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Chapter 21

Multi-scale analysis of the surface layer urban heat island effect in five higher density precincts of central Sydney

Ehsan Sharifi, Conrad Philipp and Steffen Lehmann

Summary

The urban heat island (UHI) effect is invariably present in cities, mainly due to increased urbanisation. It can result in higher urban densities being significantly hotter (frequently more than 4°C, even up to 10°C) than their peri-urban surroundings. Urban structure and land cover are key contributors to the surface layer urban heat island (sUHI) effect at city and district scale. This research aims to explore which urban configurations can make urban precincts and their microclimates more resilient to the dangerous sUHI effect. In the context of the city of Sydney, Australia, the research aims to explore the most heat resilient urban features for neighbourhoods, at precinct scale. The investigation examines five high density precincts in central Sydney. The analysis of these precincts is based on remote sensing thermal data of two independent sources: a nocturnal remote-sensing thermal image of central Sydney on 6 February 2009 and a diurnal Landsat 7– ETM+ data from 2008-2009. Comparing the surface temperature of streetscape and buildings' rooftop feature layers indicates that open spaces are the urban elements most sensitive to the sUHI effect. Therefore, the correlations between street network intensity, open public space ratio, and urban greenery plot ratio and sUHI effect are being analysed in the five high density precincts selected. Results indicate that a higher open space ratio and street network intensity have a significant correlation to a higher sUHI effect at precinct scale. However, higher urban greenery plot ratios could mitigate the sUHI effect in these precincts. In addition, annual variation of land use features of streetscape, building (rooftop), open space and urban greenery are being analysed based on diurnal Landsat 7– ETM+ data for 2008-2009. Results indicate that an increase in urban greenery is the most effective strategy for land surface that is more resilient to the sUHI, while open public space is up to 15 per cent less heat resilient. The research outcomes support the importance of increasing urban greenery, particularly in open public spaces, to achieve cooler cities.

Introduction

Cities are anticipated to accommodate up to 70% of the global population by 2050 (DESA 2012). Unlike the current urbanisation rate of 50%, almost all the expected global population growth will be accommodated in cities. Such rapid urbanisation means higher densities in existing cities and many more new urban areas will be needed to accommodate up to 2 billion new urban dwellers. However, rapid urban development in fast-growing cities tends to overlook the environmental and social aspects of urban life (Girardet 2008; Lehmann 2010; Register 2002). A considerable amount of natural landscape is transformed into building mass and hard surfaces, creating environmental threats for existing and future cities.

With huge demands for natural resources (i.e. energy, food, water and materials) cities are contributing up to 80% of greenhouse gas (GhG) emissions, resulting in global warming (UNECE 2011; UNHS 2011). Climate change projections indicate a likely increase of 2 to 5°C in Australian surface temperature by 2050 (CSIRO 2007; OECD 2010). Such an increase in temperature will have a severe impact on natural ecosystems and human life in cities, including public health and quality of public space (Guest et al. 1999; Stone 2012).

Cities also suffer from the effect of an additional form of heat, known as the urban heat island (UHI) effect. This human-made heat is trapped in the built environment’s thermal mass and can result in higher densities being significantly hotter, compared to their peri-urban surroundings. The urban-rural temperature difference frequently reaches 4.0°C and can peak at more than 10°C (Gartland 2008; Oke 2006; Wong & Yu 2008). Such additional heat can seriously impact citizens’ health and the quality of public life in cities.

Heat islands are uneven in their spatial distribution and can vary between industrial, commercial and residential areas. While cities’ higher density can bring efficiency gains, there is interplay between the increased risk of the urban heat island effect and higher densities, which needs to be well understood. Because cities are often covered in heat-absorbing surfaces and materials, such as concrete and bitumen, they absorb and store heat (e.g. through solar radiation), making urban areas warmer than the surrounding hinterland and rural areas, especially at night time.

Background to the research project

The extensive recent literature on the UHI effect indicates that the artificial increase of temperature in cities is happening because of changes in radiative energy and water budget in the built environment (Erell et al. 2011; Gartland 2008; Oke 2006; Santamouris & Geros 2006). This artificial temperature increase affects urban microclimates in different layers of the atmosphere, including the surface layer (buildings and land surfaces), the canopy layer (below the canopy of trees or at human scale) and the boundary layer (up to 1500 metres above the ground surface). These three layers of urban microclimates are tangled in complex climatic systems, while local air circulation in the built environment can moderate the UHI effect by mixing the air in each layer with other adjacent layers (Erell et al. 2011). Oke (2006) argues that the UHI effect has four major contributing factors (see Figure 21.1):

1 Urban geometry, which alters heat exchange balance in the built environment by affecting shadow and wind patterns. It affects the exposure of materials to sunlight and the consequent heat storage in

thermal mass. This complex heat radiation exchange between building mass and adjacent atmosphere can also change the intensity and patterns of airflow in urban canyons.

2 Urban cover and surface materials, which affect the heat absorption and reflection time-rate in the built environment. Thermodynamic specification, colour, texture and density of materials and their exposure to sunlight can alter the heat flux in outdoor space in complex procedures.

3 Urban landscape, which affects water and heat exchange rate in the built environment. Photosynthesis and evaporation processes in urban greenery contribute to decrease the ambient temperature. Urban greenery typology, distribution and intensity also affect lower atmospheric air turbulence.

4 Urban metabolism and anthropogenic (human made) waste heat in cities, which is mainly related to mass energy consumption for indoor air-conditioning and motorized transportation.

