



LOW CARBON LIVING
CRC

GUIDE TO URBAN COOLING STRATEGIES

2017

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GLOSSARY

ALBEDO

Reflectivity; the proportion of incident light reflected from a surface.

ASPECT RATIO

The ratio of average building height to street width of an urban canyon.

BUILDING ENVELOPE

Collective term for the building façades and roof.

COOL MATERIALS

Materials with high albedo and/or high emissivity which stay cooler than conventional materials under solar radiation.

DRY-BULB TEMPERATURE

Air temperature as measured by a thermometer freely exposed to the air but shielded from radiation and moisture.

HEAT CAPACITY

The ratio of the heat added to or removed from an object to the resulting temperature change.

HEAT RESILIENCE

The extent to which the built environment can support outdoor activities during heat stress conditions.

HEAT STRESS

Heat stress occurs when our body is unable to cool itself enough (e.g. through sweating) to maintain a healthy temperature.

HEATWAVE

Three or more days of high maximum and minimum temperatures which are unusual for that location.

MEAN RADIANT TEMPERATURE (MRT)

The theoretical uniform surface temperature of an enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform enclosure.

SKY VIEW FACTOR (SVF)

The extent of sky observed from a point on the ground as a proportion of the total possible sky hemisphere.

THERMAL COMFORT

The state of mind that expresses satisfaction with the thermal environment and is evaluated subjectively.

THERMAL CONDUCTIVITY

The amount of heat per unit time per unit area which can be conducted through a plate of unit thickness of a given material.

THERMAL EMISSIVITY

Emissivity (or emittance) is the ratio of the heat emitted from an object or surface to that of a standard "black body".

URBAN BOUNDARY LAYER

That part of the atmosphere whose characteristics are affected by the presence of an urban area at its lower boundary.

URBAN CANOPY LAYER

The layer of air in the urban atmosphere beneath the mean height of the buildings and trees.

URBAN CANYON

The space above the street and between the buildings on either side of the street.

URBAN HEAT ISLAND

The phenomenon whereby the trapping of solar radiation and release of anthropogenic waste heat leads to higher temperatures in urban areas compared to their rural surroundings.

URBAN METABOLISM

The flows of the materials, energy and information which characterize urban environments.

WET-BULB TEMPERATURE

The lowest temperature reachable through water evaporation, under ambient conditions.

INTRODUCTION

This document provides practical guidance for built environment professionals and regulatory agencies seeking to optimise development projects to moderate urban microclimates and mitigate urban heat island effects in major urban centres across a range of climates in Australia.

The emphasis is on the public realm, and the scope is project-focused. The three dimensions which contextualise the effectiveness of urban cooling strategies in this Guide are urban form, climate type and the nature of intervention. This 3D matrix provides the framework for the Guide, in terms of both process (methods) and product (the design outcomes).

This project covers urban heat mitigation strategies in climate zones relevant to Brisbane, Sydney, Parramatta, Canberra, Melbourne, Hobart, Adelaide, Perth, Darwin and Cairns. The range of urban typologies include the dense inner city, middle ring and outer suburbs. The focus for design intervention will include streetscapes, plazas, squares and malls. Urban surface properties, vegetation cover, shading and orientation are key variables. Interventions cover both active (e.g. misting systems and operable awnings) and passive systems (street trees, green roofs/walls, water bodies, cool roofs and façades).

This urban cooling guide draws on data from the three-year Urban Microclimates project at the Cooperative Research Centre for Low Carbon Living, and cross-references the CRC LCL Microclimate and Urban Heat Island Decision-Support Tool project.

It also benefits from relevant research at the CRC for Water Sensitive Cities.



THE URBAN HEAT ISLAND (UHI) EFFECT

Urban climates are distinguished by the balance between solar gain and heat lost from walls, roofs and ground; by convective heat exchange (i.e. via air movement) between ground, buildings and atmosphere; and by generation of heat within the city itself.

Global climate change and the urban heat island (UHI) phenomenon – whereby cities absorb and release more heat than the surrounding countryside – carry growing potential to make urban life at particular times and places an exercise in low-grade misery.

Studies across the world's major cities show that a systematic higher average temperature of 2°C to 12°C exists in highly-urbanised areas compared with their rural surroundings.

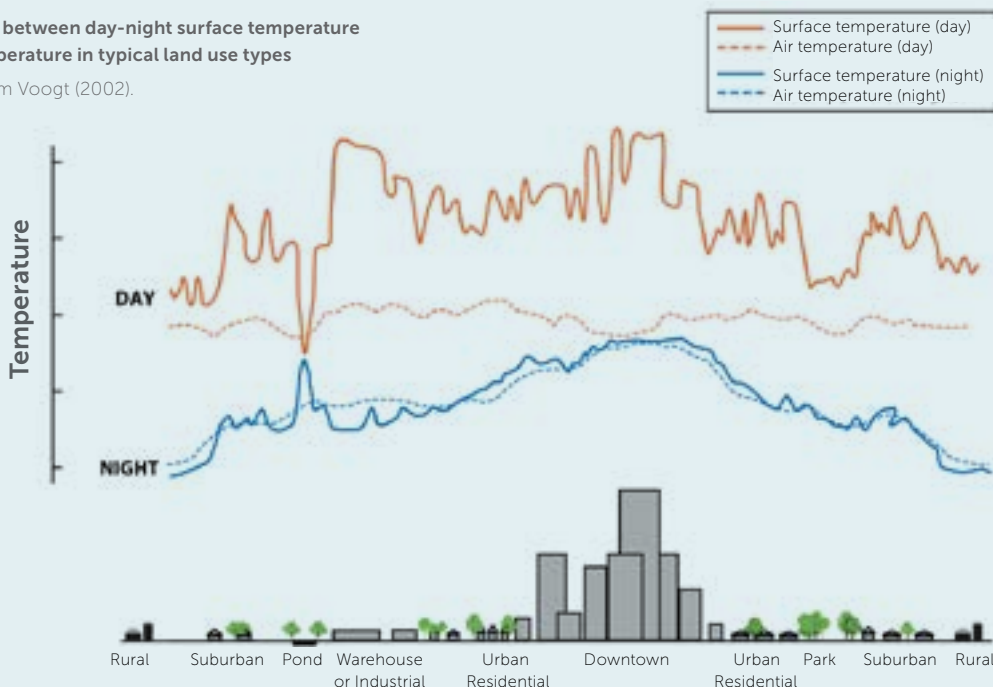
UHI INTENSITY (°C)



WHILE NIGHT TIME URBAN-RURAL TEMPERATURE DIFFERENCES ARE MORE INTENSE, DAILY UHI EFFECT HAS MORE FLUCTUATION COMPARED TO NIGHT TIME

Differences between day-night surface temperature and air temperature in typical land use types

Adapted from Voogt (2002).



UHI CONTRIBUTING FACTORS

The Urban Heat Island (UHI) effect exists because of energy and water budget variations in the built environment compared to non-urban areas. Urban materials and surfaces, land cover and metabolism are the major contributing factors

URBAN FABRICS

The geometry, orientation, and configuration of urban space mediates heat exchange in the built environment. Building volumes, orientation and the aspect ratio of the intervening spaces affect the exposure of urban surfaces to solar radiation, which is measured by the sky view factor. The complex heat exchange between building materials and adjacent air layers affects the intensity and pattern of airflow in urban canyons.

URBAN LAND COVER

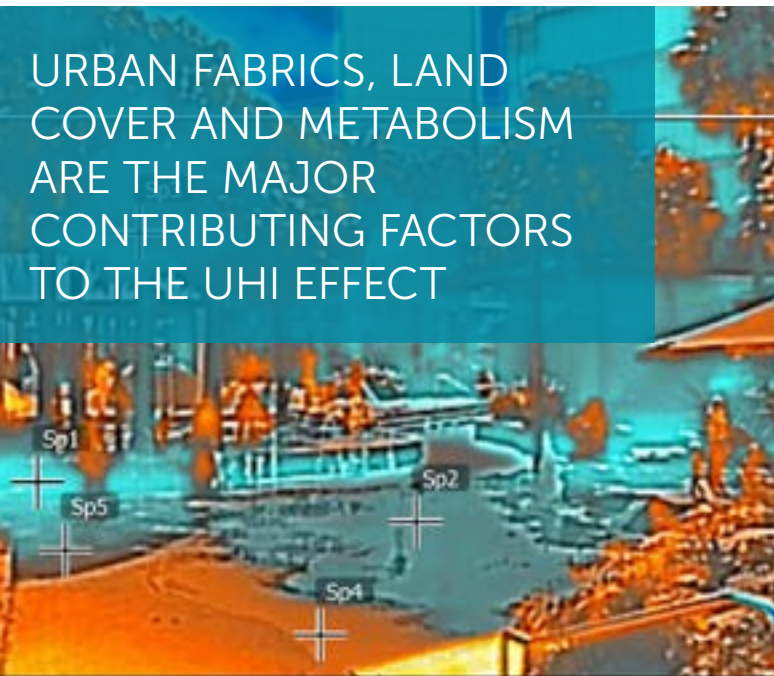
The relative proportion of residential areas, industrial sites, urban vegetation and streets affects UHI intensity and distribution. The distribution of land cover classes including paved, vegetated and bare land and water bodies contribute to the heat exchange between the urban mass and the adjacent air. These land cover differences create micro-scale turbulence which mixes hotter and cooler air and affects UHI intensity. For example, the type, distribution and density of urban greenery affect lower atmospheric turbulence. Lack of sufficient greenery – a common characteristic of urban areas – contributes to the accumulation of heat in cities. Conversely, photosynthesis and evapotranspiration contribute to decreasing the ambient temperature.

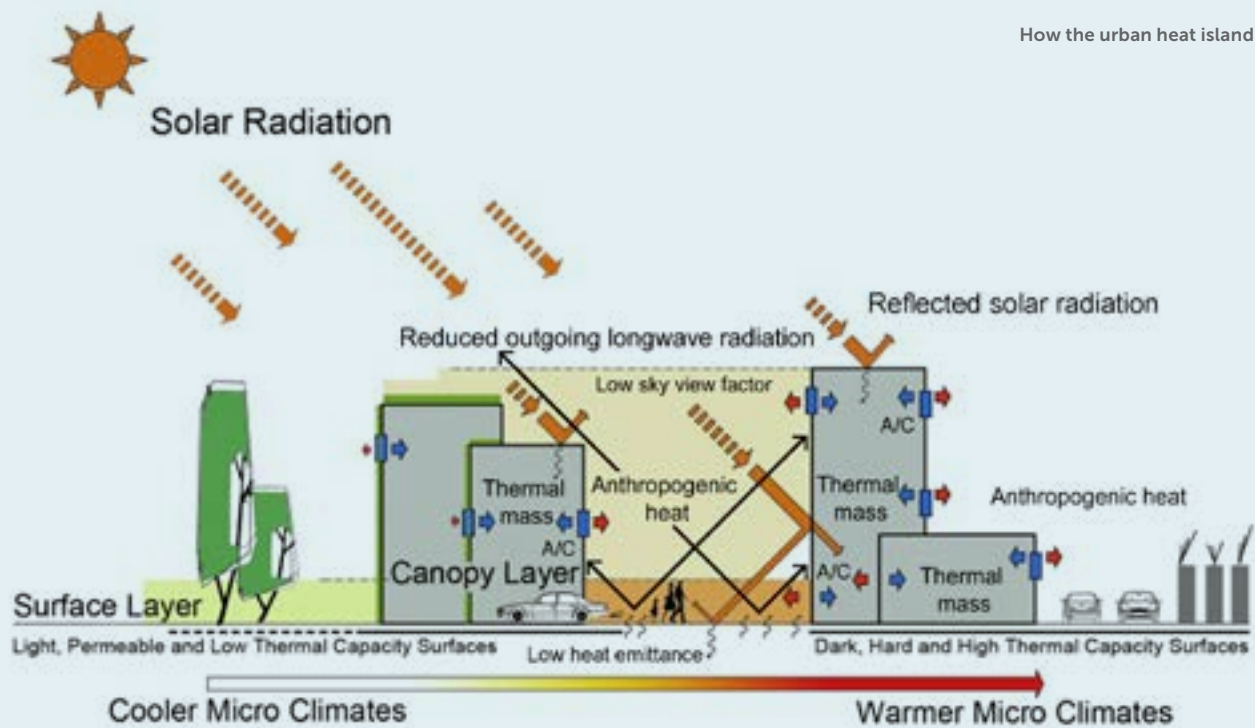
URBAN METABOLISM

Urban life is predicated on energy consumption, which generates exhausted (waste) heat. Such anthropogenic (human-made) heat is mainly related to energy consumption for indoor air-conditioning and motorised transport. Ironically, the resulting excess heat can increase the demand for more air-conditioning. Waste heat during summer is a significant contributor to the UHI effect, especially in warm and temperate climates.

The effect of urban metabolism is uneven across different land use classes such as residential, commercial or industrial. Activities in each land use class contribute to the anthropogenic heat output, in addition to the effects of the material properties and geometry of each land use class on the solar gain-driven urban heat flux.

URBAN FABRICS, LAND COVER AND METABOLISM ARE THE MAJOR CONTRIBUTING FACTORS TO THE UHI EFFECT





EXTERNAL CONTRIBUTING FACTORS LIKE REGIONAL CLIMATE, SEASONAL FACTORS & LOCATIONAL CONTEXT CAN AFFECT THE MAGNITUDE OF THE UHI

URBAN LIVING IN UHIs IN THE CONTEXT OF CLIMATE CHANGE

The UHI effect is a complex phenomenon, not only because of the complexity of urban settings and weather patterns but also due to the interplay between its contributing factors. The roughness of urban surface covers and their heat capacity cause temperature variations across the urban environment and create local air turbulence. While hard urban surfaces can store more heat, their heat loss rate is also higher than permeable and greened surfaces. Thus, non-uniform urban landscapes stimulate city breezes, which may reduce the UHI intensity.

The exhausted anthropogenic heat from air-conditioning, transport and industry is another highly contextual contributor, which can significantly magnify the UHI effect. Local topography and weather patterns also affect the UHI. The UHI effect is a common phenomenon in the majority of cities worldwide, but the way it manifests is based on the specific situation of any given city.


The global urban population increased from 40% (less than 1 billion) in 1950 to 50% (more than 3.6 billion) by 2008. According to the World Bank, urban areas contribute as much as 80% of global greenhouse gas emissions, while also becoming increasingly vulnerable to the effects of the changing climate.

Cities are expected to facilitate quality of life for their inhabitants. However, city dwellers are increasingly facing heat stress in their built environment. In the context of continuous global warming, summer heatwaves are now a common occurrence worldwide, and they are becoming more frequent, extended, and extreme in Australia.

During summer heatwaves in Australia, public spaces are frequently warmer than human comfort levels allow. This heat stress is commonly amplified by the urban heat island effect. Urban heat stress pushes citizens into air-conditioned buildings, seeking comfortable indoor microclimates at the cost of rising outdoor temperatures.

BENEFITS OF UHI MITIGATION IN AUSTRALIAN CITIES

The combination of a warming climate and summer heatwaves in Australian cities has a severe and growing impact on the quality of urban life. In addition to increased air pollution and demand for energy consumption, urban heat stress increases the rate of mortality and can exacerbate existing health problems.



URBAN HEAT MITIGATION CAN REDUCE HEAT RELATED MORBIDITY AND MORTALITY AND RESULTS IN DECREASED DEMAND FOR ENERGY AND WATER CONSUMPTION

DECREASED DEMAND FOR ENERGY & WATER CONSUMPTION

Cooler outdoor environments also decrease the cooling energy demand for air-conditioning during summer. Increased outdoor thermal comfort from urban heat mitigation initiatives decreases demand for energy consumption for air-conditioning and motorised transportation. Decreased demand for energy consumption results in less waste heat production in urban environments and prevents the feedback loop between outdoor heat stress and energy demand during summer heatwaves. In temperature ranges greater than about 22°C, each 1°C increase in temperature increases electricity demand by 2.6%. So UHI mitigation represents an important way to reduce carbon emissions in our cities.

REDUCED HEAT RELATED MORBIDITY AND MORTALITY

The human body adjusts itself to excess heat through physiological heat adaptation provided by our cardiovascular, endocrine, and renal systems. However, body heat loss mechanisms tend to break down when surrounding temperatures surpasses 36-38°C.

Thermally comfortable city environments promote outdoor activities, public life and health. On the other hand, extreme temperatures are responsible for more deaths in Australia than any other natural hazard. It is estimated that heatwaves currently contribute to the deaths of over 1000 people aged over 65 each year across Australia (older people and the very young are most at risk). Appropriately targeted urban heat mitigation initiatives can reduce these unacceptable impacts.

URBAN COOLING TOOLKIT

UHI mitigation can provide more habitable urban settings through enhanced thermal comfort and reduced energy demand. Existing UHI mitigation techniques recommend cool materials, urban vegetation, water and shading as potential solutions to moderate temperatures and increase the adaptive capacity of cities to the warming climate. The effectiveness of each UHI mitigation technique varies according to the location, urban context (density, scale) and climate zone.

SHADOW COVERAGE,
OVERLAPPING MATERIALS, SOLAR
PATTERNS AND URBAN GEOMETRY
INFLUENCE DAILY CYCLES OF HEAT
ABSORPTION-EMISSION



COOL SURFACES

Building materials are major contributors to the development of heat islands where heat is stored in the thermal mass of the built environment.

The thermal characteristics of building materials contribute significantly to such heat storage. Therefore, application of materials with greater reflectivity, less heat capacity and (in the case of paving materials) more moisture capacity or permeability can be a logical UHI reduction method. Such so-called cool materials can be applied as urban paving, building roofs and walls. A cool surface material has low heat conductivity (conducts less heat into its interior), low heat capacity (stores less heat in its volume), high solar reflectance (albedo) or (as permeable materials) a high level of embodied moisture to be evaporated or infiltrated into the soil.

DURING SUMMER HEATWAVES IN AUSTRALIA, PUBLIC SPACES ARE FREQUENTLY WARMER THAN HUMAN COMFORT LEVELS ALLOW



COOL PAVING

Paved surfaces are ubiquitous elements of urban space. Paving covers 25-50% of a typical urban setting. Paving materials in the built environment are usually impermeable, hard, thick and heavy. Asphalt, concrete and compound paving are typical examples.

With low solar reflectance of 5% to 20%, asphalt can reach a peak surface temperature of 48°C to 67°C on a hot summer day.

Concrete and other common paving materials have a solar reflectance of 25-40%. Their surface temperature can reach 65°C under full sun.

Cool pavement materials tend to store less heat compared with conventional products. Increased reflectance, emittance and permeability are basic characteristics of cool paving. Utilising lighter pigments and aggregates in asphalt, concrete, and other block pavers can increase their reflectance up to 30%. Covering the surface with a thin reflective layer is another common

method to increase reflectance. A cool asphalt compound can have a reflectance of 45% versus conventional asphalt reflectance of 5% to 20%. However, utilizing light colours and reflective surfaces in urban paving needs special care about the glare effect in public space. Recent research has seen the development of a new generation of materials and surface coatings which are reflective in the infrared and near infrared wavelengths (i.e. they reflect heat) but show darker colours in the visible spectrum.

SOLAR ENERGY RECEIVED BY URBAN SURFACES INCLUDES 5% ULTRAVIOLET (UV) RAYS, 43% VISIBLE LIGHT AND 52% INFRARED (IR) RADIATION, WHICH IS FELT AS HEAT.
SOLAR REFLECTANCE (ALBEDO) IS THE PERCENTAGE OF SOLAR RADIATION REFLECTED BY A SURFACE. CONVENTIONAL ASPHALT AND CONCRETE HAVE SOLAR REFLECTANCES OF 5-40% AND ABSORB 60-95% OF THE ENERGY REACHING THEM.



HIGH ALBEDO PAVING

Albedo has a significant effect on the maximum temperature a substance can reach. Covering conventional materials with high reflectance coatings is a fast-track method of surface cooling. High albedo light-coloured pavements can have solar reflectance greater than 75%.

High albedo paving surfaces may result in lower surface temperatures. However, they do not necessarily lead to lower mean radiant temperatures (MRT). Although increased albedo increases the reflection of sunlight from high albedo surfaces, due to canyon geometry and complex light reflection-absorption behaviour of different urban surfaces the reflected sunlight may not escape the built environment immediately. The reflected radiation from a high albedo surface can be absorbed and stored in other urban materials and cause extra heat load elsewhere in the built environment. Also, excessively bright materials can cause a glare hazard to motorists or occupants of adjacent buildings.

HIGH EMISSIVITY PAVING

A material's emissivity determines the amount of heat radiated from the material at a given temperature compared with a theoretical 'black body'. Exposed to radiant energy, every material heats up until it reaches thermal equilibrium (balance). A material with high emissivity will reach thermal equilibrium at a lower temperature than one with low emissivity – meaning that it gives heat away more readily. Emissivity determines the minimum temperature of a surface in balance with its surrounding environment.

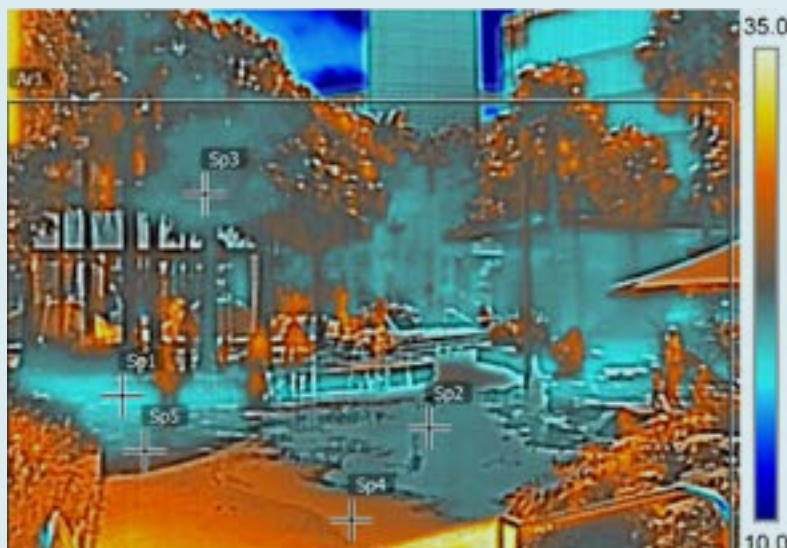
Emissivity and albedo have the greatest effect on determining how and to what extent paving materials, façades and roofs exchange heat and contribute to the UHI effect. However, albedo is easier to modify compared to emissivity since most common urban materials have inherently high emissivity values. Utilising lighter aggregates, pigments and binders in asphalt and concrete and lighter surface coatings are effective methods to cool conventional paved surfaces through increased albedo.

EMISSIVITY AND ALBEDO HAVE THE GREATEST EFFECT ON DETERMINING HOW AND TO WHAT EXTENT PAVING MATERIALS, FAÇADES AND ROOFS EXCHANGE HEAT AND CONTRIBUTE TO THE UHI EFFECT.

Temporary surface cooling can be achieved through increased wind speed, coverage with surface water and shading. The first and last of these, of course can be provided by suitably placed vegetation. These mechanisms involve active cooling systems (as compared to passive cool surfaces). Temporary coverage of conventional (impermeable) paving with surface water can increase reflectance, utilise surface heat for evaporation and decrease the surface temperature by at least 5°C.



The thermal characteristics of building materials contribute significantly to such heat storage. Therefore, application of materials with greater reflectivity, less heat capacity and (in the case of paving materials) more moisture capacity or permeability can be a logical UHI reduction method. Such so-called cool materials can be applied as urban paving, building roofs and walls. A cool surface material has low heat conductivity (conducts less heat into its interior), low heat capacity (stores less heat in its volume), high solar reflectance (albedo) or (as permeable materials) a high level of embodied moisture to be evaporated or infiltrated into the soil.



