CRC for
Water Sensitive Cities

Impacts of water sensitive urban design solutions on human thermal comfort

Green cities and microclimate

An Australian Government Initiative

CRC
AUSTRALIA

The impacts of WSUD solutions on human thermal comfort
Green Cities and Micro-climate - B3.1 -2-2014

Contributing Authors

Andrew Coutts[1,2]
Margaret Loughnan[1,2]
Nigel Tapper[1,2]
Emma White[1]
Jasmine Thom[1]
Ashley Broadbent[1]
Richard Harris[1]

[1] School of Earth, Atmosphere and Environment
Monash University, Melbourne, Australia 3800

[2] CRC for Water Sensitive Cities
Monash University, Melbourne, Australia 3800

Publisher

Cooperative Research Centre for Water Sensitive Cities

Level 1, Building 74, Clayton Campus
Monash University
Clayton, VIC 3800

p. +61 3 9902 4985
e. info@crcwsc.org.au
w. www.watersensitivecities.org.au

Date of publication: December 2014

Executive Summary

Climate sensitive urban design involves the creation of thermally comfortable, attractive and sustainable urban environments by enhancing positive natural and man-made features through architecture, planning and landscape design. This report focusses on the 'thermal comfort' component of urban design, and the role of water sensitive urban design (WSUD) in achieving climate sensitive streets, neighbourhoods and cities. Using a mix of observational, remote sensing and climate modelling approaches, research is beginning to reveal the potential benefits of WSUD and urban greening, and provide guidance on their implementation.

Understanding what humans perceive as thermally comfortable sets a benchmark in which to target when designing urban spaces. Research was conducted via surveys in Melbourne and Adelaide (Mawson Lakes) on levels of human thermal comfort and found that a comfortable air temperature in Melbourne was 21.5 °C (50th percentile) and 25.7 °C (50th percentile) in Adelaide. However, human thermal comfort is better described by thermal indices rather than air temperature, as they consider all environmental variables (air temperature, wind, humidity and radiant temperature), clothing, activity, and physiology (age, sex, weight and height). Considering the Standard Effective Temperature (SET*), HTC was 21.8 °C (50th percentile) in Melbourne and 31.04 °C (50th percentile) in Adelaide. As activity increases (walking, exercising) HTC declined, and as respondents felt hotter, they preferred more air movement. People who were outdoors for the thirty minutes before answering the survey were hotter than those from indoor environments highlighting the influence of solar exposure on HTC.

WSUD and urban greening can be utilised to improve levels of HTC. Approaches must aim to provide shade, reduce surface radiative temperatures and promote some ventilation. Research presented here demonstrates that:

- Providing shade is critical under warm sunny conditions. This means that WSUD and urban greening should prioritise trees. Further, these trees need to have healthy canopies that are actively transpiring, so trees should be supported by WSUD. Research found trees can lower the Urban Thermal Climate Index by up to 10 °C reducing heat stress from 'very strong' to 'strong'. Trees should be prioritised in wide, E-W oriented streets.

- Irrigating vegetation can reduce land surface radiative temperatures during the day. The addition of water to grass surfaces, and likely WSUD elements (e.g. swales, biofilters etc.) that have high soil moisture levels will lead to reduced surface temperature, and will lead to lower air temperatures as well, which will lead to improved HTC.

- While adding trees will reduce radiative temperatures during the day, it is important that a complete canopy cover is not present, as surface cooling and ventilation at night needs to be promoted to support nocturnal cooling.

- Green roofs must be irrigated in order to provide benefits for outdoor HTC during the day. Further, benefits of green roofs will be felt most at ground level in terms of air temperature when installed on rooftop < 2 storeys high. An alternative approach to green roofs is to use highly reflective white rooftop paints, and harvest the roof runoff for irrigation of trees at ground level.

- Green walls and façades reduce surface temperatures of walls and have a greater benefit for HTC at street level than green roofs via a reduction in radiative loading.

- There is a risk of increasing humidity from widespread irrigation and WSUD, however, humidity is just one environmental component influencing HTC and the positive benefits (reduced radiative temperature and air temperature) outweigh any negative effects of increased humidity.

Finally, it should be noted increased water availability through WSUD and urban greening is just one factor that influences the urban microclimate and human thermal comfort. HTC is extremely complex and variable at the micro-scale, varying over distances of just metres. Air temperatures are influenced by adjacent land surfaces, background local climates, wind flows and turbulence. Microclimate will also be influenced by urban structures. Therefore, the strategic location of urban greening, WSUD and irrigation in the creation of thermally comfortable, attractive and sustainable urban environments must enhancing positive natural and man-made features through architecture, planning and landscape design.

Human Thermal Comfort

Human thermal comfort (HTC) refers to 'that condition of mind which expresses satisfaction with the thermal environment' ASHRAE (ISO 7330) . It is a more accurate representation of a person's thermal condition than simply air temperature. Perceptions of this environment are affected by environmental variables of air temperature, mean radiant temperature, relative humidity and air velocity, along with personal variables of activity (e.g. sitting or running) and clothing. Mean radiant temperature is the amount of radiant load (e.g. solar radiation) on the human body, and is considered the dominant driver of HTC under warm, sunny conditions.

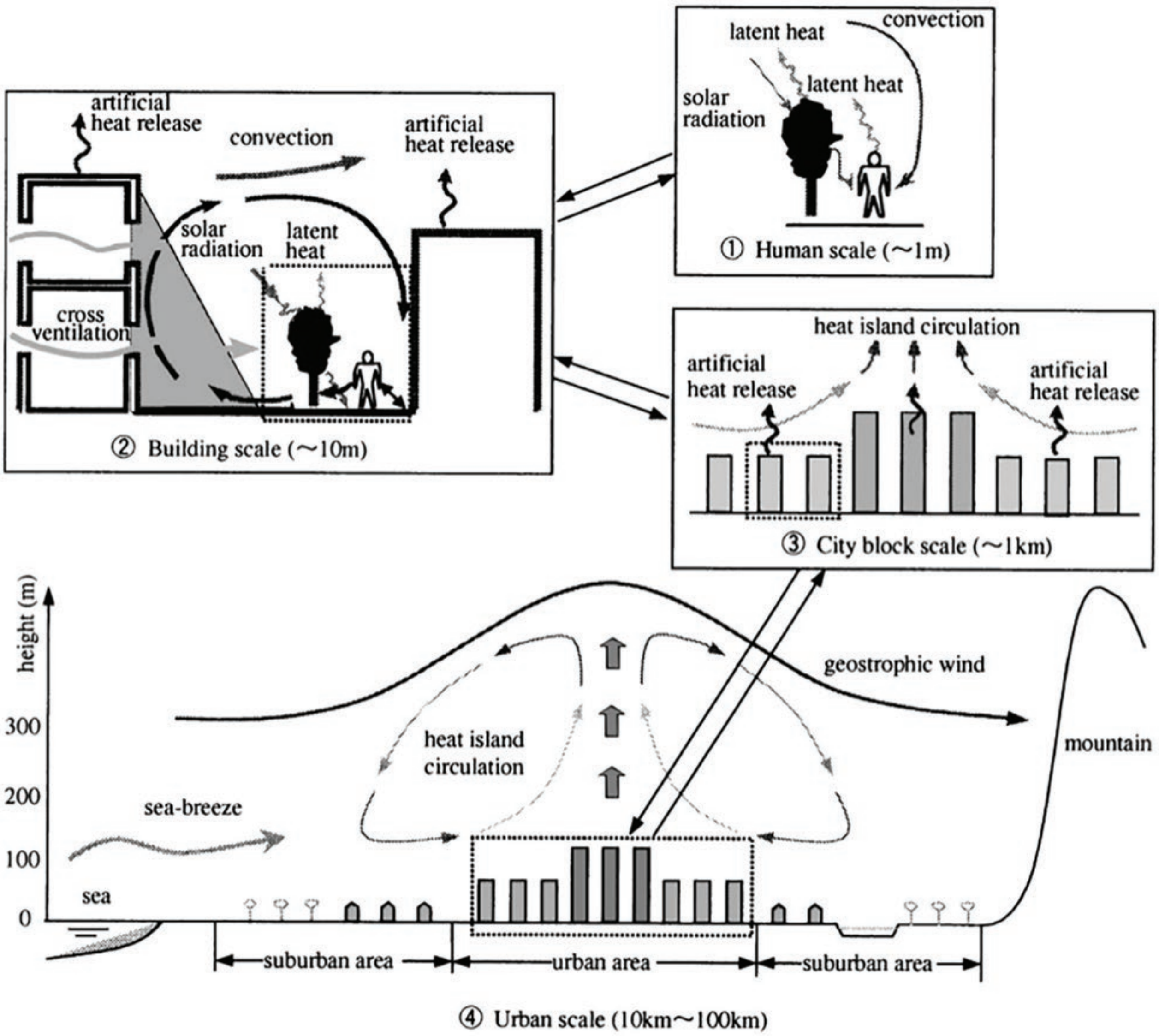


Figure 1: Various scales in urban climate and links to micro-scale human thermal comfort (Murakami et al., 1999)

[1] ASHRAE is the American Society of Heating, Refrigerating and Air-Conditioning Engineers. Its purpose is 'to advance technology for the public's benefit, a mission it fulfils through research, standards writing, publishing and continuing education'. It has more than 50,000 members in more than 120 nations and sets the most widely-used international standards for buildings

Figure 1 depicts the influence of the urban environment at a range of scales on the environmental variables that influence HTC. At the city scale, features such as the urban heat island commonly raise city air temperature, contributing to HTC. At the neighbourhood scale, features like the amount of green space, building density and landscape design influence the local climate. Finally, at the street or household scale, trees and buildings and other small structures influence climate at the micro-scale, and the perceived comfort level of a person. Air temperature is but one component of HTC.