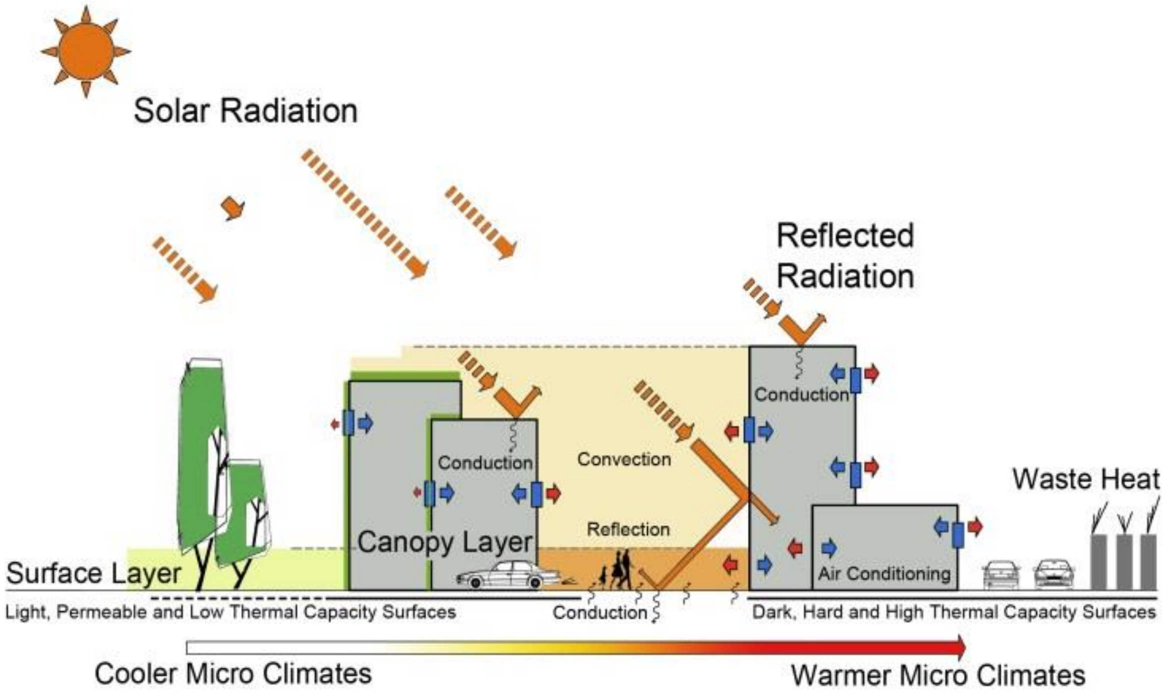


Figure 21.1 Urban structure, landscape, land-cover and metabolism contribute to the Urban Heat Island effect in cities

Existing approaches to the UHI effect are more likely to focus on large scale monitoring and mitigation strategies or micro scale material science. More research on the key contributors to the surface layer UHI (sUHI) effect at precinct scale can provide useful links between UHI investigations at city and material scales.

The temperature of some Australian cities, such as Sydney, Melbourne and Adelaide, is already up to 4°C warmer than surrounding areas. The current investigation discusses ongoing research on the City of

Sydney, which is an example of a city facing an increasing UHI effect due to its post-19th century urban development. Due to the city's sub-tropical climate and the UHI effect, public spaces in the city are already warmer in summer than humans' thermal comfort, pushing citizens into air-conditioned buildings and creating an ever-increasing rise in outdoor temperatures. Such artificial urban heat stress increases the mortality rate, especially of the elderly (Hu et al. 2007). The aim is to investigate the most effective sUHI mitigation strategies at the precinct scale in Sydney.

Materials and methods

Although major UHI contributors may be present in a wide range of regional climates, the effectiveness of urban features on the UHI effect is highly contextual (Oke 2006; Wong & Yu 2008). For example, the UHI effect's behaviour in the canopy layer of a sub-tropical city like Sydney in summer differs from drier climates, due to generally higher humidity and lower day-night temperature variations. The high dependence of UHI research on geographical, climatic and structural contexts highlights the need for climate-specific UHI case studies to achieve applicable research outcomes.

The City of Sydney has experienced significant development since 1945 (Toon & Falk 2003), which is continuing in the 21st century (McGuirk 2003). Sydney has also experienced five severe heat waves: in 1939, 2004, 2007 (Australian Bureau of Meteorology 2008), 2009 and 2012. In recent years, heat waves have become more frequent and last for longer. The maximum air temperature of 46°C on 18 January 2013 surpasses the highest temperature recorded, of 43°C on 6 February 2009. Confronted by the UHI effect, the City of Sydney has facilitated a number of UHI investigations based on remote sensing thermal imagery over the past decade, concluding with a Building Thermal Performance Index (BTPI) to evaluate building envelopes' thermal behaviour (Samuels et al. 2010). However, the BTPI is for individual buildings and is not applicable to the precinct or city scale.

The current research focuses on the surface layer UHI (sUHI) effect, which studies the surface temperature of horizontal urban features. Utilizing the literature on the UHI effect, thermal imagery, GIS information and image processing, this study aims to investigate the correlations between the urban greenery ratio, open space ratio and the surface temperature in five precincts in central Sydney.

On 5 February 2009, the temperature reached 31°C at 6 pm with a relative humidity of 33%. During the night, wind speed was less than 5 m/s, which was unable to cool down the city by the next morning. Consequently, on 6 February 2009, the air temperature reached a record of 43°C at 7 pm with a relative humidity of 10% and wind speed of less than 5 m/s. This heat stress continued in Sydney on 7 February with a maximum temperature of 39°C at 6 pm and a relative humidity of 12%. Due to higher humidity in lower temperatures, the real feeling of the (apparent) temperature did not come below 30°C on 6 and 7

February. According to Thom's Discomfort Index (Moran et al. 1998; Thom 1959) and the Human Heat Index (ASHRAE 2004), the micro climate condition in Sydney during the target days was partly in 'heavy discomfort' and mostly in 'emergency discomfort' zones, which can cause heatstroke, especially for elderly and disadvantaged people (Kovats & Hajat 2008).

Aerial thermal imagery of central Sydney was conducted on 6 February 2009 by Digital Mapping Australia for the City of Sydney, available with the resolution of 8 metres. The resulting remote-sensing maps indicate different surface temperatures in central Sydney. Building and population densities, open space and urban greenery primary data are based on GIS information provided by the City of Sydney. Spatial dimension, plot ratio and distribution of open space and urban greenery are extracted from a Google Earth image dated 4 February 2009 (to match the data to the thermal imagery of 6 February 2009).

Thermal imagery of central Sydney on 6 February 2009 maps different surface temperatures of the built environment. It also provides the average surface temperatures of ten precincts (urban districts with identifiable characters), which shape different temperature zones inside central Sydney. From these precincts, five higher density precincts have been selected for the current research. Sydney Harbour, Haymarket, Harris Street, Kings Cross and Glebe Point are being compared to investigate which urban features can be most effective in reducing the sUHI effect in Sydney's high density precincts.