MEASUREMENTS

Max	35.3°C
Min	13.3°C
Average	24.0°C
Sp1 Tree Canopy	18.9°C
Sp2 Running water on surface	21.9°C
Sp3 Tree Canopy (facing sun)	22.5°C
Sp4 Paving	27.0°C
Sp5 Tree shade on paving	22.7°C

Parameters

Emissivity 0.95
Refl. temp 27°C

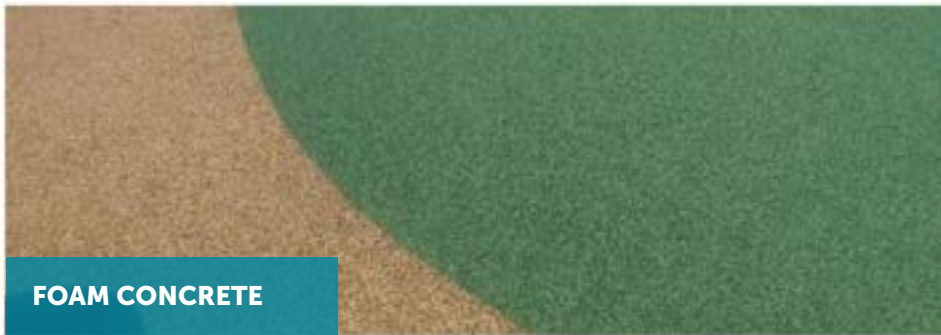
CONVENTIONAL PAVING CAN BE SIGNIFICANTLY COOLED USING SURFACE WATER AND LIGHT SURFACE COATINGS

Urban surface materials can also be cooled via increased permeability. Permeable (pervious, porous) materials facilitate water drainage and moisture evaporation more efficiently than conventional paved surfaces. This allows stormwater to drain through permeable pavement and ultimately be stored in the soil—which also supports improved urban stormwater management. Water stored in the pavement and/or the soil beneath can evaporate through the same means and cool the pavement during summer. Where conventional asphalt, concrete and paving

blocks are almost impermeable, evaporative cooling from permeable surfaces may decrease the surface temperature by up to 20°C. Utilising foam-based concrete that uses foam to make the final product permeable and light weight can be used in low traffic areas, playgrounds and pathways. An alternative method is to use permeable natural resins instead of traditional masonry binders in permeable concrete which results in permeable, light weight and light coloured pavements which can be used for walking, biking and hiking paths.

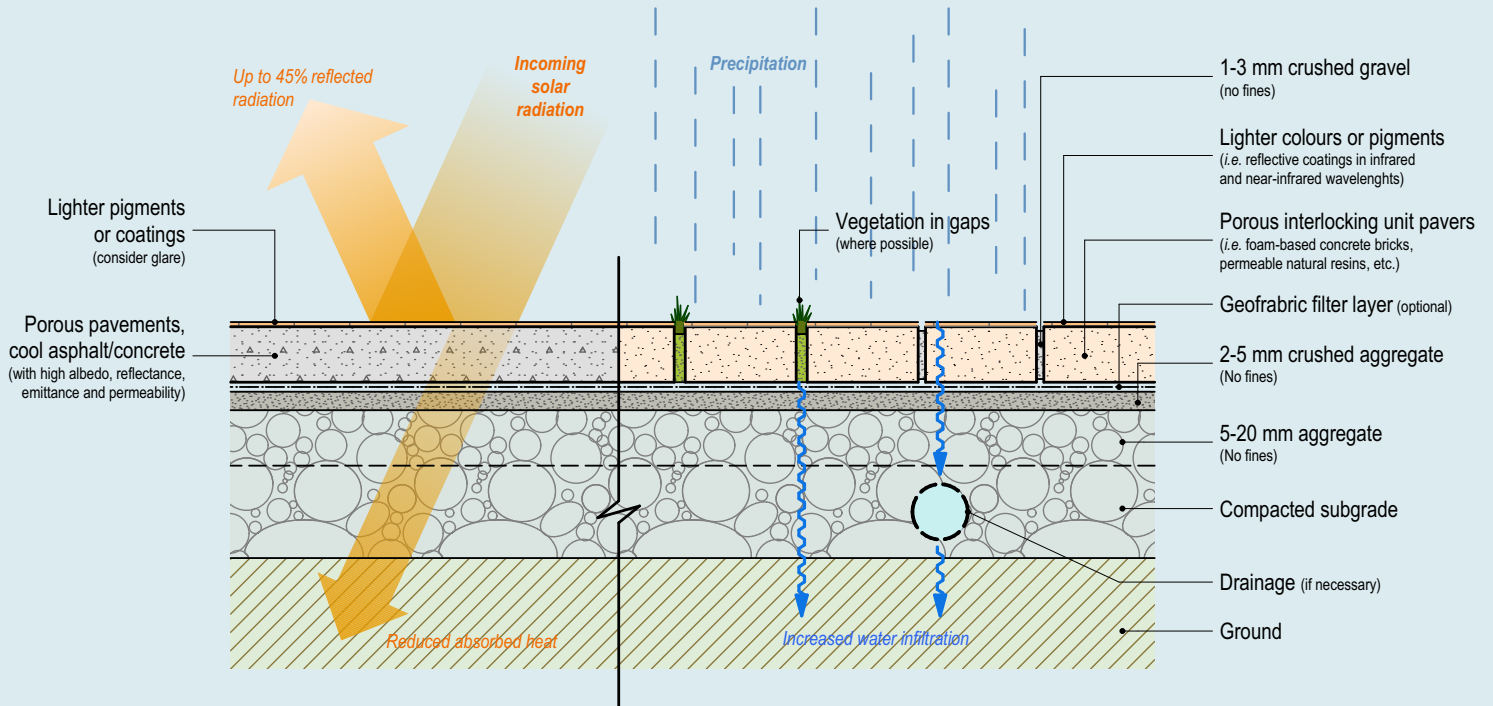
BLOCK PAVERS

Non-traditional cool pavements made from plastic, metal or concrete, filled with a variety of cool materials (even vegetation) and laid in place over a prepared base that can also be permeable. Being permeable and filled by reflective materials or vegetation, block pavers provide cool surfaces which can be used in low traffic areas such as driveways and shared pathways.



COOLING AND PERMEABLE PAVINGS

Permeable paving allows water to drain and evaporate through the urban surfaces.



COOL BUILDING ENVELOPES

Building rooftops cover almost 20% of the urban surfaces in Australian cities. Rooftops are generally more exposed to direct sunlight compared with other urban surfaces.

Thus, during a typical sunny day, rooftops retain more heat load than other urban elements. Most rooftop materials are heavy and dark and therefore they store significant heat.



Conventional roof surfaces (with a solar reflectance of 5% to 25%) can reach a surface temperature of 50–90°C on a typical hot summer day and cause significant stress to building occupants, cooling systems, energy infrastructures, roofing materials and urban microclimates. Utilising cool roofs results in increased indoor thermal comfort, decreased cooling energy demand, increased outdoor thermal comfort (including less waste heat from air-conditioning), higher urban air quality (decreased smog formation) and a longer service life for roofing materials.

Cool roofs utilise high-reflectance (albedo >0.65) and high-emissivity (emissivity >85%) surfaces to radiate away up to 75% of solar energy in the visible and IR wavelengths. Notably, solar glare is not a critical issue for most building rooftops. Cool roofs can be applied on both flat and pitched surfaces.

AROUND 1200W/M² CONTINUOUSLY REACHES THE EARTH'S SURFACE AT NOON ON A CLEAR SUMMER DAY, WHICH IS EQUIVALENT TO THE HEAT OF A COMMON DOMESTIC HEATER HEATING EVERY SQUARE METRE OF THE GROUND.

HIGH ALBEDO ROOF SURFACES

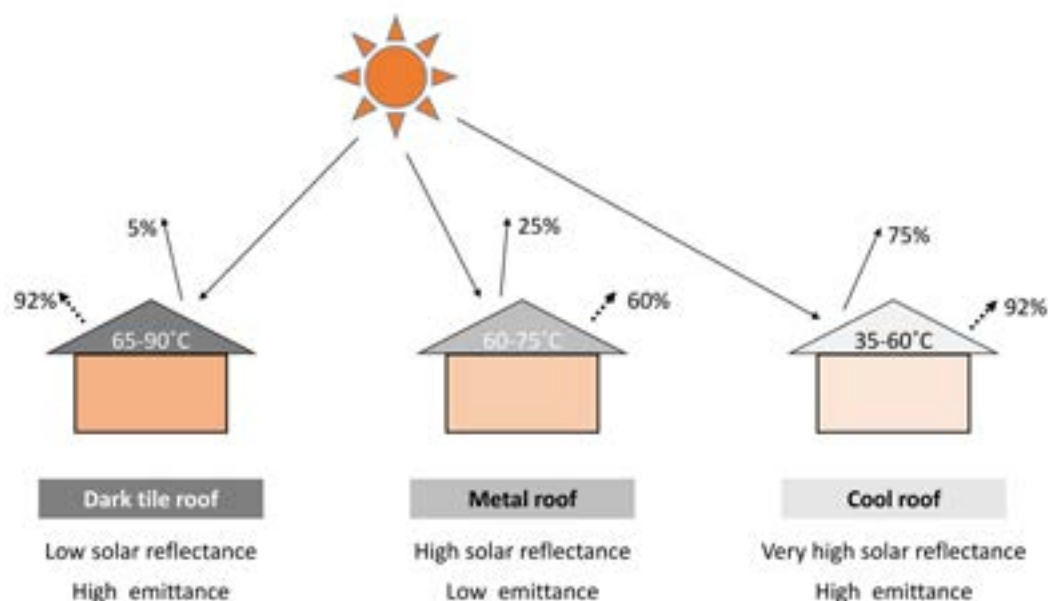
A high-albedo roof surface with cool white coating can radiate away up to 75% of incident solar energy. This means that a high-albedo cool roof absorbs only $300\text{W}/\text{m}^2$ instead of $900\text{W}/\text{m}^2$ for the best conventional roof.

THE NYC COOLROOFS INITIATIVE HAS COATED OVER 6.6 MILLION SQUARE FEET OF ROOFTOP SPACE

NYC CoolRoofs is a program in New York City that provides workforce training and coats city rooftops with a white, reflective coating that reduces building energy use and mitigates the urban heat island effect. Since its inception in 2009, the NYC CoolRoofs initiative has coated over 6.6 million square feet of rooftop space, contributing to lower cooling costs and avoiding an estimated 3,315 metric tons of carbon dioxide equivalent (tCO_2e) emissions in the city.

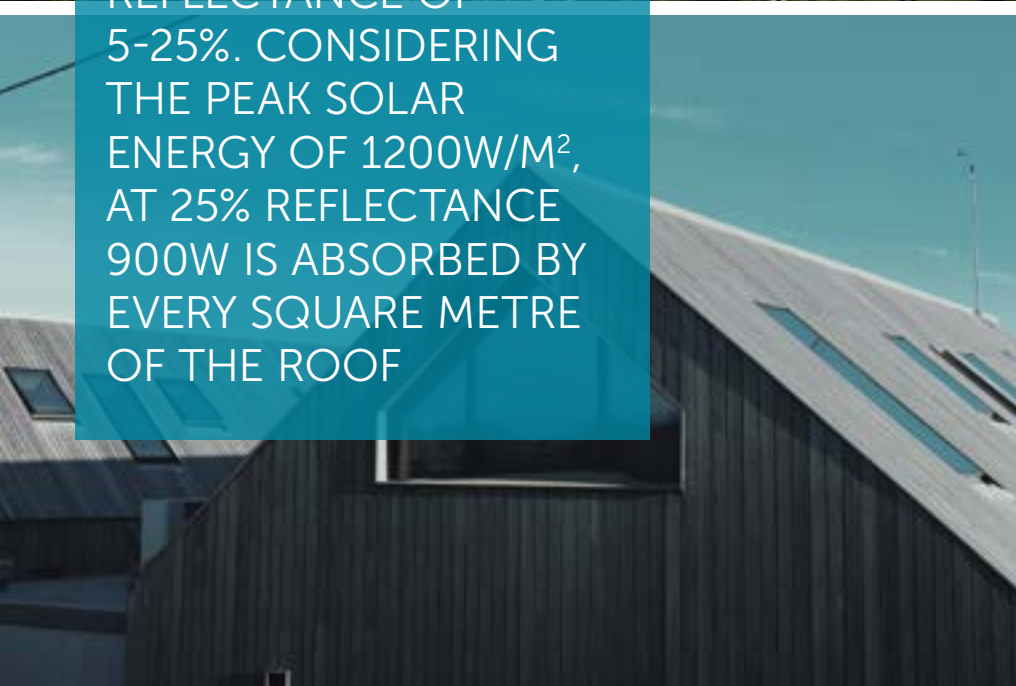
High emissivity (emittance) roof materials radiate away their stored heat at IR wavelengths. Most common roofing materials such as tiles and concrete slabs have a thermal emittance of 85% and above.

However, metal surfaces have the lowest thermal emittance of 20–60% depending on the roughness of the finish, age and cleanness.





CONVENTIONAL ROOF SURFACES HAVE OVERALL SOLAR REFLECTANCE OF 5-25%. CONSIDERING THE PEAK SOLAR ENERGY OF $1200\text{W}/\text{M}^2$, AT 25% REFLECTANCE 900W IS ABSORBED BY EVERY SQUARE METRE OF THE ROOF



THE THERMAL EMITTANCE OF A METALLIC ROOF CAN BE INCREASED BY THE USE OF A NON-METALLIC COATING SUCH AS PAINT (AND METALLIC PAINTS SHOULD NOT BE USED TO COAT NON-METAL SUBSTANCES). EFFICIENT COOL ROOFS HAVE BOTH HIGH REFLECTANCE AND HIGH EMITTANCE.

Utilising cool roofs can reduce surface temperature up to 33°C compared to conventional roofs and decrease indoor temperatures in the occupied space directly below the cool roof between 1.2°C and 4.7°C (average annual temperature reduction of 2.5°C). Such temperature reduction can save 18% to 34% energy for air-conditioning during summer in temperate climates, although 10% more energy may be needed for winter heating.

Cool roofs are relatively cheap, yet fast and efficient options to reduce the UHI effect. However, cooler roofs do not fundamentally lead to cooler air temperatures, since the reflected or emitted heat can get trapped in the built environment, especially in very dense urban settings with tall buildings, such as central business districts.

COOL PAVING TECHNOLOGIES

This gives a summary of eleven common cool paving technologies

COOL SURFACE TYPE	TECHNOLOGY	URBAN CLIMATE IMPACT	ISSUES TO CONSIDER	TARGET USE	
<u>High albedo asphalt</u>	Asphalt pavement modified with high albedo materials or treated after installation to raise albedo.	<ul style="list-style-type: none"> Can increase solar reflectance up to 20% more than conventional asphalt. Lower surface temperature day and night. 	<ul style="list-style-type: none"> Solar reflectance of asphalt increases over time. Solar reflectance of concrete decreases over time. Reflected radiation may be absorbed by other surfaces. Low surface temperature does not directly result in low air temperature. 	Paving large exposed areas such as roads and parking lots.	
<u>Chip seal, micro surfacing and white topping</u>	Applying plastic-based aggregate to resurface asphalt.				
<u>High albedo concrete</u>	Portland cement mixed with water and light aggregate.	<ul style="list-style-type: none"> Can increase solar reflectance to 40-70% Lower surface temperature day and night. 	<ul style="list-style-type: none"> Solar reflectance increase over time. Urban geometry needs to be carefully considered. 		
<u>Coloured asphalt</u>	Applying coloured pigments or seal when new or during maintenance.	<ul style="list-style-type: none"> Can increase solar reflectance to 20-70% Lower surface temperature day and night. 	Issues as above, and in addition: <ul style="list-style-type: none"> Traffic makes the pavement darker over time. Surfaces may wear away with polishing. 	Low traffic areas such as sidewalks, driveways and parking lots.	
<u>Coloured concrete</u>	Applying coloured binder or aggregate when new or during maintenance.				
<u>Resin-based concrete</u>	Using natural clear coloured tree resins in place of cement to bind the aggregate.	<ul style="list-style-type: none"> Albedo is mainly determined by the colour of the aggregate. Lower surface temperature day and night. 	<ul style="list-style-type: none"> The cooling mechanism depends heavily on available moisture. When dry, daily surface temperature may be higher than conventional surfaces but this does not affect nocturnal surface temperature. Void spaces can become filled with dirt over time. Best to use in climates with adequate moisture during summer. 	All applications including large exposed areas such as roads and parking lots and low traffic areas such as sidewalks and driveways.	
<u>Permeable asphalt</u>	Using rubber or open-grade aggregate to provide more void spaces in asphalt to drain water.	When moisture is available in or below that surface, lower surface temperature through evaporative cooling day and night		<ul style="list-style-type: none"> The cooling mechanism depends heavily on available moisture. Sustainability of the vegetation may vary with local climate conditions and available moisture. 	Low traffic areas such as sidewalks, driveways and parking lots.
<u>Permeable concrete</u>	Using foam or open-grade aggregate to provide more void spaces in concrete to drain water.				
<u>Block pavement</u>	Clay or concrete blocks filled with rocks, gravel or soil.				
<u>Vegetated pavement</u>	Clay, plastic or concrete blocks filled with soil and covered with grass or other vegetation.			Low traffic areas such as sidewalks, driveways and parking lots.	

URBAN VEGETATION

Lack of sufficient vegetation cover is a defining feature of highly developed urban areas. It is also a major contributor to the UHI effect through decreased evapotranspiration in cities.



INCREASED
EVAPOTRANSPIRATION
VIA URBAN
VEGETATION
CONTRIBUTES TO
URBAN COOLING

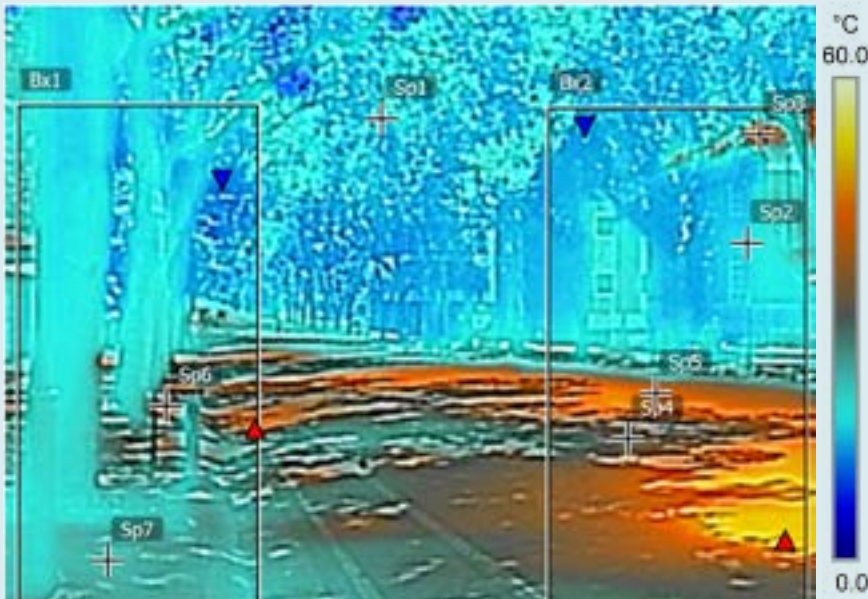
Therefore, increased urban vegetation is highlighted as a mainstream technique to mitigate the UHI effect. Vegetation facilitates UHI mitigation via evapotranspiration, shading and providing cooler surfaces to reduce MRT. Suitable species selection and planting design with taller vegetation – shrubs and trees – can also help channel cooling breezes to where they are needed.

Photosynthesis – as an energy-demanding process – makes natural landscapes cooler than unvegetated urban systems. In addition to its substantial contribution to UHI mitigation, urban vegetation supports more effective stormwater management, improved air quality, biodiversity, urban aesthetics and energy saving. While landscaping at ground level is the traditional method

of vegetating cities, green roofs and green walls are also recommended, especially for urban transformation projects, high density developments where ground space is limited, and when green roof/wall co-benefits are a design objective.

STREET TREES

Trees use solar energy to drive photosynthesis and evapotranspiration. Meanwhile, leaves and branches provide shade thus reducing the exposure of urban surfaces to solar radiation.



Frome Road, Adelaide, 11 Jan 2017

MEASUREMENTS

Max BX1	36.5°C
Min Radiant temp.	18.8°C
Average Heave tree canopy	23.6°C
Max BX2	46.9°C
Min Radiant temp.	19.5°C
Average Heave tree canopy	28.0°C
Sp1 Tree Canopy	20.7°C
Sp2 Building facade (shaded by tree)	21.0°C
Sp3 Building facade (unshaded)	35.6°C
Sp4 Asphalt (shaded by tree)	30.1°C
Sp5 Asphalt (unshaded)	22.7°C
Sp6 Paving (unshaded)	31.9°C
Sp6 Paving (shaded by tree)	25.0°C

Parameters

Emissivity 0.95	Air temp. 23.9°C
Refl. temp 27°C	Global temp. 27.1°C

Tree canopy cover in most of Australia's major cities is less than 20% (e.g. 13% in Melbourne CBD). An additional 10% tree canopy coverage can be achieved by planting more trees in laneways and residential streets. Such an increase could contribute to surface temperature reduction of around 15°C by providing shade over paving, walls, and roofs. This results in a UHI reduction of 1.5°C at precinct scale. Street tree canopy can be increased by planting shade trees in footpaths, forecourts and street medians.

NATURAL TURFS AND GRASS COVER

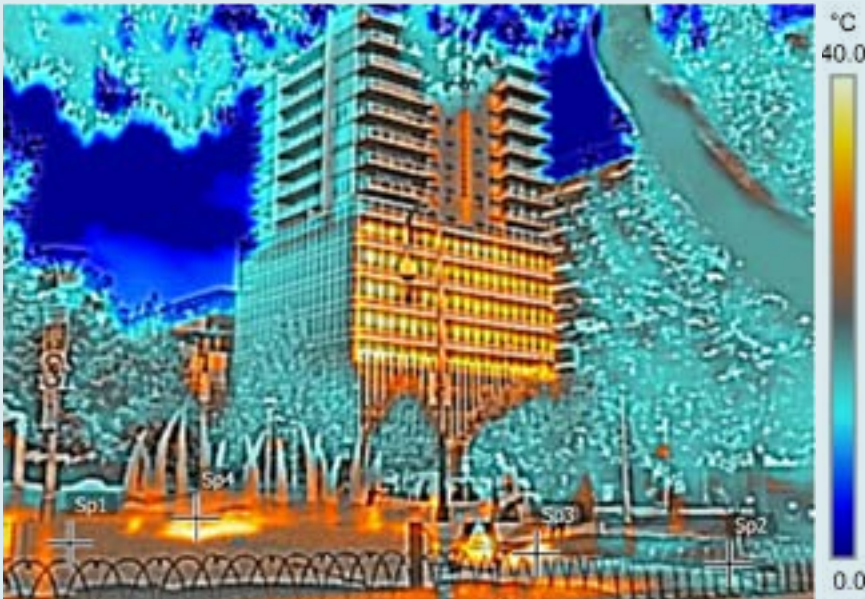
Natural turfs use similar principles for surface cooling through evapotranspiration. However, unlike trees they do not provide shade, so the cooling effect of turf is highly dependent on availability of water for irrigation.

The surface temperature of well-irrigated grassed areas can be up to 15°C cooler than surrounding

paved areas under full solar radiation in summer. However, such surface temperature reduction may become less than 5°C for dry turfs. Surface temperature reduction of natural turfs contributes to lower mean radiant temperature in the built environment.

PARKS

Radiant temperatures in urban parks with sufficient irrigation are 2-4°C cooler compared with adjacent unvegetated or built-up areas, while air temperature reduction varies between 1-2°C according to the park's extent and the proportion of trees.



Hindmarsh Square, Adelaide, 23 Mar 2014).

