CRC for
Water Sensitive Cities

Managing urban heat in water sensitive cities:
research and policy responses

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Contents

Introduction

Urban heat is an increasing threat to the liveability and productivity of cities, made worse by more frequent and extreme heat days and heat waves caused by climate change. Exacerbated by population growth and urban densification, urban heat has emerged as a key policy and planning issue for governments around the world.

The design of cities, the conversion of vegetated surfaces to hard surfaces with higher heat storage capacity, surfaces with lower albedos (heat reflectivity), reduction of available water, waste heat from buildings and transport, and reduced shading and reduced canopy cover have altered the energy balances in urban areas. This has left cities vulnerable to extreme heat.

The impact of urban heat manifests at a range of spatial and temporal scales and is influenced by climatic, biophysical and social variables. There is no "one size fits all" approach to good evidence-based urban heat policy. Rather, a locally nuanced approach is required reflecting the specific dimensions of urban heat relevant to the policy's boundary (area of application) and unique urban context. This requires policy makers to have a deeper understanding of urban heat beyond the often referenced and used Urban Heat Island (UHI) effect, which in itself is not particularly useful for formulating locally relevant mitigation and adaptation responses. More importantly, this focus can be a limitation. Through careful management of surfaces, shading, and vegetation, urban areas have the potential to provide greater thermal comfort and reductions in heat stress compared with unmitigated rural areas.

This paper explains urban heat science in a way intended to inform good evidence based urban heat policy. The paper draws from the extensive portfolio of urban heat research conducted by the Cooperative Research Centre for Water Sensitive Cities (CRCWSC) and from the broader published scientific literature.

PART A: Synthesis of key information

This PART summarises key information and scientific evidence from the published scientific literature to inform good evidence-based urban heat policy and procedures. It is intended primarily for use by local government policy makers and city planners to gain a sufficiently detailed understanding of urban heat causes, impacts and management responses at different spatial and temporal scales to formulate tailored policy and planning responses.

Mitigating excess urban heat can bring multiple benefits but is especially important to reduce public health impacts such as sharp increases in mortality and morbidity rates when temperatures exceed certain heat thresholds.

Urban heat is best examined at two scales: a neighbourhood scale that incorporates wind and air temperature, and a street scale that incorporates radiant temperatures and human thermal comfort.

Urban heat island (rural/urban temperature differences) has become a common shorthand for urban heat but does not accurately measure excess heat due to urban forms. Alternative methods to analyse urban heat are recommended.

CRCWSC urban heat research examined these two scales using observations, remote sensing, database mapping and modelling.

Trees are a key means to enable urban cooling, providing shading of urban surfaces and evapotranspiration cooling. Large increases in canopy cover can result in 1°C or more of air temperature reductions as well as localised UTCI (thermal comfort index) reductions of 5–15°C.

Temperature reductions will be highly localised so interventions should be evenly spread through an area to provide the widest benefit. In addition, the local context should be considered (such as street width and orientation) to maximise the benefit.

Waterbodies can reduce air temperatures by 1–2°C, although these cooling plumes extend only a short distance (downwind) from the waterbody. Similarly, irrigation can be a highly effective method of cooling, with low to moderate amounts of irrigation resulting in 0.5°C air temperature and 20°C surface temperature reductions. Heavy amounts of irrigation can reduce air temperature by up to 2.5°C. For emergency cooling during heat waves, irrigating very dry soil or even impervious surfaces (streets or pavements) can be very effective for high efficiency cooling.

All urban green infrastructure must be well watered and maintained to perform most effectively. Green roofs provide only limited benefit for street level cooling, but green walls can provide some cooling relief for areas where street trees are not viable.

Urban cooling strategies can be quantified through a number of temperature metrics. Air temperature is the simplest and reasonable expectations of reductions are in the range of 1–2°C. Surface temperatures can show wide variations of 20–30°C between nearby shaded and unshaded surfaces. Linking air temperatures to surface temperatures is difficult.

The use of human thermal comfort indexes (such as UTCI) allow many elements of urban heat (including air temperature, radiant temperature, wind and humidity) to be incorporated into a ‘feels like’ temperature and levels of heat stress. These indexes also allow transferability of results to different types of climates (i.e. from a low humidity to high humidity area).

The CRCWSC has developed several urban cooling assessment tools and methods, including the TARGET and VTUF-3D models. The TARGET model has been incorporated into the WSC Scenario Tool and assesses urban heat outcomes alongside other urban water cycle outcomes such as water demand, infiltration and stormwater runoff.

PART B: Overview of urban heat causes and impacts

1 Urban heat

The design of cities, the conversion of vegetated surfaces to hard surfaces with higher heat storage capacity, surfaces with lower albedos, reduction of available water, waste heat from buildings and transport, and reduced shading and reduced canopy cover, have altered the energy balances in urban areas. This has left cities vulnerable to extreme heat.

1.1 Impacts of urban heat

Excess heat in Australia has significant impacts and costs across a wide range of concerns (Zuo et al., 2015). The effects of extreme heat are seen through impacts on mental health, domestic violence, strains on emergency and health services, damage to urban infrastructure, economic disruptions, and in many other areas (Harlan and Ruddell, 2011). The 2009 heat wave in southern Australia affected 1 million people and caused 420 casualties, in addition to costs of AU$800 million from power disruptions, transportation outages (from infrastructure damage from heat), and response costs (Kiem et al., 2010). PWC (2011) reports building material failures (e.g. concrete or steel structure) during extreme heat. Costs to agriculture, livestock, and forests during the 2003 European heatwave was estimated to be US$15 billion (Stern, 2008). The press and pulse of climate change trends are leading to population collapses of a wide variety of Australian biota (Harris et al., 2018), such as when temperatures over 42°C caused high rates of mortality in Australian flying foxes (Welbergen et al., 2008).

While urban heat is a problem with wide-ranging implications, CRCWSC (and other) research shows heat impacts on human health can be especially costly. Extreme heat events cause more deaths in Australia than any other natural hazard (4555 in the period 1900–2010) (Coates et al., 2014), with risk disproportionately borne by the elderly and the very young (Nicholls et al., 2008). Predicting the exact health impacts of urban heat is difficult. In the long term, annual heat-related mortality in China is predicted to increase under climate change from 32 per million persons to 48–67 per million with 1.5°C warming and 59–81 per million with 2.0°C warming (Wang et al., 2019). For short term heat wave impacts, health impacts depend on local acclimatisation and other factors. Nicholls et al. (2008) found heat thresholds where mortality increases significantly. In Melbourne, for over 64-year-olds, mortality rates increased from 12per 100,000 persons to 13 per 100,000 then 15 as the daily mean temperature increased from 28°C to 30°C and 32°C respectively (Figure 1).

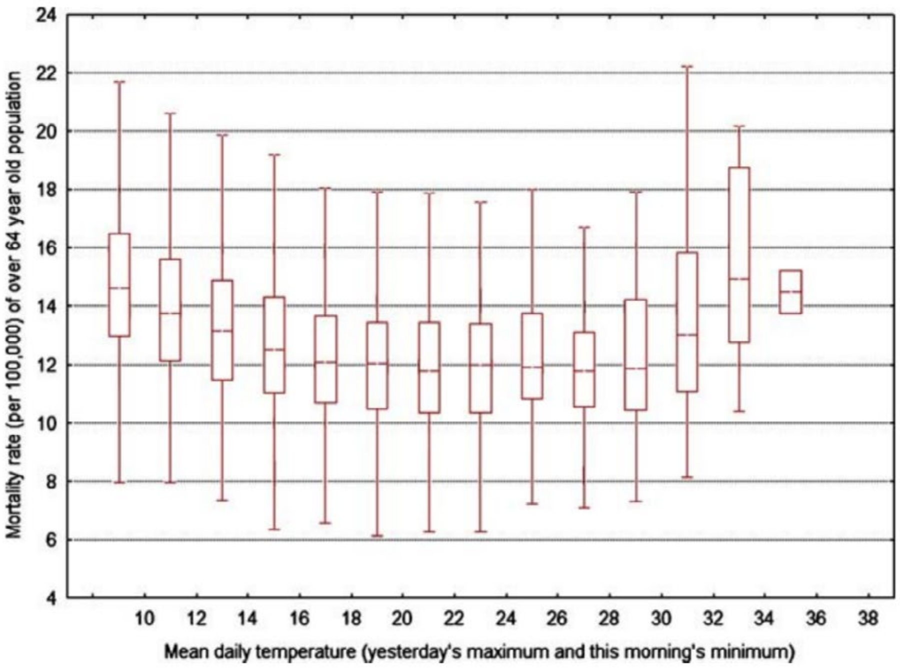


Figure 1: Median and lower upper quartile points (boxes) and ranges (whiskers) of daily death rates (per 100,000 persons) of over 64-year-olds in Melbourne for 2°C ranges of mean temperature. Source: Nicholls et al. (2008).

1.2 Urban scales

Analysis of urban heat can proceed at multiple scales. Figure 2 shows the two scales most relevant to cooling strategies using water sensitive urban design (WSUD). At a neighbourhood (local) scale, cooling strategies will be manifested in air temperature reductions. Cooling plumes from waterbodies and irrigated parks and other green spaces can be seen downwind.

At a micro-scale, the impacts of WSUD can be seen through increased human thermal comfort with the processes illustrated in Figure 3. As cities shift from a conventional design to a water sensitive one, important changes occur in the energy balances during the daytime and at night. Denser canopies supported by increased irrigation provide shade to surfaces and reduce the amount of radiative heat on people. Decreased heat is stored in the surfaces during the day, reducing the amounts of heat re-radiating at night.

These hot surfaces and stored heat are a major factor in urban heat island (UHI), the relative differences in temperatures between urban areas and rural surroundings (Oke, 1995), which can be substantial. Coutts et al. (2010) found a peak air temperature difference of about 4°C between inner city and rural outskirts at 1am on 23 March 2006. Torok et al. (2001) observed a peak UHI intensity of about 7.1°C at 9pm on 26 August 1992.