Because of the dominance of mean radiant temperature on HTC during the day under warm, sunny conditions, shade is critical to providing a comfortable thermal experience in urban areas. Also, because of this shading effect, HTC is extremely variable at the micro-scale. HTC varies from street to street, from under trees to out in the open, and between streets to parks. It is this micro-scale climate and its links to HTC that is the focus of this report.

The report on 'Assessing impacts on human health (heat related stress and mortality' focused on city-to-neighbourhood scale air temperatures and the links with heat stress and mortality. Air temperature best relates to human health at those scales, while measures of HTC are most appropriately represented at the micro-scale.

There are a number of indices that have been developed to better represent human thermal comfort levels than simply air temperature. These indices take into account the environmental variables of HTC, as well as activity levels, clothing and physiological responses based on models of thermoregulation. These include (Blazejczyk et al., 2012) (pg 520-521):

- Physiological Equivalent Temperature (PET) – "The physiological equivalent temperature (°C) is based on a complete heat budget model of the human body …. PET provides the equivalent temperature of a isothermal reference environment with a water vapour pressure of 12 hPa (50% at 20°C) and light air (0.1 m s-1), at which the heat balance of a reference person is maintained with core and skin temperature equal to those under the conditions being assessed".

- Standard Effective Temperature (SET*) – "The (rational) standard effective temperature, SET*, is defined as the equivalent air temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for the activity concerned, has the same heat stress (skin temperature Tsk) and thermoregulatory strain (skin wettedness, w) as in the actual environment. SET* uses skin temperature and skin wettedness as the limiting conditions".

- Universal Thermal Climate Index (UTCI) – "The Universal Thermal Climate Index (UTCI) is expressed as an equivalent ambient temperature (°C) of a reference environment providing the same physiological response of a reference person as the actual environment".

These definitions are complex and difficult to understand, but essentially they all predict an air temperature that your body feels and experiences. They are like other well-known indices such as the wind-chill factor. While the air temperature may be 30 °C, but you are standing in the sun, in a humid environment with no wind, the air temperature may actually 'feel' like 40 °C, and this will change depending on whether you are walking or running, what clothes you are wearing, and your physiology including age, gender and weight. These indices incorporate all of these factors into estimating HTC as demonstrated in Figure 2.

As HTC is influenced by so many drivers at a range of scales, this presents an opportunity to purposefully modify and design urban environments in a way that provides more attractive, thermally comfortable and sustainable urban environments. This is achieved through climate sensitive urban design. Water sensitive urban design (WSUD) is one component of the landscape that influences HTC and Figure 3 highlights the role of WSUD in HTC, in particular its interactions with vegetation. Figure 3 also highlights that while WSUD can be used to manipulate HTC, there are many other factors at the urban planning and urban design level that also influence HTC. In addition, large scale drivers of climate and weather are also large drivers of HTC. This report focuses on how effective WSUD and green infrastructure can be in improving HTC by influencing the environmental variables of HTC (air temperature, mean radiant temperature, wind speed and humidity), and how to design and use WSUD to maximise HTC benefits.

Heat Balancing (MEMI) – Summer

T_a = 30 °C	RH = 50%	
T_{mrt} = 60 °C	v = 1.0 m/s	
PET = 43 °C		
Internal heat production:	258 W	
Mean skin temperature:	36.1 °C	
Body core temperature:	37.5 °C	
Skin wettedness:	53%	
Water loss:	525 g/h	
Respiratory heat loss:	-27 W	
Imperceptable perspiration:	-11 W	
Sweat evaporation:	-317 W	
Convection:	-143 W	
Net radiation:	+240	
Body parameters:	1.80 m	75 kg
	35 years	0.5 clo
	walking	(4 km/h)

Figure 2: Example of the Physiological Equivalent temperature (Höppe, 1999)

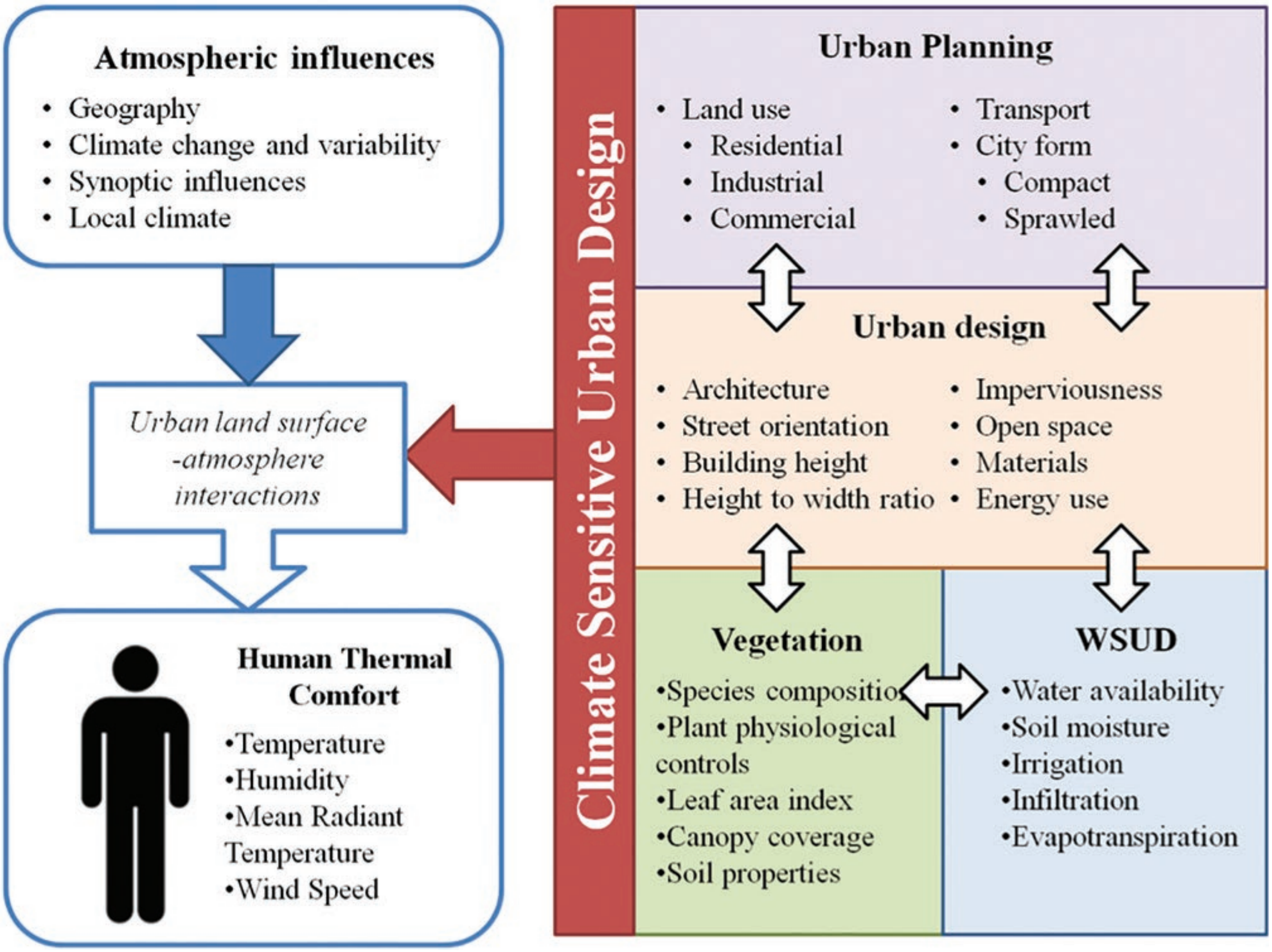


Figure 3: Conceptual diagram demonstrating the connection between Water Sensitive Urban Design and the environmental parameters influencing human thermal comfort – through Climate Sensitive Urban Design and urban land surface-atmosphere interactions (Coutts et al., 2013)

Benchmarking Human Thermal Comfort Levels

There is no global or absolute number that can reflect HTC. Not surprising as humans occupy every climate zone, thermal comfort will be region specific. The current international ASHRAE standards are based on physiological measurements taken in climate chambers and refer to indoor environments. Adaptive models have been developed to assess outdoor HTC and suggest that humans are more tolerant of temperature changes than the laboratory studies indicate, and respond using physiological thermoregulation (unconscious response), behavioural adaptations (clothing, activity, location) and technological adaptations (windows, doors, blinds, fans, and air-conditioning, characteristics of a building such as materials, orientation, moveable shading, vegetation/green spaces) to maintain comfortable temperatures. In Australia adaptive models have been applied in Sydney but data for other capital cities are lacking.