MEASUREMENTS

Sp1 Natural turf (unshaded)	23.7°C
Sp2 Natural turf (shaded by tree)	20.9°C
Sp3 Building facade (unshaded)	35.6°C
Sp4 Paving (unshaded)	46.4°C
Sp6 Paving (shaded by tree)	32.0°C

Parameters

Emissivity 0.95
Refl. temp 28°C

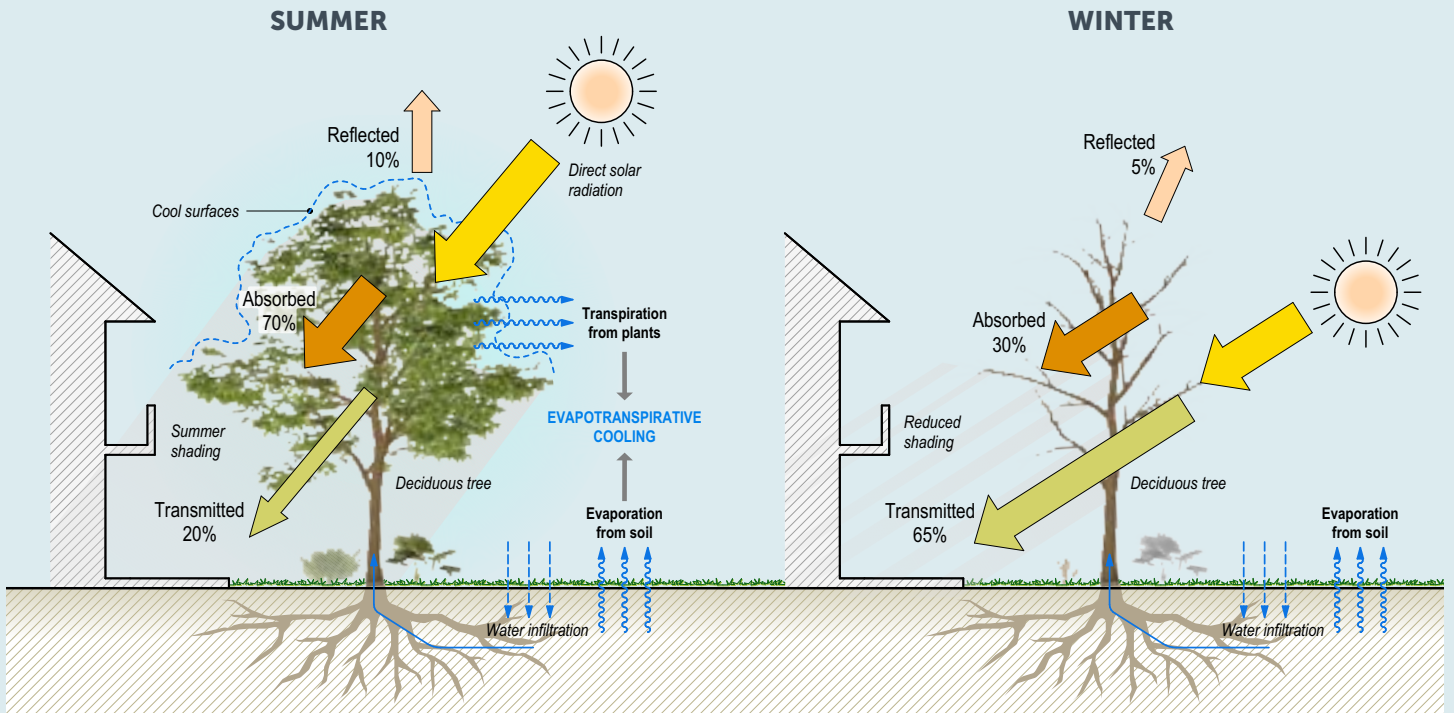
COMBINATION OF TREE CANOPY AND NATURAL TURFS IN URBAN PARKS RESULTS IN 5-10°C COOLER RADIANT TEMPERATURES AND 1-2°C AIR TEMPERATURE REDUCTION IN URBAN PARKS

Occurrence of relatively cooler temperatures in parks is known as the park cool island (PCI) effect. The magnitude of cooling in PCIs varies due to vegetation type and irrigation. Parks with moderate tree canopies which rely on natural precipitation in dry climates tend to achieve their highest cooling capacity several hours after sunset when the UHI effect is at its peak. This is mainly the result of a high sky view factor that enhances longwave heat loss. PCIs associated with the above type of park have a

relatively higher temperature during the day compared with adjacent neighbourhoods. Parks with dense tree canopies such as in tropical areas, or parks with significant water supply, reach their maximum cooling capacity during the afternoon.

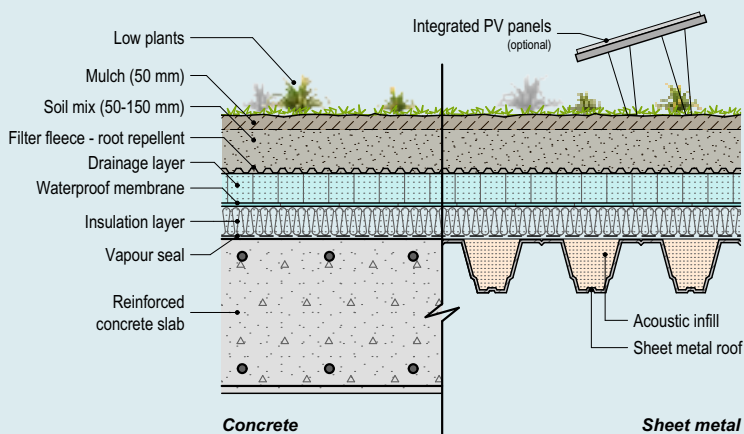
GREEN ROOFS

Cooling effect of a tree in a sunny day in summer and winter.

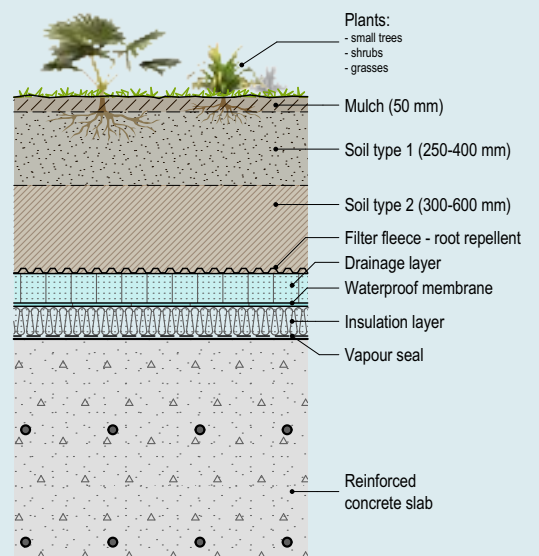


Based on Hunter et al. (2012)

Extensive green roofs



Intensive green roofs





GREEN ROOFS AT THE UNIVERSITY OF WARSAW, POLAND

When there is a shortage of space for parks and street trees, “living architecture” or landscapes on structure may be a viable proposition. Application of greenery on flat surfaces such as shallow roofs is less complicated and costly.

Green roofs require adequate load-bearing structure (to support the extra load of soil and plants), an extra insulation layer, waterproofing membrane, specialized drainage layer, root barrier, engineered growing medium (with or without soil) and appropriate plant selection. Green roofs are typically classified into extensive (with shallower growing medium and lighter vegetation cover) and intensive (full rooftop gardens).

An extensive green roof is planted with grasses, wildflowers, and other native plants to produce a

low-maintenance and light-weight feature. Use of local native plants can reduce the cost of irrigation and drainage layers. Extensive roofs generally weigh between 25 kg/m² and 150 kg/m² (up to 10cm of soil excluding the water weight) and can be applied to roof structures of up to 30° slope. Extensive green roofs need much less structural support than intensive roof gardens, making them a cost-effective method for retrofitting existing roofs, especially in suburban areas.

An intensive green roof is essentially a traditional garden located on

the rooftop. To remove planting limitations, intensive green roofs use more soil and add drainage and root control layers, which make them heavier and more expensive. Typical intensive green roofs weigh between 100 and 200kg/m², with ≥25cm of soil. The extra weight necessitates additional structural engineering considerations compared with conventional roofs or extensive green roofs. Intensive green roofs are more common on commercial and flat roofs and are often accessible for recreation and relaxation.

A comparative study of [green roofs](#) and [cool roofs](#) in a Mediterranean climate indicates that well-irrigated green roofs and high emissivity cool roofs have the best performance in summer and hot climates. Dry green roofs which require no or minimal irrigation improve building energy and thermal performance in winter and colder climates. An Australian study on the retrofitting potential of green roofs in city CBD areas suggests that only a limited

proportion of [existing structures](#) can adopt green roofs without significant modifications. Extensive green roofs with a substrate depth of 10-20cm require supplementary irrigation in the Australian climate. Thus, water management is a major parameter in Australian green roof research and practice.

Green roofs can be [integrated with photovoltaic \(PV\) panels](#) to provide both energy and cooling. Extensive

green roof surfaces can be combined with PV panels.

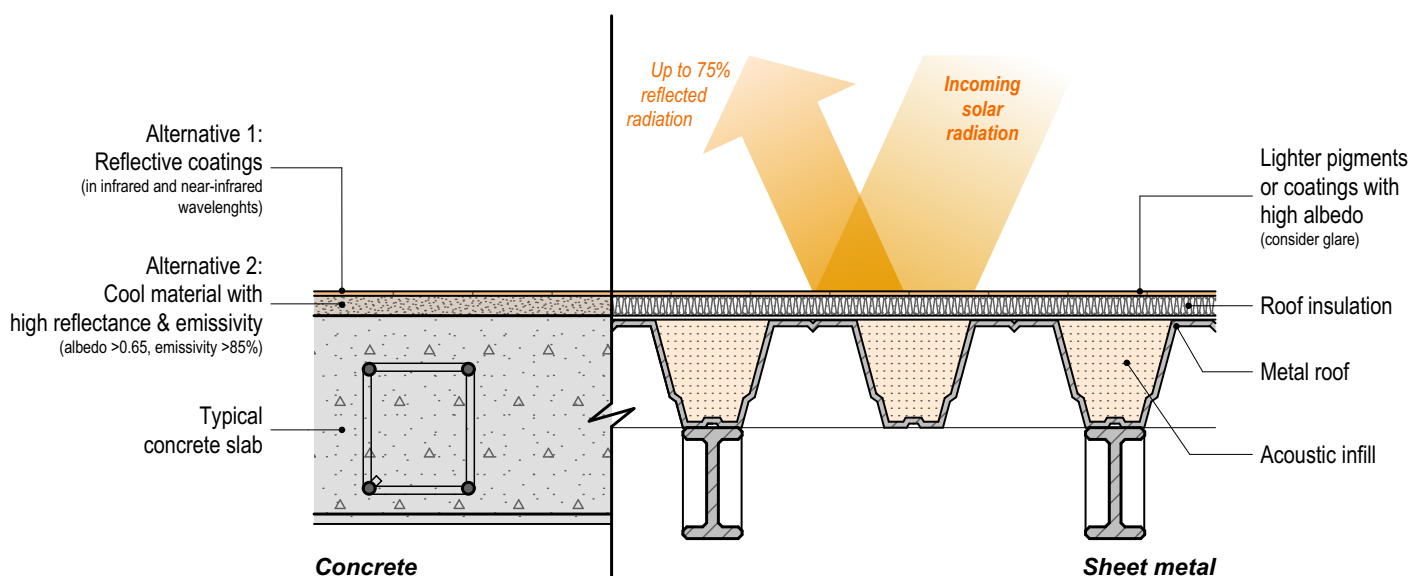
Replacing a dark roof with a PV-covered white or green roof [reduces total sensible flux by up to 50%](#).

The cooling effects of green roof vegetation can [improve efficiency of PV energy production](#) depending on factors such as plant species, climatic conditions, evapotranspiration and albedo.

SELECTION GUIDE FOR EXTENSIVE AND INTENSIVE GREEN ROOFS

	EXTENSIVE /LOW-PROFILE/ECO ROOFS	INTENSIVE/HIGH-PROFILE/ROOF GARDENS
Growth media	50-150mm	<ul style="list-style-type: none"> • 150-400mm and deeper
Weight	75-250km/m ²	<ul style="list-style-type: none"> • More than 250km/m²
Plants height	Low growing plants 5-600mm	<ul style="list-style-type: none"> • All heights
Tree variety	Alpine types, succulents, herbs, some grasses and mosses	<ul style="list-style-type: none"> • Trees, shrubs and architectural features depending on loads, design & budget
Usage	Usually non-accessible and non-recreational	<ul style="list-style-type: none"> • Designed for human recreation, gardening and social activities
Slope	Up to 30° & higher	<ul style="list-style-type: none"> • Relatively flat
Cost	\$50-250/m ²	\$250-400/m ²
Water requirement	Low water required	Irrigation usually necessary
Maintenance	Low maintenance	Higher maintenance

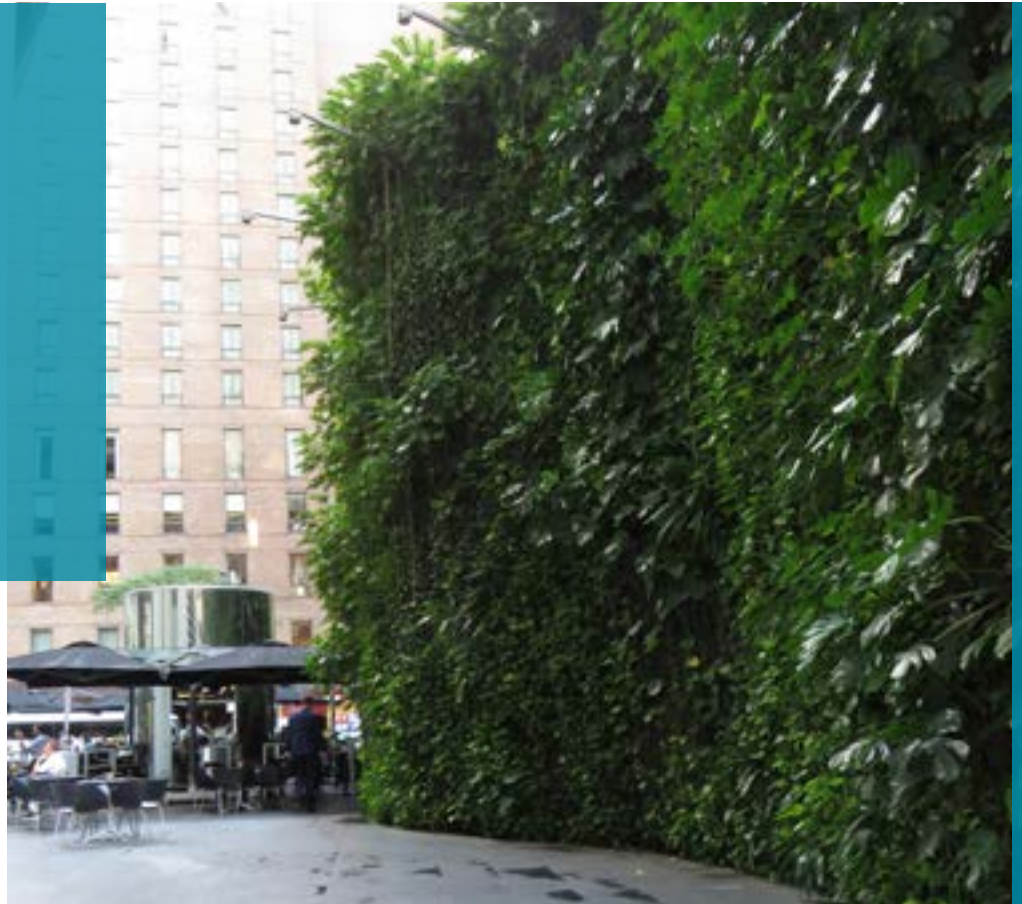
Concrete & metal cool roofs



GREEN WALLS

Vertical urban surfaces may also accept vegetation, especially when the ground space is very limited in cities.

AN INTENSIVE GREEN WALL PROVIDES SHADE AND EVAPORATIVE COOLING EFFECT AND CAN FACILITATE QUALITY SOCIAL ACTIVITIES



The plant choice for green wall systems (also known as vertical landscaping) is more limited compared with green roofs. Green walls can offer both microclimate and aesthetic benefits. Similar to green roofs, green walls are categorized into extensive (also known as green facade) and intensive (also called living wall) systems. In both systems, the green wall provides additional thermal insulation and passive energy saving to the building. Intensive green walls can provide shading and more evaporative cooling. Intensive green walls need more structural support and are costlier to build and maintain.

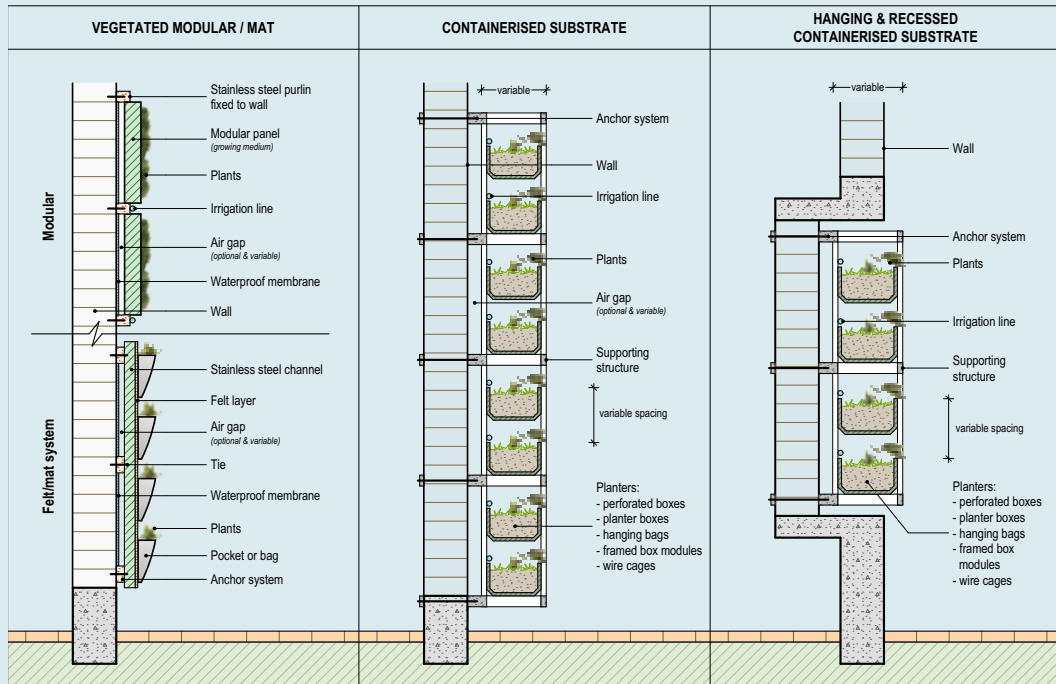
A balcony scale green wall consists of small, modular proprietary systems fixed to the wall, containing small planting pockets or pots. A domestic scale green wall typically covers between one and four storeys in height and is usually modular, fixed to the wall or on a supporting framework. Commercial scale systems cover the building facade from four to around thirty floors high and are fixed to the facade by a support framework integrated into the building facade.

Vertical landscaping can reduce building envelope surface temperatures between 5°C and 15°C. A mean annual air temperature reduction of 2°C is reported for spaces immediately adjacent to green walls. The cooling effect of green walls is highly dependent on their orientation, plant density and water content.

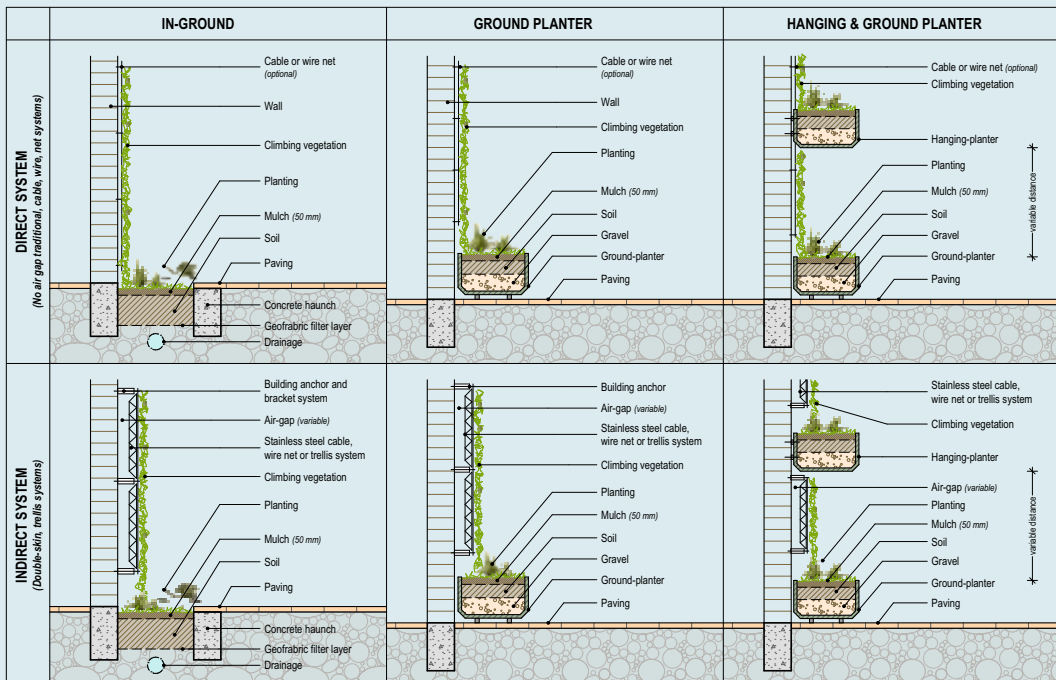
TYPES OF LIVING GREEN WALLS

This explains different type of living green walls that are rooted on walls or on ground.

ON WALLS



ON GROUND



EVAPORATIVE COOLING

Water needs energy to change phase from liquid to vapour (evaporation); this physical process may be harnessed to remove heat from the atmosphere.

EVAPORATIVE COOLING SYSTEMS AND SURFACE WATER ARE HIGHLY EFFECTIVE COOLING STRATEGIES IN CITIES WITH DRIER CLIMATES SUCH AS ADELAIDE, MELBOURNE AND PERTH



Increased evaporative cooling can be implemented via passive or active systems in public spaces.

The efficacy of evaporative air-conditioners in the dry climate of Adelaide, Melbourne and Perth can be ten-times that of refrigerative air-conditioners. Multi-stage evaporative coolers and misting fans can be effective in more humid regions. The evaporation of water utilised in hot arid regions was able to achieve a drop of about 10 °C below ambient temperature in still air, while the temperature fell by 15 °C under forced convection.

SURFACE/RUNNING WATER


In dry climates surface water can use ambient heat for evaporation, thus cooling the air temperature. Passive direct evaporative cooling can occur in outdoor space with the aid of natural wind flow. This can be achieved through use of fountains or through architectural design interventions such as the evaporative downdraft cooling system.

Passive evaporative cooling is an efficient cooling strategy in cities with dry summer climates such as Perth or Adelaide. The use of running water on urban surfaces,

water features or contained water bodies in humid climates may result in increased relative humidity, which can cause uncomfortable microclimates. Passive evaporative cooling is highly dependent on dry air and air movement, and can lead to ambient temperature reduction of 3-8 °C when relative humidity is less than 50%.

EVAPORATIVE COOLING

Evaporative spray cooling systems provide thermal relief on hot days, even in a subtropical climate.



THE FINE WATER DROPLETS ABSORB AMBIENT HEAT FROM THE ENVIRONMENT

IN THE SEVILLA 1992 EXPO THIS EFFECT WAS WIDELY USED, LARGE FOUNTAINS AND WATER BASINS WERE PLACED ALL AROUND THE EXPO ALONG ALL THE MAIN PATHS AND SQUARES TO INCREASE THERMAL COMFORT; SOME AREAS EVEN INCLUDED VERTICAL WALLS OF WATER.