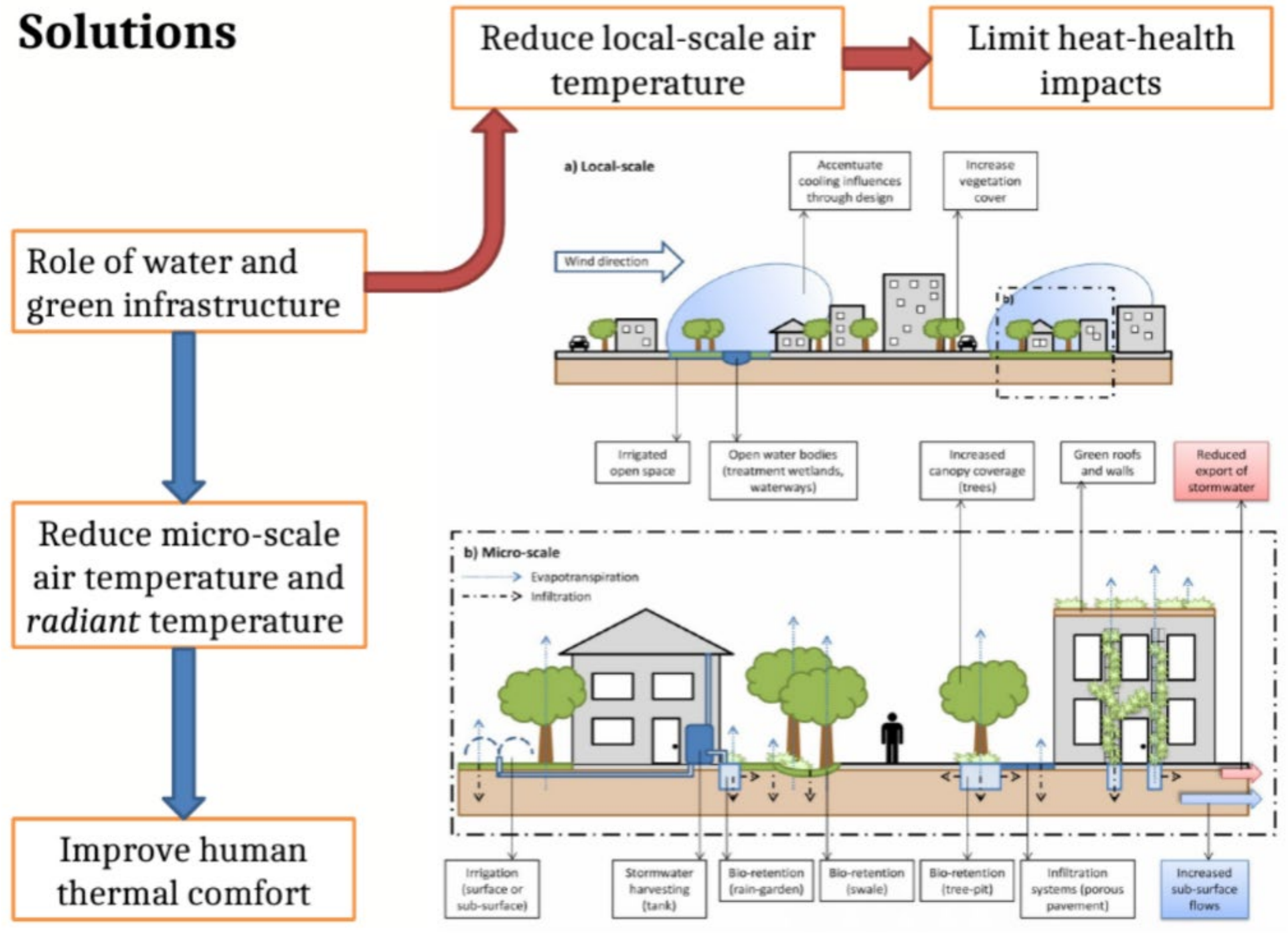


Figure 2: Schematic representation of widespread implementation of stormwater harvesting and water sensitive urban design elements at the micro-scale in the restoration of a more natural water balance, along with increased vegetation cover. This enhances urban evapotranspiration and shading resulting in local-scale cooling effects that can improve human thermal comfort. Adapted from Coutts et al. (2012).

The concept of UHI is frequently used to describe and quantify levels of excess heat in urban areas. The temperature differences from UHI observations (such as the 4°C example above) are used as (possibly unrealistic) goals for urban cooling strategies. However, as Martilli et al. (2020) point out, there are a number of problems with this approach. The largest differences in urban/rural temperatures are generally observed in the night time, not during daytime when daily temperatures reach their maximum and thermal stress is highest. In addition, as cities become larger and more novel environments, it is doubtful that measuring temperatures in increasingly distant rural/agricultural land is an accurate measure of the amount of extra heat added by the existence of the urban form. More importantly, with careful management of surfaces, shading and vegetation, urban areas actually have the potential to show improved thermal comfort over that of unmitigated rural areas.

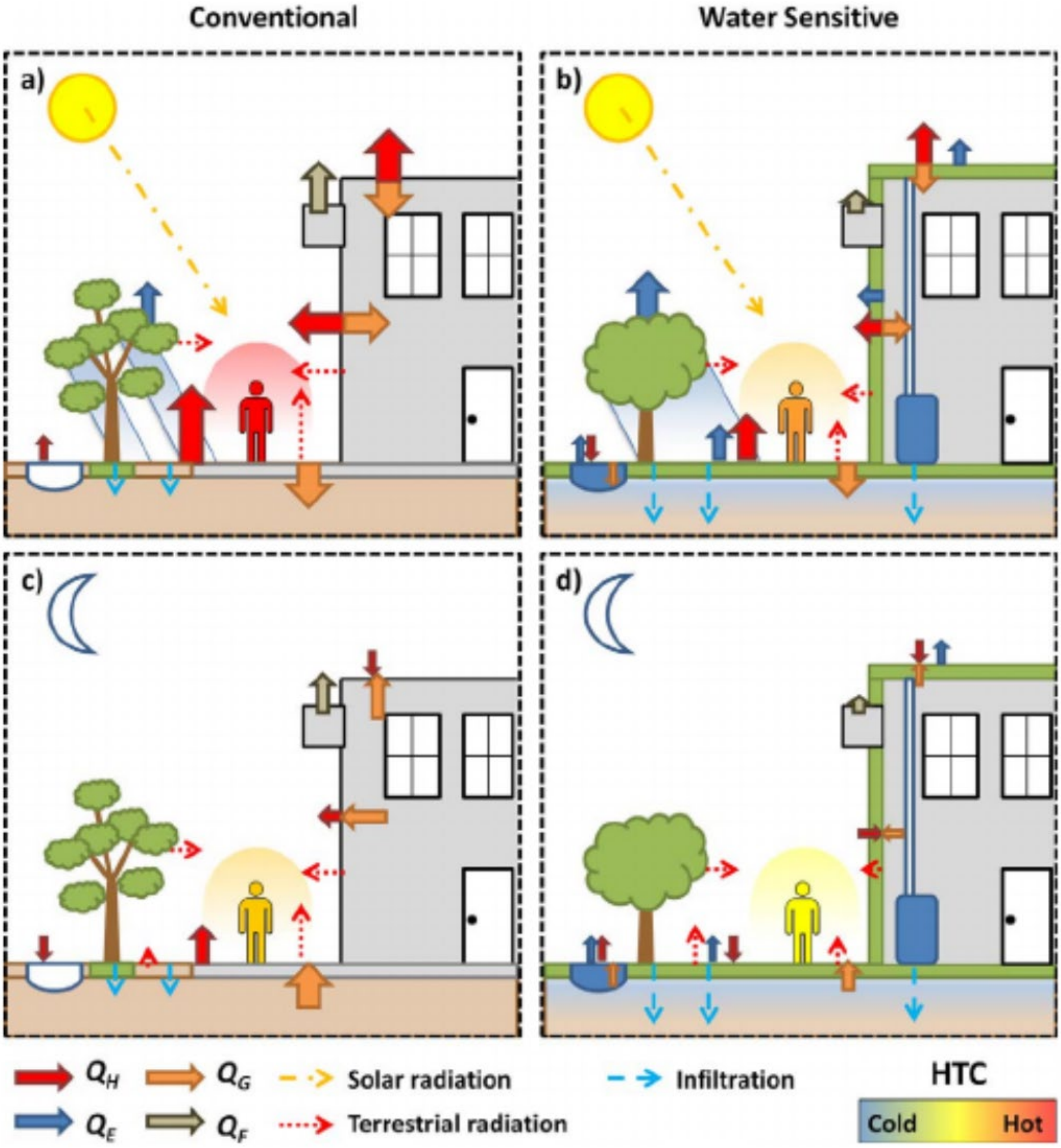


Figure 3: Generalisation of key processes in the formation of urban micro-climates during summer for conventional (water limited) urban landscapes (a and c) and water sensitive urban landscapes (b and d). Day (a and b) and night (c and d) conditions are presented. Source: Coutts et al. (2012).

With this in mind, this report will concentrate on the research shown to improve thermal comfort at smaller scales (neighbourhoods and blocks). By concentrating on the specific techniques that can provide the maximum cooling for each unique local area type, better targeted inventions can be implemented across a city and provide the maximum thermal comfort benefits for that wider area.

1.3 Scope of CRCWCS urban heat research

The CRCWSC has undertaken research into urban heat across these different scales using four different methods. The first was through direct observations of existing areas, setting up equipment and measuring these areas across days and months. The second method was through remote sensing, measuring amounts and distribution of water, vegetation, and different surface types and the resulting land surface temperatures. The third method used database mapping. This allows analysis of questions such as what is the spatial distribution of heat vulnerability based on layers of urban form types, thermal performance of those forms, and demographics. The fourth method was through modelling. Using the results of the first three methods to validate the proper functioning of models, modelling allows for greater detail of difficult to measure temporal and spatial variability in existing environments as well as testing of new scenarios.

2 CRCWSC research: from tree to street to neighbourhood

To examine the causes and impacts of urban heat, it is useful to start at the smallest scales and work upward. This allows for seeing the smallest interactions and identifying the root causes of urban heat. Figure 4 shows a range of scales important in urban areas and types of features they include, from the smallest scale of an individual tree or building to block and neighbourhood, up to city scale.

2.1 Trees

CRCWSC research into urban heat focused on trees and other types of urban greening as a key means of enabling urban cooling. An overall goal of WSUD is to provide alternative sources of water to cities by capturing stormwater. In turn, utilising this augmented water supply to establish and maintain a healthy urban canopy has multiple benefits for urban heat strategies.

Starting at a micro-scale – that is the area that can resolve a single tree or a person in a street – the mechanisms driving thermal performance of urban areas can be studied, along with the direct impacts on thermal comfort and humans. This is the scale of Figures 2 and 3.

Trees have a complex role in street canyon environments (Figure 5), intercepting solar radiation, reflecting and storing energy, and driving extraction of soil moisture into evapotranspiration, shifting energy balances away from sensible heat toward latent heat. While the shading provided by trees and the moisture from evapotranspiration generally

				Dimensions			
Unit	**Built features**	**Tree features**	**Climate phenomena**	**H**	**W**	**L**	**Scale**
1. Building	building	tree, garden	wake, plume shadow	10	10	10 m	micro γ
2. Canyon	street	avenue, boulevard, shelterbelt	street vortex, thermal climate, shade	10	30	300 m	micro β
3. Block	city block, factory	park, wood	local breezes, cumulus, park cooling	—	0.5	5 km	micro α
4. Land-use zone	residential, industrial, city centre	greenbelt, suburban forest	air quality and climate districts	—	5	5 km	meso γ
5. City	built-up area	urban forest	heat, humidity island, city breezes, smog dome, precip. modification		25	25 km	meso β

Figure 4: Scale classification of the urban canopy. Source: Oke et al. (1989).

have a cooling effect, they can also impede wind flow and trap heat at night, causing slight heating effects.