This project undertook field surveys to apply adaptive models of HTC in both Adelaide and Melbourne. The field surveys involved 693 questionnaires and corresponding weather station data using static weather stations to collect and record ambient temperature, wind speed, humidity, solar radiation, and black globe temperature. Seventy-five percent of respondents were aged between 35-54 years.

Overall the results indicated that persons walking or exercising in the thirty minutes before answering the survey were statistically more likely to report feeling very warm to hot. Consideration should be given to protecting exercise areas and public thoroughfares to limit exposures. People who were outdoors for the thirty minutes before answering the survey were hotter than those from indoor environments. The preference for more air movement (ventilation) increased as respondents recorded feeling hotter. Differences in thermal comfort between the two cities are highlighted (Table 1 and 2), with thermally comfortable temperature ranges being higher in Mawson Lakes, Adelaide than Melbourne. Both cities show an approximate 3°C range in thermally comfortable temperature.

Figure 4: Collecting surveys beside weather station and adjacent to a water body in Mawson Lakes 2011

Melbourne	
Percentile	Temperature (°C)
25th	20.05
50th	21.5
75th	23.2
Mawsons Lakes	
Percentile	Temperature (°C)
25th	25.3
50th	25.7
75th	27.9

Table 1: Thermal comfort reported as 4 (comfortable) median and interquartile points (ranges) for temperature

The www.thermal comfort calculator indicated that at an ambient temperature of 28°C an average person in the sunshine for 30 minutes during the middle of the day would have an effective temperature of 33-36°C. Exercising outdoors in the sun changes their thermal comfort considerably. A person standing in the sun for 30 minutes at an ambient temperature of 31.5°C in summer will have a core body temperature of 37.06°C (within the normal range of 36.2-37.5°C), walking casually under the same conditions core body temperature rises to 37.8°C, walking briskly causes the core body temperature to rise to 39.0°C (this is an equivalent thermoregulatory response to a nasty viral infection). This increase in core body temperature can result in heat stress if exposure is prolonged. During hot/warm summer weather people need respite from the sun (solar radiation). The provision of shade and good ventilation is paramount in protecting humans from heat stress. HTC models indicated that persons in exposed environments either resting or physically active experience some level of heat stress. This can occur at lower ambient temperatures than expected. Public education is an important factor in heat stress mitigation as is modifying urban environments to reduce temperatures and minimise exposures. Differences in thermal comfort for two activities (sitting and casually walking in direct sunlight for 30 minute periods) are noted (see Table 2 below). As activity increases thermal comfort decreases and core body temperature rises.

Developing liveable cities underpins urban development for the future. Greater insight into how humans interact within urban environments and what the limits are for human thermal comfort are needed to design thermally appropriate spaces. Reducing environmental heat exposure through water sensitive and climate sensitive urban design (CSUD) will provide a more liveable and healthy space for human activity. The results from this study provide information about thermally comfortable temperature ranges for two urban regions within Australia. Proponents of water and climate sensitive urban design can utilise this information to create urban spaces that are safe, productive, and socio-culturally acceptable spaces.

	Mawson Lakes			Melbourne		
Comfort model	**Percentile (temp)**	**Activity 1**	**Activity 2**	**Percentile (temp)**	**Activity 1**	**Activity 2**
SET	25th (25.3 °C)	23.9	28.8	25th% (20.5°C)	18.5	24.5
TSENS	25th (25.3 °C)	0.07 (neutral)	0.73 (slightly warm)	25th% (20.5°C)	0.28 (neutral)	0.12 (neutral)
HSI	25th (25.3 °C)	13.4	65.22	25th% (20.5°C)	-1.56	44.9
Core body temp.	25th (25.3 °C)	36.8	37.11	25th% (20.5°C)	36.8	36.9
SET	50th (25.7 °C)	31.04	33.8	50th% (21.6°C)	21.8	25.9
TSENS	50th (25.7 °C)	1.60 (warm)	1.65 (warm)	50th% (21.6°C)	0.14 (neutral)	0.35 (neutral)
HSI	50th (25.7 °C)	45.87	99.2	50th% (21.6°C)	6.07	4.69
Core body temp.	50th (25.7 °C)	36.92	37.3	50th% (21.6°C)	36.82	37.02
SET	75th (27.9 °C)	32.9	35.03	75th% (23.2°C)	23.4	27.04
TSENS	75th (27.9 °C)	2.07 (warm)	2.3 (very warm)	75th% (23.2°C)	0.03 (neutral)	0.56 (slightly warm)
HSI	75th (27.9 °C)	54.69	107.92	75th% (23.2°C)	11.8	52.04
Core body temp.	75th (27.9 °C)	36.97	37.48	75th% (23.2°C)	36.82	37.07

Table 2: HTC for two activities levels for median and interquartile points of temperature in each city

All calculations completed using WWW thermal comfort calculator (Richard DeDear)

Notes:
Activity 1 = sitting (60Wm-2)
Activity 2 = walking at average pace on level ground (150Wm-2)
All values for subject weight of 70kgs and clothing factor 0.6
Exposure time = 30minutes
SET = standard effective temperature
TSENS = thermal sensation
HSI = heat stress index