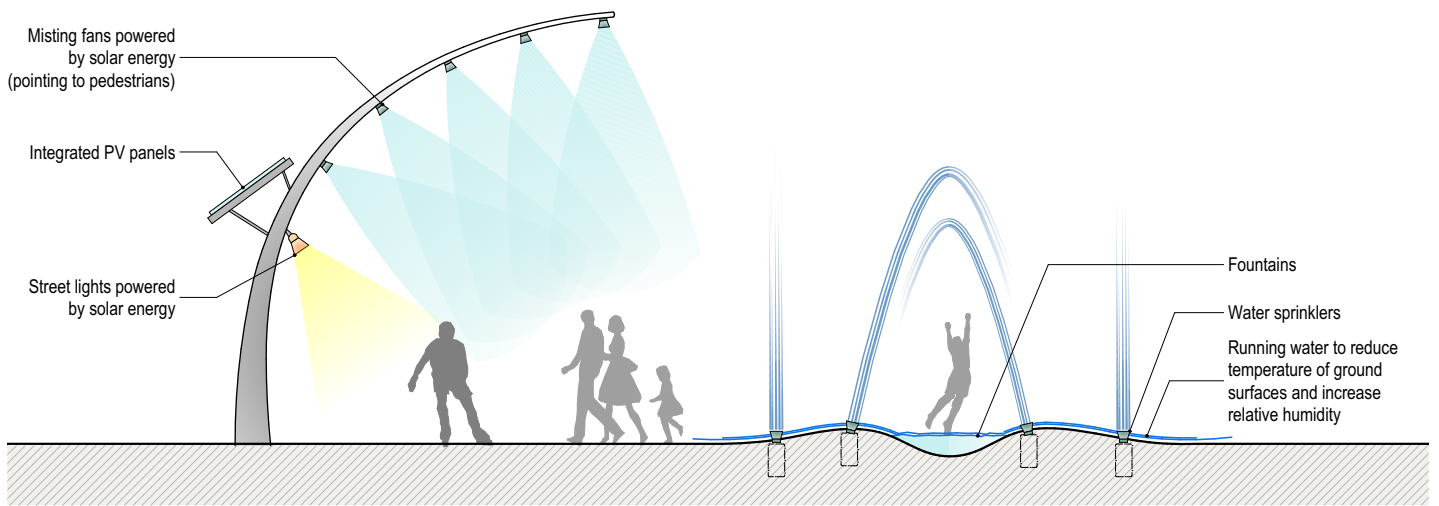
Calle Torricelli, EXPO 1992, Sevilla

Evaporative spray cooling systems provide thermal relief on hot days, even in a subtropical climate. Misting fans produce a cloud of very fine water droplets through forced mixing between the airstream and water, allowing the ambient air to cool from its dry-bulb temperature to its wet bulb temperature if the droplets are fully vaporised.

Misting fans use high pressure to deliver a cool mist of very fine water droplets of less than 10µm in size. Ambient air temperature is reduced by forcing water

through small nozzles under high pressure, producing clouds of fine mist which absorb ambient heat to be evaporated in the air. The combination of high pressure and ultra-fine water particles result in a cool and relatively dry feeling on the skin. Misting fans affect distances up to 5m from the fan. Depending on the weather conditions an air temperature reduction of 5-15°C may occur in the immediate area around the misting fan. Misting fans are more effective when installed 2.4-3m above ground level.

EVAPORATIVE SPRAY COOLING SYSTEM



Evaporative spray cooling systems



SHADING

Exposure to solar radiation is the obvious driver of heat storage in urban materials, so casting shade on surfaces can be a logical way to decrease heat accumulation.



COMBINATION OF BUILDINGS, TEMPORARY SHADE STRUCTURES, TREE CANOPY, GREEN WALL AND SURFACE WATER MAKES DARLING QUARTER A VIBRANT PUBLIC SPACE DURING HEATWAVES IN SYDNEY

Blocking solar radiation can decrease surface temperature and mean radiant temperature in the canopy layer (human scale) and affect outdoor thermal comfort in the

public realm. While shading does not necessarily decrease the air temperature, it can decrease radiant temperature significantly and lead to enhanced outdoor thermal comfort in public spaces.

Shading may be provided by natural (trees) or artificial structures or a combination of both, discussed below.

SHADING STRUCTURES

Buildings provide permanent yet moving shade over urban surfaces (daily and annually).

In Arizona Science Centre (Phoenix), the design goal was to combine solar energy generation with a PV Pavilion act a visual backdrop for the outdoor grass covered amphitheatre and create a shaded meeting spot adjacent to the new Science Centre main entrance. _Arizona Science Centre PV Pavilion



The Sierpiński gasket as a shading device. Fabricated from weather-resistant material, this common fractal figure represents a kind of artificial tree, which cuts off all incident radiation when the sun is directly overhead but allows increasing light penetration as the sun angle becomes more acute. This example is from the Japanese National Museum of Emerging Science and Innovation (Miraiikan) in Tokyo.



BUILDINGS' SHADE CAN DECREASE DIRECT SOLAR RADIATION ON URBAN SURFACES AND DECREASE THEIR SOLAR GAIN DURING THE DAY.

However, building volumes can prevent radiant heat from escaping from the built environment during the night. Decreased sky view factor (the visible sky from a particular point in space) reduces radiative heat loss and in case of light wind flow reduces turbulent heat transfer. The balance between solar gain and radiant loss can be influenced by buildings' volume, their orientation towards the sun, and envelope and

canyon materials. Thus, buildings around a public space need to be carefully designed for their specific context to increase outdoor thermal comfort.

Shading structures provide cost-effective solutions to prevent solar radiation from urban surfaces. A wide variety of shading structures has been used in the design of shopping streets, building entries and public venues.

TEMPORARY SHADING

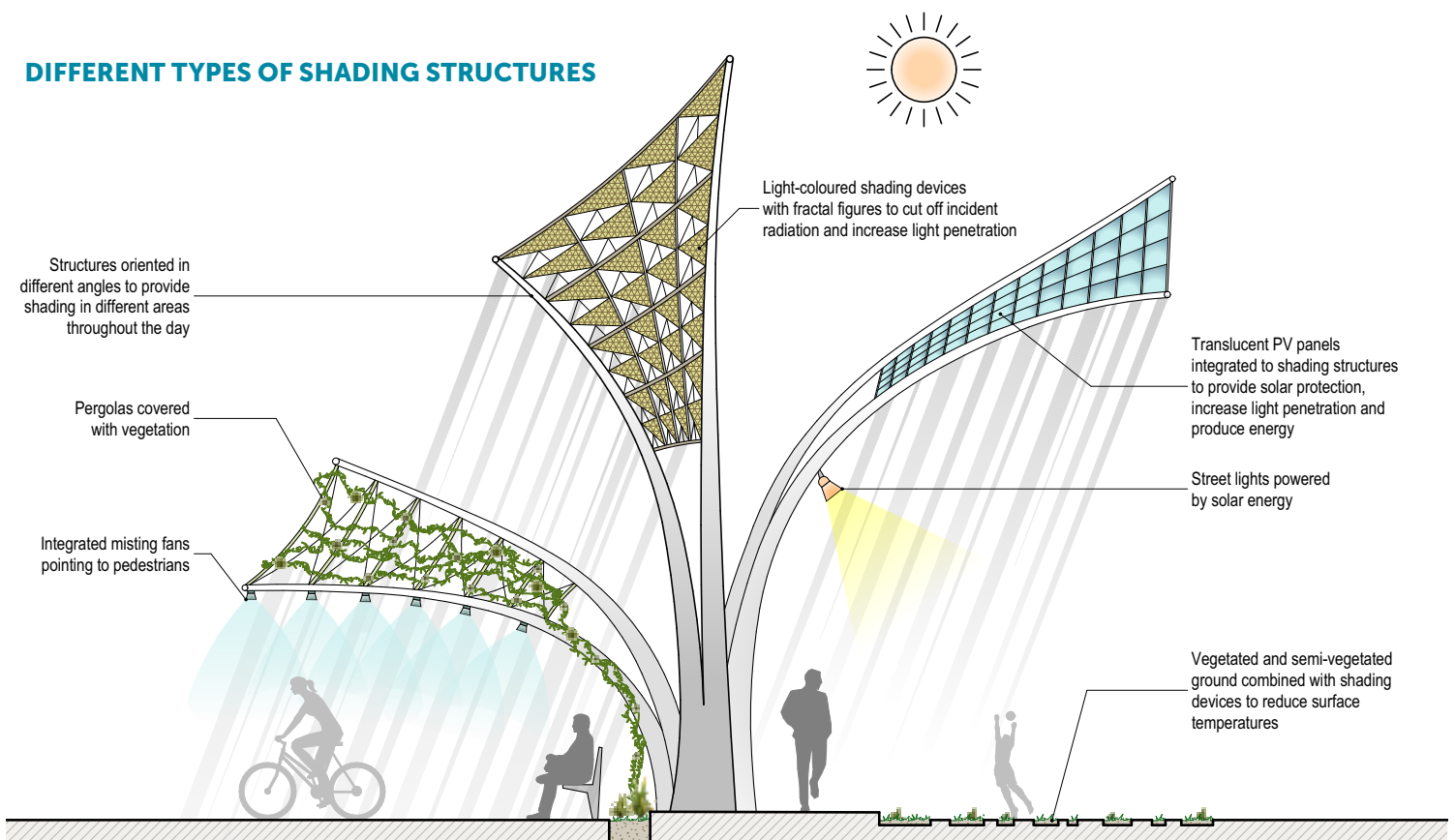
Shading over street canyons via light coloured fabrics is a traditional urban canyon cooling method in Southern Europe and the Middle East.

TEMPORARY SHADES CAN PREVENT UP TO 98% OF SOLAR RADIATION DIRECTING ONTO PEOPLE AND URBAN SURFACES

Temporary shades, awnings and market umbrellas can protect public space users from direct solar radiation and enhance outdoor thermal comfort through decreased radiant temperature.

Temporary shades can be relocated based on occupational, daily and seasonal requirements. They can prevent up to 98% of solar radiation directing onto people and urban surfaces. Occasional usage of temporary shades is a customary practice in the dining and entertainment industry in Australia.

DIFFERENT TYPES OF SHADING STRUCTURES



COOLING CAPACITY OF DIFFERENT STRATEGIES

	MAX EFFECT ON SURFACE TEMPERATURE AROUND THE SPOT OF APPLICATION	MAX EFFECT ON AIR TEMPERATURE AROUND THE SPOT OF APPLICATION	MAX EFFECT OF PRECINCT SCALE AIR TEMPERATURE	MAIN CONSTRAINT
Cool paving	33.0°C	2.5°C	2.0°C	Changes in reflectance over time (aging, dirt accumulation)
Permeable paving	20°C	2.0°C		<ul style="list-style-type: none"> • Water supply • Less efficiency in humid climates
Cool envelope treatments	33°C	2.5°C (indoors)		Complex reflectance in street canyons
Green envelope	20°C	4.0°C		<ul style="list-style-type: none"> • Water supply • Horticultural maintenance
Street trees	15°C	4.0°C		
Parks	15°C	4.0°C		
Evaporative cooling	N/A	8.0°C		Water supply
Misting fan	N/A	15°C	N/A	Effect is temporary
Shading	15°C	N/A	N/A	

- Passive and active cooling strategies and their key potentials and constraints
- The UHI mitigation methods can be categorized into three major approaches: cool materials, increased greenery and energy efficiency.
- Water supply is the main constraint for cooling effect of urban greenery. The peak demand for water is similar to that of electricity during heatwaves.

Effective cooling of public spaces can be achieved via a combination of the strategies discussed in the previous pages. Each cooling strategy provides specific opportunities and constraints. For example, permeable paving may not be as effective in humid climates as it is in dry climates in cooling urban surfaces. Tree canopies provide shade and evaporative cooling simultaneously

while the cooling effect of natural turf is highly dependent on its irrigation. A summary of the cooling capacities of various strategies is presented in this section. Details for application of urban cooling strategies in different public spaces in Australian cities are presented in the subsequent sections.

URBAN COOLING CONTEXT-INTERVENTION MATRIX

Application and effectiveness of urban cooling techniques including cool and green surface covers, evaporative cooling and shading vary with locational context.

Depending on the state of development, aspect ratio and sky view factor a range of urban cooling guidelines may become more appropriate and cost-effective in inner city/CBD, inner suburb and outer suburb contexts.

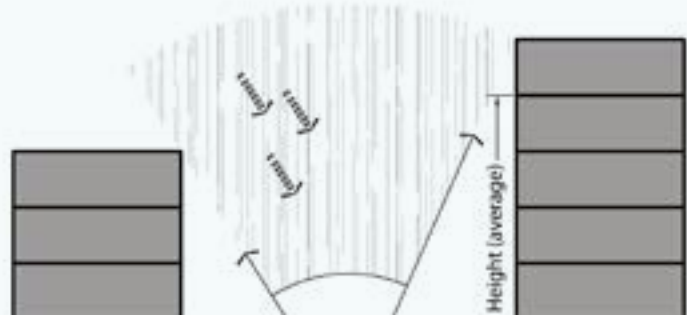
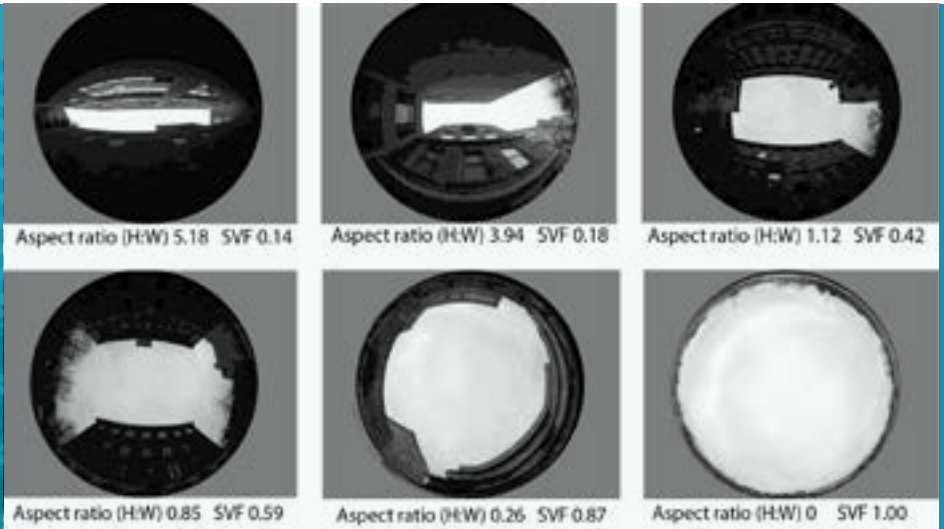
URBAN CONTEXT	SVF	COOL PAVING			COOL ENVELOPE		GREEN ENVELOPE		TREE CANOPY	EVAPORATIVE COOLING		SHADING STRUCTURES	
		HIGH ALBEDO PAVING	HIGH EMITTANCE PAVING	PERMEABLE PAVING	HIGH ALBEDO ENVELOPE TREATMENTS	HIGH EMITTANCE ENVELOPE TREATMENTS	GREEN ROOF	GREEN WALL		SURFACE WATER AND EVAPORATIVE COOLING	MISTING FAN		
INNER CITY	Plaza	Low	N	3	3	R-3	WR-3	3	3	1	D-3	HD-3	2
	Square	Medium	2	3	3	R-3	WR-3	3	3	3	D-3	HD-3	3
	Street	Low	N	3	3	R-3	WR-3	-	3	3	-	-	2
	Pedestrian mall	Low	N	3	3	R-3	WR-3	3	3	2	D-3	HD-3	3
INNER SUBURBS	Plaza	Low	N	3	3	R-3	WR-3	3	3	1	D-3	HD-3	3
	Square	Medium	2	3	3	R-3	WR-3	2	2	3	D-3	HD-3	-
	Street	Medium	N	3	3	R-3	WR-3	-	2	3	-	-	-
	Pedestrian mall	Medium	N	3	3	R-3	WR-3	2	2	2	D-3	HD-3	3
OTHER SUBURBS	Plaza	Medium	N	3	3	R-3	WR-3	3	2	1	D-3	HD-3	3
	Square	High	2	3	3	R-3	WR-3	1	1	3	D-3	HD-3	-
	Street	High	N	3	3	R-3	WR-3	-	1	3	-	-	-
	Pedestrian mall	High	N	3	3	R-3	WR-3	1	1	2	D-3	HD-3	3

D = Dry climate W = Wall Effectiveness
H = Humid climate R = Roof High = 3 Medium = 2 Low = 1 N = negative

INNER CITY CONTEXT

Inner city locations in Australian cities are generally associated with high-density development and low sky view factor ($SVF < 0.5$), particularly in CBDs of major cities such as Sydney, Melbourne, Brisbane, Perth and Adelaide.

INNER CITY OF MAJOR AUSTRALIAN CITIES IS ASSOCIATED WITH TALL BUILDINGS CAST THEIR SHADE ON PUBLIC SPACES AND LOW SKY VIEW FACTOR



Inner city context in smaller cities such as Hobart and Darwin is similar to the inner suburb context in major cities, with medium density and mid-range SVF.

In inner cities, public spaces are commonly surrounded by tall buildings. Urban surfaces are partially protected from the solar radiation due to the shade of surrounding buildings. However, low SVF decreases radiant and turbulent heat loss. Therefore, using high emittance cool paving and cool envelope treatments facilitates less heat storage in small public spaces such as plazas, street canyons and pedestrian open air malls.

Inner cities are commonly associated with low tree canopy ($TC < 15\%$). Increasing tree canopies by 10-20% can enhance shadow coverage, evapotranspiration and micro-

scale air turbulence (due to temperature differences above, below and around the tree canopy).

Larger public spaces such as squares and parks can benefit more from evaporative cooling from permeable paving, water features and tree canopy and vegetation in general. Also, more space is available for trees in parks and squares compared to the very limited space in urban canyons and plazas (although when space is available, providing tree canopy is the best practice).

High albedo surfaces are normally not suggested in the public realm due to glare and health issues of increased reflectance. They may be used on building rooftops or in combination with high emittance surfaces in wider public spaces with low human traffic.

Cool and green covers may be used on both horizontal and vertical surfaces of buildings and spaces between them due to limited space availability. Water features such as fountains and water walls can be used whenever space is available to increase evaporative cooling (unless in very humid climates) and misting fans can assist immediate space cooling when needed.

Public spaces in inner city locations are generally shaded at least partially during the day. Temporary and tree canopy shade may be used to complete the shadow over urban canyons or in plazas and squares. However, species selection for any urban vegetation in these locations, whether on structure or at grade, will be reliant on the plants' light requirements.

INNER SUBURB CONTEXT

The inner suburb context in major Australian cities is associated with medium-density development, medium sky view factor ($0.5 < SVF < 0.8$).



Inner suburb context in Australian cities is associated with medium height (two to six-story) buildings with medium sky view factor.

In smaller cities, inner suburban locations have higher SVF, similar to the outer suburbs.

In the inner suburbs, public spaces are commonly surrounded by two to six-storey buildings and public space surfaces are partially protected from solar radiation due to the shade of surrounding buildings. However, in most cases solar radiation can reach the public space most of the day, depending also on the city's latitude. Temporary and tree canopy shade may be used to complete the shadow over urban canyons or around plazas and squares.

Due to the medium SVF, using high emittance cool paving and cool envelope treatments facilitates less heat storage in all public spaces such as plazas, street canyons and pedestrian open air malls.

In these areas, tree canopy cover is commonly below 20%. Having more available open spaces such as building frontages, backyards and wider streetscapes, inner suburbs can benefit from 10-20% increased tree canopy more conveniently than inner cities.

Public spaces such as plazas, squares and streets can benefit more from evaporative cooling from permeable paving, water features and tree canopy. Parks can have more extensive canopy cover and larger areas of surface water since more space is available for trees in parks and squares compared to very limited space of the inner city.

High albedo surfaces are normally not suggested for the public realm due to glare and health issues. As in

the inner city, they may be used on building rooftops or in combination with high emittance surfaces in wider public spaces with low human traffic.

In general there is a lower proportion of flat rooftops in the inner suburbs, so more opportunity is available for cool roofs as compared to green roofs (which prefer flat surfaces). Cool and green covers may be used on both horizontal and vertical surfaces of buildings and the spaces between them. Water features such as fountains and water walls can be used in public spaces to increase evaporative cooling (unless in very humid climates) and misting fans can assist immediate space cooling in open air shopping malls when needed.

SUBURBAN CONTEXT

Most Australians live in conventional suburban settings. Our major cities are undergoing rapid growth making this a key area of concern for many councils and for urban planning more broadly – including dealing with heatwaves and UHI.

SUBURBAN
CONTEXT IN
AUSTRALIAN
CITIES IS ALMOST
UNIFORM AND
ASSOCIATED WITH
ONE/TWO STORY
BUILDINGS WITH
FRONT AND BACK
YARDS AND HIGH
SKY VIEW FACTOR.



The suburban context in major Australian cities is associated with low-density development and a high sky view factor ($0.8 < SVF$). This context does not change significantly regardless of the size of the city or its climate. Typical urban form in these areas comprises single and double storey buildings with front yards, and streets with low height to width ratios.

Public spaces also are commonly surrounded by single or double story buildings, so public space surfaces are generally not protected from solar radiation by the shade of surrounding buildings. Tree canopy and shading structures are the main sources of shade in street canyons, plazas and squares.

Tree canopy cover is commonly higher than 25% while significant open space is available for increasing urban greenery. Therefore, increasing street trees and parks is the most convenient cooling strategy in the suburban context.

Due to high SVF, using high emittance cool paving and cool envelope treatments facilitates less heat storage in public spaces such as plazas, street canyons and pedestrian open air malls.

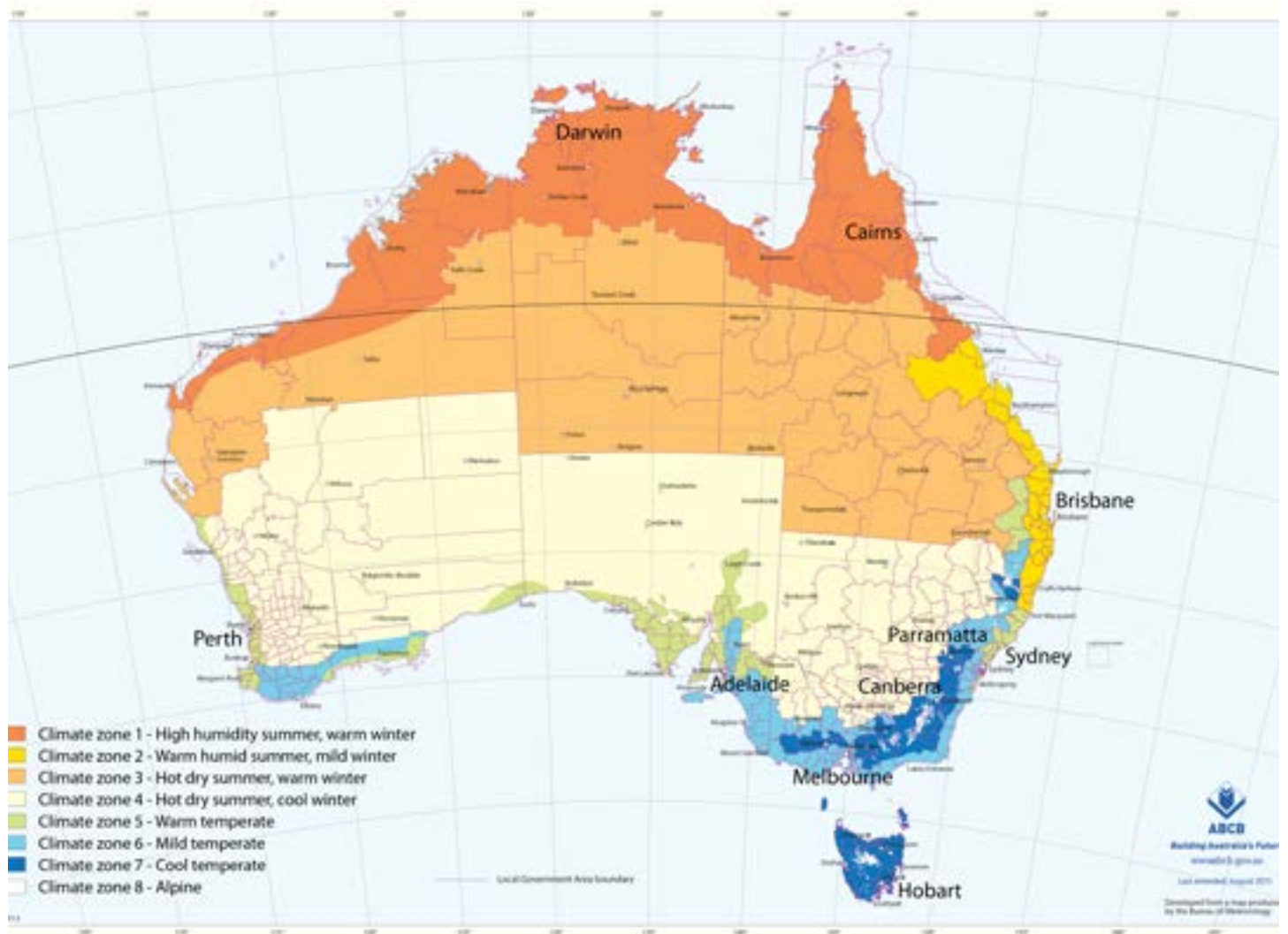
Squares and plazas are very limited in the suburbs. They are replaced by covered shopping malls and parks. Parks can benefit more from evaporative cooling from permeable paving, water features and tree

canopy. Parks can have more intense tree canopy and larger areas of surface water due to their relatively larger scale compared with inner suburban and inner city spaces.