This research project uses Landsat 7– ETM+ thermal layer data from 2008-2009. The sUHI is being calculated in four isolated timeframes during 2008-2009, based on diurnal Landsat 7– ETM+ satellite imagery on 28 September 2008, 1 December 2008, 23 March 2009 and 11 June 2009. This satellite-based remote sensing thermal data covers four different regional climatic conditions in Central Sydney and helps to analyse the sUHI effect on an annual basis.

Data calculation method

The civil remote sensing satellite Landsat-7 was launched by NASA in 1999 and has been providing its data from eight spectral bands; the most interesting of them for the evaluation of land surfaces temperatures is the thermal infrared (TIR) channel #6 from 10.31 µm to 12.36 µm with an in-nadir resolution of 30 m x 30 m (however, resulting for the TIR from an automatic post-processing of the original data of double grid size).

Each image is filled with digital numbers (DN) out of the interval [0; 255], and frequent calibrations are published on how to recalculate the spectral radiation density at the ETM+ sensor. Furthermore, the combination of sensor parameters with the fundamental Planck's equation of black body heat radiation allows to assigning an at-sensor brightness temperature (TB) to every pixel. The new method applied here uses the relative spectral response (RSR) curve of ETM+ and a best-possible numerical approximation of the reverse Planck's equation instead of a simplified analytic one.

As the temperatures of the ground surface's emitting areas are the final objects of interest, at least two influences should be eliminated: (i) the deviation of the surface from a "black body" and (ii) the influence of the atmosphere on heat radiation. The first effect is generally handled by introducing an emissivity ε within [0; 1] as a proportionality factor to characterize the reduction of real body emission compared to the black body. In this project, the classification-based emissivity method (CBEM) (Li et al. 2012) was used. Based on the literature (Nichol 1994; Nichol 1995; Valor & Caselles 1996; Schott et al. 2001; Weng 2001; Nichol 2005; Zhang et al. 2006; Stathopoulou & Cartalis 2007; Mallick et al. 2008; Van et al. 2009; Coll et al. 2010; Sun et al. 2010), the most likely emissivity values were derived for the four LUT of central Sydney: streetscape (0.91), building (rooftop) (0.90), open space (0.91) and urban greenery (0.98).

As radiation is absorbed when passing through a transparent medium, in this case the air column between ground surface and satellite, an atmospheric correction (AC) of the temperature estimates must be done by using the transmission τ within [0; 1]. After extensive testing of a variety of AC methods, the mono-window algorithm (MWA) (Qin et al. 2001; Li 2006; Zhang et al. 2006; Liu & Zhang 2011; Deng & Wu 2013) was chosen, and some modifications were introduced to generalize the quantitative effect of air humidity on τ. However, this algorithm demands on actual temperature and humidity profiles of the atmosphere being measured by meteorological balloons, e. g. from Sydney's airport.

Preliminary observations

According to the map of temperature zones (Figure 21.2), Haymarket precinct had the hottest surface temperature with an average of 31.03°C, while the overall surface temperature in Sydney Harbour precinct was 30.88°C, in Harris Street 30.95°C, in Kings Cross 30.34°C and in Glebe Point 30.65°C. Although the temperature variance is only 0.69°C, it is a significant variance, because each average temperature is the mean of over 2000 data points. Furthermore, in this thermal map the average surface temperature of central Sydney is only 30.56°C (standard deviation=0.26). The temperature variance among the Kings Cross (minimum average) and Haymarket (maximum average) precincts is 0.69°C. However, smaller urban elements' (e.g. streetscapes and rooftops) surface temperature varies from 28 to 33°C (see Figure 21.3 and Figure 21.4). Overlapping the surface temperature maps of individual urban elements and average precincts indicates that the overall temperature in the Haymarket precinct (31.03°C) is very close to the surface temperature in the Barangaroo site (31.08°C. see Figure 21.2 centre top). At the time of this thermal mapping, Barangaroo was an industrial site fully covered by concrete (a greener redevelopment plan is underway). Concrete, along with asphalt, is among the hottest and most undesired urban surfaces identified by sUHI studies (Erell et al. 2011; Gartland 2008; Oke 1988). This cross mapping reveals that the sUHI effect in Haymarket precinct is significant and intense. The questions are: what physical configurations at precinct scale contribute to this extremely hot temperature and is it possible to mitigate it?

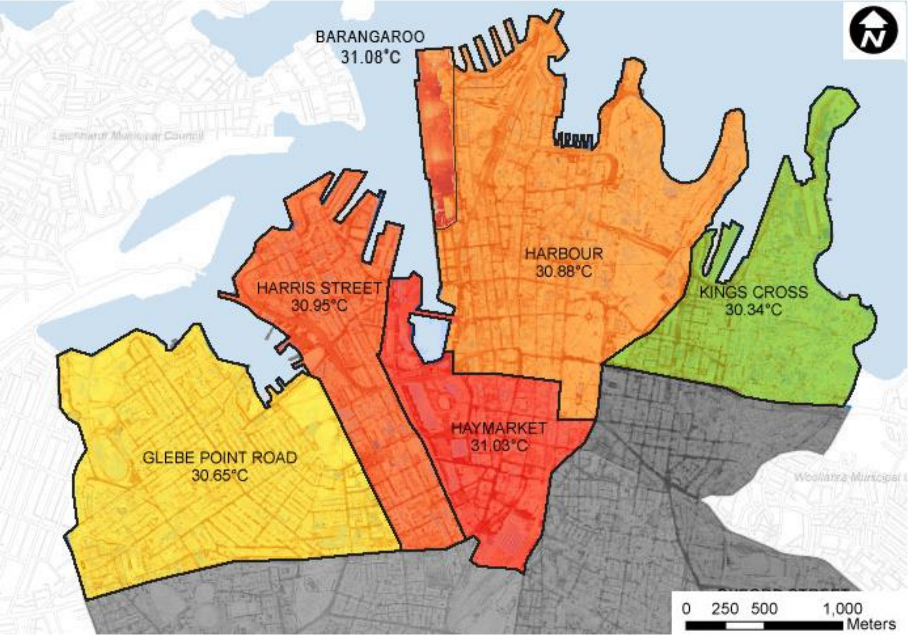


Figure 21.2 Average surface temperature of precincts in Glebe Point, Harris Street, Sydney Harbor, Haymarket and Kings Cross precincts. Based on: (City of Sydney, 2010)

Controlled variables: residential and building density

Density, the number of dwelling units and people per hectare in a given land area, is still a controversial term in urban design. Both building and urban (population) densities are being controlled in this study to enable more focused analysis on urban elements and features in higher densities.