CRCWSC research has included observation campaigns on isolated trees and street trees to discover the exact role trees can play in urban cooling. In general, the benefits of a good tree canopy cover were found to include increased evapotranspiration, reduced surface temperatures, reduced air temperatures, and reduced night-time temperatures (Coutts and Tapper, 2017). These improvements can improve thermal comfort and help compensate for high levels of impervious surfaces in urban areas.

In more specific examples, Coutts et al. (2016) found air temperature differences of 1.2°C below the canopy compared with above, and differences in UTCI of up to 7°C (Figure 6a). In other observations of canopy cooling, Thom et al. (2016) found a 4.0°C reduction in mean radiant temperature and 7.0°C in UTCI during heat waves. In two nearby residential streets in Melbourne (Figure 6b), temperature reductions were observed between a street with an open canopy versus a treed street (12% plan area canopy coverage versus 45%) of up to 1.0°C air temperature and 12.0°C UTCI (Coutts et al., 2015).

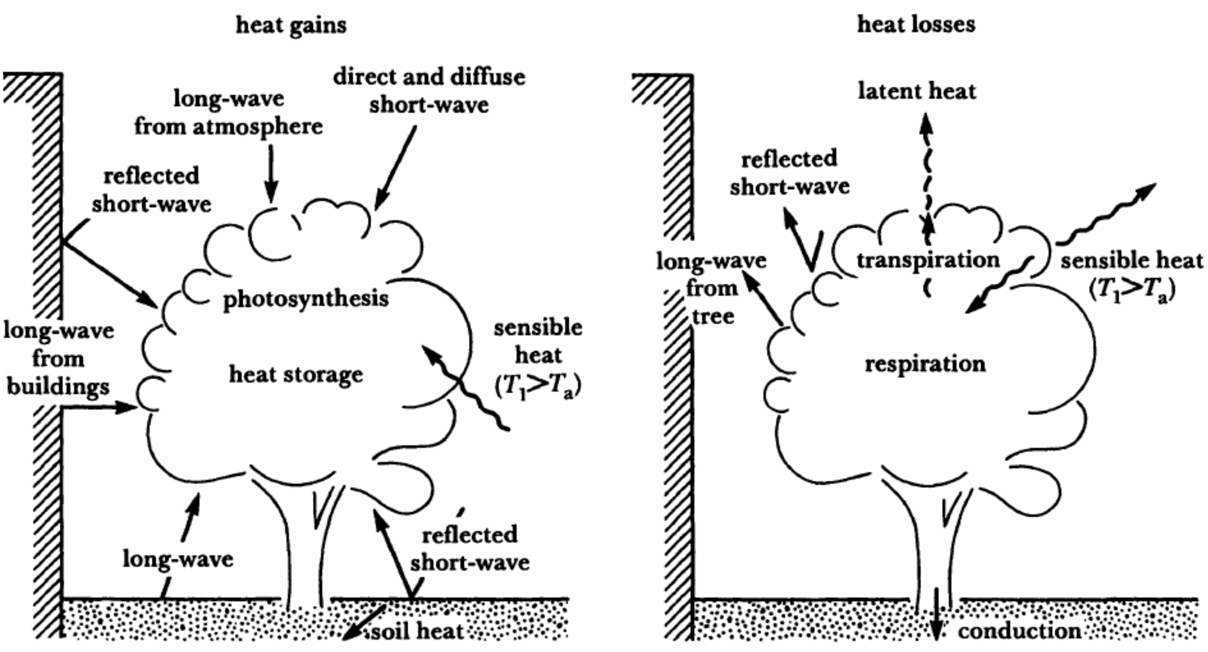


Figure 5: Scheme of the daytime energy exchanges between an isolated tree and its street canyon environment. Source: Oke et al. (1989).

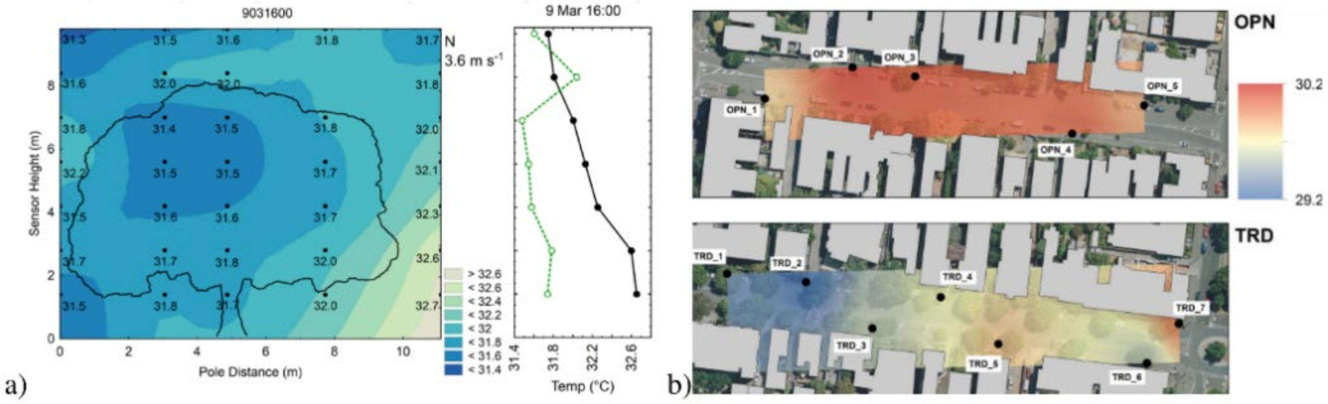
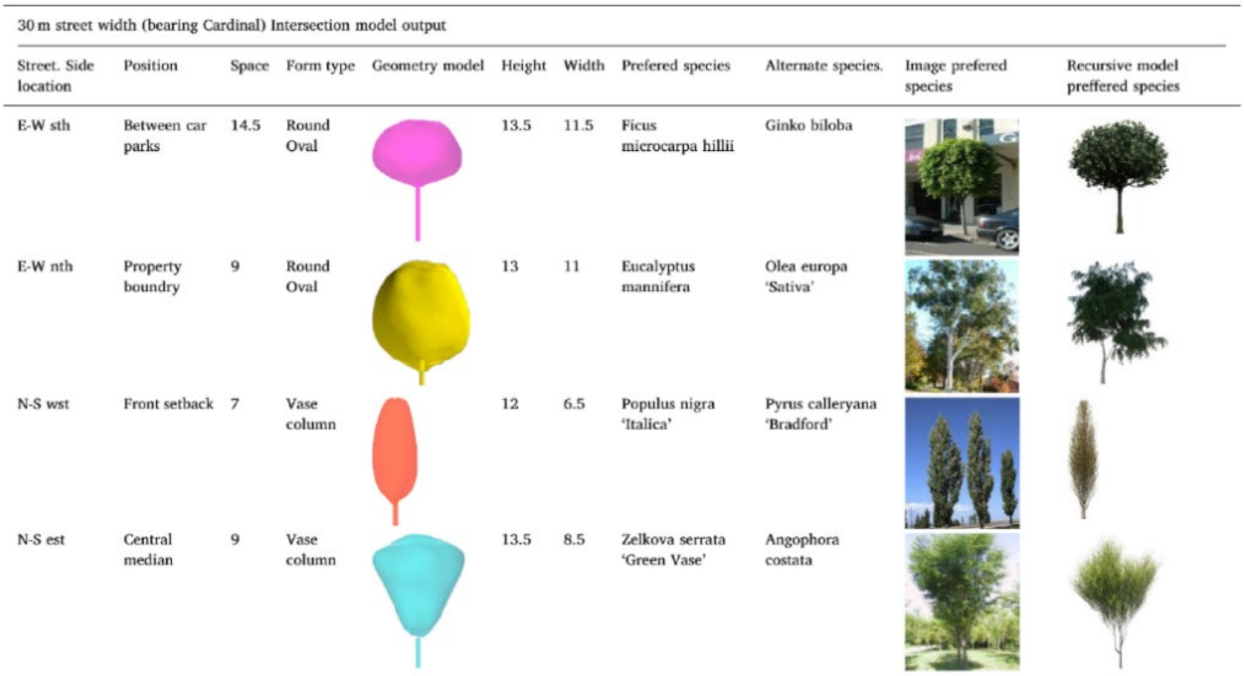


Figure 6: a) Air temperature within and around isolated tree in Melbourne Cemetery on 9 March 2014 at 4 pm. Source: Coutts et al. (2016). b) Mean daytime air temperature across two Melbourne streets with an open canopy (OPN) and treed street (TRD) during the heat event over 4–12 March 2013. Source: Coutts et al. (2015).

Across a wider area, in a modelling study, Jacobs et al. (2018) found that increasing vegetation cover across Melbourne by 10% can deliver a 0.2°C air temperature reduction, and up to 1.0°C with a 100% increase of vegetation cover. Nury (2015) using remote sensing across a number of local councils in Melbourne, observed that increasing the vegetation fractions from 0.2 to 0.8 can reduce surface temperatures by up to 6.0°C.

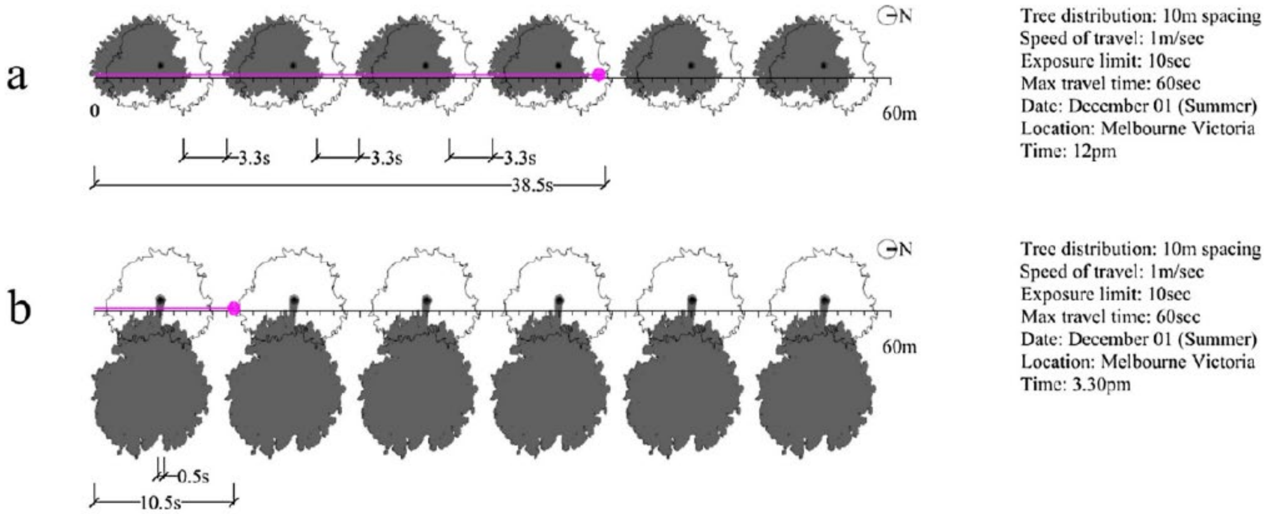
At a micro-scale, urban heat distributions are highly variable and highly localised. Picking the right tree for the right place is necessary to maximise the benefits. As shown in Figure 7, certain species and heights deliver the best shading results based on the orientation, side location, and position on streets in relation to other features (median, between car parks, property boundary, or setback) (Langenheim et al., 2020).