High albedo surfaces can be heavily used on building rooftops. Due to the domination of steep roofs in suburban context more opportunity is available to use cool roofs compared with green roofs (which prefer flat surfaces). Utilisation of cool and green skin covers is possible but not usually necessary on both building surfaces. Water features such as fountains and water walls can be used in public spaces to increase evaporative cooling (unless in very humid climates).

AUSTRALIAN CITIES

Application of urban cooling methods requires careful consideration of local weather conditions and spatial configurations.



AUSTRALIAN CLIMATE ZONES BASED ON TEMPERATURE AND HUMIDITY IN SUMMER AND WINTER.

For example, using running water will not cool urban surfaces in very humid summer days due to lack of evaporative cooling, and high albedo surfaces may not be effective in cooling narrow urban canyons surrounded by tall buildings.

To tailor urban cooling guidelines for the diverse circumstances of Australian cities, this section considers local climate and built form of selected urban settings in Sydney, Melbourne, Adelaide, Brisbane, Perth, Parramatta, Canberra, Hobart, Darwin and Cairns.

UCS MATRIX OF CLIMATE-INTERVENTION

Urban cooling strategies are climate sensitive, meaning that the local climate of cities can affect their practicality and effectiveness.

City	Local climate		Record temperature (°C)		Average rainfall (mm/y)	Cool paving			Cool envelope		Green envelope		Tree canopy	Evaporative cooling		Shading structures
	Summer	Winter	Min	Max		High albedo paving	High emittance paving	Permeable paving	High albedo envelope treatments	High emittance envelope treatments	Green roof	Green wall		Surface water and evaporative cooling	Misting fan	
Brisbane	Hot subtropical	Mild	2.3	43.2	1149	1	3	3	R-3 W-1	RW-3	3	3	3	1	2	3
Sydney	Hot subtropical	Cool	2.1	45.8	1221	1	3	3	R-3 W-1	RW-3	3	3	3	2	3	3
Parramatta	Hot continual	Cool	-1.0	45.5	964	1	3	3	R-3 W-1	RW-3	3	3	3	3	3	3
Canberra	Hot continual	Cool	-10.0	42.2	625	1	3	3	R-3 W-1	RW-3	3	3	3	3	3	3
Melbourne	Hot continual	Cool	-2.8	46.4	650	1	3	3	R-3 W-1	RW-3	3	3	3	3	3	3
Hobart	Warm	Cool	-2.8	40.8	621	1	2	3	R-2 W-1	RW-2	3	3	2	3	3	2
Adelaide	Hot continual	Cool	-0.4	46.1	566	1	3	3	R-3 W-1	RW-3	3	3	3	3	3	3
Perth	Hot continual	Cool	-0.7	46.2	855	1	3	3	R-3 W-1	RW-3	3	3	3	3	3	3
Darwin	Tropical	Mild	10.4	38.9	1703	1	3	3	R-3 W-1	RW-3	2	2	3		2	3
Cairns	Tropical	Mild	6.2	40.5	1999	1	3	3	R-3 W-1	RW-3	2	2	3		2	3

The matrix of climate-intervention set out above shows a summary of best-fit, useful and not applicable urban cooling strategies for selected Australian cities.

Roof	R	Effectiveness
Wall	W	
High	3	
Medium	2	
Low	1	
Not applicable		
Negative		

BRISBANE

Brisbane has a humid subtropical summer. It experiences a monthly mean maximum temperature of 29.1°C, an average 8.5 hours of daily sunshine and highest monthly mean rainfall of 157mm during summer (statistics based on 50-year average data).



DUE TO HIGH RELATIVE HUMIDITY IN SUMMER, SURFACE WATER AND OTHER EVAPORATIVE COOLING STRATEGIES HAVE VERY LOW COOLING AND THERMAL COMFORT EFFECT IN BRISBANE.

An afternoon sea breeze averaging 21.5km/h may help in removing humidity from the city. Utilising misting fans for temporary cooling is still possible due to the dry feel of mist cooling. However, this may increase air moisture and cause further discomfort.

Brisbane summer days usually experience high solar radiation intensity and UV level. Considering the significant precipitation and solar radiation during summer, increased

tree canopy and shading are the best strategies, especially in higher density urban locations. Since maximum daily temperatures frequently surpass 35°C in summer, high emittance paving is an appropriate strategy to radiate away the urban heat.

High annual rainfall makes permeable paving a good option for urban cooling while addressing storm water management and flood prevention

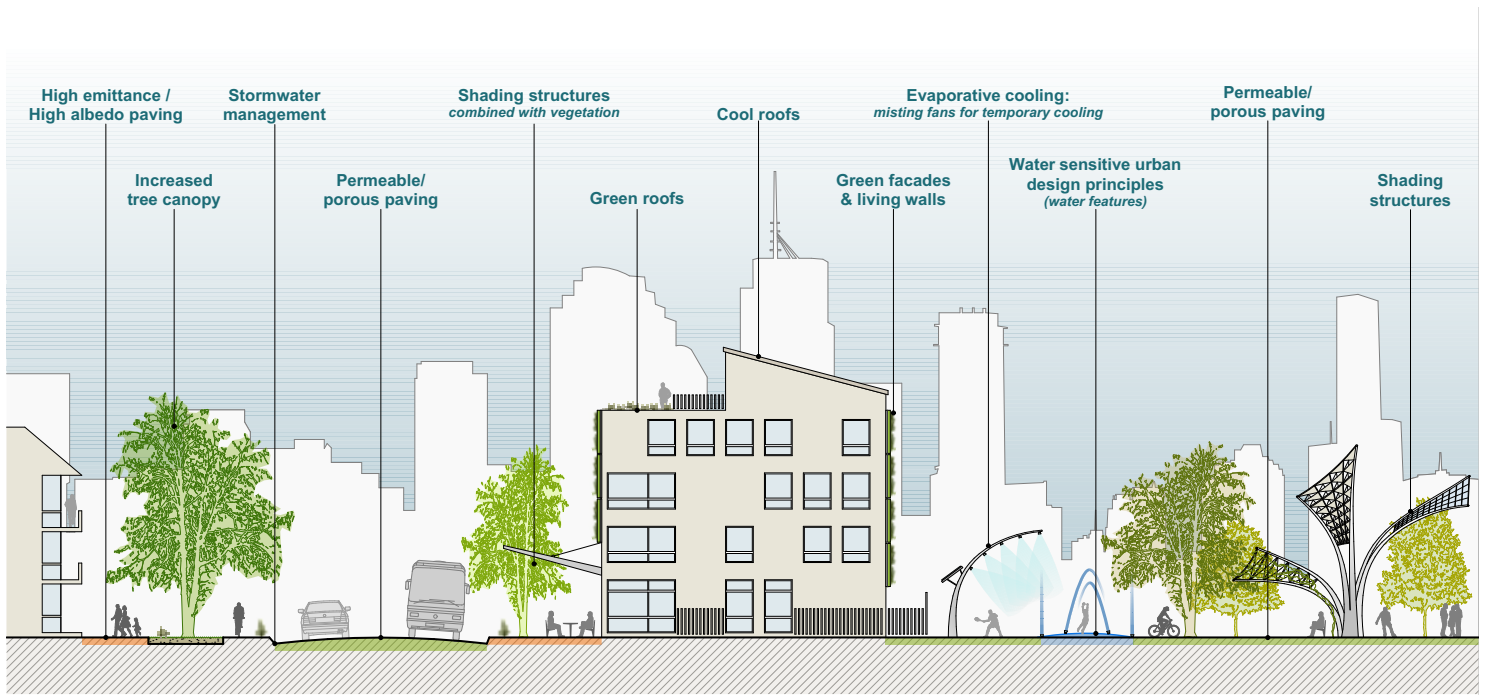
in Brisbane. High albedo paving is a possible urban cooling strategy that is suggested to be used in low where pedestrian and car traffic is low (to prevent glare).

LOCAL CLIMATE		RECORD TEMPERATURE	AVERAGE RAINFALL (MM/Y)	COOL PAVING			COOL ENVELOPE		GREEN ENVELOPE		TREE CANOPY	EVAPORATIVE COOLING		SHADING STRUCTURES
SUMMER: HOT SUBTROPICAL	WINTER: MILD			HIGH ALBEDO PAVING	HIGH EMITTANCE PAVING	PERMEABLE PAVING	HIGH ALBEDO ENVELOPE TREATMENTS	HIGH EMITTANCE ENVELOPE TREATMENTS	GREEN ROOF	GREEN WALL		SURFACE WATER AND EVAPORATIVE COOLING	MISTING FAN	
		Min 2.3°C Max 43.2°C	1149	1	3	3	R-3 W-1	RW-3	3	3	3	1	2	3

Effectiveness
High = 3 Low = 1
Medium = 2

W = Wall
R = Roof

COOLING STRATEGIES DURING SUMMER



SYDNEY (CENTRAL AND EASTERN SUBURBS)

Sydney's summers are typically hot and humid. The city experiences its highest monthly mean maximum temperature of 25.9°C and average 7.1 hours of daily sunshine during summer.



RAINFALL IN SUMMER IS SLIGHTLY LOWER THAN IN AUTUMN BUT HIGHER THAN SPRING AND WINTER, WITH THE MAXIMUM MONTHLY MEAN RAINFALL OF 117MM (STATISTICS BASED ON 50-YEAR AVERAGE DATA).

In days with high relative humidity surface water and other evaporative cooling strategies may have low or reverse effects on outdoor thermal comfort. However, central Sydney and the eastern suburbs benefit from regular sea breezes during summer afternoons (average 19.5km/h at 3pm) which enhances the cooling effect of water features. Utilising misting fans for temporary cooling is an appropriate strategy at pedestrian scale due to the dry feel of mist cooling.

Summer days in Sydney usually have high solar radiation intensity and UV level. Thus, increased tree canopy and shading are the best strategies, especially in higher density urban settings of Sydney.

Maximum daily temperature surpasses 35°C a few times each summer but over most summer days the maximum temperature stays below 30°C. High emittance paving is

the best practice to radiate away the urban heat. Having 1221mm of annual rainfall makes permeable paving a good option for urban cooling while addressing storm water management.

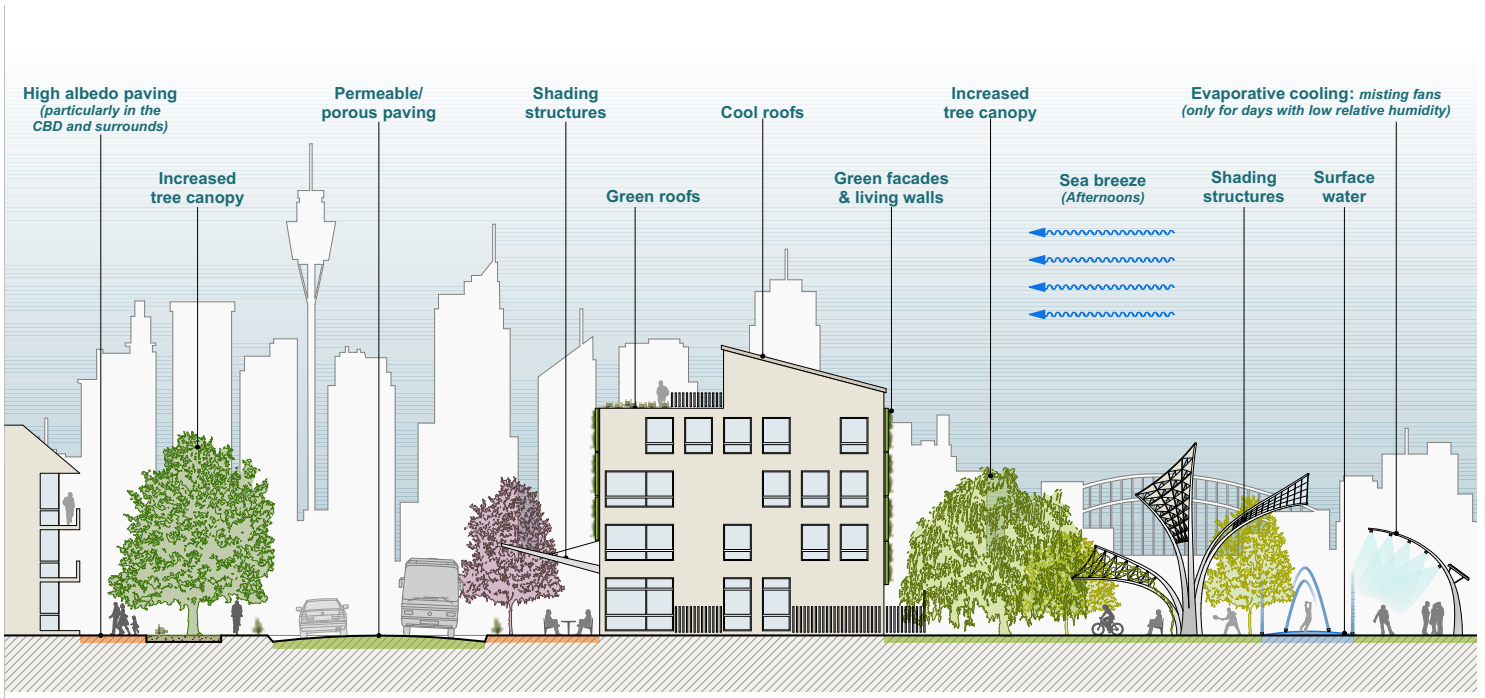
High albedo paving is a possible urban cooling strategy that is suggested to be used in low pedestrian and car traffic areas (particularly in the CBD and surrounds).

LOCAL CLIMATE		RECORD TEMPERATURE	AVERAGE RAINFALL (MM/Y)	COOL PAVING			COOL ENVELOPE		GREEN ENVELOPE		TREE CANOPY	EVAPORATIVE COOLING		SHADING STRUCTURES
SUMMER: HOT SUBTROPICAL	WINTER: COOL			HIGH ALBEDO PAVING	HIGH EMITTANCE PAVING	PERMEABLE PAVING	HIGH ALBEDO ENVELOPE TREATMENTS	HIGH EMITTANCE ENVELOPE TREATMENTS	GREEN ROOF	GREEN WALL		SURFACE WATER AND EVAPORATIVE COOLING	MISTING FAN	
		Min 2.1°C Max 45.8°C	1121	1	3	3	R-3 W-1	RW-3	3	3	3	2	3	3

Effectiveness
 High = 3 Low = 1
 Medium = 2

W = Wall
 R = Roof

COOLING STRATEGIES DURING SUMMER



PARRAMATTA (AND SYDNEY'S WESTERN SUBURBS)

The western suburbs of Sydney including Parramatta have a hotter and drier climate than areas closer to the coast. They don't receive any cooling sea breezes in the afternoon when the heat reaches its maximum, so in summer the maximum temperature can be up to 9 degrees hotter than the Sydney City forecast.



THE NUMBER OF DAYS OVER 35 DEGREES IN WESTERN SYDNEY HAS INCREASED BY 250% SINCE 1965 (COMPARED WITH 22% IN CENTRAL SYDNEY).

PARRAMATTA EXPERIENCES ITS HIGHEST MONTHLY MEAN MAXIMUM TEMPERATURE OF 28.4°C AND AVERAGE 7.1 HOURS OF DAILY SUNSHINE DURING SUMMER.

Rainfall in summer ranges from a monthly mean of 73.6mm in December to 121mm in February. Average summer rainfall is lower than in autumn and higher than spring and winter. Wind speed is considerably lower in the afternoon, with an average of 14.5km/h at 3pm in Parramatta. (statistics based on to [50-year average data](#)).

In Parramatta's hot summers, utilising misting fans for temporary cooling, surface water and other evaporative cooling strategies are suggested, especially when combined with shade from trees, buildings and

shading structures. Due to the high solar radiation intensity, increased tree canopy and shading are the best strategies specially in higher density urban settings of Parramatta where the [tree canopy cover](#) is lower than 10%.

Maximum daily temperature surpasses 35°C many times each summer and can reach 45°C during extreme heatwaves. High emittance paving is the best practice to radiate away the urban heat. With 964mm of annual rainfall, permeable paving and additional tree canopy represent the best urban cooling strategies while addressing storm water management.

High albedo paving is a possible urban cooling strategy that is suggested to be used in low pedestrian and car traffic areas. Due to the suburban context of Parramatta, high albedo surfaces can be used extensively on building rooftops.

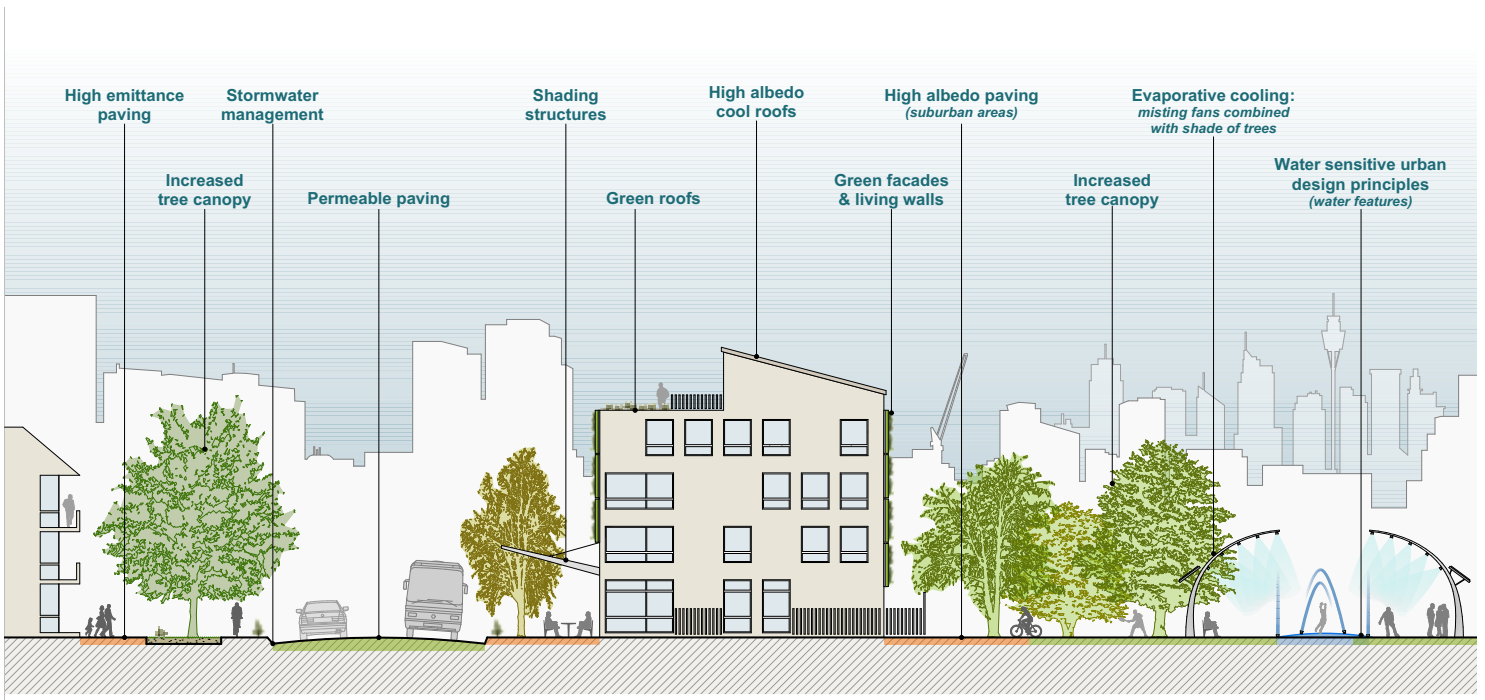
While the above discussion relates to Parramatta, similar considerations apply to other Western Sydney suburban locations.

LOCAL CLIMATE		RECORD TEMPERATURE	AVERAGE RAINFALL (MM/Y)	COOL PAVING			COOL ENVELOPE		GREEN ENVELOPE		TREE CANOPY	EVAPORATIVE COOLING		SHADING STRUCTURES
SUMMER: HOT CONTINUAL	WINTER: COOL			HIGH ALBEDO PAVING	HIGH EMITTANCE PAVING	PERMEABLE PAVING	HIGH ALBEDO ENVELOPE TREATMENTS	HIGH EMITTANCE ENVELOPE TREATMENTS	GREEN ROOF	GREEN WALL		SURFACE WATER AND EVAPORATIVE COOLING	MISTING FAN	
		Min -1.0°C Max 45.5°C	964	1	3	3	R-3 W-1	RW-3	3	3	3	3	3	3

Effectiveness
High = 3 Low = 1
Medium = 2

W = Wall
R = Roof

COOLING STRATEGIES DURING SUMMER



CANBERRA

Among Australian capital cities, Canberra is known for its cold weather in winter. However, its summer weather is hot and dry due to its inland location. Canberra experiences its highest monthly mean maximum temperature of 28.5°C and average 9 hours of daily sunshine during summer.



RAINFALL IN SUMMER RANGES FROM A MONTHLY MEAN OF 46.1MM IN DECEMBER TO 59.8MM IN JANUARY. AVERAGE SUMMER RAINFALL IS LOWER THAN IN AUTUMN AND SPRING BUT SLIGHTLY HIGHER THAN WINTER. WIND SPEED AVERAGES 11.5KM/H AT 3PM IN CANBERRA (STATISTICS BASED ON 50-YEAR AVERAGE DATA).

In Canberra's hot and relatively dry summers, utilising misting fans for temporary cooling, surface water and other evaporative cooling strategies is highly recommended.

Summer days in Canberra usually feature high solar radiation intensity and UV level. Thus, increased tree canopy and shading are the best strategies specially in higher density

urban settings of Canberra. Maximum daily temperature regularly surpasses 32°C in summer and can reach 42°C during heatwaves. High emittance paving is the best practice to radiate away the urban heat.