There is evidence that cities of lower density produce more greenhouse gas emissions per capita, however, over-development and too much density can be detrimental and reduce liveability and health (high-density areas in Hong Kong and Mumbai are good examples of this). The densities of Australian cities are notoriously low, like those of North American cities. The average city density can vary widely, from 25 habitants per hectare in Sydney, to 100 habitants per hectare in Rio de Janeiro, to over 300 habitants per hectare in Shanghai and Seoul. Research indicates that the world’s most liveable cities have a density range of 60 habitants per hectare (London) to 170 habitants (Barcelona), which leads to compact and walkable cities where green spaces and gardens are well integrated.

Discussion about the effect of building density on the magnitude of sUHI shapes a considerable portion of the urban microclimate literature (Lee et al. 2013; Yuan and Chen 2011; Giridharan et al. 2004). Since the early sUHI studies, it has been argued that higher densities are likely to have higher temperature (Givoni 1998; Oke 1988; Tapper 1990) due to their physical structure.

Background sUHI research indicates that high density building blocks can magnify the sUHI effect in cities by increasing the opportunity for surface materials to absorb direct and reflected sunlight radiation (Priyadarsini 2009; Erell et al. 2011; Giridharan et al. 2007). Generally, reflected solar radiation has more chance to exit the built environment from lower density and less compact areas (Wong & Yu 2008). During each reflection phase between building facades and street surfaces, a portion of solar energy is transmitted into built environment surfaces in the form of heat (Erell et al. 2011). Thus the general surface temperature is likely to be higher in higher densities.

The five precincts selected have a building density of more than 100 units per acre (Sydney Harbour and Haymarket have up to 200 units per acre). According to Campoli and MacLean's (2007) classification of building density, over 100 units per acre can be considered as very high building density. Higher building density can also intensify energy consumption in cities and consequently increase anthropogenic waste heat (Sivam & Karuppannan 2012; Ichinose et al. 2008). Although population density is not a direct contributor to the UHI effect, it can increase the need for energy consumption for air conditioning and transport. Citizens in higher densities consume a considerable amount of energy in their daily life, especially for indoor air conditioning and transportation. This higher rate of energy consumption increases the amount of anthropogenic (human-made) waste heat in higher densities and therefor contributes to the UHI effect in cities. However, a clear link between anthropogenic waste heat and sUHI has not been identified yet.

Central Sydney has the highest population density in Australia with an estimated residential population of 180,679 residents living in an area of 4.48 km^2 in 2010 (City of Sydney 2011). The overall urban density of the City of Sydney is 40330 p/km^2. However, the five selected sites represent a higher average urban density of over 74136 p/km^2. Therefore, the case studies selected have very high urban densities compared to other Australian cities and even other precincts in central Sydney.

However, the number of people visiting central Sydney on a daily basis for shopping, entertainment and education reaches up to 483,000. This is in addition to the 385,000 people who arrive every day to work in central Sydney. The considerable proportion of temporary residents compared to permanent dwellers (more than fourfold) makes it difficult to consider residential density as a factor, contributing to the sUHI effect in Sydney. Furthermore, population density is usually discussed regarding to ambient temperature

UHI effect, while the current study focuses on the surface layer urban heat island (sUHI) effect. As such the variable of population density is being controlled in the current study.

Analysis and results

Urban features can influence the surface temperature in higher densities by affecting the overall rate of materials' exposure to sunlight and heat exchange between them (ASHRAE 2004; Oke 2006). Specific heat capacity, conductivity and albedo (reflectivity) of materials are the major factors that can cause the built environment to store sunlight energy in the form of heat in its thermal mass and to postpone the energy departure process from the built environment (Ashie 2008; Dahl 2010; Oke 1988). Still the location of materials needs to be carefully considered, as shading can significantly influence the heat absorption and reflection process. Two of the most common places where the sUHI is being investigated are urban open space (including streetscapes and public space) and buildings' rooftops.

Public space usability: thermal behaviour of horizontal surfaces (streetscapes and rooftops)

The performance of public space can be categorized using conventional indicators for effective measuring of public domain performance over time, for instance, by looking at the public domain as a connective social and economic space, with a high value of exchange occurring within it. While it is difficult to compare one public space with another and the types of interaction that occur in the public domain vary, most urban researchers agree that effective measurement of public domain performance examines key planning principles and public space characteristics, such as continuity, safety, enclosure, connectivity and adaptability. This research examines the usability and resilience of public space networks during heatwaves, introducing new criteria and indicators for evaluation and retrofitting existing as well as emerging public spaces.

The comparison between surface temperatures of different horizontal urban features can indicate which elements are more heat-sensitive and therefore need more examination in sUHI mitigation studies. Comparing 300 randomly selected data points indicates that a higher temperature exists on streetscape surfaces than on building rooftops (see Figure 21.3 and Figure 21.4). The average temperature of streetscape surface layer is 31.39°C, which is 0.37°C higher than the Haymarket precinct overall surface temperature (the hottest precinct in Figure 21.2). Some streetscape surfaces, especially in the Haymarket precinct, reached the highest temperature of 34.15°C with 5.10°C variance from the minimum streetscape temperature (see Table 21.1). The average surface temperature of buildings' rooftop layer is 30.26°C (with the maximum value of 33.61°C), which is 1.13°C less than the average streetscape surface temperature, 0.77°C less than the average temperature of the Haymarket precinct, 0.69°C less than Harris

Street, 0.62°C less than Sydney Harbour and 0.39°C less than Glebe Point (the rooftop layer average surface temperature is very close to the average surface temperature of Kings Cross: 30.34°C).