30 m street width (bearing Cardinal) Intersection model output

Street. Side location	Position	Space	Form type	Geometry model	Height	Width	Prefered species	Alternate species.	Image prefered species	Recursive model preffered species
E-W sth	Between car parks	14.5	Round Oval		13.5	11.5	Ficus microcarpa hillii	Ginko biloba		
E-W nth	Property boundry	9	Round Oval		13	11	Eucalyptus mannifera	Olea europa 'Sativa'		
N-S wst	Front setback	7	Vase column		12	6.5	Populus nigra 'Italica'	Pyrus calleryana 'Bradford'		
N-S est	Central median	9	Vase column		13.5	8.5	Zelkova serrata 'Green Vase'	Angophora costata		

Figure 7: Tree species fitting for form, height and width requirements to achieve shading objective. Source: (Langenheim et al., 2020).



Tree distribution: 10m spacing
Speed of travel: 1m/sec
Exposure limit: 10sec
Max travel time: 60sec
Date: December 01 (Summer)
Location: Melbourne Victoria
Time: 12pm

Tree distribution: 10m spacing
Speed of travel: 1m/sec
Exposure limit: 10sec
Max travel time: 60sec
Date: December 01 (Summer)
Location: Melbourne Victoria
Time: 3.30pm

Figure 8: Shows different levels of solar exposure for a pedestrian traversing a single footpath moving at 1m per second, with a maximum walking time of 60s, and maximum solar exposure time of 10s, with trees spaced at 10 m.
Source: (Langenheim et al., 2020).

If street trees are intended to increase pedestrian thermal comfort, spacing and distribution also needs to be considered. The amount of heat exposure a pedestrian on a footpath will be exposed to as they pass in and out of shaded areas will be determined by the spacing and orientation of the trees (Figure 8).

2.2 Street tree placement

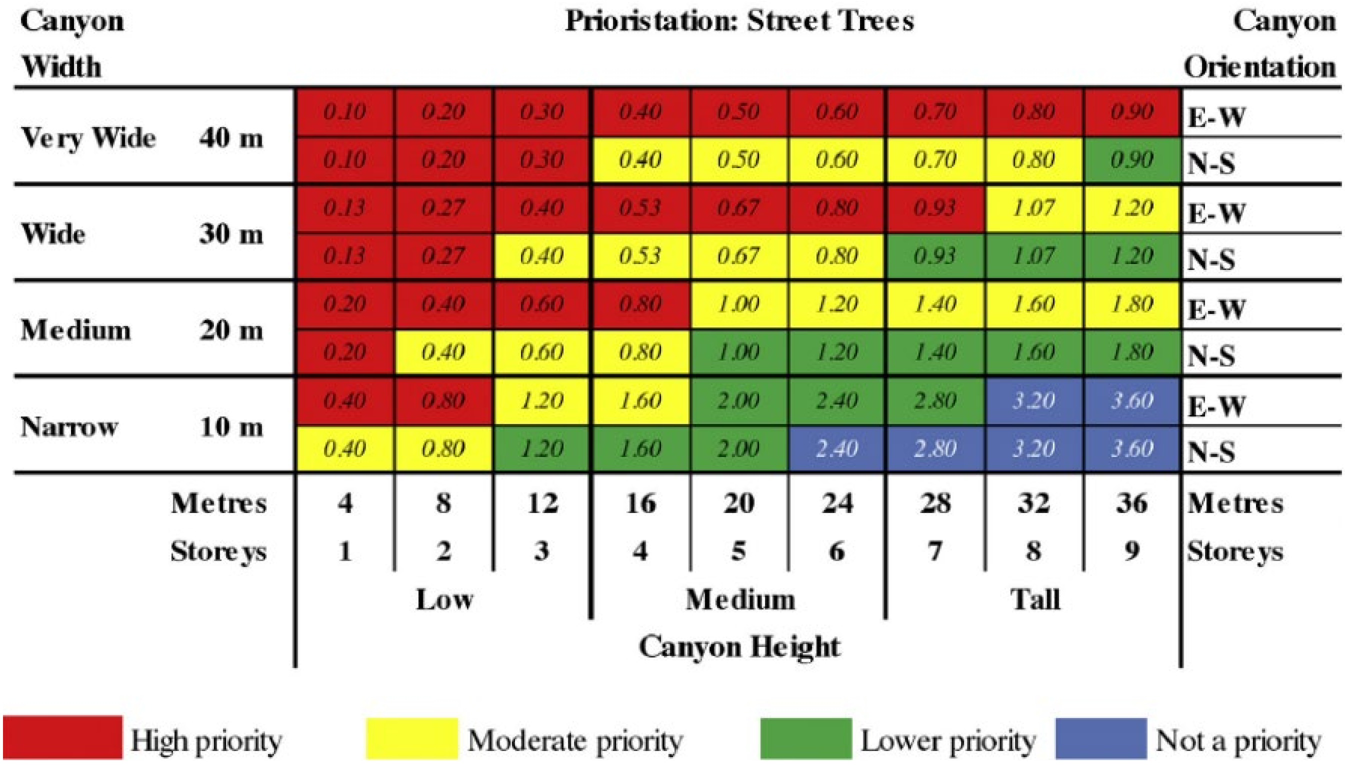
At a wider scale, tree placement within a block should consider the orientation and height to width ratio of the street (Figure 9). East-west streets should generally be prioritised because they will receive the largest amounts of solar exposure over the day. Very wide streets or streets with very low buildings should also receive higher priority.

2.3 Neighbourhood cooling through waterbodies and irrigation

At a neighbourhood scale, CRCWSC research has examined the cooling benefits of waterbodies and irrigation. Waterbodies can provide some cooling benefit to areas nearby. In Mawson Lakes, a WSUD suburban environment in Adelaide, air temperatures near waterbodies (within 50m) were found to be 1.8°C cooler than the suburb maximum (Broadbent et al., 2017). Also, overall there was a 2.0°C variability across the neighbourhood during the day and at night.

Using irrigation has also been found to be an effective cooling technique. Irrigated sections of the Melbourne Botanic Gardens were observed to be up to 3.5°C cooler (in air temperature) during heatwave conditions (Lam et al., 2016; Lam and Hang, 2017). Areas of Lincoln Square in Melbourne that were lightly irrigated had reductions of air temperature of 1.0°C and 10.0°C in UTCI (Motazedian, 2017; Motazedian et al., 2020).

To test the effectiveness of irrigation for cooling, Broadbent et al. (2018) performed a modelling study of Mawson Lakes (Figure 10). Low to moderate levels of irrigation reduced air temperature across the neighbourhood by about 0.5°C and surface temperatures by up to 20°C. Using very heavy amounts of irrigation (30Lm^2/day), air temperature reductions increased at non-linear rates of up to 2.5°C, but cooling plateaued when the soil reached saturation. The threshold for maximum cooling peaked at 20Lm^2/day. Further, irrigating bare dry ground had a very high cooling efficiency (the temperature reduction per volume of water). This means that watering streets or pavements during a heat wave can be a very effective method of emergency cooling.



Prioristation: Street Trees

Canyon Width											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
		Low			Medium			Tall			
		Canyon Height									

🟥 High priority 🟨 Moderate priority 🟩 Lower priority 🟦 Not a priority

Figure 9: Prioritisation of street tree installation where sites with high solar exposure and resulting high temperatures are high priority targets for mitigation. Numbers inside the boxes are H:W ratios. Source: Norton et al. (2015).

2.4 Urban green infrastructure

A range of urban green infrastructure (UGI) has been found to provide cooling benefits, but optimal use requires the right type to be used in the right way. Figure 11 compares the use of green open spaces, trees, green roofs, and vertical greening. In almost all cases, irrigation is required to maintain the vegetation and provide evapotranspirative cooling benefits. Green roofs provide moderate amounts of cooling for buildings but are of little benefit for street level cooling. Green walls can provide some cooling relief for streets where street trees are not viable.

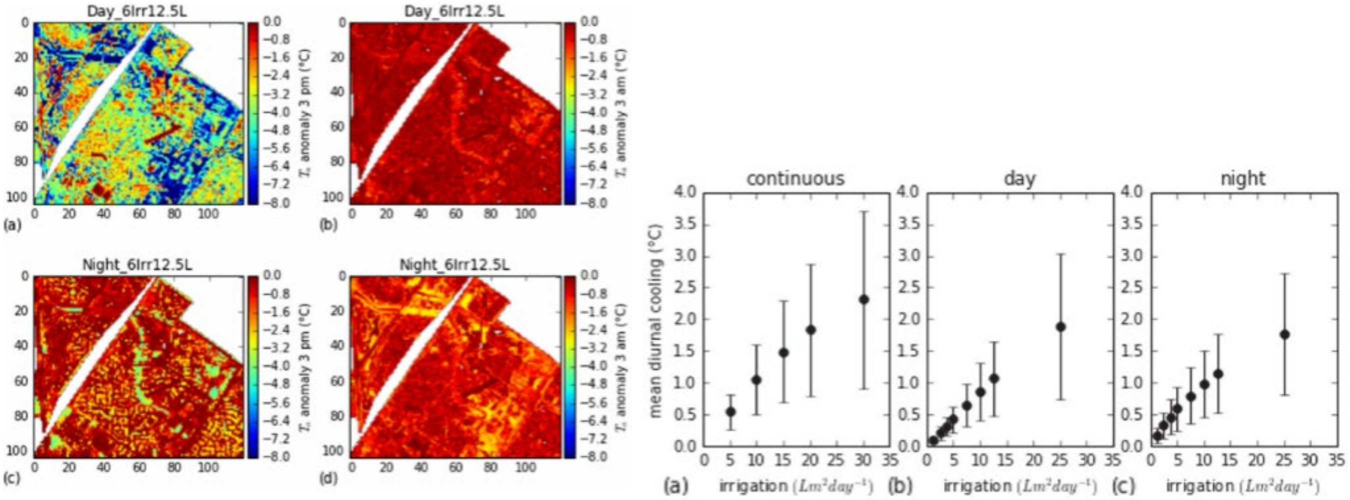


Figure 10: (Left) Spatial representation of cooling from Day/Night_6Irr12.5L scenario at (a/c) 3pm and (b/d) 3am on Julian day 37. Source: Broadbent et al. (2018). (Right) Heatwave average diurnal cooling for (a) continuous, (b) day, and (c) night irrigation. Source: Broadbent et al. (2018).