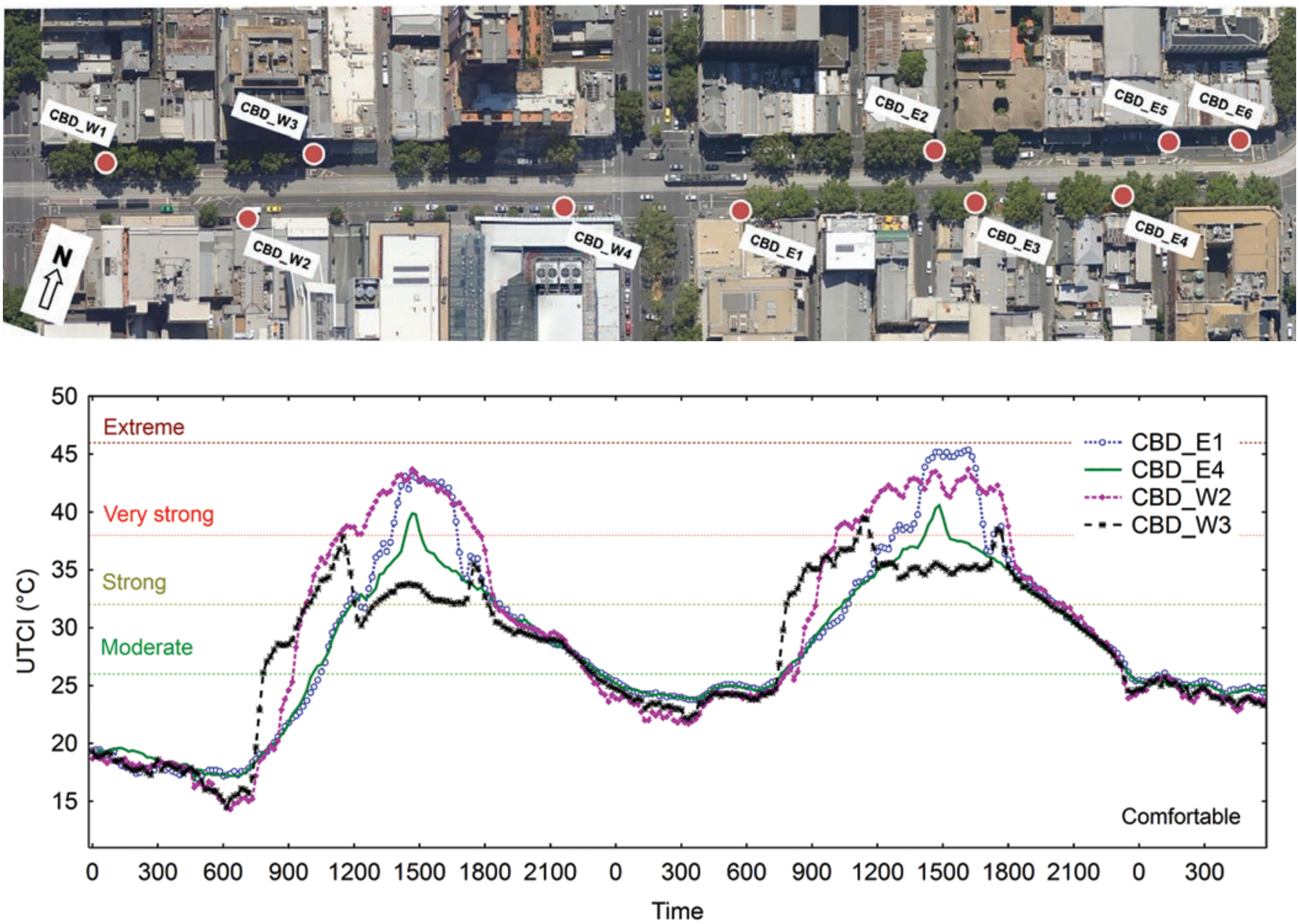
Trees and Human Thermal Comfort

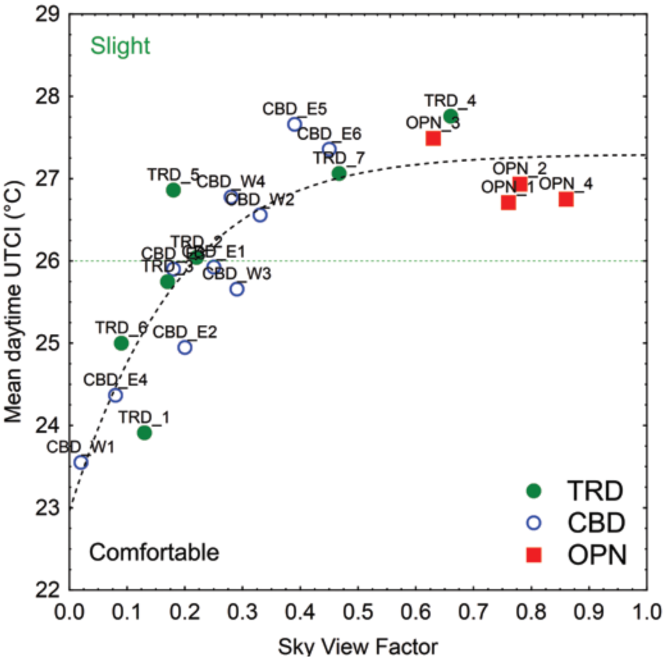
As outlined in the report 'Determining the microclimatic influence of harvesting solutions and WSUD at the micro-scale' we undertook a study in partnership with the City of Melbourne investigating the human thermal comfort benefits of street trees. To recap, we installed a number of microclimate monitoring stations in three streets in the City of Melbourne. This study investigated the benefits of trees on the average street micro-climate and HTC, and also compared HTC under and away from tree canopies.

In this study, we used the Universal Thermal Climate Index (UTCI) as the thermal comfort index. We confirmed that mean radiant temperatures are the dominant driver of HTC under warm sunny conditions, with UTCI closely following patterns of mean radiant temperature during the day. Figure 5 demonstrates the drastic changes in HTC simply depending on whether monitoring was in the sun or shade. Under the extreme heat event conditions presented here for 24-25 February 2012, shade can reduce peak UTCI by up to 10 °C and can lower levels of daytime heat stress from very strong heat stress down to strong heat stress.

It is important to note that shade from either trees or buildings will improve HTC, and trees with dense foliage cover will be more effective. This is shown in Figure 6 which shows the relationship between sky view factor (SVF – the proportion of the sky blocked by buildings], trees ranging from 0 [completely open] to 1 [completely blocked] and UTCI during January 2012. What this shows is that because of the dominant effect of mean radiant temperature on HTC under warm, sunny conditions, shade is critical for reducing daytime thermal heat stress. As such, WSUD elements that provide shade will have the greatest benefits for daytime HTC. Considering the raft of WSUD elements, e.g. biofiltration systems, infiltration systems, swales, porous pavements, constructed wetlands, while they will provide a microclimate benefit, if they do not incorporate a means of shading (e.g. trees) then benefits for daytime HTC will not be as large. This is why we suggest prioritising trees as a heat mitigation measure over other approaches, as outlined in blueprint2011.

Figure 5: Universal Thermal Climate Index (UTCI) and human thermal comport at selected stations Bourke St. Melbourne (CBD) over the 24-25 February 2012 extreme heat event (Coutts et al 2014)





Prioritising trees as an approach for improving HTC is important, but so is prioritising their location. Where should we place trees in order to maximise their benefit? Because buildings also provide shade, trees should be located in wide streets and where the heights of buildings are low. One measure that can easily be estimated is the height to width ratio (H:W) of a street. This can then guide where to protect and plant trees as shown in Table 3. East-West oriented streets should be prioritised over North-South oriented streets.

Figure 6: Relationship between total daily solar radiation received and the Universal Thermal Climate Index (UTCI)

Canyon Width	Priorisation: Street Trees									Canyon Orientation
Very Wide 40 m	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	E-W
	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	N-S
Wide 30 m	0.13	0.27	0.40	0.53	0.67	0.80	0.93	1.07	1.20	E-W
	0.13	0.27	0.40	0.53	0.67	0.80	0.93	1.07	1.20	N-S
Medium 20 m	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	E-W
	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	N-S
Narrow 10 m	0.40	0.80	1.20	1.60	2.00	2.40	2.80	3.20	3.60	E-W
	0.40	0.80	1.20	1.60	2.00	2.40	2.80	3.20	3.60	N-S
Metres	4	8	12	16	20	24	28	32	36	Metres
Storeys	1	2	3	4	5	6	7	8	9	Storeys
Canyon Height	Low			Medium			Tall			

Table 3: Table of Height to Width ratio (H:W) for streets and their priority rating for protection and implementation of trees to improve daytime human thermal comfort (Norten, Coutts et al., 2014)

High priority
Moderate priority
Lower priority
Not a priority

When siting trees within these streets, they should be placed where they receive maximum amounts of solar radiation (so they provide maximum shade). They should also be placed so as to allow surface cooling at night. While a complete tree canopy cover in a street will provide excellent shading coverage, at night the canopy can restrict longwave surface cooling and ventilation, meaning heat can be trapped and keep the street warm at night. This can be seen in Figure 5 where the station under the tree canopy (CBD_E4) has a slightly higher UTCI in the evening. A larger canopy cover is required in the high priority streets, but less so in the lower canopy streets. An example of possible tree configurations is given in Figure 7 where shading is provide during the day, but the heat from the street can still escape at night. Large, broad trees should be used in wider streets, while slimmer trees should be used in narrow streets on the sunlit side of the street. Further, irrigation using non-potable water needs to be provided to maintain healthy trees.

Using this guidance, we have explored the benefits of street trees on mean radiant temperatures (the dominant driver of HTC during the day) using a model called the SOlar and LongWave Environmental Irradiance Geometry (SOLWEIG) model (Lindberg and Grimmond, 2011). This model estimates mean radiant temperature based on simple meteorological data and surface LiDAR data of topography, buildings and trees. We validated the model using mean radiant temperatures observed across 10 selected locations of various urban forms at Mawson Lakes, Adelaide (Figure 8). Mean radiant temperatures were collected using black globe thermometers and corrected for convection and conduction effects. We found that SOLEWIG performed well in modelling the mean radiant temperatures (Figure 8).