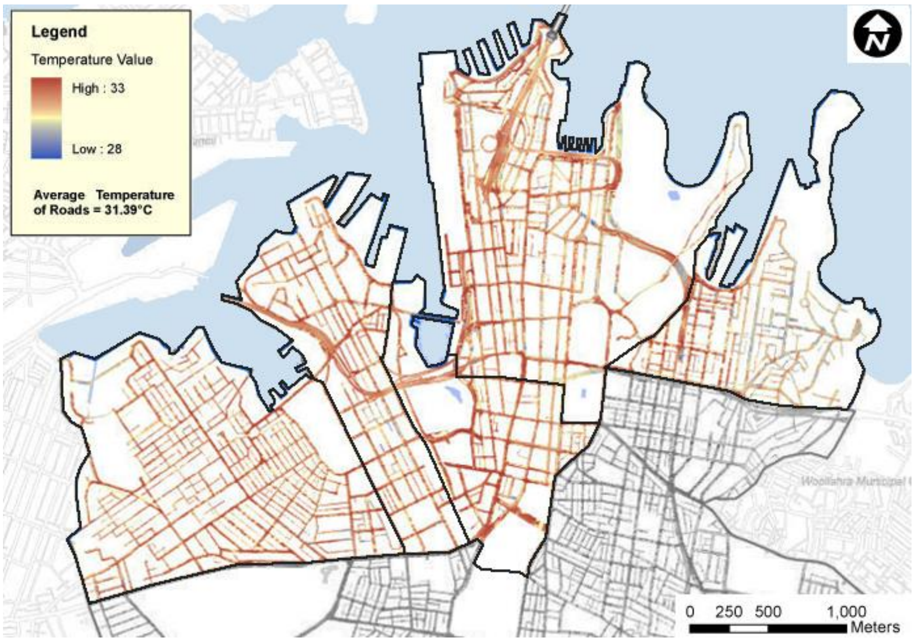


Figure 21.3 Street surface temperature in five adjacent high density precincts in central Sydney, Based on: (City of Sydney, 2010).

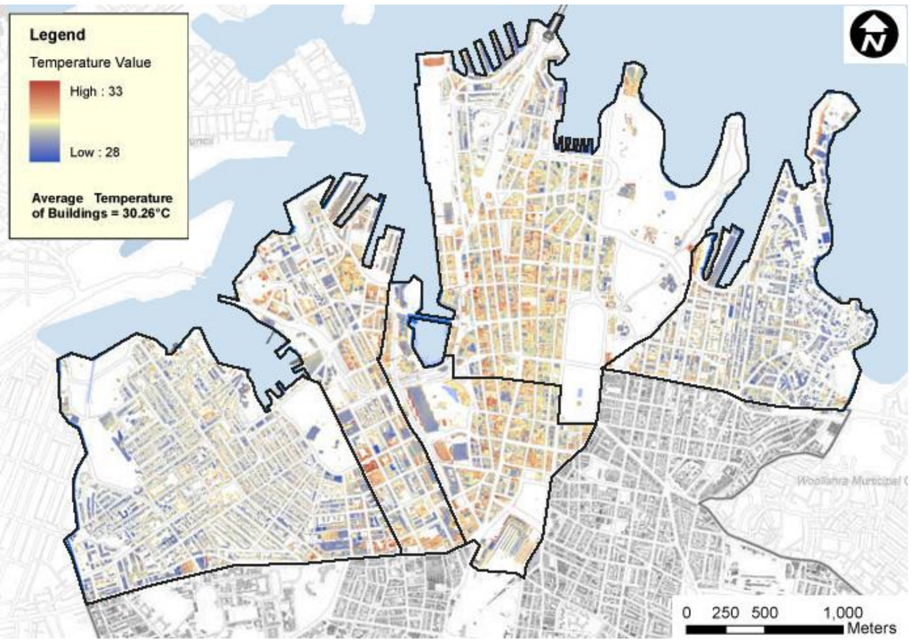


Figure 21.4 Rooftop surface temperature in in five adjacent high density precincts in central Sydney. Based on: (City of Sydney, 2010).

According to Table 21.1 the streetscape has a considerably higher surface temperature and temperature variance than building rooftops do. This underlines the streetscape as the more heat-sensitive urban feature at precinct scale. To undertake more detailed sUHI analysis, the street network intensity is compared against open public space plot ratio.

Table 21. 1. Temperature variance of streetscape surfaces and building rooftops in five high density precincts of central Sydney

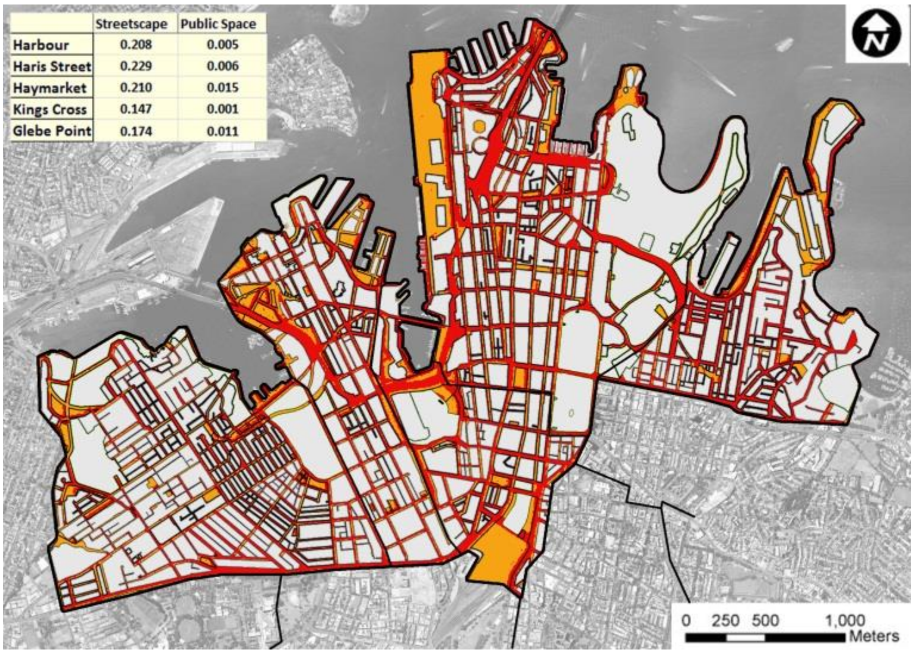
	Min Temp. (°C)	Max Temp. (°C)	Average Temp. (°C)	Temp. variance (°C)
Streetscape	29.05	37.30	31.15	8.25
Building rooftop	27.70	33.61	30.26	5.91
Temp Variance (Street-Roof)	2.65	3.69	0.89	2.24

Correlation between open space plot ratio, street network intensity, public space plot ratio and the sUHI effect

As heat sensitivity occurs more in between buildings rather than on their rooftops, it is worthwhile analysing further the correlations between the general land use of open space and the sUHI effect. To this end, the streetscape and public space are being analysed separately in this section. The analysis of this correlation can indicate to what degree the sUHI effect is a dependent variable of streetscape or public space plot ratio.