UGI	Green open spaces	Trees	Green roofs	Vertical greening
Shades canyon surfaces?	Yes, if grass rather than concrete	Yes	Shades roof, not internal canyon surfaces	Yes
Shades people?	Yes, if treed	Yes	No, only very intensive green roofs	No
Increases solar reflectivity?	Yes, when grassed	Yes	Yes, if plants healthy	Yes
Evapo-transpirative cooling?	Yes, with water	Yes (unless severe drought)	Yes, with water when hot	Yes, with water when hot
	No, without water		No, without water	No, without water
Priority locations	• Wide streets with low buildings - both sides • Wide streets with tall buildings - sunny side	• Wide streets, low buildings - both sides • Wide streets, tall buildings - sunny side • In green open spaces	• Sun exposed roofs • Poor insulated buildings • Low, large buildings • Dense areas with little available ground space	• Canyon walls with direct sunlight • Narrow or wide canyons where trees are unviable

Figure 11: Modes of cooling provided by different urban green infrastructure options during summer and priority locations to optimise those cooling benefits. Source: Norton et al. (2015).

PART C: Overview of urban cooling metrics and goals

3 Urban cooling

The research undertaken by the CRCWSC shows WSUD presents an opportunity to mitigate urban heat. WSUD infrastructure deployed through urban areas increases the amount of water available in cities to support vegetation. This increased vegetation and modified urban areas can greatly reduce thermal stress and impacts from heat.

Urban cooling strategies often set 1–2°C air temperature reductions as their goal. Judging whether this is a suitable goal or if the goal has been (can be measured) achieved requires understanding what this goal means and how effective it is in mitigating health and other impacts.

3.1 Urban cooling metrics

A multitude of different metrics can be used to measure urban heat. Different types of temperatures are often used interchangeably, causing considerable confusion about the actual outcomes. Air temperature is the most common. Air temperatures will show the least variability across a neighbourhood or precinct, differing by 1–2°C at most in nearby locations. Air temperature can be easily measured using simple equipment, but observations of variability across a local area requires a dense network of instruments.

Surface temperatures, on the other hand, can show wide ranges in variability. Surface temperatures of shaded surfaces will be similar to the surrounding air temperatures while nearby unshaded surfaces can be 20–30°C hotter. Land surface temperatures can be observed using satellite or aircraft remote sensing, quickly mapping wide areas. However, customised or high-resolution mapping beyond scheduled acquisition times of a standard source such as Landsat or higher resolution than MODIS will require commissioning expensive aircraft flights.

Surface temperatures will vary widely depending on the surface types and whether the surfaces are shaded or not. As observed in Figure 12, during the day, surfaces such as concrete, roofs and roads are significantly hotter than many natural surfaces, especially if they are irrigated. However, non-irrigated grass can be just as hot as roads. At night, surfaces such as concrete, roads and tile roofs that have stored heat during the day will remain hot far into the night, while most other surfaces will cool down quickly.

It is difficult to link land surface temperatures to air temperatures at a micro-scale. Figure 13 shows a transect across Melbourne at night. Some correlations were found between the air and surface temperatures in areas with deep urban canyons where the buildings restricted the airflow, but these relationships broke down in more open areas.

Nury (2015) performed a statistical regression on air temperature (T_a) measurements from weather stations and Landsat TM5 land surface temperatures (LST) and developed a relationship of $T_a = 0.753 \times \text{LST} + 1.942$ (Figure 14).

South Melbourne	DAY (°C)	St. Dev. (°C)	NIGHT (°C)	St. Dev. (°C)
Concrete	50.45	7.66	31.63	5.26
Irrigated grass	42.81	8.34	25.59	3.92
Non irrigated grass	48.00	6.80	26.27	3.74
Road	48.83	7.63	29.16	4.28
Tile roof	52.20	7.82	30.35	4.35
Galv. steel roof	51.95	11.20	26.53	8.60
Trees	41.59	6.66	26.62	2.90
Water	44.41	7.97	27.72	3.90
AVERAGE	**47.53**		**27.98**	

Figure 12: Average land surface temperatures of the major land surface types for the City of Port Phillip areas.
Source: Coutts and Harris (2013).

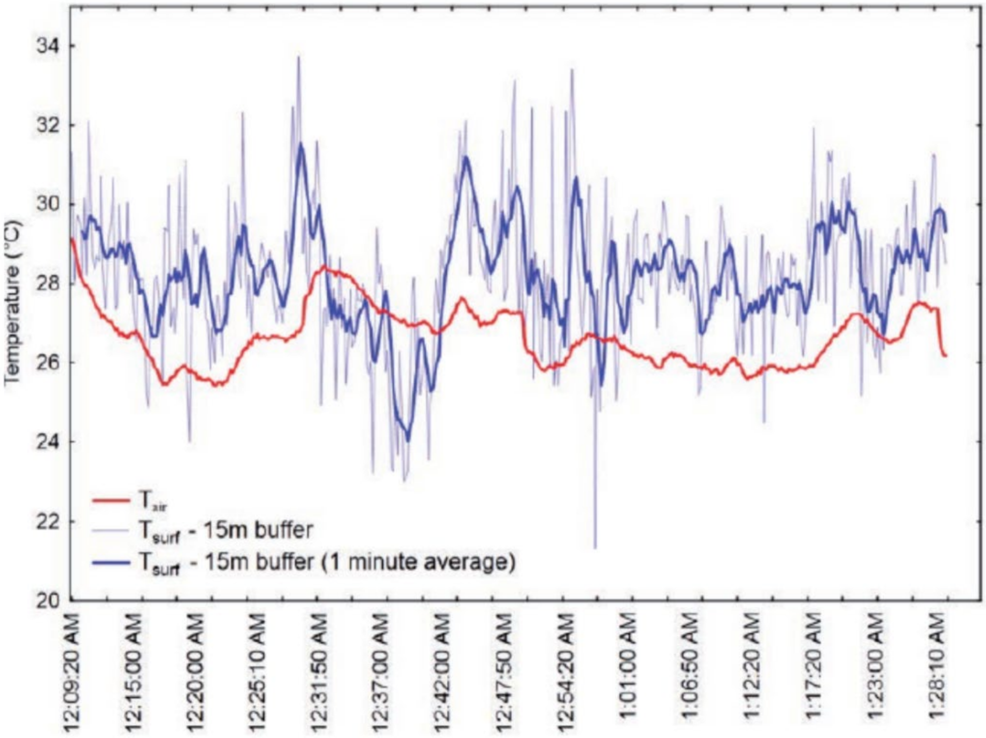


Figure 13: Plot of air temperature (10 second average) and land surface temperature using instantaneous 15 m buffers over the equivalent of 1 minute of travel for the air temperature transect on 25 February 2012.
Source: Coutts and Harris (2013).

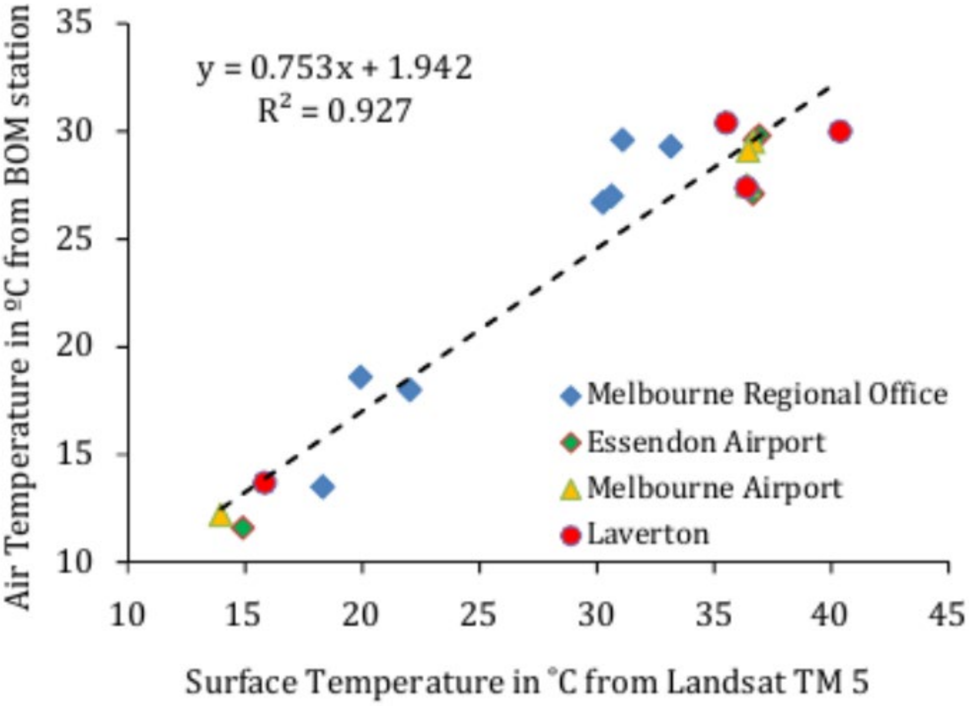


Figure 14: The relationship between measured LST from satellite imagery (Landsat TM5) and air temperature from weather stations.
Source: Nury (2015).

3.2 Human thermal comfort

Measuring the success of an urban cooling strategy through improvements in human thermal comfort (HTC) allows the direct quantification of thermal stress on people resulting from the complex mix of elements of urban environments. An important parameter necessary to measure HTC is mean radiant temperature. Mean radiant temperature is a summation of shortwave radiation (sunlight and reflected sunlight) and longwave radiation (radiated heat from surrounding surfaces) on a human body (Kántor and Unger, 2011) (see Figure 15). Incorporating all of these types of temperatures are human thermal comfort (HTC) indexes such as the Universal Thermal Climate Index (UTCI) (Bröde et al., 2009). UTCI gives equivalent temperatures of heat stress (see Figure 16).