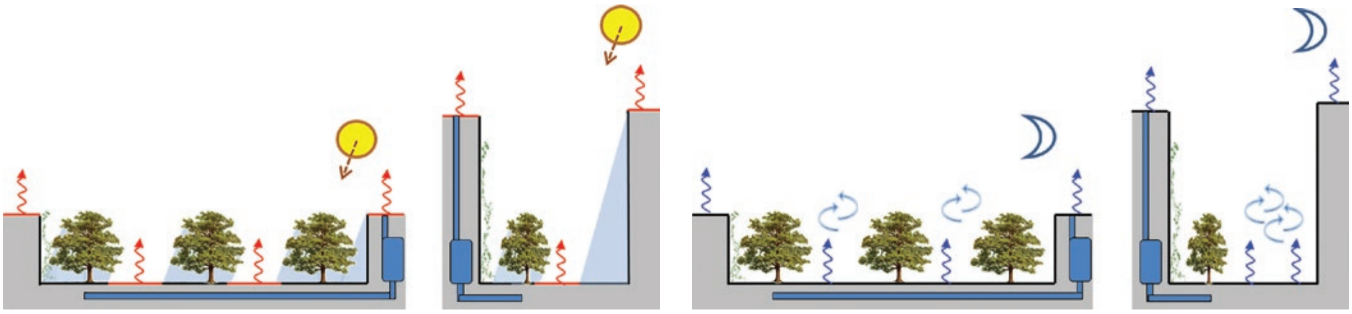


Figure 7: Broad guidance on strategic tree placement for improved human thermal comfort in urban streets (Coutts 2013)

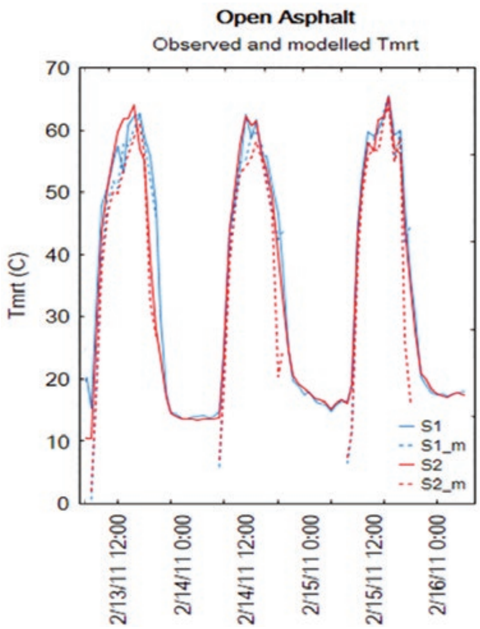
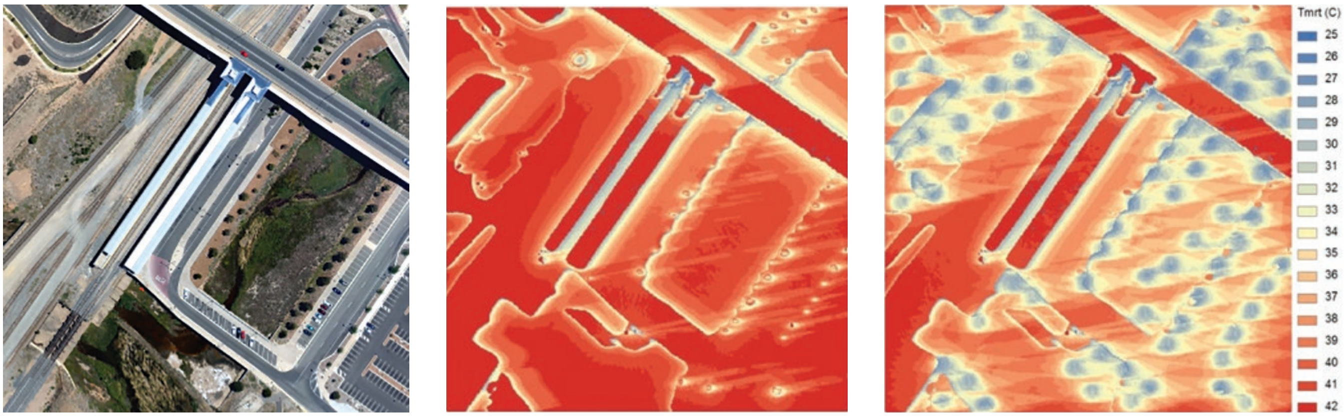


Figure 8: Observations of mean radiant temperature at Mawson Lakes (left panel) and comparison of observed and modelled data for two monitoring stations located in open asphalt areas

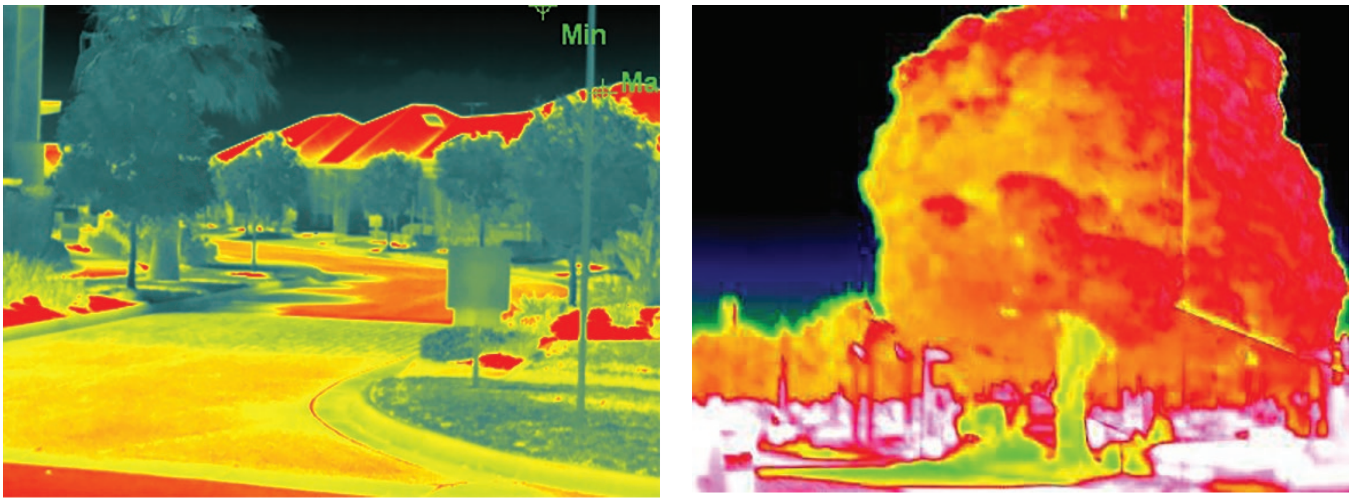
SOLWEIG was used to model the influence of adding trees to the landscape on mean radiant temperature. An example of this is given in Figure 9 for one of the selected locations in Mawson Lakes and shows the average radiant temperature for the daytime. Here, we added trees based on the guidance above, and Figure 9 shows the mean radiant temperatures before and after the addition of trees. The trees were based on the mature size of Lophostemon confertus (Queensland brush box), a common street tree. Clearly, the addition of trees leads to a significant reduction in mean radiant temperatures which will have a strong positive influence on HTC during the day.

To emphasise again, street trees are an excellent approach for improving HTC due simply to their shading effects. Where shading is not provided by buildings or other structures, street trees should be implemented and maintained to improve the liveability of urban spaces. Because of the additional benefits from trees (e.g. stormwater benefits and amenity), trees are an excellent approach for providing shade rather than man-made structures (e.g. shade cloth and awnings), and trees also transpire which helps to reduce air temperatures too.



↑ *Figure 9: Mean radiant temperatures at the transport interchange at Mawson Lakes, Adelaide, before and after the addition of trees (Thom et al 2014)*

↓ *Figure 10: example of the shading effect on surface temperatures under trees which leads to further reductions in radiative load on the human body*



The street trees example above has shown the benefits of blocking direct solar radiation through shade on HTC, but radiation also reaches the human body in the form of longwave (terrestrial) radiation from surfaces such as walls and ground surfaces. Impervious surfaces heat up intensely during the day and can re-radiate heat onto the human body. As such, shading is also beneficial for reducing the surface temperature of surrounding impervious surfaces, further reducing the amount of radiation from surfaces and benefiting human thermal comfort. This is displayed well in Figure 10 for two examples: a tree lined street at Mawson Lakes where shading reduces the road surface temperatures; and an example from the isolated tree study in Melbourne (see our previous 'Determining the microclimatic influence of harvesting solutions and WSUD at the micro-scale' for more information).

As such, the radiative load on the human body under and nearby tree canopies is drastically reduced under warm, sunny conditions. However, the effect is highly localised which means trees need to be distributed throughout the urban landscape, rather than just in parks, or concentrated in isolated areas, in order to deliver the largest benefit.

Water and Human Thermal Comfort

Stormwater harvesting can help to capture and retain rainfall runoff in our cities and this water can subsequently be used for irrigation. This can offset the use of potable water that would otherwise be used. Irrigation increases soil moisture levels and serves to reduce surface temperatures, which can then reduce radiative loading on the human body from the ground and reduce mean radiant temperatures. Oke (1987) argues that large scale irrigation can modify the climate, especially in otherwise arid or semi-arid locations and this is clearly evidenced in land surface temperatures.