Table 21.2 shows that street network intensity (streetscape plot ratio) has the correlation coefficient (R) value of +0.94 to the average precinct surface temperature. It means that a higher streetscape plot ratio correlates almost directly to higher overall surface temperatures in Sydney precincts. This high and positive coefficient value indicates that higher streetscape surfaces strongly correlate with the sUHI effect at precinct scale (the maximum R value could be 1, which shows complete correlation).

The open space plot ratio (i.e. all hard-landscaped open spaces including streetscapes and other public spaces) has an even greater coefficient value of +0.97 to overall surface temperature in Sydney precincts. This high coefficient value indicates strong correlation of overall surface temperate to the proportion of hard-landscaped open space (e.g. paved with concrete and asphalt). However, separating other open spaces from the streetscape results in a relatively lower coefficient value of +0.64 between the hard-landscaped public space plot ratio and the precinct surface temperature, which still indicates a higher correlation than average (moderate R value is +0.5).



	Streetscape	Public Space
Harbour	0.208	0.005
Haris Street	0.229	0.006
Haymarket	0.210	0.015
Kings Cross	0.147	0.001
Glebe Point	0.174	0.011

Figure 21.5 Streetscape and public space plot ratio in five precincts of Sydney. Feature Extraction from Google Earth Imagery 2009, resolution: 1 meter

High and positive coefficient values between hard-landscaped open spaces (i.e. streetscape and public space layers) and sUHI on-the-ground surface layer indicates that harder landscapes can increase the surface temperature of urban precincts. Under question is whether there are any urban land covers capable of mitigating the sUHI effect at precinct scale?

Table 21.2. Street network intensity and average surface temperature in the five precincts of central Sydney

Precinct	Sydney Harbor	Harris Street	Haymarket	Kings Cross	Glebe Point
Street network plot ratio (per cent)	20.8%	22.9%	21.0%	14.7%	17.4%
Open space plot ratio (per cent)	21.3%	23.5%	22.4%	12.8%	18.5%
Public space plot ratio (other than streetscape)	0.5%	0.6%	1.5%	0.1%	1.1%
Average Surface Temperature (°C)	30.88	30.95	31.03	30.34	30.65

Correlation between urban greenery plot ratio and the sUHI effect

An extensive amount of literature supports the idea that greenery can mitigate the sUHI effect (Erell et al. 2011; Oke 2006; Gartland 2008; Ashie 2008; Butera 2008; Correa et al. 2012; Dahl 2010). At the micro scale, this heat mitigation occurs in two ways: first, through using solar energy and photosynthesis to facilitate greenery metabolism and second, through evapotranspiration (evaporative cooling) in reaction to the ambient heat on the surface of leaves (just like human skin). Therefore, green infrastructures can counteract the sUHI effect by cooling down air and surface temperatures at the micro scale.

Various forms of greenery can exist in urban precincts, such as parklands, gardens, green roofs, vertical greenery, urban farming, nature reserves and planting of extensive vegetation; all acting as sources of moisture for evapotranspiration, where the absorbed solar radiation can be dissipated as latent heat and thus aid in reducing urban temperature. Recent research by Wong (2008) shows that vegetated spaces could be a few degrees cooler than their surroundings. Under question is to what extent this is applicable at precinct scale? To investigate the effect of urban greenery on sUHI mitigation at precinct scale, urban greenery plot ratio (UGPR) is being compared to the sUHI effect in the five Sydney precincts.

The total study area (the five precincts selected) covers 1.75 km^2, which includes an overall area of 0.36 km^2 of urban greenery (UGPR=20.7%). However, there is a significant variance in urban UGPR in the five selected precincts. As shown in Table 21.3, UGPR is 26.6% in Sydney Harbour and 29.1% in Glebe Point. However, UGPR in Kings Cross is 11.2%, in Harris Street 7.69% and in Haymarket only 3.31%. Significant variance of UGPR and proximity of these precincts make them appropriate cases to study further.

Table 21.3. Urban vegetation ratio in the five precincts of Sydney Central

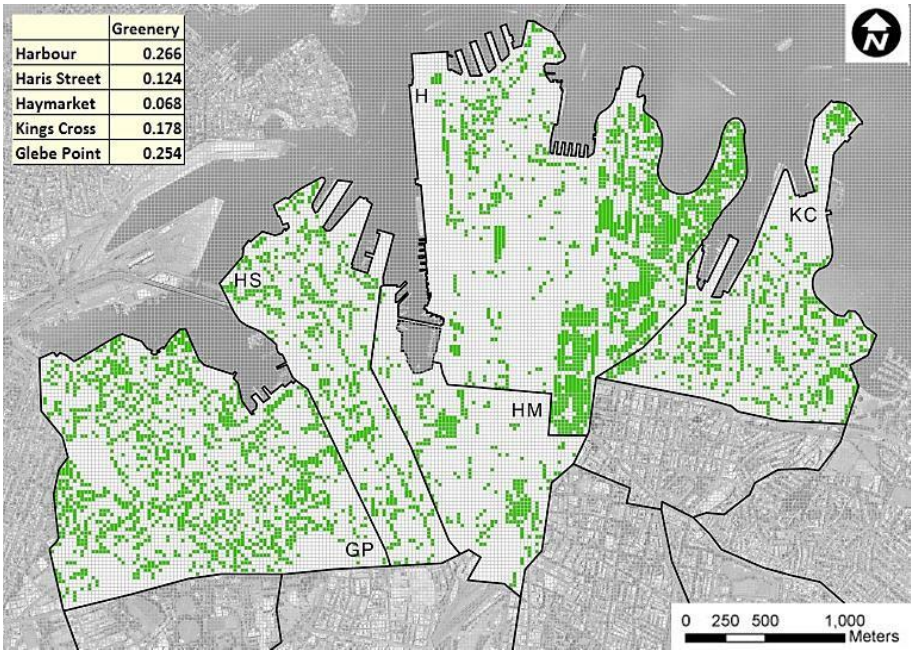
Precinct	Sydney Harbor	Harris Street	Haymarket	Kings Cross	Glebe Point
Urban Greenery (km^2)	0.15	0.03	0.01	0.04	0.12
Precinct Area (km^2)	0.58	0.25	0.20	0.25	0.47
Urban Greenery Plot Ratio (UGPR)	26.6%	12.4%	6.7%	17.8%	25.3%
Average Surface Temperature (°C)	30.88	30.95	31.03	30.34	30.65