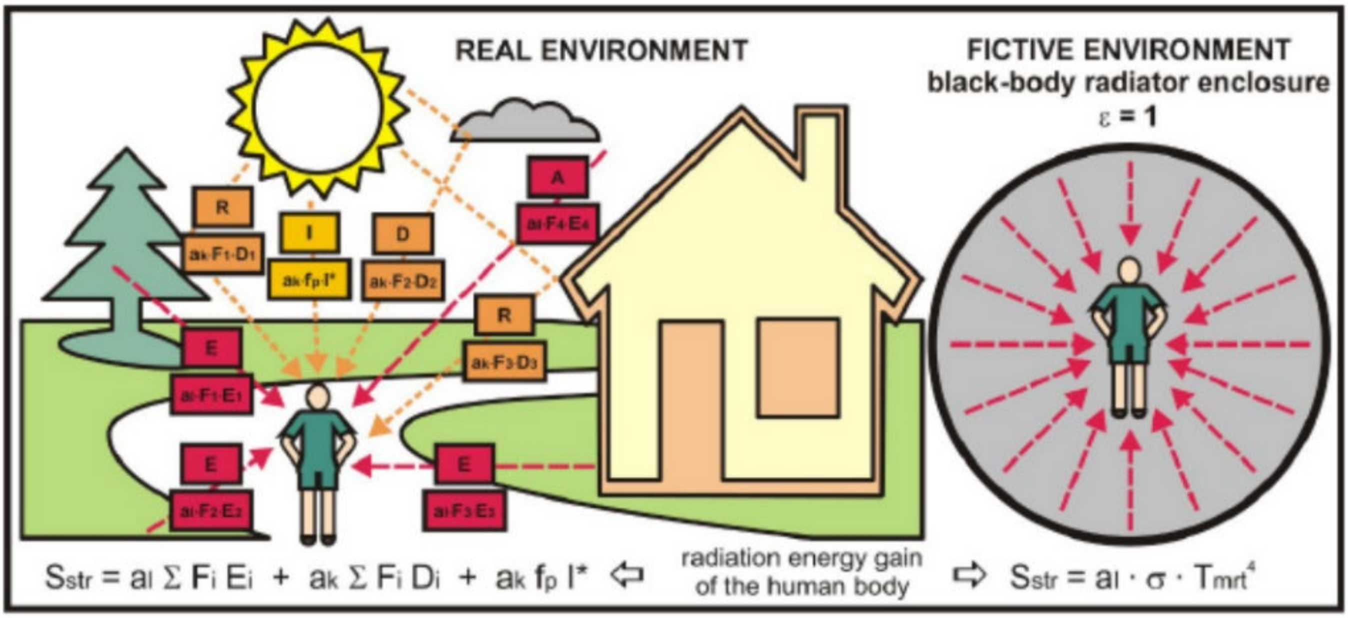


Figure 15: Illustration supporting the understanding of the definition and calculation of mean radiant temperature.
Source: Kántor and Unger (2011).

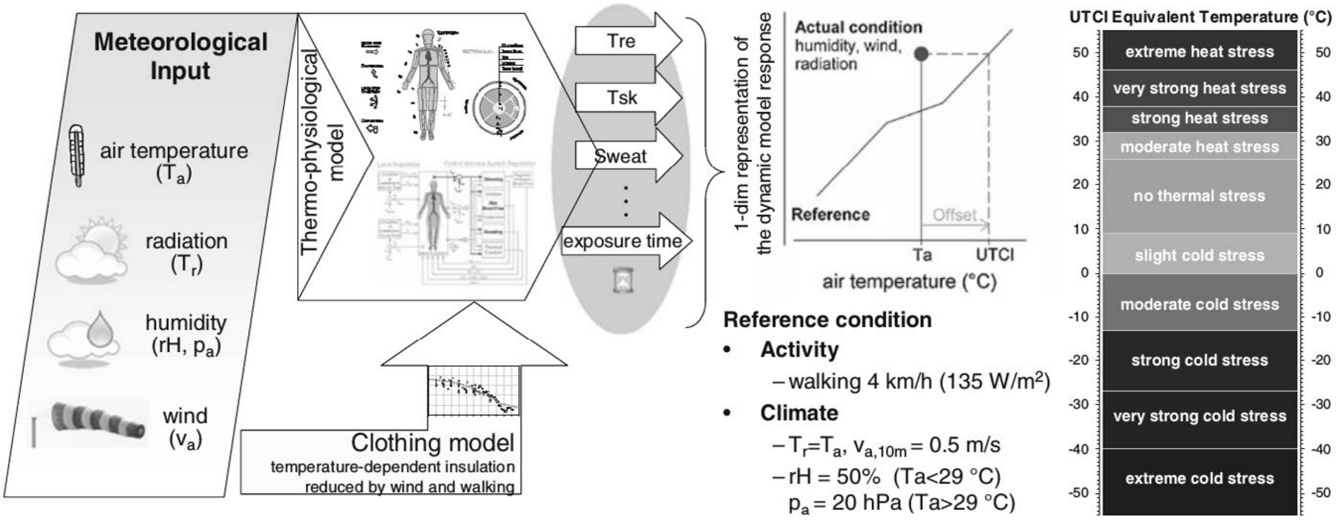


Figure 16: Elements of the operational procedure and concept of UTCI as categorised equivalent temperature derived from the dynamic response of a thermo-physiological model coupled with a behavioural clothing model.
Source: Bröde et al. (2013).

3.3 Urban cooling goals

Based on CRCWSC observations and modelling research, some reasonable goals of cooling through different interventions can be set. Widespread reductions of air temperature of 1–2°C have been observed and modelled in cases where canopy cover is increased from small amounts to high levels, or in cases where green space is actively irrigated with large amounts of water. These goals should also specify whether these benchmarks are reductions of a maximum temperature at the hottest part of the day, are averaged across the day, or are a measure of the UHI and compare different areas at night.

Surface temperature reductions can be modelled or measured through thermal imagery. Other measures such as mean radiant temperature or UTCI might require modelling. But for each of these, the variability in micro-climates can make it difficult to assess the success of interventions and designs to mitigate urban heat.

By incorporating additional shading into urban areas (i.e. increased tree canopy cover), reducing the amounts of hard impervious surfaces, and increasing the use of water features and irrigation, some surfaces in the area can show reduction of surface temperatures of 10–20°C. However, unshaded hard surfaces that remain will show no reductions. Through the reduction in surface temperatures, there will be a corresponding reduction in UTCI temperatures of up to 10°C.

As an example of how mitigation strategies can be assessed at a micro-scale, Todorovic et al. (2019) created several site and neighbourhood designs for infill development in Salisbury, South Australia. The heat performance of the scenarios was modelled, which included an existing urban design, business as usual (BAU) future development, and a water sensitive (WS) approach (Figure 17). Because each scenario had completely different spatial layouts, calculating the difference between the scenarios is not possible. Instead, the distributions of UTCI temperatures (a heat stress index) across the different scenarios were compared (Figure 18) to show how they changed across the different designs. Using these shifts in heat stress distributions, urban thermal comfort could then be incorporated into a multiple performance criteria comparing the different designs (Figure 19).

Much of the CRCWSC research has concentrated on the warm and dry climates of southern Australia. A strength of making assessments using UTCI is its transferability to other local climate types, because UTCI accounts for the impacts of air temperature, solar radiation, wind and humidity.

Reductions in surface temperatures and direct solar radiation loads on pedestrians through shading will reduce thermal heat stress in all climate types. The impacts of higher humidity levels due to increased vegetation and water features in sub-tropical climates such as Singapore will be reflected in the calculated UTCI equivalent temperatures of heat stress. In addition, modifications to wind flow will also be reflected in the UTCI equivalent temperatures.

Some of the transferability of results might also be impacted by acclimatisation to local climate conditions. Figure 20 shows threshold temperatures in all the Australian capital cities. Across Australia, residents of Adelaide have the highest tolerance to higher temperatures while Hobart shows higher mortality and morbidity at lower threshold temperatures.

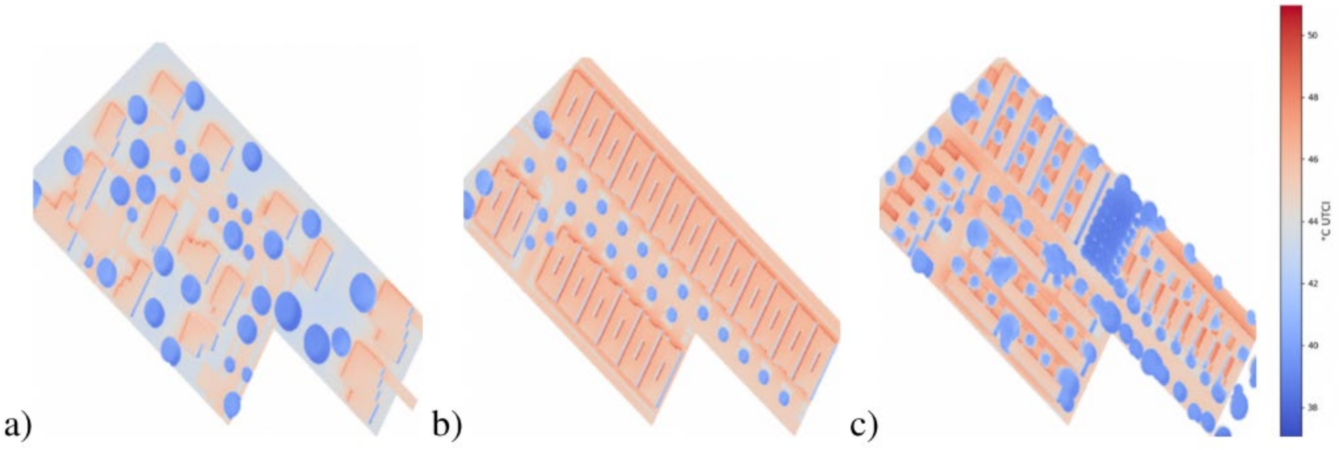


Figure 17: UTCI temperatures (degrees C) for three scenarios: a) Typical Existing; b) BAU; c) WS1 – Townhouses.
Source: Todorovic et al. (2019).