Having 625mm of annual rainfall makes permeable paving a good option for urban cooling while addressing storm water

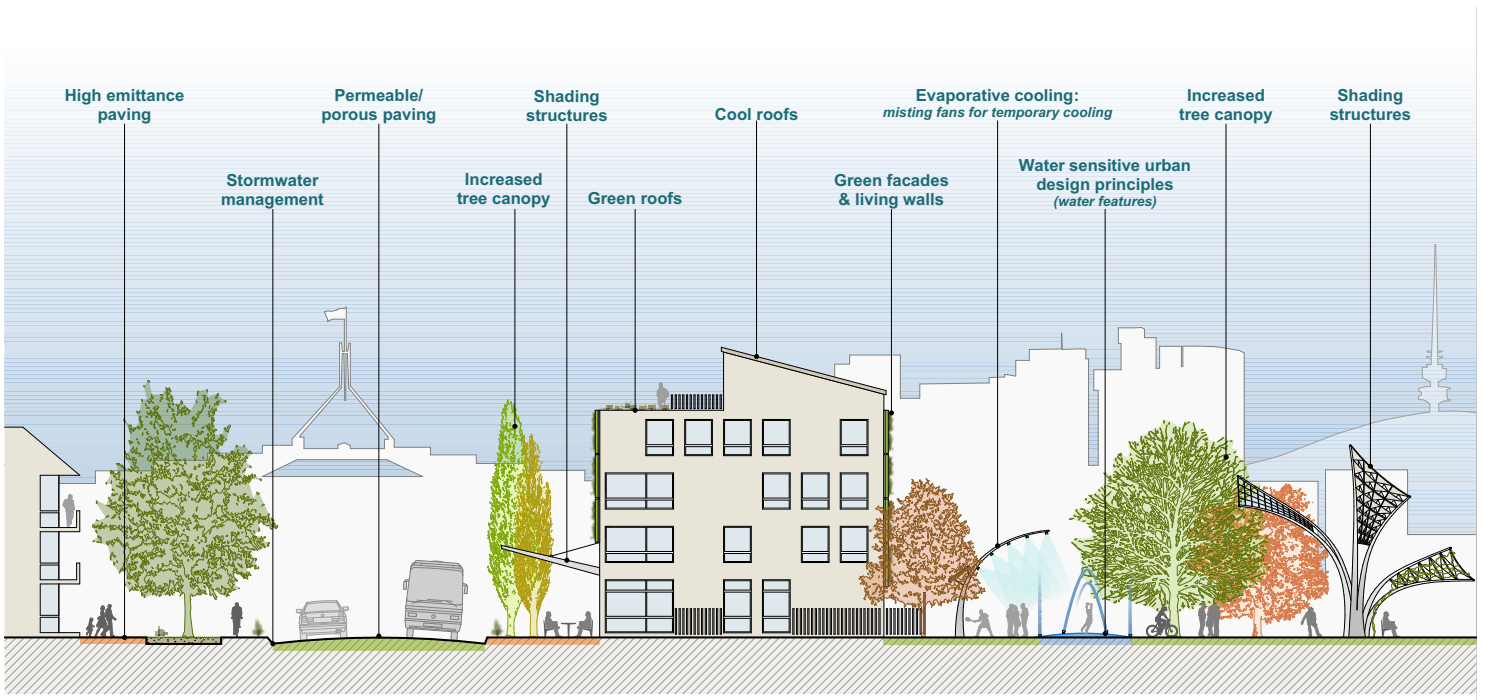
management. High albedo paving is a possible urban cooling strategy that is suggested to be used in low pedestrian and car traffic areas and building rooftops, particularly in Canberra's suburbs.

LOCAL CLIMATE		RECORD TEMPERATURE	AVERAGE RAINFALL (MM/Y)	COOL PAVING			COOL ENVELOPE		GREEN ENVELOPE		TREE CANOPY	EVAPORATIVE COOLING		SHADING STRUCTURES
SUMMER: HOT CONTINUAL	WINTER: COOL			HIGH ALBEDO PAVING	HIGH EMITTANCE PAVING	PERMEABLE PAVING	HIGH ALBEDO ENVELOPE TREATMENTS	HIGH EMITTANCE ENVELOPE TREATMENTS	GREEN ROOF	GREEN WALL		SURFACE WATER AND EVAPORATIVE COOLING	MISTING FAN	
		Min -10.0°C Max 42.2°C	625	1	3	3	R-3 W-1	RW-3	3	3	3	3	3	3

Effectiveness
 High = 3 Low = 1
 Medium = 2

W = Wall
 R = Roof

COOLING STRATEGIES DURING SUMMER



MELBOURNE

Melbourne has a hot and relatively dry summer climate. It experiences its highest monthly mean maximum temperature of 26.0°C and average 9 hours of daily sunshine during summer.



RAINFALL IS LOWEST IN SUMMER – AVERAGE RAINFALL DECREASES TO AS LOW AS 46.8MM DURING JANUARY – AND WIND SPEED AVERAGES 14.4KM/H AT 3PM IN MELBOURNE (STATISTICS BASED ON 50-YEAR AVERAGE DATA).

In Melbourne's hot dry summers, utilising misting fans for temporary cooling, surface water and other evaporative cooling strategies is highly recommended. Relatively low rainfall during summer makes [water sensitive urban design principles](#) essential to ensure evaporative cooling.

Summer days in Melbourne usually feature [high solar radiation intensity](#) and UV level. Thus, increased tree canopy and shading are the best

strategies specially in higher density urban settings of Melbourne's CBD where the [tree canopy cover](#) is 12.9%. Maximum daily temperature regularly surpasses 32°C in summer and can reach 46°C during heatwaves. High emittance paving is the best practice to radiate away the urban heat.

Having 650mm of annual rainfall makes permeable paving an essential strategy for urban cooling while addressing storm water management.

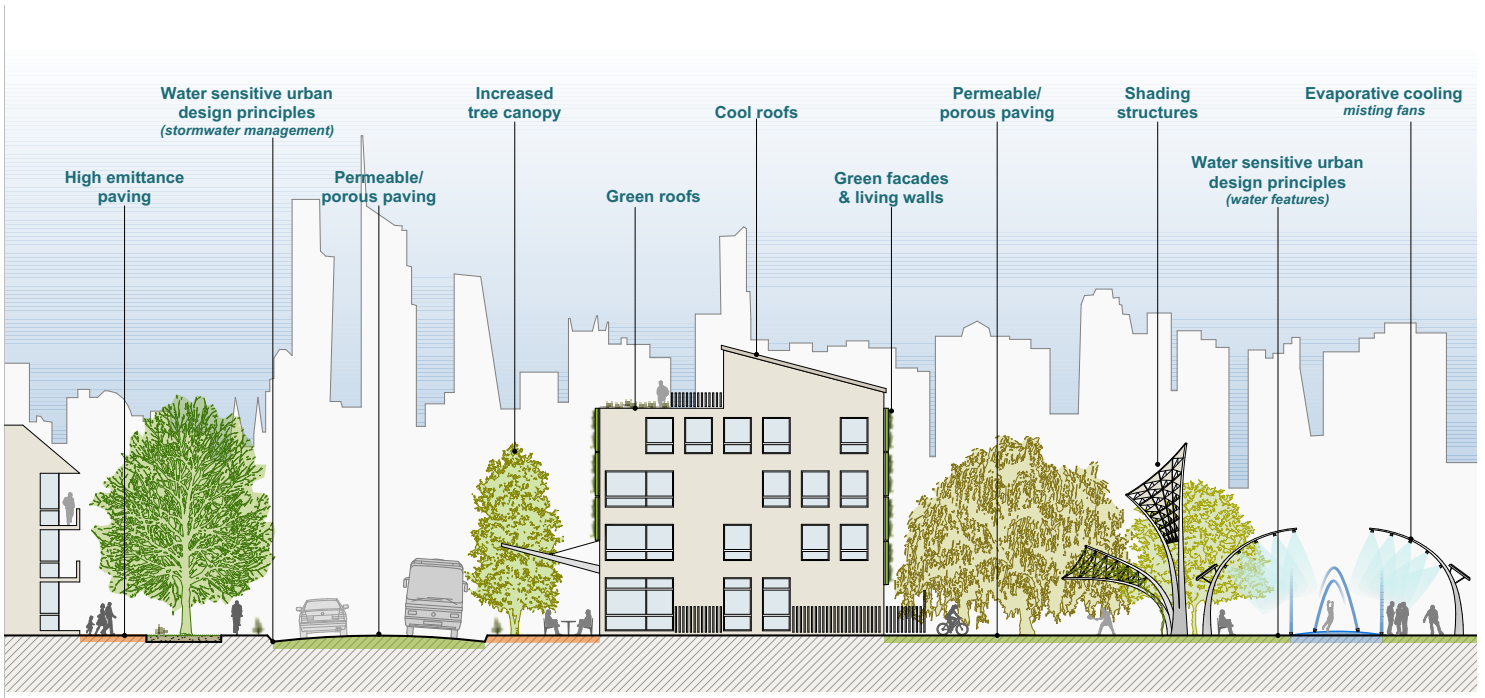
High albedo paving is a possible urban cooling strategy that is suggested to be used in low pedestrian and car traffic areas and building rooftops particularly in the suburbs.

LOCAL CLIMATE		RECORD TEMPERATURE	AVERAGE RAINFALL (MM/Y)	COOL PAVING			COOL ENVELOPE		GREEN ENVELOPE		TREE CANOPY	EVAPORATIVE COOLING		SHADING STRUCTURES
SUMMER: HOT CONTINUAL	WINTER: COOL			HIGH ALBEDO PAVING	HIGH EMITTANCE PAVING	PERMEABLE PAVING	HIGH ALBEDO ENVELOPE TREATMENTS	HIGH EMITTANCE ENVELOPE TREATMENTS	GREEN ROOF	GREEN WALL		SURFACE WATER AND EVAPORATIVE COOLING	MISTING FAN	
		Min -2.8°C Max 46.4°C	650	1	3	3	R-3 W-1	RW-3	3	3	3	3	3	3

Effectiveness
High = 3 Low = 1
Medium = 2

W = Wall
R = Roof

COOLING STRATEGIES DURING SUMMER



HOBART

Hobart has a mild and relatively dry summer climate. It experiences its highest monthly mean maximum temperature of 21.7°C and average 8 hours of daily sunshine during summer. Summer rainfall monthly averages vary from 39.7mm during February to 56.2mm in December.



RAINFALL IS LOWEST IN SUMMER AND WIND SPEED AVERAGES 19.0KM/H AT 3PM IN HOBART (STATISTICS BASED ON 100-YEAR AVERAGE DATA).

Summer days in Hobart usually feature [high solar radiation intensity](#) and UV level. The City of Hobart has [58.6% tree canopy cover](#). Thus, increased temporary shading is an appropriate strategy to prevent solar radiation from reaching public space surfaces. Utilising misting fans for temporary cooling and temporary shading are the most appropriate

strategies to cool public space during summer heatwaves when the maximum daily temperature can reach 42°C.

Having 621mm of annual rainfall makes permeable paving an essential strategy for urban cooling while addressing storm water management.

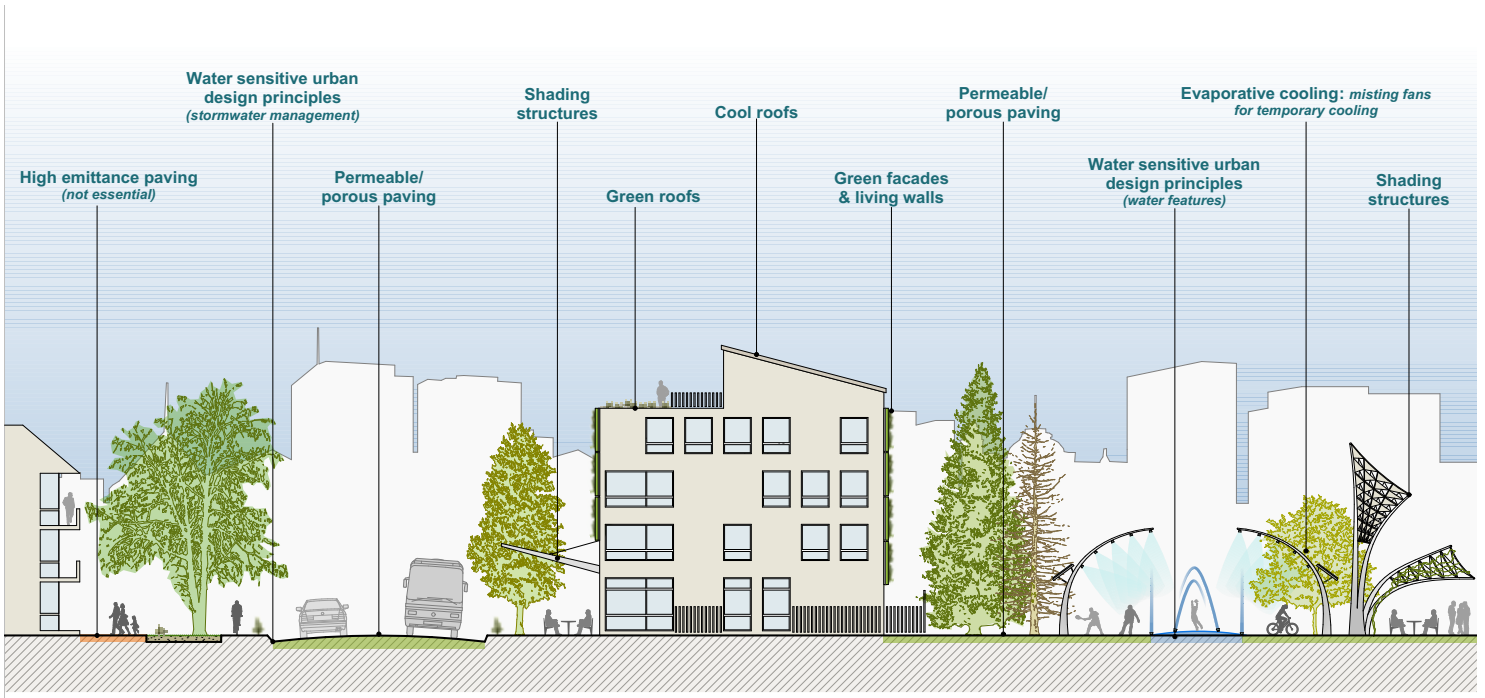
High emittance paving is not as essential as in Melbourne, Adelaide and Perth and high albedo paving is only suggested on building rooftops in Hobart's suburbs to decrease energy use.

LOCAL CLIMATE		RECORD TEMPERATURE	AVERAGE RAINFALL (MM/Y)	COOL PAVING			COOL ENVELOPE		GREEN ENVELOPE		TREE CANOPY	EVAPORATIVE COOLING		SHADING STRUCTURES
SUMMER: WARM	WINTER: COOL			HIGH ALBEDO PAVING	HIGH EMITTANCE PAVING	PERMEABLE PAVING	HIGH ALBEDO ENVELOPE TREATMENTS	HIGH EMITTANCE ENVELOPE TREATMENTS	GREEN ROOF	GREEN WALL		SURFACE WATER AND EVAPORATIVE COOLING	MISTING FAN	
		Min -2.8°C Max 40.8°C	621	1	2	3	R-2 W-1	RW-2	3	3	2	3	3	2

Effectiveness
High = 3 Low = 1
Medium = 2

W = Wall
R = Roof

COOLING STRATEGIES DURING SUMMER



ADELAIDE

Adelaide is Australia's driest capital city and encounters particularly hot summers. It experiences its highest monthly mean maximum temperature of 29.5°C and averages 10.5 hours of daily sunshine during summer. Summer rainfall can be as low as 15.4mm during February.



**WIND SPEED AVERAGES
16.6KM/H IN MID-
AFTERNOON IN ADELAIDE
(STATISTICS BASED ON
50-YEAR AVERAGE DATA).**

Summer days in Adelaide usually feature [high solar radiation intensity](#) and UV level. Thus, increased tree canopy and shading are the best strategies, especially in Adelaide's CBD where the [tree canopy cover](#) – including Adelaide's vast parklands – is only 20.3%, and in the outer southern and northern suburbs where the tree canopy cover is lower than 15%.

Maximum daily temperature regularly surpasses 32°C in summer and can

reach 45°C during heatwaves, which can last for up to a week. Misting fans for temporary cooling are highly effective particularly when mixed with shading.

With an annual average rainfall of 566mm, permeable paving an essential strategy for urban cooling, while addressing storm water management.

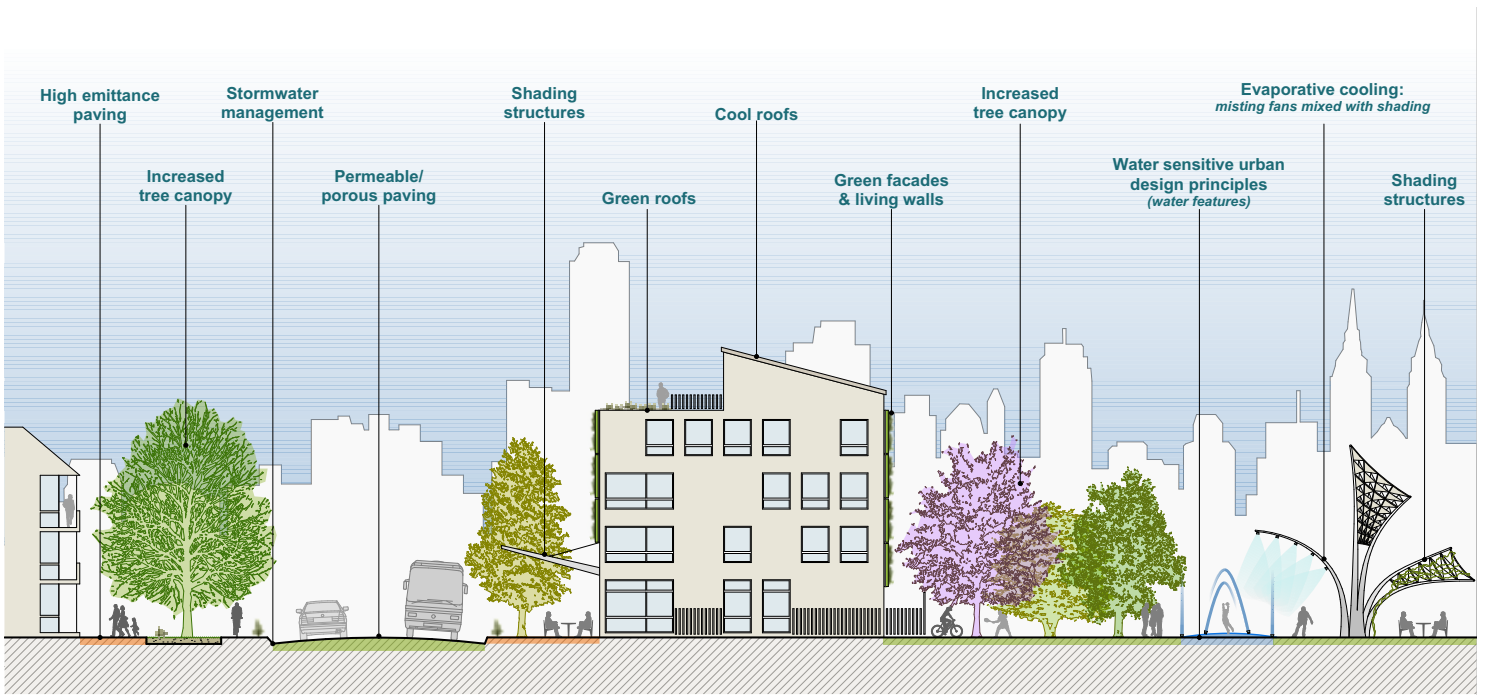
High emittance paving is the best practice to radiate away the urban heat. High albedo paving is a possible urban cooling strategy that is suggested to be used in low traffic areas and building rooftops in Adelaide's suburbs.

LOCAL CLIMATE		RECORD TEMPERATURE	AVERAGE RAINFALL (MM/Y)	COOL PAVING			COOL ENVELOPE		GREEN ENVELOPE		TREE CANOPY	EVAPORATIVE COOLING		SHADING STRUCTURES
SUMMER: HOT CONTINUAL	WINTER: COOL			HIGH ALBEDO PAVING	HIGH EMITTANCE PAVING	PERMEABLE PAVING	HIGH ALBEDO ENVELOPE TREATMENTS	HIGH EMITTANCE ENVELOPE TREATMENTS	GREEN ROOF	GREEN WALL		SURFACE WATER AND EVAPORATIVE COOLING	MISTING FAN	
		Min -0.4°C Max 46.1°C	566	1	3	3	R-3 W-1	RW-3	3	3	3	3	3	3

Effectiveness
High = 3 Low = 1
Medium = 2

W = Wall
R = Roof

COOLING STRATEGIES DURING SUMMER



PERTH

Perth has a very hot and dry summer climate (hotter and drier than Adelaide). It experiences its highest monthly mean maximum temperature of 31.7°C and average 11 hours of daily sunshine during summer. Maximum daily temperature regularly surpasses 32°C in summer and can reach 46°C during heatwaves, which can last for up to a week.



RAINFALL DECREASES TO AS LOW AS 8.5MM DURING FEBRUARY IN PERTH. AVERAGE SUMMER RAINFALL IS SIGNIFICANTLY LOWER THAN DURING OTHER SEASONS (MONTHLY AVERAGE RAINFALL IS 44MM IN JULY). WIND SPEED HAS A RELATIVELY HIGH AVERAGE OF AROUND 20KM/H IN MID-AFTERNOON IN PERTH WHICH MAKES EVAPORATIVE COOLING MORE EFFICIENT DURING SUMMER (STATISTICS BASED ON 25-YEAR AVERAGE DATA).

Utilising misting fans for temporary cooling, surface water and other evaporative cooling strategies is highly recommended during Perth's hot summer. The significantly low rainfall during summer makes water sensitive urban design principles essential to ensure evaporative cooling. Summer days in Perth usually feature [high solar radiation intensity](#) and UV level. Thus, increased tree canopy and shading

are the best strategies, especially in most outer suburban areas where the [tree canopy cover](#) is currently less than 15%.

With 855mm of annual rainfall and significant seasonal variation in precipitation, permeable paving is a key option for urban cooling while also addressing storm water management.

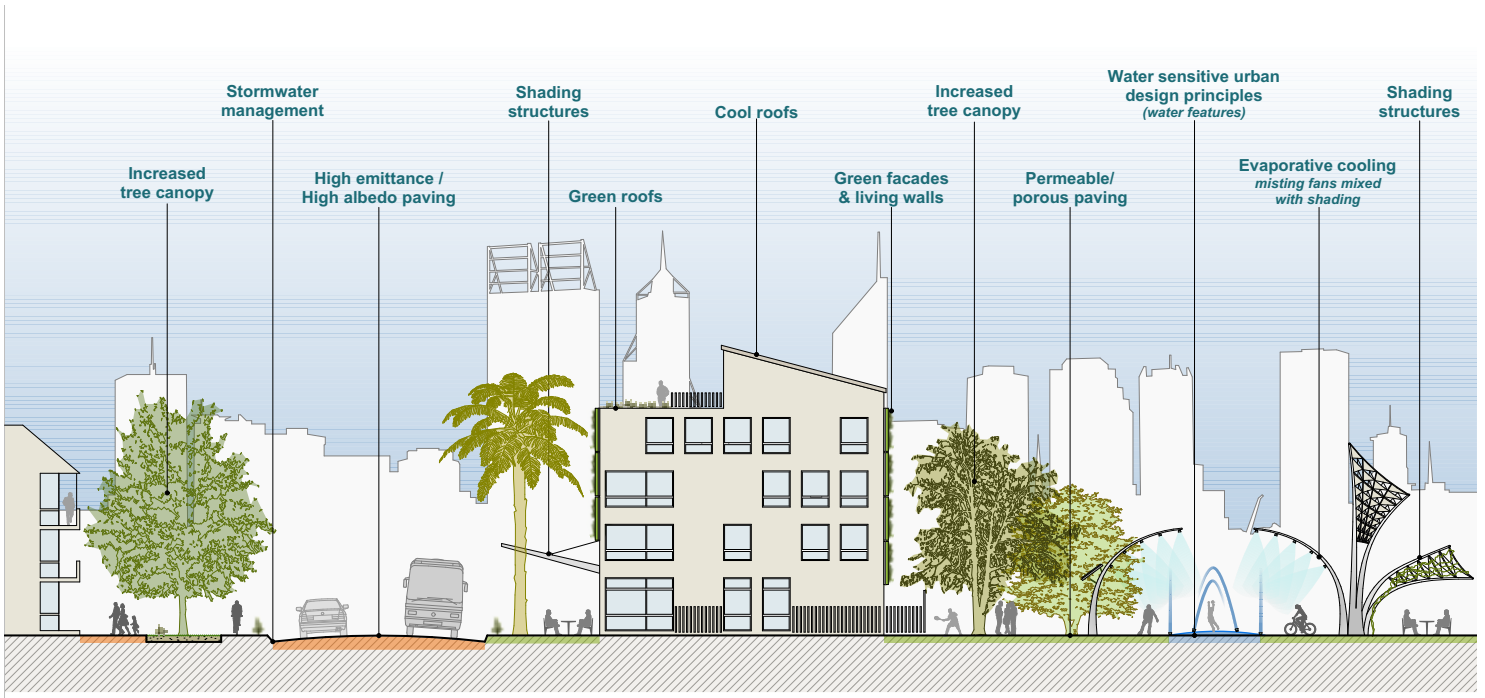
High emittance paving is the best practice to radiate away the urban heat. High albedo paving is a possible urban cooling strategy that is suggested to be used in low pedestrian and car traffic areas and building rooftops, particularly in the suburbs.