With the correlation coefficient (R) value of -0.40 for precincts and -0.78 for smaller random sample areas (120 samples were studied, each with an exact area of 100 m^2), precinct surface temperature shows medium to high dependency to UGPR. This also indicates that the effect of UGPR on sUHI is moderated by other factors at larger scales.

Urban greenery distribution in Figure 21.6 reveals that Kings Cross and Glebe Point (the lowest average surface temperature) have the most homogenous urban greenery distribution, while hot Haymarket has the lowest and most scattered greenery spots. In the Sydney Harbour precinct, the large area of the Royal Botanic Gardens and Hyde Park can explain its relatively lower sUHI compared to Haymarket and Harris Street.

Resilience of urban land uses to the sUHI on an annual basis based on Landsat 7– ETM+ data

As Table 21.4 and Figure 21.7 show, the annual variation of surface heat is greatest at open space layers with a value of 32.39°C (2.46°C more than precinct average surface temperature variance) and least at urban greenery layers with a value of 28.88°C (1.05°C less than precinct average surface temperature variance). Surface temperature variance of streetscape is the second highest with a value of 31.74°C (1.81°C more than precinct average surface temperature variance), which makes it a low heat resilient urban land use at precinct scale, alongside open space. Considering the surface temperature of urban greenery (the most resilient) against open space land use (the least resilient) shows 3.51°C sUHI variation, which means urban greenery is 10% more resilient to sUHI compared to streetscape surfaces at precinct scale. Although these sUHI differences cannot directly indicate exact variance in ambient (air) temperature (due to thermal characteristics of surface materials in reflection, absorption and conduction of heat), we can expect homological variance in ambient temperature with some delay (usually less than 4 hours).



	Greenery
Harbour	0.266
Haris Street	0.124
Haymarket	0.068
Kings Cross	0.178
Glebe Point	0.254

Figure 21.6 Urban vegetation ratio in five precincts of Sydney, Extraction from Google Earth imagery 2009, resolution: 8 meters

Considering data distribution of annual surface temperature of selected land uses shows similar differences between them. Standard deviation describes the normal data distribution in a dataset. What it reveals in this investigation is that urban greenery surface temperature varies less on an annual basis (maximum variance of 9.92°C from the median of 29.35°C) compared to streetscape (maximum variance of 10.83°C from median of 33.01°C), building rooftop (maximum variance of 10.85°C from median of 34.10°C), open space (maximum variance of 12.69°C from median of 34.29°C) and the precinct average surface temperature (maximum variance of 10.37°C from median of 32.63°C). Therefore, urban greenery has the coolest median temperature of 29.35°C (4.94°C cooler than open space) and 10% more normal data distribution (StDev 9.92 vs StDev 10.78 for open space, StDev 10.83 for streetscape and 10.85 for building rooftop) among the selected land uses.

Table 21.4. variation of urban land surfaces in an annual basis 2008-2009 in the five precincts of Sydney Central

		Streetscape Ave. (°C)	Building Rooftop Ave. (°C)	Open Space Ave. (°C)	Urban Greenery Ave. (°C)	Precinct Surface Heat (°C)
September 2008	Sydney Harbour	31.22	32.11	33.96	27.51	30.28
	Harris Street	32.90	33.57	33.30	28.69	32.73
	Haymarket	31.09	33.12	29.64	27.82	31.31
	Kings Cross	32.67	33.47	34.62	28.13	31.72
	Glebe Point	33.48	34.25	32.42	29.12	32.53
December 2008	Sydney Harbour	44.18	45.14	46.38	38.10	42.35
	Harris Street	45.91	46.90	45.95	41.02	45.43
	Haymarket	44.79	46.56	44.62	39.07	43.93
	Kings Cross	46.16	46.53	46.14	40.09	44.14
	Glebe Point	46.78	47.46	45.49	40.94	45.05
March 2009	Sydney Harbour	33.07	33.95	36.30	29.63	32.16
	Harris Street	35.44	36.14	36.20	31.83	35.21
	Haymarket	32.95	34.87	33.68	30.06	33.07
	Kings Cross	34.04	34.31	36.30	29.58	32.74
	Glebe Point	36.23	37.04	35.62	32.26	35.33
June 2009	Sydney Harbour	16.34	17.01	18.02	13.61	15.80
	Harris Street	16.12	16.98	16.45	13.20	16.44
	Haymarket	15.04	16.25	14.00	12.14	15.50
	Kings Cross	17.37	18.05	18.52	13.54	16.96
	Glebe Point	15.76	16.57	16.37	12.82	15.52
	Max Variation	**31.74**	**31.21**	**32.39**	**28.88**	**29.93**
	Median	**33.01**	**34.10**	**34.29**	**29.35**	**32.63**
	Standard Dev.	**10.83**	**10.85**	**10.78**	**9.92**	**10.37**

As such, the findings of part one of the current research, which indicates urban greenery is the most resilient urban feature and open space is the least resilient urban feature to the sUHI are being aligned with satellite-based thermal data. On an annual basis, however, streetscape and building rooftop layers show very similar behaviour.