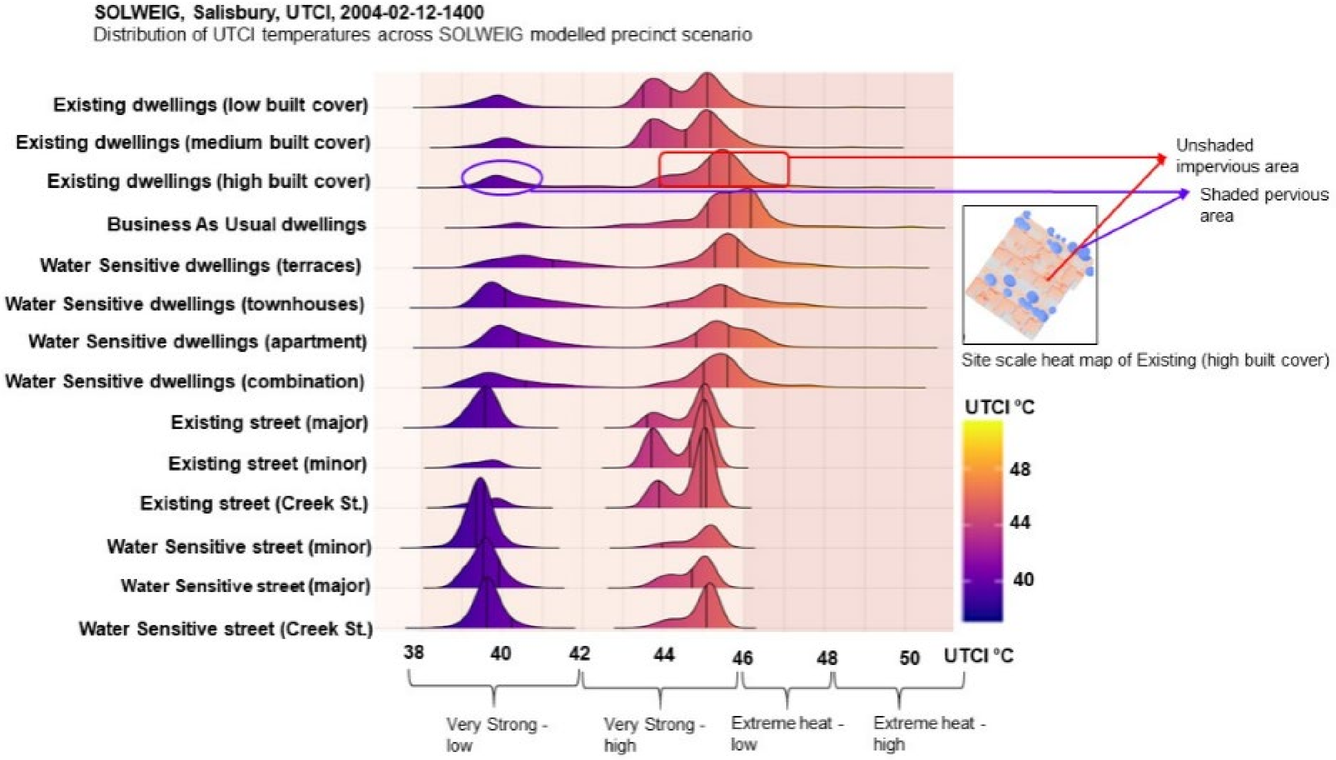


Figure 18: Distribution of outdoor UTCI ('feels like') temperatures for each of the individual dwelling and street typology site plans.
Source: Renouf et al. (2020).

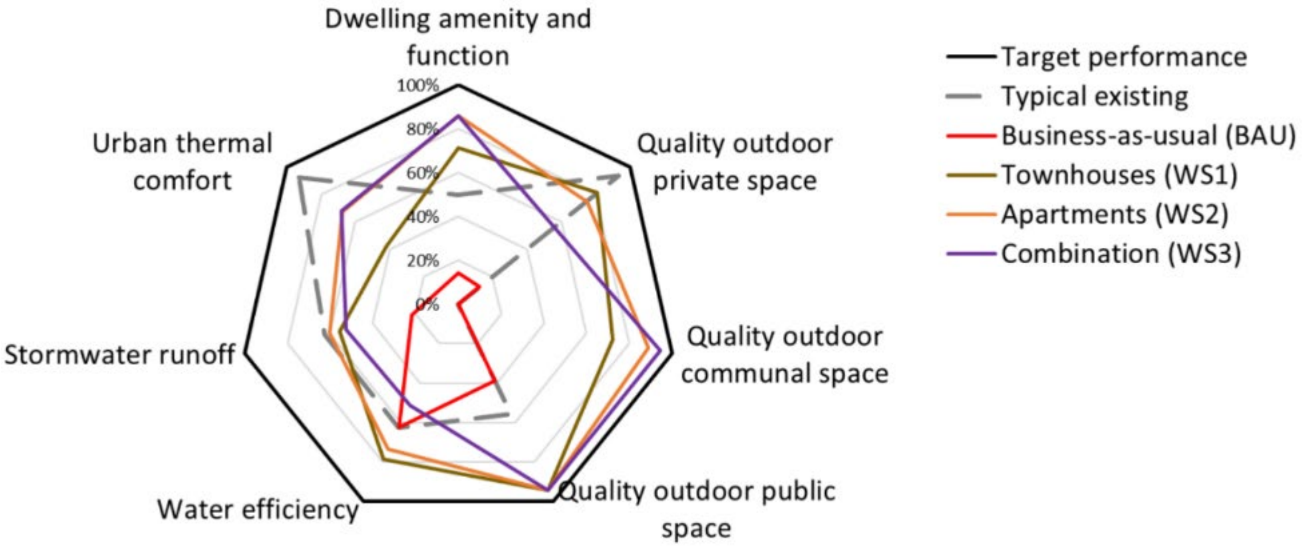


Figure 19: Overall performance comparison across multiple performance criteria for Salisbury scenarios.
Source: Renouf et al. (2020).

PART D: Overview of urban cooling assessment methods

3.4 Urban cooling assessment tools

The CRCWSC has developed several tools to assist with assessing urban cooling strategies.

3.4.1 TARGET

TARGET – The Air-temperature Response to Green/blue-infrastructure Evaluation Tool (Broadbent et al., 2019) – is a model to evaluate the heat impacts of urban form and especially green and blue infrastructure. TARGET produces 2m air temperature predictions as well as UTCI values. It was designed to be accessible to non-expert users and can be configured and run using GIS data and on a standard desktop computer. This tool can be used to examine the air temperature reductions from increasing tree canopy cover or through irrigation, as in Figure 21.

As a very efficient model, it is suitable to model even city-scaled areas as in this example of modelled surface temperatures of Melbourne (Figure 22).

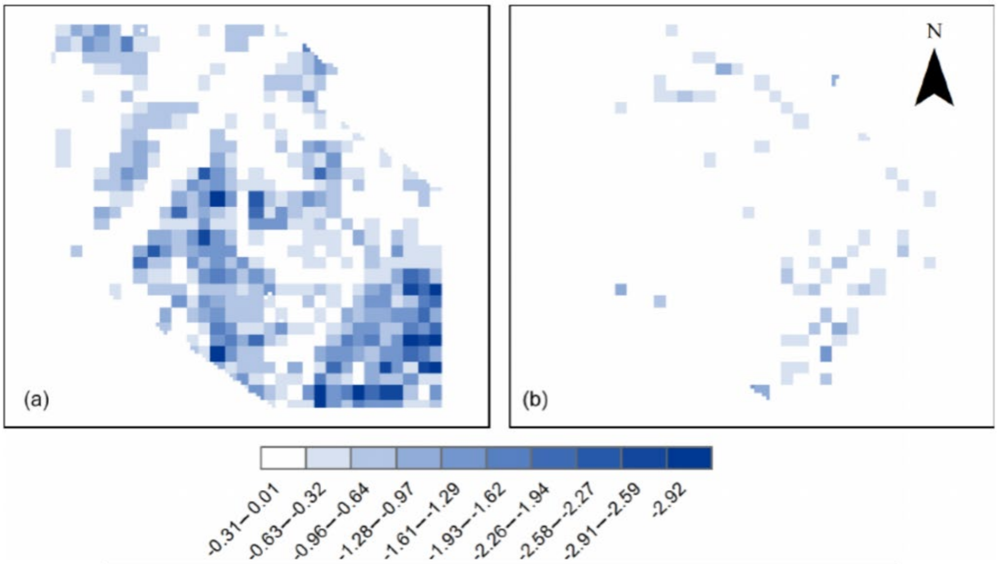
3.4.2 CRC Scenario Tool

The CRCWSC Scenario Tool is a planning support tool to evaluate outcomes of different scenarios of urban development. These include several urban water cycle outcomes such as water demand, infiltration and stormwater runoff. Heat assessments were enabled through the surface temperature/air temperatures discussed in Section 3.1 (Urban cooling metrics) and Figure 14 (Figure 23).

In 2020, the tool was updated to include the TARGET model. This will now allow air temperatures and UTCI to be modelled in conjunction with the urban water cycle outcomes.

City	Number of days of data	Tmax	% increase in median	Tmin	% increase in median	meanT	% increase in median	AT	% increase in median
Brisbane									
Morbidity	2956	36 (55)	2.5–12%	26 (7)	2.5%	34 (2)	9%	40 (25)	4–11%
Mortality	4007	36 (58)	12%	22 (11)	5%	31 (6)	15%	40 (9)	8%
Canberra									
Morbidity	2320	37 (33)	5–10%	20 (30)	5%	28 (28)	5–8%	38 (11)	8–10%
Mortality	4007	33 (179)	5%	20 (43)	2%	28 (16)	2%	41 (4)	5%
Darwin									
Morbidity	1826	36 (4)	5%	28 (17)	5%	31 (19)	7%	35 (5)	5%
Mortality	4007	37 (11)	5%	29 (19)	8%	31 (94)	3%	47 (5)	10–20%
Hobart									
Morbidity	2953	NA		18 (28)	5–20%	27 (3)	5%	36 (5)	4–10%
Mortality	4007	35 (13)	11%	20 (5)	2%	28 (5)	6%	37 (6)	5–20%
Melbourne									
Morbidity	3287	44 (5)	3%	26 (6)	3%	34 (6)	3%	42 (10)	2–3%
Mortality	4007	39 (23)	2–65%	26 (9)	5%	28 (112)	3–13%	36 (68)	4%
Perth									
Morbidity	2007	43 (3)	14%	26 (4)	4%	NA		43 (8)	2–5%
Mortality	4007	44 (3)	30%	NA		32 (20)	3–10%	45 (3)	10%
Adelaide									
Morbidity	3045	NA		31 (4)	5%	39 (1)	24%	NA	
Mortality	4007	42 (21)	2–8%	NA		34 (2)	8%	43 (16)	2–10%
Sydney									
Morbidity	4162	41 (3)	5–38%	25 (5)	4%	31 (5)	2%	41 (3)	5%
Mortality	4007	38 (3)	2–18%	25 (3)	5%	30 (12)	5%	37 (27)	2–24%

Figure 20: Threshold temperature derived from analyses of daily all-cause mortality, daily emergency hospital admissions, daily ambulance call-outs or emergency department presentations in Australian capital cities. Source: Loughnan et al. (2013).



Scenario	03:00		15:00		Daily	
	ΔT_{ac}	γ	ΔT_{ac}	γ	ΔT_{ac}	γ
2×TREE	−0.13	−0.10	−0.50	−0.50	−0.28	−0.09
IRRIGATION	0.34	0.09	−0.58	−0.20	−0.20	−0.04

Figure 21: Modelled air temperature reductions (°C) from doubling tree canopy cover in Mawson Lakes. 2xTree - BASE at a) 15:00 and b) 03:00. Source: Broadbent et al. (2018).