LOCAL CLIMATE		RECORD TEMPERATURE	AVERAGE RAINFALL (MM/Y)	COOL PAVING			COOL ENVELOPE		GREEN ENVELOPE		TREE CANOPY	EVAPORATIVE COOLING		SHADING STRUCTURES
SUMMER: HOT CONTINUAL	WINTER: COOL			HIGH ALBEDO PAVING	HIGH EMITTANCE PAVING	PERMEABLE PAVING	HIGH ALBEDO ENVELOPE TREATMENTS	HIGH EMITTANCE ENVELOPE TREATMENTS	GREEN ROOF	GREEN WALL		SURFACE WATER AND EVAPORATIVE COOLING	MISTING FAN	
		Min -0.7°C Max 46.2°C	855	1	3	3	R-3 W-1	RW-3	3	3	3	3	3	3

Effectiveness
High = 3 Low = 1
Medium = 2

W = Wall
R = Roof

COOLING STRATEGIES DURING SUMMER



DARWIN

Darwin has a hot tropical climate. Monthly mean maximum temperature is constantly over 30°C all through the year. The average sunshine hours are 5.7°C in January and 10.3 in August.



THE HIGHEST MONTHLY MEAN RAINFALL OF 423MM OCCURS IN JANUARY AND THE LOWEST RAINFALL OF 1MM TAKES PLACE IN JULY (STATISTICS BASED ON 75-YEAR AVERAGE DATA).

Due to the high relative humidity in summer, surface water and other evaporative cooling strategies is not appropriate in Darwin. An afternoon sea breeze averaging around 18km/h may help to reduce humidity. Utilising misting fans for temporary cooling is still possible due to the dry feel of mist cooling. However, this may increase air moisture and cause further discomfort away from the direct vicinity of the misting.

Darwin has high solar radiation intensity and UV level throughout the year. Considering its combination of high precipitation and solar radiation depending on season, increased tree canopy and all types of shading are the best strategies, especially in higher density inner urban settings of Darwin.

Maximum daily temperature surpasses 32°C in summer and rarely may reach as much as 40°C during heatwaves. High emittance paving

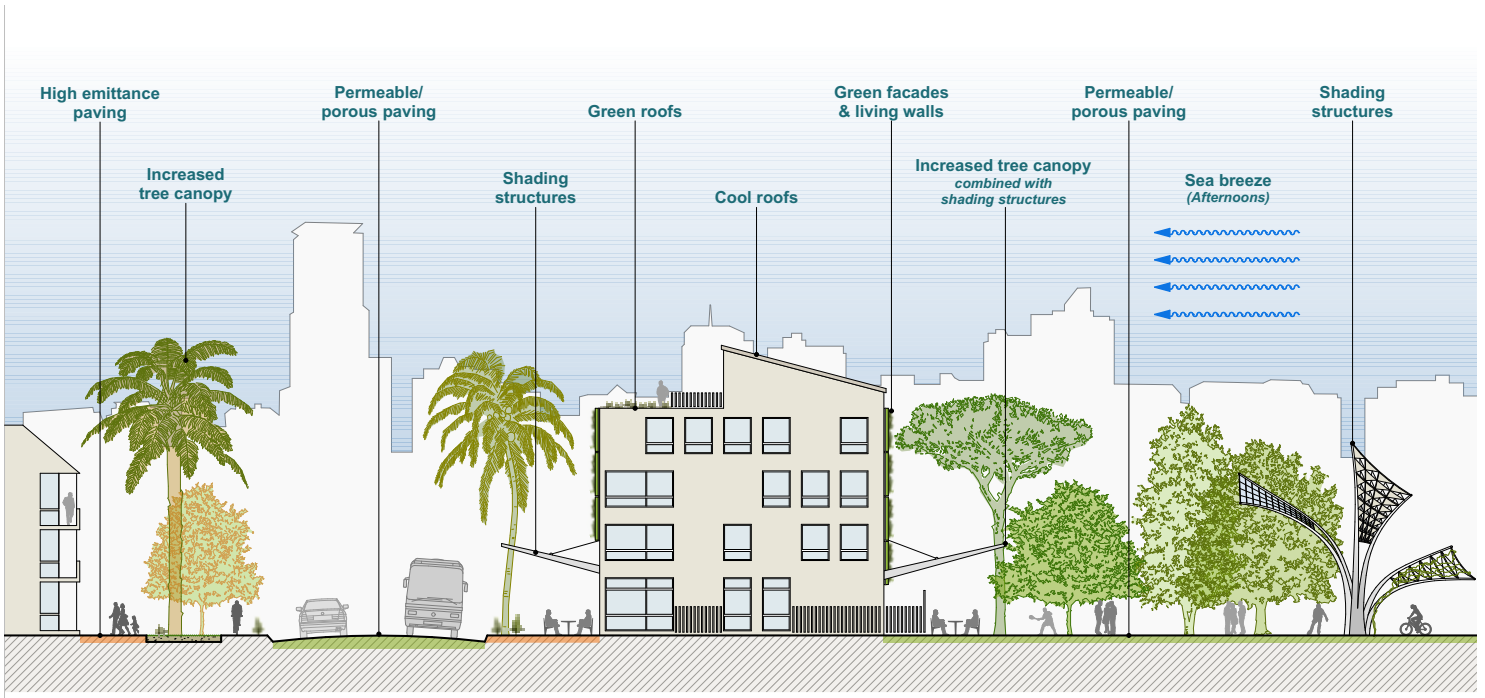
is an appropriate strategy to radiate away the urban heat without increasing humidity. Having 1703mm of annual rainfall makes permeable paving an essential urban design strategy to address storm water management and flood prevention in Darwin. High albedo paving is a possible urban cooling strategy that is suggested to be used in low pedestrian and car traffic areas and building rooftops, particularly in the suburbs.

LOCAL CLIMATE		RECORD TEMPERATURE	AVERAGE RAINFALL (MM/Y)	COOL PAVING			COOL ENVELOPE		GREEN ENVELOPE		TREE CANOPY	EVAPORATIVE COOLING		SHADING STRUCTURES
SUMMER: TROPICAL	WINTER: MILD			HIGH ALBEDO PAVING	HIGH EMITTANCE PAVING	PERMEABLE PAVING	HIGH ALBEDO ENVELOPE TREATMENTS	HIGH EMITTANCE ENVELOPE TREATMENTS	GREEN ROOF	GREEN WALL		SURFACE WATER AND EVAPORATIVE COOLING	MISTING FAN	
		Min 10.4°C Max 38.9°C	1703	1	3	3	R-3 W-1	RW-3	2	2	3	N	2	3

Effectiveness
 High = 3 Low = 1
 Medium = 2 Negative = N

W = Wall
 R = Roof

COOLING STRATEGIES DURING SUMMER



CAIRNS

Cairns has a tropical climate slightly less hot but more humid than Darwin's. Monthly mean maximum temperature is 31.5°C in summer. The average sunshine hours are 6.8 in January and 8.8 in October.



THE HIGHEST MONTHLY MEAN RAINFALL OF 447MM OCCURS IN FEBRUARY AND THE LOWEST RAINFALL OF 26.7MM TAKES PLACE IN AUGUST (STATISTICS BASED ON 75-YEAR AVERAGE DATA).

Due to the high relative humidity in summer, surface water and other evaporative cooling strategies are not appropriate in Cairns. An afternoon sea breeze of around 16km/h may help to reduce humidity. Utilising misting fans for temporary cooling is still possible due to the dry feel of mist cooling. However, this may increase air moisture and cause further discomfort away from the direct vicinity of the misting.

Cairns has high solar radiation intensity and UV level all through the year. Considering its high level of precipitation and solar radiation during summer, all types of shading are appropriate strategies in Cairns.

Maximum daily temperature surpasses 30°C in summer and occasionally may reach up to 40°C during heatwaves. High emittance paving is an appropriate strategy to radiate away the urban heat without increasing humidity.

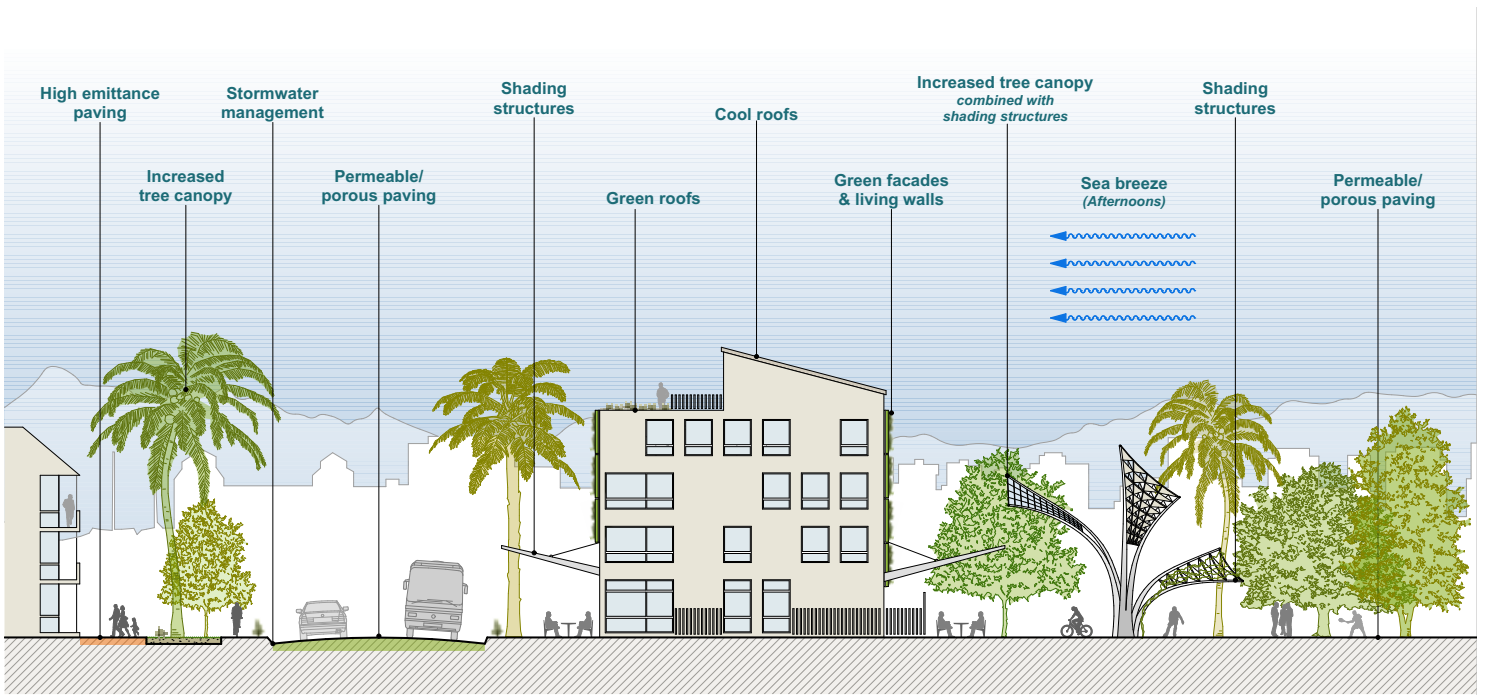
Having 1999mm of annual rainfall makes permeable paving an essential urban design strategy to address storm water management and flood prevention in Cairns. High albedo paving is a possible urban cooling strategy that is suggested to be used in low pedestrian and car traffic areas and building rooftops.

LOCAL CLIMATE		RECORD TEMPERATURE	AVERAGE RAINFALL (MM/Y)	COOL PAVING			COOL ENVELOPE		GREEN ENVELOPE		TREE CANOPY	EVAPORATIVE COOLING		SHADING STRUCTURES
SUMMER: TROPICAL	WINTER: MILD			HIGH ALBEDO PAVING	HIGH EMITTANCE PAVING	PERMEABLE PAVING	HIGH ALBEDO ENVELOPE TREATMENTS	HIGH EMITTANCE ENVELOPE TREATMENTS	GREEN ROOF	GREEN WALL		SURFACE WATER AND EVAPORATIVE COOLING	MISTING FAN	
		Min 6.2°C Max 40.5°C	1999	1	3	3	R-3 W-1	RW-3	2	2	3	N	2	3

Effectiveness
 High = 3 Low = 1
 Medium = 2 Negative = N

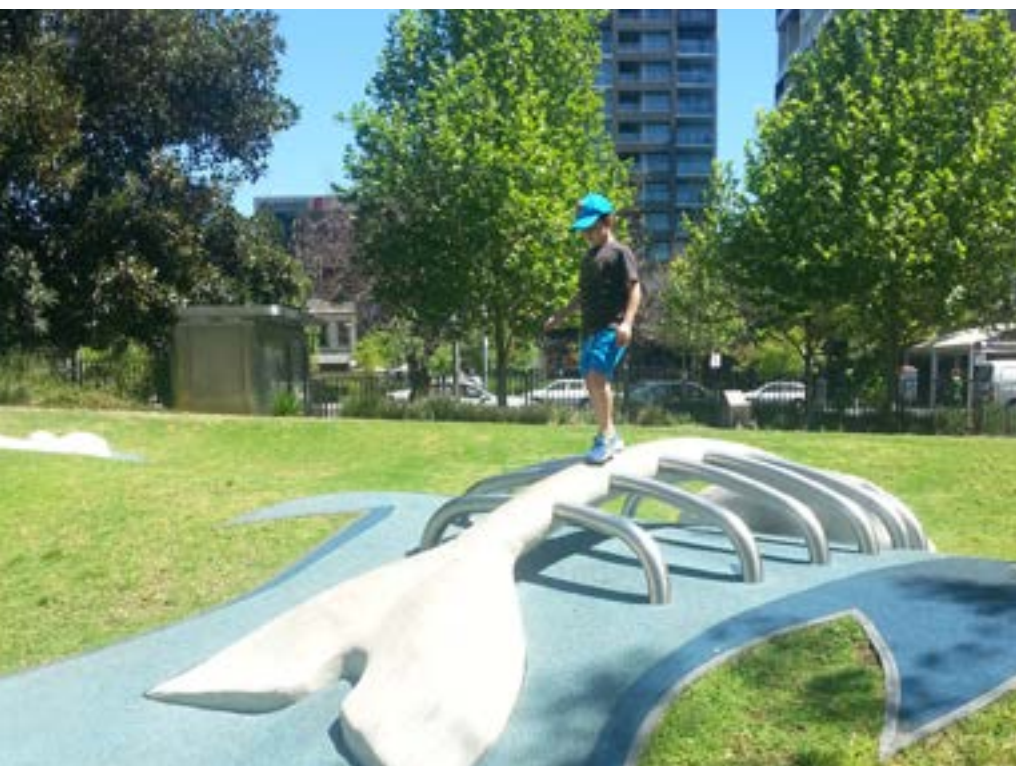
W = Wall
 R = Roof

COOLING STRATEGIES DURING SUMMER



HUMAN ADAPTATION, BUILDING DESIGN AND RETROFITTING

Humans are a significant contributor to the urban heat island effect through air-conditioning. The waste heat from air-conditioning, which cools the indoor environment at the expense of heating up the outdoors, can be reduced through human behaviour changes and heat stress resistant building design.



The waste heat from air-conditioning, which cools the indoor environment at the expense of heating up the outdoors, can be reduced through human behaviour changes and heat stress resistant building design. Behaviour changes include adaptation techniques relating to how occupants use a building or utilising natural ventilation at night when the outdoor environment is cooler than indoors. Our buildings can encourage the use of natural adaptation techniques, while the availability of air-conditioning has the reverse effect.

Climate responsive building design can minimise our demand for cooling and reduce the indoor temperatures during heat waves, creating safe indoor conditions during heat waves with no or minimal use of air-conditioning.

These design and potential building retrofitting techniques partly overlap with energy efficient measures, such as increased level of insulation in roofs and walls, implementation of double-

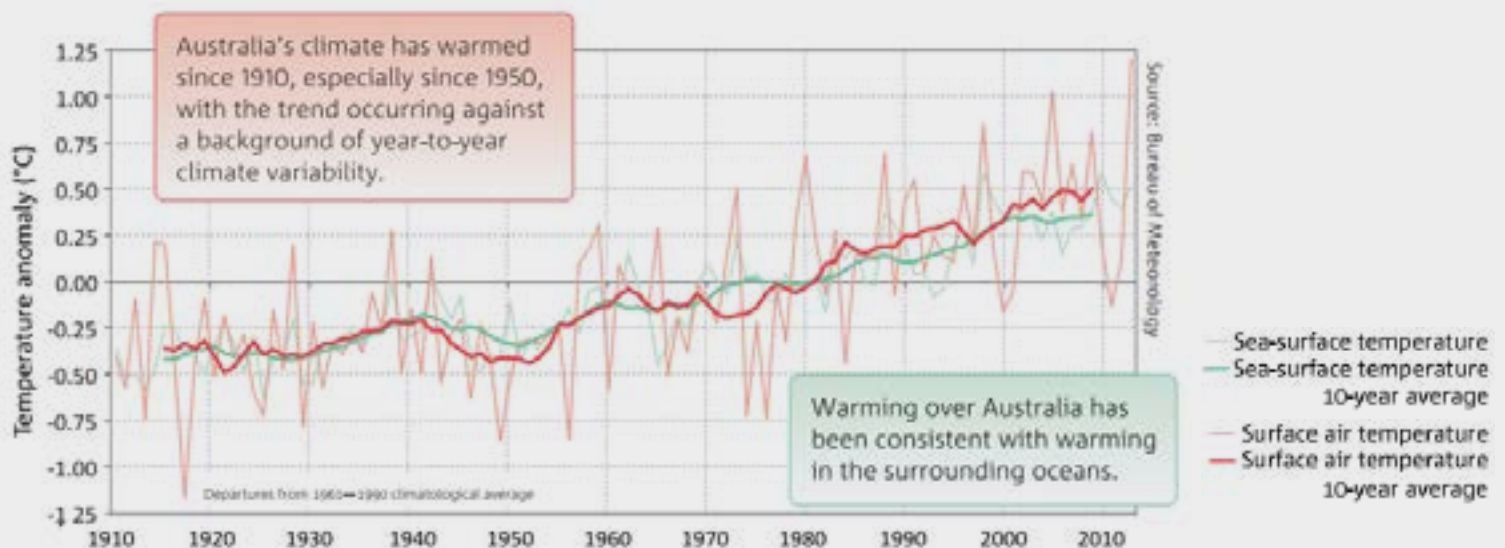
glazing and appropriate orientation. The heat stress resistance of a building can be further developed with low emissivity glazing, internal thermal mass (works best where there is a substantial day/night temperature difference), increased shading, the application of reflective painting on the building envelope and slab-on-ground structures with ceramic floor covering.

The integration of these adaptation and design techniques in existing building stock, in the design of new buildings and as performance-based standards could effectively reduce air-conditioning and increase occupants' indoor thermal comfort and health during heatwaves.

URBAN COOLING STRATEGIES IN LOW CARBON AND WATER SENSITIVE CITIES

Global warming is not simply a matter of forecasting, it is happening now, and climate change mitigation strategies can only decrease the intensity of this process.

TIME SERIES ANALYSIS OF AUSTRALIAN NEAR-SURFACE AIR TEMPERATURE FROM 1910 TO 2014 AND PROJECTIONS TO 2090 (CSIRO 2014, P.5)



Thus, adaptation to climate change is a crucial emerging agenda for Australian cities.

Time series analysis of historical climate data in Australia reveals a likely 0.7 C increase in near-surface temperatures by 2030, and 1.2 C increase by 2090 compared to the baseline of 1910. The basic assumption in this time series analysis is that the pattern of climate

change remains constant in future (no step change or accelerating change is taken into consideration), which represents a conservative assessment.

Australian mean surface temperatures in 2014 shows that most of the continent – including the capital cities of Sydney, Melbourne and Adelaide – has already experienced a mean temperature change of

between 0.5 C and 1 C compared to 1910. Climate change scenarios based on three representative concentration pathways (RCPs) of greenhouse gases in the earth's atmosphere indicate that total mean temperature change in Australia can vary from 0.5°C (RCP2.6) to 0.8°C (RCP4.5) by 2030 and 0.7°C (RCP2.6) to 3.8°C (RCP8.5) by 2090.

URBAN COOLING TARGETS FOR 2030

PASSIVE ENERGY USAGE

ENHANCED WIND FLOW

LOW CARBON LIVING

ENERGY EFFICIENCY

SHADING

SOLAR AND WIND POWER

SURFACE WATER

An ideal urban landscape transformation of 30% tree canopy cover (currently between 10% and 20% depending on the city), 30% soft, natural and permeable landscape cover (currently between 5% and 20% in different cities), and 40% hard surface cover could decrease the ambient temperature in urban precincts by up to 1°C in winter and 2°C in summer. Such cooling effect can be extended by 0.6°C by using 35% cool paving instead of conventional paving in precinct scale. Utilising cool roof instead of conventional roofs in urban and suburban areas can have an indoor cooling effect of 1.3°C in residential scale. This can indirectly effect outdoor temperatures by decreased demand for air-conditioning and waste heat reduction around buildings.



