data capture level means that a larger overview of the hot thermal areas can be seen. This can help show the thermal patterns of the urban area and the areas for maximum UHI potential and place the area monitored through airborne thermal imagery in the context of a the broader Surface UHI. There are a variety of satellite remote sensing products available including MODIS Terra and Aqua thermal products which provide 1km resolution images twice daily, Landsat ETM+ which provide 60m resolution, with a 16 day frequency. More details about satellite thermal remote sensing products is available in Tomlinson et al. (2011).

3.3.2 Aerial image

With the use of an aerial image taken at the same time as the flight or even by another sensor can be used for many different applications, as has been shown in a number of studies, for example creating a land use/ cover classification and NDVI for vegetation studies. Aerial imagery can be used to identify particular factors (e.g. irrigated surfaces, sources of heat combustion, etc) that may influence observed surface temperatures. Other products such as Worldview-2 can provide aerial imagery, along with additional bands that can assist in land surface classifications.

3.3.3 Land cover classification

Studies of urban heat islands have used aerial imagery to calculate the different land uses around the urban environment and have linked this to the thermal image to better understand the spatial thermal relationship with urban environment. For this project we would use the aerial image to do a supervised classification, using parallel-piped and minimum distance parametric rules, of land use of the urban area. This will be done by hand selecting areas of interest and classifying them with user's knowledge. Using the areas of interest selected the statistics of these pixels are calculated as representation of relevant classes used and then used to classify other regions in the image and assign them the same class as the training site. From previous studies it seems eight classes are appropriate for classification and these are 1) Vegetation-grass; 2) Vegetation – Trees; 3) Impervious Surface-Light; 4) Impervious surface – dark; 5) Soil- light; 6) Soil – Dark; 7) Shadow; and 8) Water (Gluch et al., 2006).

Using the land classification map, land use can be related to the thermal temperatures recorded and can show potential areas of urban heat island. This classification also allows the statistics of the impervious surfaces to be done which is another useful indicator of the possible magnitude of the surface UHI.

3.3.4 NDVI

Vegetation has been shown to have a cooling influence on surface temperatures, and if green infrastructure is being considered as a mitigation strategy, an understanding of existing vegetation is beneficial. Using the visible red and near infrared bands of the aerial or satellite image a Normalised Difference Vegetation Index (NDVI) can be carried out. Healthy vegetation has a high reflectance in the near infrared (NIR) and an absorption trough in the red. This unique spectral property, the red edge, is unique and therefore can be shown easily by the equation:

$$\text{NDVI}= \frac{(\text{NIR-RED})}{(\text{NIR+RED})}$$

By doing a simple NDVI, highly vegetated areas of the city can be shown and this can be related to temperatures from the thermal image and show the importance of green infrastructure thoughout the city. The NDVI index allows vegetated areas to be located and also the health or condition of those areas as well. It can be used to calculate the photosynthetic capacity of the vegetated area. NDVI can be calculated with any sensor that has a red and near infra-red band, which includes most of the satellites currently in orbit. This means that NDVI can be calculated on many different scales and can show local vegetation health or city wide vegetation location and health depending on the resolution.

3.3.5 LiDAR

Light Detection And Ranging (LiDAR) data can be used for terrain mapping. It can accurately capture the 3 dimensional characteristics of an urban landscape, being both the spatial representation but also accurately recording heights of objects. Sky view factors, which have been shown to have a strong influence on surface temperatures, can be calcualted using LiDAR data. Accessing LiDAR data therefore can be beneficial in intepretation of airborne thermal mapping. LiDAR data can also be processed to separate out 3 dimensioanl characterisicts of vegetation and buildings.

3.4 Post-processing of airborne thermal imagery

3.4.1 Thermal data

It is absolutely critical that full details of the thermal capture are known. In cases where a service provider acquires the thermal image, full details of the capture and any post processing must be fully documented and supplied. Raw radiometric data from the capture should also be provided so that re-processing can be completed if required.

Key details are the minimum forward and side overlaps, the pixel sixe, the spatial accuracy, and whether the image pixel resolution has been re-sampled. In cases where a geo-referenced and orth-rectified mosaic image is provided, precise details of the approach used should be provided.

3.4.2 Atmospheric correction

With some low altitude thermal imaging studies, atmospheric correction has been applied, while with others there is no mention of it. Depending on atmospheric conditions like humidity during the flight, and the flight altitude, atmospheric correction may need to be applied to the thermal data.

3.4.3 Emissivity

Different materials have different abilities to emit thermal radiation due to the amount of incoming solar radiation they absorb, the ability to store heat and the wavelength of energy emitted. As different materials have different emissivity values these will need to be taken into account when calculating the temperatures. This will be aided by ground validations and knowledge from previous studies about land use emissivity.

Following any necessary correction for atmospheric effects, the emissivity values can be applied in an adjustment to the image. The emissivity corrections are done by using a land use classification layer with typical emissivity values assigned different urban surface types, and reprocessing the image depending on type of land cover. Emissivity corrections should also include

Table 4: Typical emissivity values of common materials (Lillesand et al., 2004 in Tomlinson et al 2011)

Material	Typical average emissivity (over 8-14 μm)
Wet snow	0.98 – 0.99
Healthy green vegetation	0.96 – 0.99
Wet soil	0.95 – 0.98
Brick	0.93 – 0.94
Wood	0.93 – 0.94
Dry vegetation	0.88 – 0.94
Dry snow	0.85 – 0.90
Glass	0.77 – 0.81
Aluminium foil	0.03 – 0.07

3.5 Summary

Airborne thermal imagery is an excellent tool for visualising the surface UHI across an area, and in identifying relative warm and cool spots. The real benefits of airborne thermal imagery come from a properly acquired and corrected image, in combination with auxiliary data to assist in interpretation and analysis. Those seeking to use airborne thermal imagery in green infrastructure policy development and implementation should consider each aspect of the process of thermal image capture, processing, analysis and interpretation, and be aware of the key themes raised from this analysis. Understanding the thermal data, recognising the limitations in the data and correctly interpreting the data are all critical.

Green infrastructure is commonly cited as a key mechanism for limiting UHI effects (Rosenzweig et al., 2006; Wong et al., 2003). While studies may demonstrate that increasing vegetation cover cools urban environments, little guidance is available on specific approaches to implementing vegetation, or grenn infrastucture into the landscape to maximise cooling effects. Analysis of airborne thermal imagery, in combination with other data sources and resarch approaches, could help to inform on-the-ground implementation of green infrastructure to maximise cooling benefits from green infrastrucute investment, and reduce the Surface UHI.

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VCCCAR Publication 3/12 ISBN: 978 0 7340 4794 6
Document available from VCCCAR website at:
www.vcccar.org.au/content/pages/vcccar-publications

Layout and design by Inprint Design
www.inprint.com.au