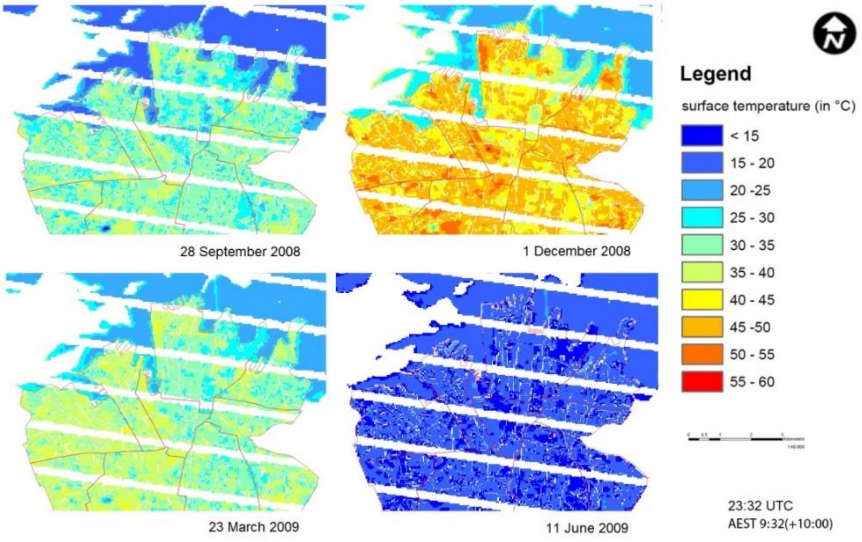


Figure 21.7 Annual variation of surface temperature in five precincts of Sydney, Extraction from Landsat 7– ETM+ 2008-2009, resolution: 30 meters

Discussion

The surface temperature zones map (Figure 21.2) of central Sydney shows that Haymarket precinct has the highest surface temperature with an average of 31.03°C. The overall surface temperature of the Haymarket precinct is very close to the surface temperature of extremely hot urban features in the study area (e.g. 31.08°C in Barangaroo and 31.15°C for average streetscape layer). This means that sUHI in the Haymarket precinct is significantly higher (mathematically) than central Sydney's average (30.56°C), which highlights Haymarket as the precinct most vulnerable to the sUHI effect.

Comparing streetscape surface temperatures (Figure 21.3) and urban greenery distribution (Figure 21.6) reveals that the sUHI effect is greater in less vegetated areas. Although all five precincts have high building densities, streetscape surfaces in Sydney Harbour are up to 1.6°C cooler than similar areas in Haymarket. This relative coolness correlates with the higher rate of UGPR in the Sydney Harbour precinct (19.9% higher than Haymarket).

Overall, the surface temperature of open space and rooftops is slightly more in the Sydney Harbour and Haymarket precincts (with twice the building density of the other three precincts). This could be due to the lower sky view factor (i.e. the amount of sky visible from the surface) for streetscapes. It needs to be noted that the rooftops of high rise buildings in Haymarket and Sydney Harbour are flat roofs (also partly the case in Harris Street), whereas the rooftops in Kings Cross and Glebe Point are a combination of flat roofs and pitched roofs, which have different solar gain due to the way they face solar radiation (i.e. in the southern hemisphere, horizontal surfaces generally have more daily solar gain than surfaces sloped towards the south, east and west). For an indepth discussion about streetscape and rooftops' surface temperature, more detailed data about land cover surface materials is needed.

A comparison between Figure 21.3, Figure 21.4 and Table 21.1 reveals that streetscape surfaces are generally hotter than rooftops (up to 3.69°C). Rooftops are exposed to sunlight radiation almost all day long, while street canyons have partial shadow coverage due to surrounding high-rise buildings. Therefore, in theory, rooftops should gain more heat compared to streetscape surfaces, but in practice streetscapes have the hotter surfaces. In the current study, streetscape surfaces represent a higher minimum temperature (2.65 °C), higher maximum temperature (3.69 °C) and higher average temperature (0.89 °C) than rooftops, as well as more surface temperature variance (2.24 °C). This indicates the importance of focusing on cooler land covers and urban greenery on the ground surface layer rather than on rooftops in the central Sydney.

The higher ratio of urban greenery in the Sydney Harbour precinct (UFPR=26.6%) compared to Haymarket (6.7%) and Harris Street (12.4%) seems to be the most effective factor in mitigating the sUHI effect at precinct scale. A significant area of urban greenery in the Royal Botanic Gardens and Hyde Park (located in the Sydney Harbour precinct, see Figures 21.2 and 21.6) is cooling down the precinct's overall surface temperature.

Satellite-based thermal data of Landsat 7– ETM+ 2008-2009 (Figure 21.7 and Table 21.4) indicates that on an annual basis, urban greenery is the most resilient urban feature to the sUHI effect, with a lower average temperature (29.35°C) and less temperature variance (28.88°C), while open public space is the least heat resilient urban feature with a 4.94°C hotter average temperature and 3.51°C more temperature variance during a year (10% to 15% less resilient). The interesting point is that public open space is the easiest and most cost-effective space in which to increase urban greenery. In other words the least resilient urban feature to the sUHI has the potential to be transformed into a somewhat cooler place (up to 5°C) by using urban greenery (the most resilient feature).

Conclusions

Urban temperatures are predicted to increase due to climate change. The temperatures in our cities are likely to increase further, because more heat will be stored and re-radiated by expanses of asphalt, concrete and other heat-storing building materials. In this context, it is crucial to understand the possibilities for the transformation of existing urban fabrics towards a more liveable and sustainable future (Bosselmann 2008; Lehmann 2010). This can be implemented by smart and small-scale spatial transformation of existing urban spaces.

The basic argument underlined in this comparative case study is that the higher sUHI effect at precinct scale correlates with a greater hard-landscaped public space plot ratio, more street network intensity and a lower urban greenery plot ratio. Higher open space plot ratio and street network intensity correlate significantly to higher sUHI effect at precinct scale. However, higher urban greenery plot ratio can mitigate the sUHI effect in high density precincts. Therefore, increasing urban greenery and decreasing hard-landscaped urban features (e.g. streetscapes and vast hard-covered open spaces) can cool down existing precincts. A fine distribution of urban greenery can also mitigate the sUHI at precinct scale.

Research limitations and further opportunities

This research is based on remote sensing thermal photography and desktop spatial data. It utilizes the surface temperature which is different from the real feeling of the temperature in public space. Further studies could benefit from including on-the-spot climate measurements and air temperature data. The effect of local airflow and surface water is subject to further investigation. To move towards more certainty about the research outcomes, on-the-spot microclimate measurement at smaller scales could be beneficial. Due to the limited scope of this study and controlled variables, the results need to be validated in other cities.

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