Using high resolution airborne thermal remote sensing, surface temperatures across the urban landscape have been documented under warm summertime conditions (Figure 11). Areas that have been irrigated, such as the sporting ovals, are clearly cooler than non-irrigated areas that surround them. Non-irrigated surfaces here are as hot as impervious surfaces of concrete and asphalt. Irrigating these surfaces increases evapotranspiration from the surface, and the presence of water increases the heat capacity of the soil, so more energy is needed to warm the soil. The result is a decrease in atmospheric heating. Irrigating can slow surface cooling of the ground surface slightly at night but it is marginal and was not evident in this study. The treetops can also clearly be seen. The tree canopy leaf temperature remains low because of transpiration processes and reflection of solar radiation from the leaf surface. Irrigating surfaces is a rapid way to provide extensive surface cooling if the water is available. Research from park cool island studies show that irrigation can enhance the cooling effect of parks during the day, and dry non-irrigated parks can actually be warmer than surrounding areas (Spronken-Smith and Oke, 1998).

The addition of water to grass surfaces, and likely WSUD elements (e.g. swales, biofilters etc.) that have high soil moisture levels will lead to reduced surface temperature, and will lead to lower air temperatures as well, which will lead to improved HTC. However, because there is no shade, areas that are irrigated may still show high levels of heat stress. In fact, while a park cool island may exist during the day within an irrigated park where air temperatures are low relative to surrounding urban streets, HTC levels in the urban streets may be more comfortable due to shading from buildings. This is why it is important to distinguish between air temperature and human thermal comfort.

Like irrigated ground surfaces, water bodies show low surface temperature during the day under warm, sunny conditions because of evaporation from the water surface, and the high heat capacity of the water which absorbs energy through great depths during the day. The surface temperature of water bodies can be 20 °C or more cooler, than urban surfaces during the day. We investigate here how the differences in wet and dry surfaces influence the environmental variables that influence human thermal comfort.

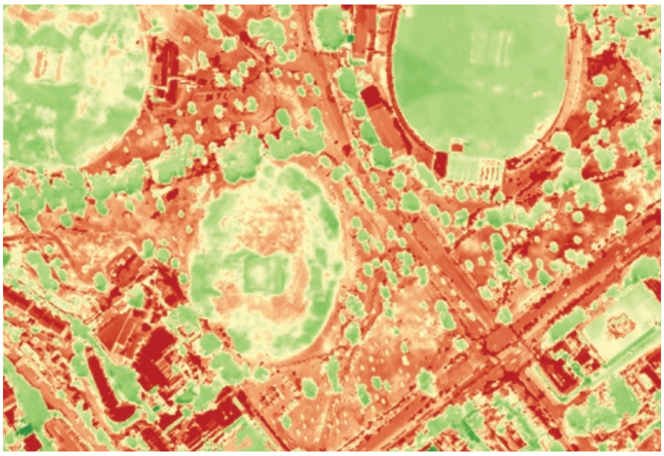


Figure 11: High resolution land surface temperatures in the City of Port Phillip on a day with a maximum air temperature of 37.1 °C

Recalling that HTC is influenced by air temperature, humidity, wind speed and mean radiant temperature, each of these are plotted in Figure 13 for a clear sunny day on the 13 February 2011, for the four locations pictured in Figure 12. This example demonstrates just how complicated microclimates can be and how human thermal comfort and urban microclimates can be extremely variable over short distances. Unexpectedly in this example, air temperatures were high at one of the wetland sites (Wetland 1). This was because at this site, wind speeds were very low, so heat was not mixed and distributed away from the site. The lower topography and sheltered nature of this site led to the lower wind speeds.

Wetland 2 and the dry grass sites had similar air temperatures. In addition vapour pressure (humidity) was slightly elevated at this site because of evapotranspiration. However, the healthy green vegetation, high soil moisture and nearby water bodies led to a lower surface temperature at the wetland sites (Figure 12) and this contributed to a lower mean radiant temperature, despite all four sites being exposed to direct solar radiation all day. The net effect of all these variables is presented in the plot of the UTCI (Figure 13) and demonstrates this complexity. The lowest UTCI was seen at Dry grass 1 where the high wind speed helped to improve HTC, and at Wetland 2, where the lower mean radiant temperature appeared to benefit the UTCI the most. In contrast, the high air temperature at Wetland 1 contributed to a high UTCI.

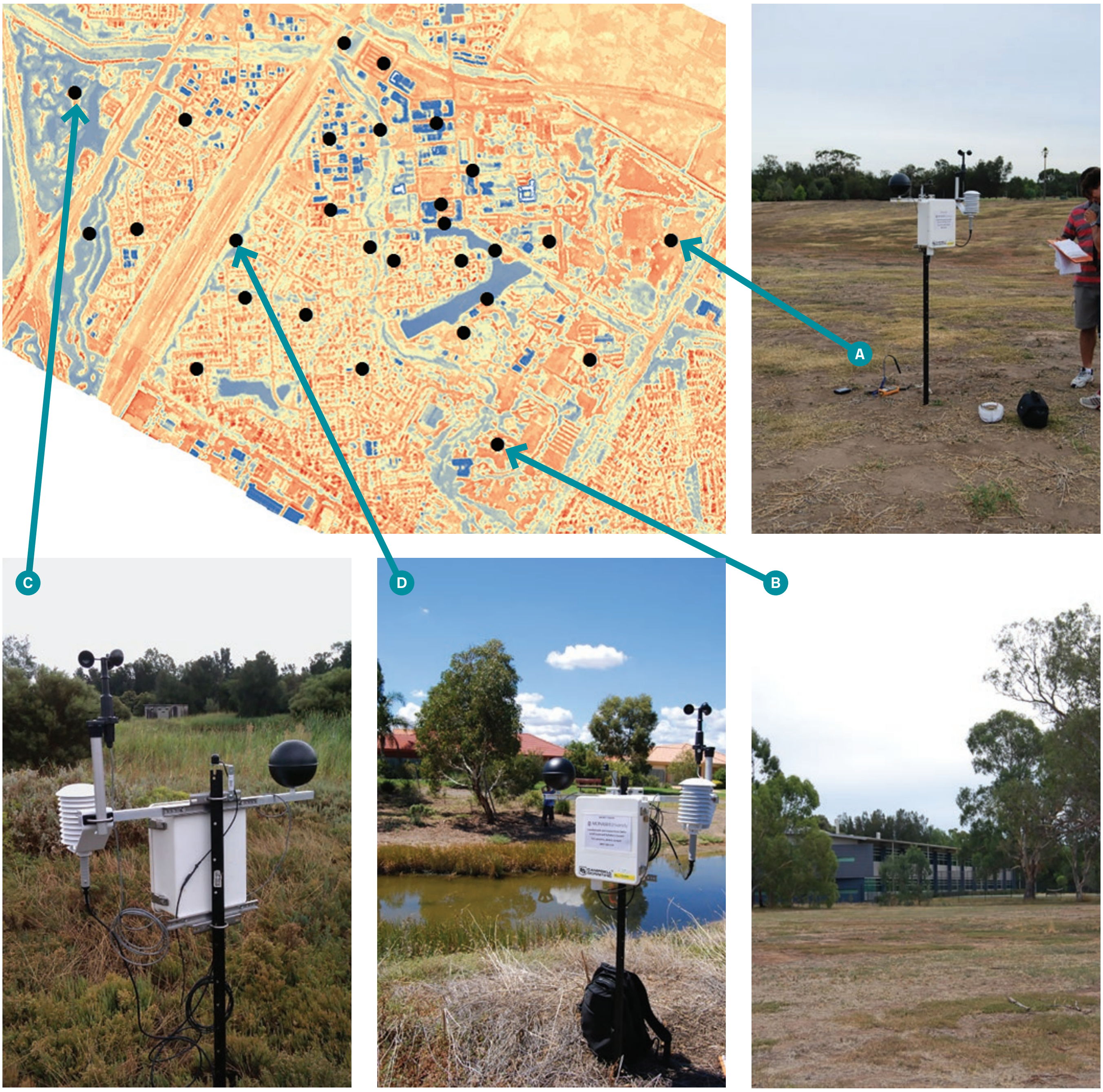


Figure 12: Four selected stations for comparison of environmental components of HTC: two sites in wetlands, and two sites on dry grassland