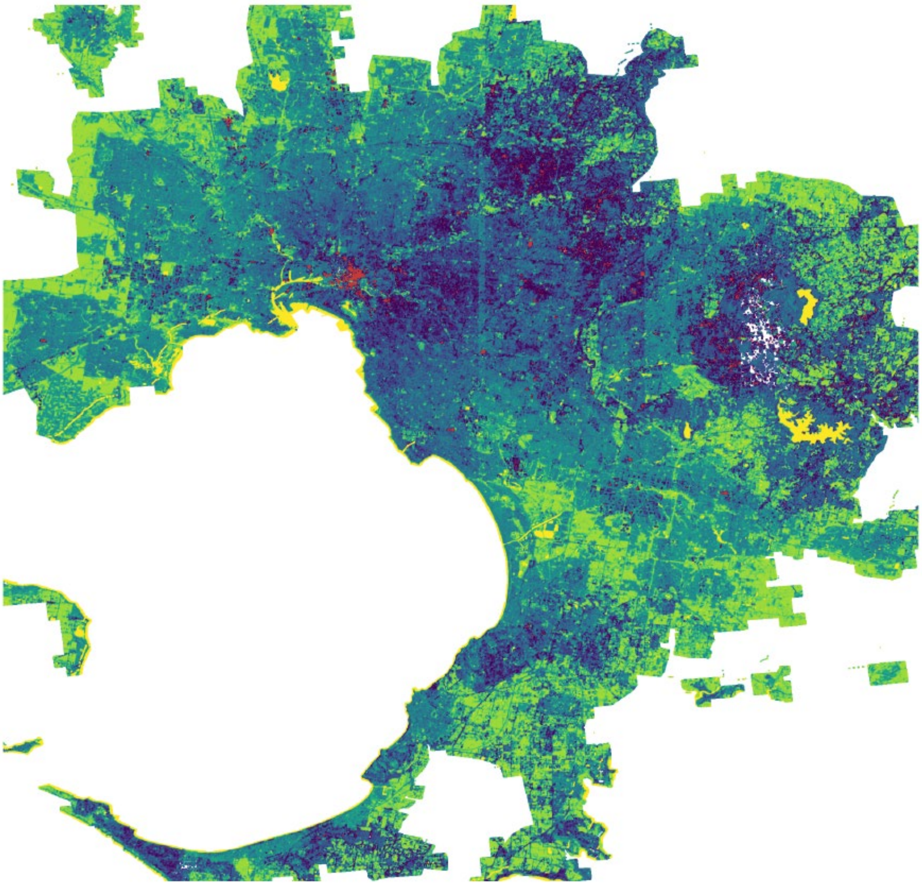


Figure 22: City-wide modelling of Melbourne surface temperatures using the TARGET model. Source: Nice (2020).

3.4.3 VTUF-3D

For more detailed micro-climate assessments of urban greening benefits, the VTUF-3D model (Nice et al., 2018) was also developed through CRCWSC research. This is a true micro-scaled model that allows modelling urban canyons at a very small scale (2-5m) in 3 dimensions including trees and vegetation. Figure 24 shows the level of detail across this city park with a cooler area under the canopy cover in the centre.

3.4.4 SOLWEIG / UMEP

Another modelling tool often used in CRCWSC research is the SOLWEIG module of the Urban Multi-scale Environmental Predictor (UMEP) (Lindberg et al., 2018). This is available as a plugin to QGIS (QGIS Development Team, 2009) and allows micro-scaled modelling of air temperature and mean radiant temperature using GIS input layers. This model was used for the Salisbury scenarios in Figure 17.

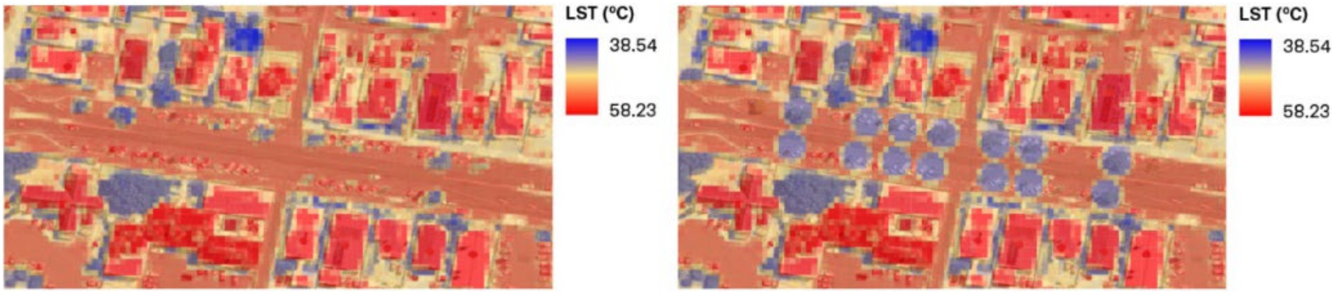


Figure 23: CRCWCS Scenario Tool, modelled land surface temperature of Dubbo (left) before and (right) after tree planting. Source: Urich and Harold (2020).

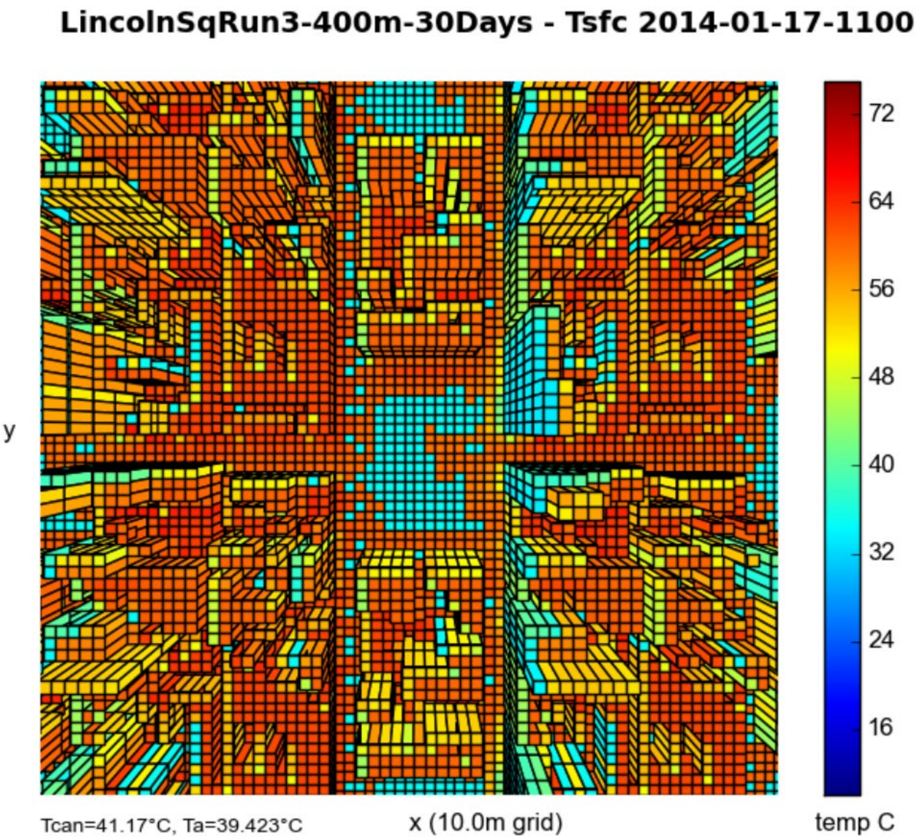


Figure 24: VTUF-3D output of surface temperature in Lincoln Square, Melbourne, 17 January 2014, 11am. Source: Nice et al. (2014).

PART E: References

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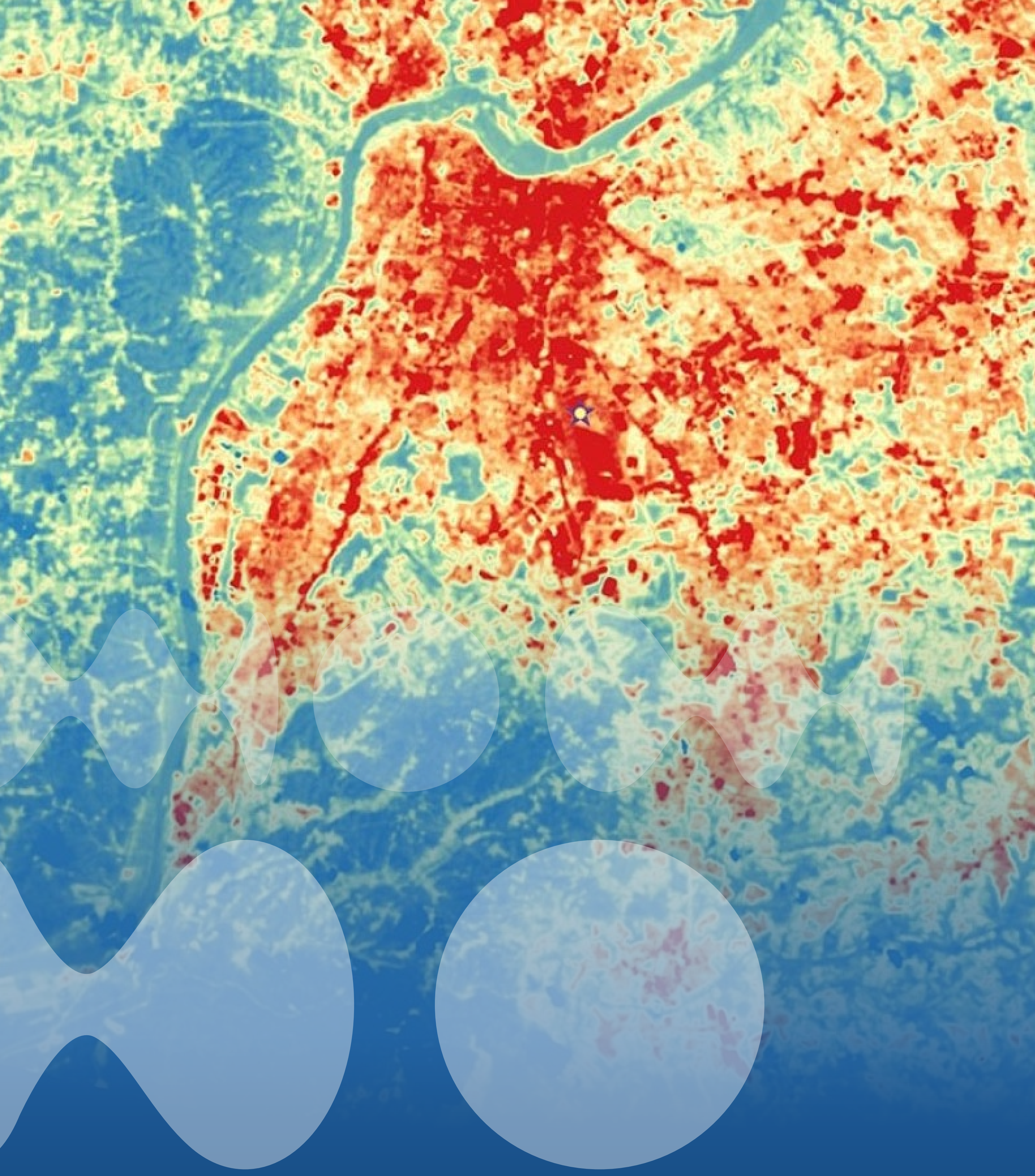

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