A: Dry grass 1
B: Dry grass 2
C: Wetland 1
D: Wetland 2

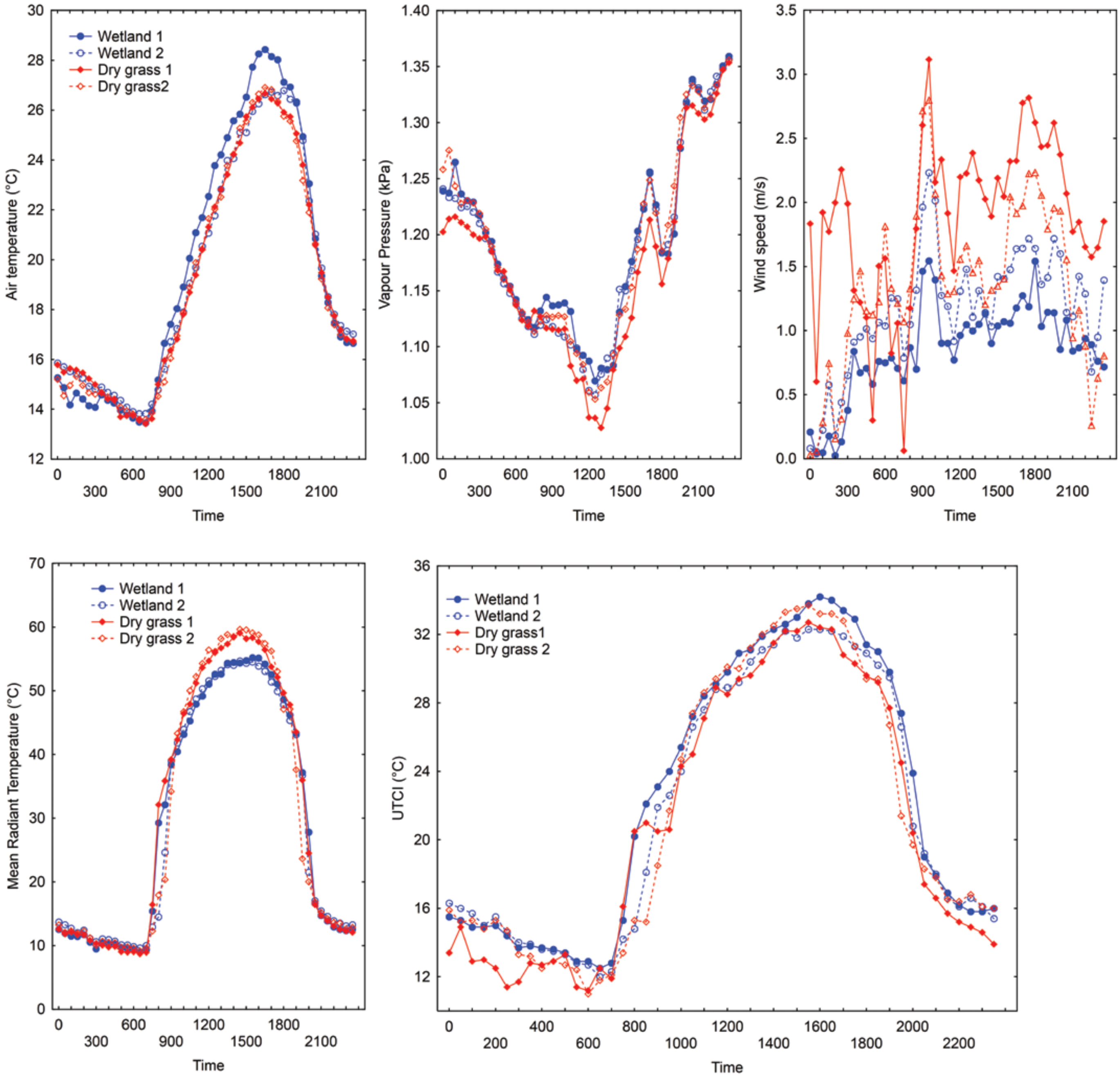


Figure 13: Environmental components (air temperatures, humidity, wind speed and mean radiant temperature) of human thermal comfort (Physiological Equivalent Temperature) at four sites at Mawson Lakes (2 dry grass and 2 wetland)

This example shows that the amount of water in the landscape is just one influencing factor on the micro-climate of a site. While Wetland 1 may have been warmer, if water was not present and rather the site was covered with asphalt, temperatures may have been even higher. Further analysis of the data from the monitoring stations at Mawson Lakes is attempting to disentangle the influence of various surface features on the microclimate, including vegetation, water, building heights and density, imperviousness and meteorological factors (Broadbent, et al 2014). However simply providing shade can significantly improve levels of human thermal comfort.

Green Roofs and Walls and Human Thermal Comfort

Green roofs and green walls are often promoted as a means for reducing urban heat. Our research has shown that unless extensive green roofs are irrigated, they may not be providing the expected kind of benefits to human thermal comfort. In the report titled 'Determining the impacts of harvesting solutions and WSUD on evaporation and the water balance and feedbacks to urban hydrology and stream ecology' we showed that white roofs were more effective at reducing daytime atmospheric heating than extensive green roofs, and green roofs were only comparable when well irrigated, had a dense coverage of vegetation and that vegetation had a high leaf area index. However green roofs did reduce the amount of energy storage in the rooftop, which will have a benefit for mitigating nocturnal urban heat. We further suggest that implementing highly reflective white painted roofs, and harvesting the roof runoff for irrigation at ground level is likely to have a greater benefit for outdoor human thermal comfort (Figure 14).

Providing water at ground level can be used to support tree health and transpiration. Because of the localised cooling of features, much of the rooftop cooling will have limited benefit at street level though will contribute to improved neighbourhood scale air temperatures. Because of this, it is often recommended that green roofs be applied to low-rise buildings, as there is a larger roof surface area to relation to the building volume, and there will be a larger street level benefit. Again, investing in trees that provide shade will have a more dramatic benefit on HTC than a green roof. If green roofs are to be installed, irrigating them is important so that they are providing a cooling benefit when it is most needed, under warm, sunny conditions. Figure 15 shows the surface temperatures of a 'living' roof during a warm, sunny day in April 2012, using thermography. Despite the presence of the living roof, surface temperatures were still high because of the dry surface, relatively sparse vegetation, dark, rock surface and succulent vegetation types.

Green walls are likely to provide a larger benefit for street level HTC than green roofs. Green walls and facades act as an insulating layer on buildings and other surfaces, reducing heat absorption and storage. Walls are considered a major driver of canopy layer urban heat at night, so adding green facades can reduce daytime heat build up. Thermography was used to examine a green wall over the course of a day in March 2012 (Figure 15), and the lower surface temperature of the green wall is clearly visible. These lower surface temperatures mean that there is less radiative energy being emitted from the wall and therefore it produces a thermal comfort benefit by reducing mean radiant temperatures.

The green wall will also be actively transpiring (if light and water is available) compared to a bare building wall where energy will either be absorbed by the building materials or atmospheric heating will occur. More research is needed on green walls and their effects on HTC at street level, comparisons between designer green walls and green facades (e.g. ivy and fig) and their influence on the surface energy balance of street canyon walls. Green walls do not necessarily need to be placed up against building walls (Figure 16) – climbing plants can be trained along wires adjacent to the wall that can be used as support – these could then provide shade for people.

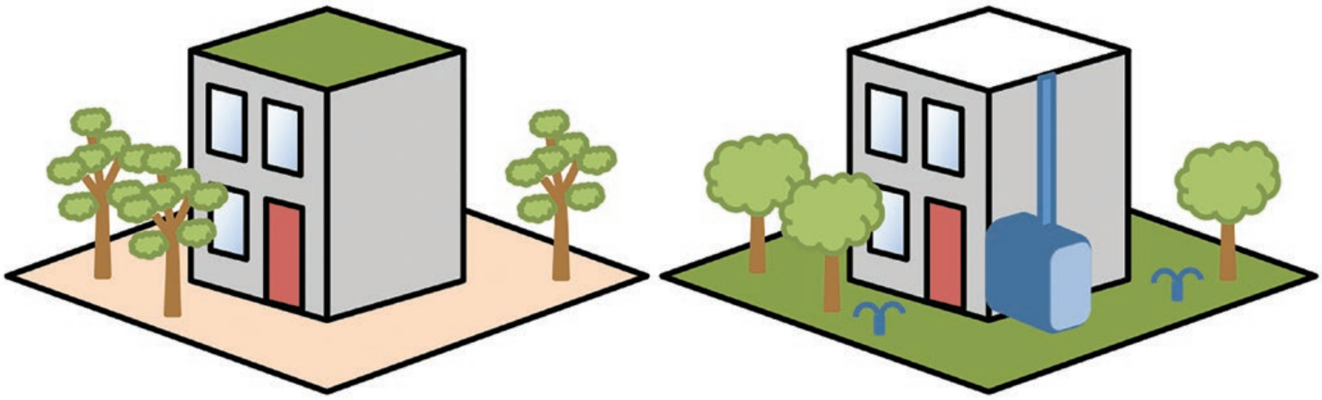
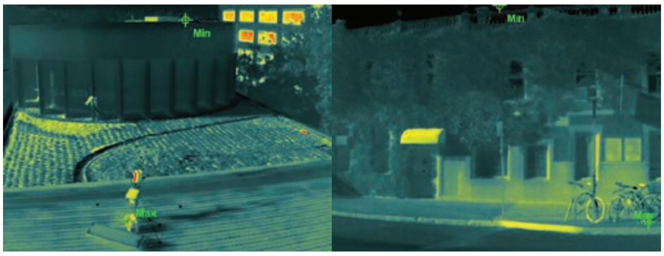
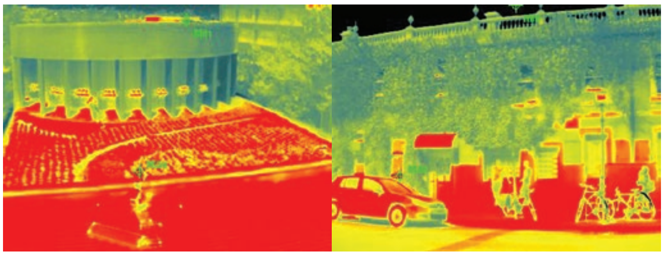


Figure 14: Human thermal comfort can be maximised by providing water at street level, rather than retaining on the rooftop

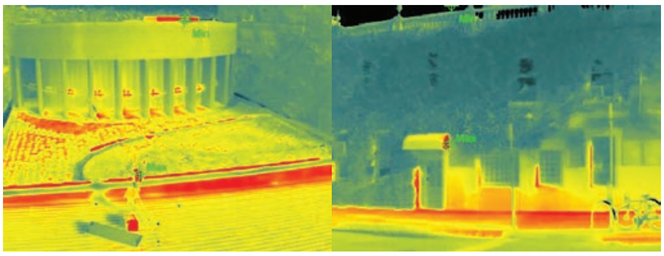
5 April 2012 — 26.8 °C *20 March 2012 — 27.2 °C*



10:10 am *9:15 am*



2:05 pm *1:00 pm*



5:30 pm *5:30 pm*

Figure 15: Selected thermal images of a living roof (left images) and a green façade at (right images) (Coutts and Harris 2012)

40 °C	30 °C
38 °C	28 °C
35 °C	25 °C
33 °C	23 °C

Figure 16: Green facades providing shade.

Summary

Overall, from these examples, we can conclude that overall WSUD solutions have a positive influence on human thermal comfort (Table 4). Green infrastructure and WSUD reduce surface temperatures, which leads to a reduction of radiation on people from the ground. Incorporating trees into WSUD features to provide shade where other structures (buildings) are not present is critical for improving HTC. This work has shown just how variable micro-scale HTC is spatially, depending on the nature of the local and micro-scale urban landscape. Strategic placement of WSUD features is needed to maximise benefits to HTC. Further, not only will WSUD solutions influence HTC, so will the existing surrounding landscape that influences the environmental variables that drive HTC.

Elevated humidity is one outcome of increased irrigated green infrastructure, but this potentially negative effect is outweighed by the positive effect of decreased air temperature and reduced mean radiant temperature. To demonstrate the sensitivity of HTC to different environmental variables, Figure 17 compares changes in the UTCI as changes to air temperature, wind speed, mean radiant temperature and vapour pressure (humidity) are made. Using a reference condition of air temperature = 30°C, wind speed of 0.5 m/s, mean radiant temperature of 30°C and a vapour pressure of 21 hPa, we varied each of these variables one by one through a typical range, while holding the other three variables constant, to see how much each one influenced HTC (Figure 17) . The reference condition is for a 35 year old male, with a weight of 73.5 kg, 1.8 metres tall, walking and with a clothing factor of 0.9. The UTCI is seen to be mostly sensitive to air temperature and mean radiant temperature, and to a lesser extent to wind and humidity.

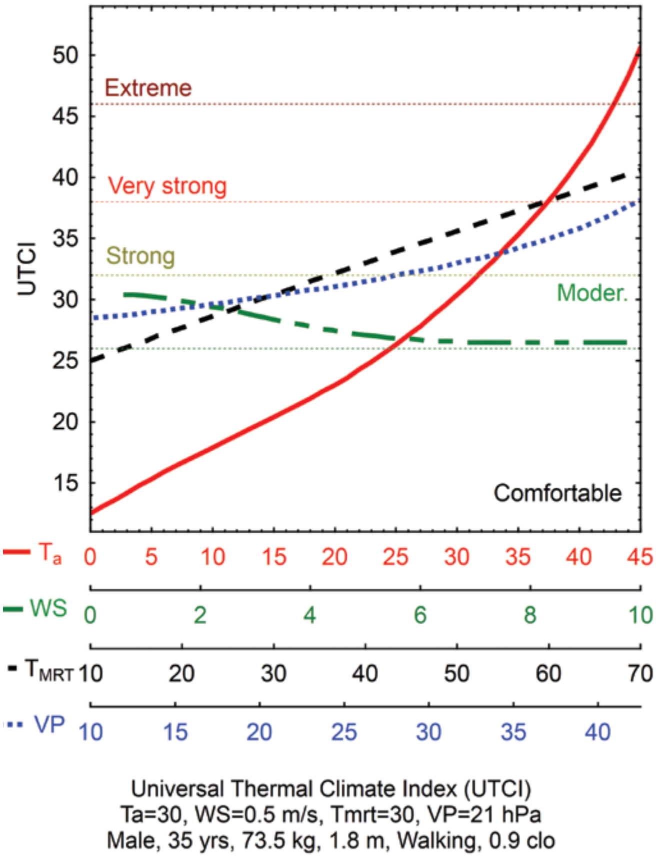


Figure 17: Sensitivity of human thermal comfort to changes in the environmental variables that influence human thermal comfort, compared to a reference condition.

	Positive	Negative	Net effect on street level HTC
Street trees	· Large reduction in Tmrt during the day · Reduced air temperature	· Slight increase in Tmrt at night · Elevated humidity · Lower wind speed	Positive
Irrigation (parks)	· Reductions in Tmrt · Reduced air temperature	· Elevated humidity	Positive
Water bodies / Wetlands	· Reduction in Tmrt · Reduced air temperature	· Elevated humidity	Positive
Green wall	· Reduction in Tmrt · Reduction in air temperatures*	· Elevated humidity*	Positive
Green roofs (irrigated)	· Reduction in rooftop air temperature · Reduction in rooftop Tmrt	· Elevated humidity	Neutral

*Table 4: Summary of findings from observations in our program. Tmrt = mean radiant temperature. * = not observed/confirmed thus far in our program.*

References

Broadbent, A.M. Coutts, A.M. Demuzere, M. Beringer, J. Tapper, N.J. The effect of land surface characteristics on microscale air temperature variability in a suburb incorporating water sensitive urban design (In preparation)

Thom, J., Coutts, A.M. Broadbent, A.M. (2014) Validation and application of a model for mean radiant temperature in a diverse urban environment (In preparation)

Coutts, A.M. (2013) – Design and placement of WSUD for improved micro-climate. Presentation at WSUD 2013, Gold Coast, November 2013,

Norten, B.A. Coutts, A.M Livesley, S.J. Harris, R.J. Hunter, A.M. Williams, N.G.S. (2014) Planning for cooler cities: prioritising the use of green infrastructure to mitigate high temperatures in urban landscapes, Landscape and Urban Planning (Submitted)

Coutts, A., Harris, R., 2012, A multi-scale assessment of urban heating in Melbourne during an extreme heat event and policy approaches for adaptation, Victorian Centre for Climate Change and Adaptation Research, Melbourne,

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H. & Tinz, B. 2012. Comparison of UTCI to selected thermal indices. International Journal of Biometeorology, 56, 515-535.

Coutts, A. M., Tapper, N. J., Beringer, J., Loughnan, M. & Demuzere, M. 2013. Watering our Cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context. Progress in Physical Geography, 37, 2-28.

Höppe, P. 1999. The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. International Journal of Biometeorology, 43, 71-75.

Lindberg, F. & Grimmond, C. 2011. The influence of vegetation and building morphology on shadow patterns and mean radiant temperatures in urban areas: model development and evaluation. Theoretical and Applied Climatology, 105, 311-323.

Murakami, S., Ooka, R., Mochida, A., Yoshida, S. & Sangjin, K. 1999. CFD analysis of wind climate from human scale to urban scale. Journal of Wind Engineering and Industrial Aerodynamics, 81, 57-81.

Oke, T. R. 1987. Boundary Layer Climates, Great Britain, Cambridge University Press.

Spronken-Smith, R. A. & Oke, T. R. 1998. The thermal regime of urban parks in two cities with different summer climates. International Journal of Remote Sensing, 19, 2085 - 2104.

CRC for
Water Sensitive Cities

Cooperative Research Centre for Water Sensitive Cities

Level 1, Building 74
Monash University, Clayton
Victoria 3800, Australia

info@crcwsc.org.au

www.watersensitivecities.org.au