FURTHER READING

- Akbari, H., & Muscio, A. (2015). Cooling Heat Islands. *Urban Climate*, 14, Part 2, 139-140. doi: <http://dx.doi.org/10.1016/j.uclim.2015.11.005>
- Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas. *Solar Energy*, 70(3), 295-310.
- Akbari, H., & Rose, L. S. (2001). Characterizing the Fabric of the Urban Environment: A Case Study of Salt Lake City, Utah. Berkeley: Lawrence Berkeley National Laboratory.
- Arnfield, A. J. (2003). Two Decades of Urban Climate Research: a Review of Turbulence, Exchanges of Energy and Water, and The Urban Heat Island. *International Journal of Climatology*, 23(1), 1-26.
- Ashie, Y. (2008). Management of Urban Heat Environment. In K. Hanaki (Ed.), *Urban Environmental Management and Technology* (Vol. 1, pp. 215-238). Tokyo: Springer Japan.
- Bähring, L., Mattsson, J. O., & Lindqvist, S. (1985). Canyon Geometry, Street Temperatures and Urban Heat Island in Malmö, Sweden. *Journal of Climatology*, 5(4), 433-444. doi: 10.1002/joc.3370050410
- Bartesaghi Koc, C., Osmond, P., & Peters, A. (2016). A Green Infrastructure Typology Matrix to Support Urban Microclimate Studies. *Procedia Engineering*, 169, pp. 183-190. doi:10.1016/j.proeng.2016.10.022
- Bartesaghi Koc, C., Osmond, P., & Peters, A. (2016). Towards a comprehensive green infrastructure typology: A systematic review of approaches, methods and typologies. *Urban Ecosystems*, 1-21. doi:10.1007/s11252-016-0578-5
- Bell, R., Berghage, R., Doshi, H., Goo, R., Hitchcock, D., Lewis, M., . . . Zalph, B. (2008). Green Roofs. In E. Wong, K. Hogan, J. Rosenberg & A. Denny (Eds.), *Reducing Urban Heat Islands: Compendium of Strategies* Berkley: Environmental Protection Agency (EPA).
- Bell, R., Cole, D., DeAngelo, B., Desautles, L., Dickerhoff, E., Estes, M., . . . Zalph, B. (2005). Trees and Vegetation. In E. Wong, K. Hogan, J. Rosenberg & A. Denny (Eds.), *Reducing Urban Heat Islands: Compendium of Strategies* Berkley: Environmental Protection Agency (EPA).
- Bencheikh, H., & Rchid, A. (2012). The Effects of Green Spaces (Palme Trees) on the Microclimate in Arides Zones, Case Study: Ghardaia, Algeria. *Energy Procedia*, 18(0), 10-20. doi: <http://dx.doi.org/10.1016/j.egypro.2012.05.013>
- BOM. (2014). Bureau of Meteorology Retrieved 2014/12/15, 2014, from <http://www.bom.gov.au/lam/humiditycalc.shtml>
- Bush J., Aye L. & Hes D. (2015). Mitigating the urban heat island effect with vegetation in Australian cities: a policy analysis framework, *State of Aust. Cities Conference December 2015*
- Chen, Y., Jiang, W. M., Zhang, N., He, X. F., & Zhou, R. W. (2009). Numerical Simulation of the Anthropogenic Heat Effect on Urban Boundary Layer Structure. *Theoretical and Applied Climatology*, 97(1-2), 123-134. doi: 10.1007/s00704-008-0054-0
- Chin, G., Desjarlais, A., Estes, M., Hitchcock, D., Lewis, M., Parker, D., . . . Barry, Z. (2005). Cool Roofs. In E. Wong, K. Hogan, J. Rosenberg & A. Denny (Eds.), *Reducing Urban Heat Islands: Compendium of Strategies* Berkley: Environmental Protection Agency (EPA).
- Chow, W. T. L., Salamanca, F., Georgescu, M., Mahalov, A., Milne, J. M., & Ruddell, B. L. (2014). A Multi-method and Multi-scale Approach for Estimating City-wide Anthropogenic Heat Fluxes. *Atmospheric Environment*, 99(0), 64-76. doi: <http://dx.doi.org/10.1016/j.atmosenv.2014.09.053>
- Clay, R., Guan, H., Wild, N., Bennett, J., Vinodkumar, & Ewenz, C. (2016). Urban Heat Island traverses in the City of Adelaide, South Australia. *Urban Climate*, 17, 89-101. doi: <http://dx.doi.org/10.1016/j.uclim.2016.06.001>
- Correa, E., Ruiz, M. A., Canton, A., & Lesino, G. (2012). Thermal Comfort in Forested Urban Canyons of Low Building Density. An Assessment for the City of Mendoza, Argentina. *Building and Environment*, 58, 219-230. doi: <http://dx.doi.org/10.1016/j.buildenv.2012.06.007>
- Coutts, A., Beringer, J., & Tapper, N. J. (2007). Impact of Increasing Urban Density on Local Climate: Spatial and Temporal Variations in the Surface Energy Balance in Melbourne, Australia. *Journal of Applied Meteorology and Climatology*, 46(4), 477-493. doi:10.1175/JAM2462.1
- Coutts, A. M., Tapper, N. J., Beringer, J., Loughnan, M., & Demuzere, M. (2012). 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*, 1-27.
- Dahl, T. (2010). *Climate and Architecture*. Milton Park: Routledge.
- Djen, C. S., Jingchun, Z., & Lin, W. (1994). Solar Radiation and Surface Temperature in Shanghai City and Their Relation to Urban Heat Island Intensity. *Atmospheric Environment*, 28(12), 2119-2127. doi: [http://dx.doi.org/10.1016/1352-2310\(94\)90478-2](http://dx.doi.org/10.1016/1352-2310(94)90478-2)

- Erell, E. (2008). The Application of Urban Climate Research in the Design of Cities. *Advances in Building Energy Research*, 2(1), 95-121.
- Erell, E., Pearlmutter, D., & Williamson, T. (2011). *Urban Microclimate: Designing the Spaces between Buildings*. London: Earthscan.
- Ferguson, B., Fisher, K., Golden, J., Hair, L., Haselbach, L., Hitchcock, D., . . . Wayne, D. (2005). Cool Pavements. In E. Wong, K. Hogan, J. Rosenberg & A. Denny (Eds.), *Reducing Urban Heat Islands: Compendium of Strategies* Berkley: Environmental Protection Agency (EPA).
- Fox J. & Osmond P. (2016), Building cool cities for a hot future. *The Conversation*. <https://theconversation.com/building-cool-cities-for-a-hot-future-57489>
- Gartland, L. (2008). Heat Islands: *Understanding and Mitigating Heat in Urban Areas*. Washington, DC: Earthscan.
- Giridharan, R., Ganesan, S., & Lau, S. S. Y. (2004). Daytime Urban Heat Island Effect in High-Rise and High-Density Residential Developments in Hong Kong. *Energy & Buildings*, 36(6), 525-534. doi: 10.1016/j.enbuild.2003.12.016
- Giridharan, R., Lau, S., Ganesan, S., & Givoni, B. (2007). Urban Design Factors Influencing Heat Island Intensity in High-rise High-density Environments of Hong Kong. *Building and Environment*, 42(10), 3669-3684. doi: 10.1016/j.buildenv.2006.09.011
- Givoni, B. (1998). *Climate Considerations in Building and Urban Design*. New York: Van Nostrand Reinhold.
- Guan, H., Bennett, J., Ewenz, C., Bengler, S., Vinodkumar, Zhu, S., . . . Soebarto, V. (2013). Characterisation, Interpretation and Implications of the Adelaide Urban Heat Island. Adelaide: Flinders University.
- Hanaki, K., & SpringerLink. (2008). *Urban Environmental Management and Technology*. Tokyo: Springer Japan.
- Harman, I. N., & Belcher, S. E. (2006). The Surface Energy Balance and Boundary Layer over Urban Street Canyons. *Quarterly Journal of the Royal Meteorological Society*, 132(621), 2749-2768.
- Hathway, E. A., & Sharples, S. (2012). The Interaction of Rivers and Urban Form in Mitigating the Urban Heat Island Effect: A UK Case Study. *Building and Environment*, 58, 14-22.
- Hatvani-Kovacs, G., Belusko, M., Pockett, J., & Boland, J. (2016). Assessment of Heatwave Impacts. *Procedia Engineering*, 169, 316-323. <http://dx.doi.org/10.1016/j.proeng.2016.10.039>
- Hatvani-Kovacs, G., Belusko, M., Skinner, N., Pockett, J. & Boland, J. (2016). Drivers and Barriers to Heat Stress Resilience. *Science of The Total Environment* 15(571), 603-614. doi:10.1016/j.scitotenv.2016.07.028.
- Hatvani-Kovacs, G., Belusko, M., Pockett, J. & Boland, J. (2016). *Does the Nationwide Australian House Energy Rating Scheme Ensure Heat Stress Resistance? A Report Prepared for the Australian Building Codes Board.* Canberra. doi:10.13140/RG.2.2.13490.61129.
- Hawkins, T. W., Brazel, A. J., Stefanov, W. L., Bigler, W., & Saffell, E. M. (2004). The Role of Rural Variability in Urban Heat Island Determination for Phoenix, Arizona. *Journal of Applied Meteorology*, 43(3), 476-486.
- Hopkins, G., & Goodwin, C. (2011). *Living Architecture : Green Roofs and Walls*. Collingwood, Vic : CSIRO Publishing
- Hoverter, S. P. (2012). *Adapting to Urban Heat: A Tool Kit for Local Governments*. Washington DC: Harrison Institute for Public Law, Georgetown Climate Center.
- Hu, W., Becker, N., McMichael, T., & Tong, S. (2007). Heat-related Mortality during Summer in Sydney, Australia, 1990-2004. *Epidemiology*, 18(5), S113-S114.
- Ichinose, T., Matsumoto, F., & Kataoka, K. (2008). Counteracting Urban Heat Islands in Japan. In D. Peter (Ed.), *Urban Energy Transition: From Fossil Fuels to Renewable Power* (pp. 365-380). Amsterdam: Elsevier.
- Ip, K., Lam, M., & Miller, A. (2010). Shading Performance of a Vertical Deciduous Climbing Plant Canopy. *Building and Environment*, 45(1), 81-88. <http://dx.doi.org/10.1016/j.buildenv.2009.05.003>
- Karatasou, S., Santamouris, M., & Geros, V. (2006). Urban Building Climatology. In M. Santamouris (Ed.), *Environmental Design of Urban Buildings: An Integrated Approach* (pp. 95-119). London: Earthscan.
- Kawashima, S., Ishida, T., Minomura, M., & Miwa, T. (2000). Relations between Surface Temperature and Air Temperature on a Local Scale during Winter Nights. *Journal of Applied Meteorology*, 39(9), 1570-1579. doi:0.1175/1520-0450(2000)039<1570:RBSTAA>2.0.CO;2
- Kevern, J. T., Haselbach, L., & Schaefer, V. R. (2012). Hot Weather Comparative Heat Balances in Pervious Concrete and Impervious Concrete Pavement Systems. *Journal of Heat Island Institute International*, 7(2).
- Kolokotroni, M., Gowreesunker, B. L., & Giridharan, R. (2013). Cool Roof Technology in London: An Experimental and Modelling Study. *Energy and Buildings*, 67(0), 658-667. doi: <http://dx.doi.org/10.1016/j.enbuild.2011.07.011>

- Konstantinov, P. I., Varentsov, M. I., & Malinina, E. P. (2014). Modeling of thermal Comfort Conditions Inside the Urban Boundary Layer during Moscow's 2010 Summer Heatwave (Case-study). *Urban Climate*, 10, Part 3, 563-572. doi: <http://dx.doi.org/10.1016/j.uclim.2014.05.002>
- Kontoleon, K. J., & Eumorfopoulou, E. A. (2010). The Effect of the Orientation and Proportion of a Plant-covered Wall layer on the Thermal Performance of a Building Zone. *Building and Environment*, 45(5), 1287-1303. doi: <http://dx.doi.org/10.1016/j.buildenv.2009.11.013>
- Kusaka, H., & Kimura, F. (2004). Thermal Effects of Urban Canyon Structure on the Nocturnal Heat Island: Numerical Experiment Using a Mesoscale Model Coupled with an Urban Canopy Model. *Journal of Applied Meteorology*, 43(12), 1899-1910.
- Lee, T. W., Lee, J. Y., & Wang, Z.-H. (2012). Scaling of the Urban Heat Island Intensity Using Time-Dependent Energy Balance. *Urban Climate*, 2(0), 16-24. doi: <http://dx.doi.org/10.1016/j.uclim.2012.10.005>
- Lehmann, S. (2015). *Low Carbon Cities*. New York: Routledge.
- Lemonsu, A., Vigiú, V., Daniel, M., & Masson, V. (2015). Vulnerability to Heatwaves: Impact of Urban Expansion Scenarios on Urban Heat Island and Heat Stress in Paris (France). *Urban Climate*, 14, Part 4, 586-605. doi: <http://dx.doi.org/10.1016/j.uclim.2015.10.007>
- Lyle, J. T. (1996). Sun, Wind And Water in the Arid Landscape. In W. O' Reilly (Ed.), *Sustainable Landscape Design in Arid Climates* (pp. 24-33). Washington D.C.: The Aga Khan Trust for Culture
- Meyn, S. K., & Oke, T. R. (2009). Heat Fluxes through Roofs and Their Relevance to Estimates of Urban Heat Storage. *Energy and Buildings*, 41(7), 745-752. doi: <http://dx.doi.org/10.1016/j.enbuild.2009.02.005>
- Montávez, J. P., Rodríguez, A., & Jiménez, J. I. (2000). A Study of the Urban Heat Island of Granada. *International Journal of Climatology*, 20(8), 899-911. doi:10.1002/1097-0088(20000630)20:8<899::AID-JOC433>3.0.CO;2-I
- Morris, C., Simmonds, I., & Plummer, N. (2001). Quantification of the Influences of Wind and Cloud on the Nocturnal Urban Heat Island of a Large City. *Journal of Applied Meteorology*, 40(2), 169-182.
- Morris, C. J. G., & Simmonds, I. (2000). Associations between Varying Magnitudes of the Urban Heat Island and the Synoptic Climatology in Melbourne, Australia. *International Journal of Climatology*, 20(15), 1931-1954. doi: 10.1002/1097-0088
- Nichol, J. E. (1996). High-Resolution Surface Temperature Patterns Related to Urban Morphology in a Tropical City: A Satellite-Based Study. *Journal of Applied Meteorology*, 35(1), 135-146. doi: 10.1175/1520-0450
- Nordbo, A., Karsisto, P., Matikainen, L., Wood, C. R., & Järvi, L. (2015). Urban Surface Cover Determined with Airborne Lidar at 2 m Resolution – Implications for Surface Energy Balance Modelling. *Urban Climate*, 13, 52-72. <http://dx.doi.org/10.1016/j.uclim.2015.05.004>
- Oke, T. R. (1973). City Size and The Urban Heat Island. *Atmospheric Environment*, 7(8), 769-779. doi: [http://dx.doi.org/10.1016/0004-6981\(73\)90140-6](http://dx.doi.org/10.1016/0004-6981(73)90140-6)
- Oke, T. R. (1987). *Boundary Layer Climates* (Second edition ed.). New York: Wiley
- Oke, T. R. (1988). The Urban Energy Balance. *Progress in Physical Geography*, 12(4), 471-508. doi: 10.1177/030913338801200401
- Oke, T. R. (2006a). Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites: Instruments and Observing Methods. IOM Report No. 81. Canada: World Meteorological Organization.
- Oke, T. R. (2006b). Towards Better Scientific Communication in Urban Climate. *Theoretical and Applied Climatology*, 84(1), 179-190. doi: 10.1007/s00704-005-0153-0
- Osmond, P., & Irger, M. (2016). Green roof retrofit and the urban heat island. In S. J. Wilkinson, & T. Dixon (Eds.), *Green Roof Retrofit: Building Urban Resilience* (pp. 37-61). Oxford: Wiley-Blackwell.
- Ottelé, M., Perini, K., Fraaij, A. L. A., Haas, E. M., & Raiteri, R. (2011). Comparative life Cycle Analysis for Green Façades and Living Wall Systems. *Energy and Buildings*, 43(12), 3419-3429. doi: <http://dx.doi.org/10.1016/j.enbuild.2011.09.010>
- Pakzad P and Osmond P (2016). A conceptual framework for assessing green infrastructure sustainability performance in Australia, *State of Australian Cities Conference, Proceedings*, State of Australian Cities Research Network, Gold Coast, 09 - 11 December 2015.
- Pérez, G., Rincón, L., Vila, A., González, J. M., & Cabeza, L. F. (2011). Behaviour of Green Façades in Mediterranean Continental Climate. *Energy Conversion and Management*, 52(4), 1861-1867. doi: <http://dx.doi.org/10.1016/j.enconman.2010.11.008>
- Pérez, G., Rincón, L., Vila, A., González, J. M., & Cabeza, L. F. (2011). Green Vertical Systems for Buildings as Passive Systems for Energy Savings. *Applied Energy*, 88(12), 4854-4859. doi: <http://dx.doi.org/10.1016/j.apenergy.2011.06.032>

- Perini, K., Ottel , M., Fraaij, A. L. A., Haas, E. M., & Raiteri, R. (2011). Vertical Greening Systems and the Effect on Air Flow and Temperature on the Building Envelope. *Building and Environment*, 46(11), 2287-2294. doi: <http://dx.doi.org/10.1016/j.buildenv.2011.05.009>
- Pianella A., Bush J., Chen D., Williams N.S. & Aye L. (2016). Green roofs in Australia: review of thermal performance and associated policy development, *Architectural Science Association 50th Anniversary Conference* December 2016
- Pisello, A. L., & Cotana, F. (2014). The Thermal Effect of an Innovative Cool Roof on Residential Buildings in Italy: Results from two Years of Continuous Monitoring. *Energy and Buildings*, 69(0), 154-164. doi: <http://dx.doi.org/10.1016/j.enbuild.2013.10.031>
- Priyadarsini, R. (2009). Urban Heat Island and its Impact on Building Energy Consumption. *Advances in Building Energy Research*, 3(1), 261-261. doi: 10.3763/aber.2009.0310
- Romeo, C., & Zinzi, M. (2013). Impact of a Cool Roof Application on the Energy and Comfort Performance in an Existing Non-Residential Building. A Sicilian Case Study. *Energy and Buildings*, 67(0), 647-657. doi: <http://dx.doi.org/10.1016/j.enbuild.2011.07.023>
- Rosenfeld, A. H., Akbari, H., Bretz, S., Fishman, B. L., Kurn, D. M., Sailor, D., & Taha, H. (1995). Mitigation of Urban Heat Islands: Materials, Utility Programs, Updates. *Energy and Buildings*, 22(3), 255-265. doi: [http://dx.doi.org/10.1016/0378-7788\(95\)00927-P](http://dx.doi.org/10.1016/0378-7788(95)00927-P)
- Roth, M. (2007). Review of Urban Climate Research in (sub) Tropical Regions. *International Journal of Climatology*, 27(14), 1859-1873. doi: 10.1002/joc.1591
- Sailor, D. J. (2015). A Holistic View of the Effect of Urban Heat Island Mitigation. In S. Lehmann (Ed.), *Low Carbon Cities* (pp. 270-281). New York: Routledge.
- Samuels, R., Randolph, B., Graham, P., McCormick, T., & Pollard, B. (2010). Micro-Urban-Climatic Thermal Emissions: in a Medium-Density Residential Precinct. Sydney.
- Santamouris, M. (2015). Analyzing the Heat Island Magnitude and Characteristics in One Hundred Asian and Australian Cities and Regions. *Science of the Total Environment*, 512-513(0), 582-598. doi: <http://dx.doi.org/10.1016/j.scitotenv.2015.01.060>
- Santamouris, M., Ding, L., Fiorito, F., Oldfield, P. F., Osmond, P., Paolini, R., Prasad, D. & Synnefa, A. (2016). Passive and active cooling for the outdoor built environment – Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. *Solar Energy*. doi:10.1016/j.solener.2016.12.006
- Santamouris, M., Gaitani, N., Spanou, A., Saliari, M., Giannopoulou, K., Vasilakopoulou, K., & Kardomateas, T. (2012). Using Cool Paving Materialsto Improve Microclimate of Urban Areas – Design Realization and Results of the Flisvos Project. *Building and Environment*, 53(0), 128-136. doi: <http://dx.doi.org/10.1016/j.buildenv.2012.01.022>
- Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., & Assimakopoulos, D. N. (2001). On the Impact of Urban Climate on the Energy Consumption of Buildings. *Solar Energy*, 70(3), 201-216. doi: [http://dx.doi.org/10.1016/S0038-092X\(00\)00095-5](http://dx.doi.org/10.1016/S0038-092X(00)00095-5)
- Schwarz, N., Schlink, U., Franck, U., & Gromann, K. (2012). Relationship of Land Surface and Air Temperatures and its Implications for Quantifying Urban Heat Island Indicators: An Application for the City of Leipzig (Germany). *Ecological Indicators*, 18, 693-704. doi: <http://dx.doi.org/10.1016/j.ecolind.2012.01.001>
- Sharifi, E., & Lehmann, S. (2014). Comparative analysis of surface urban heat island effect in central Sydney. *Journal of Sustainable Development*, 7(3), 23-34. doi: 10.5539/jsd.v7n3p23
- Sharifi, E., Sivam, A., & Boland, J. (2016). Resilience to heat in public space: a case study of Adelaide, South Australia. *Journal of Environmental Planning and Management*, 59(10), 1833-1854. <http://dx.doi.org/10.1080/09640568.2015.1091294>
- Souch, C., & Grimmond, S. (2006). Applied Climatology: Urban Climate. *Progress in Physical Geography*, 30(2), 270-279. doi: 10.1191/0309133306pp484pr
- Svensson, M. K., Institutionen f r, g., G teborgs, u., Department of Earth, S., Faculty of, S., University of, G., & Naturvetenskapliga, f. (2004). Sky View Factor Analysis: Implications for Urban Air Temperature Differences. *Meteorological Applications*, 11(3), 201-211. doi: 10.1017/s1350482704001288
- Swaid, H., & Hoffman, M. E. (1990). Climatic impacts of urban design features for high- and mid-latitude cities. *Energy and Buildings*, 14(4), 325-336. doi: [http://dx.doi.org/10.1016/0378-7788\(90\)90095-Z](http://dx.doi.org/10.1016/0378-7788(90)90095-Z)
- Synnefa, A., Dandou, A., Santamouris, M., Tombrou, M., & Soulakellis, N. (2008). On the Use of Cool Materials as a Heat Island Mitigation Strategy. *Journal of Applied Meteorology and Climatology*, 47(11), 2846-2856.

- Synnefa, A., Karlessi, T., Gaitani, N., Santamouris, M., Assimakopoulos, D., & Papakatsikas, C. (2011). Experimental Testing of Cool Colored Thin Layer Asphalt and Estimation of its Potential to Improve the Urban Microclimate. *Building and Environment*, 46(1), 38-44.
- Tapper, N. (2012). Adapting Urban Environments to Climate Change: A Case Study of Melbourne Australia. In M. Robertson (Ed.), *Schooling for Sustainable Development*: (Vol. 3, pp. 185-198): Springer.
- Tapper, N., Coutts, A., Loughnan, M., & Pankhania, D. (2015). Urban Populations' Vulnerability to Climate Extremes. In S. Lehmann (Ed.), *Low Carbon Cities: Transforming Urban Systems* (pp. 361-374): Routledge.
- Tapper, N. J. (1990). Urban Influences on Boundary-Layer Temperature and Humidity - Results from Christchurch, New-Zealand. *Atmospheric Environment Part B-Urban Atmosphere*, 24(1), 19-27.
- Thatcher, M., & Hurley, P. (2012). Simulating Australian Urban Climate in a Mesoscale Atmospheric Numerical Model. *Boundary-Layer Meteorology*, 142(1), 149-175. doi: 10.1007/s10546-011-9663-8
- Voogt, J. A. (2002). Urban Heat Island. In T. Munn, I. Douglas, M. C. MacCracken, H. A. Mooney, P. Timmerman, M. K. Tolba, J. G. Canadell & J. S. Perry (Eds.), *Encyclopedia of Global Environmental Change* (Vol. 3, pp. 660-666). Chichester, UK: Wiley.
- Voogt, J. A., & Oke, T. R. (2003). Thermal Remote Sensing of Urban Climates. *Remote Sensing of Environment*, 86(3), 370-384. doi: [http://dx.doi.org/10.1016/S0034-4257\(03\)00079-8](http://dx.doi.org/10.1016/S0034-4257(03)00079-8)
- Weng, Q., Lu, D., & Schubring, J. (2004). Estimation of Land Surface Temperature-Vegetation Abundance Relationship for Urban Heat Island Studies. *Remote Sensing of Environment*, 89(4), 467-483. doi: <http://dx.doi.org/10.1016/j.rse.2003.11.005>
- Williams, S., Nitschke, M., Weinstein, P., Pisaniello, D. L., Parton, K. A., & Bi, P. (2012). The Impact of Summer Temperatures and Heatwaves on Mortality and Morbidity in Perth, Australia 1994-2008. *Environment International*, 40(Journal Article), 33-38. doi: 10.1016/j.envint.2011.11.011
- Wong, N. H., & Jusuf, S. K. (2010). Study on the Microclimate Condition Along a Green Pedestrian Canyon in Singapore. *Architectural Science Review*, 53(2), 196-212.
- Wong, N. H., Jusuf, S. K., & Tan, C. L. (2011). Integrated Urban Microclimate Assessment Method as a Sustainable Urban Development and Urban Design Tool. *Landscape and Urban Planning*, 100(4), 386-389.
- Wong, N. H., & Yu, C. (2008). *Tropical Urban Heat Islands: Climate, Buildings and Greenery*. New York: Taylor & Francis
- Yamashita, S. (1996). Detailed Structure of Heat Island Phenomena from Moving Observations from Electric Tram-cars in Metropolitan Tokyo. *Atmospheric Environment*, 30(3), 429-435. doi: [http://dx.doi.org/10.1016/1352-2310\(95\)00010-0](http://dx.doi.org/10.1016/1352-2310(95)00010-0)
- Yow, D. M. (2007). Urban Heat Islands: Observations, Impacts, and Adaptation. *Geography Compass*, 1(6), 1227-1251. doi: 10.1111/j.1749-8198.2007.00063.x
- Yuan, C., & Chen, L. (2011). Mitigating Urban Heat Island Effects in High-density Cities Based on Sky View Factor and Urban Morphological Understanding: A Study of Hong Kong. *Architectural Science Review*, 54(4), 305.
- Zinzi, M., & Agnoli, S. (2012). Cool and Green Roofs. An Energy and Comfort Comparison between Passive Cooling and Mitigation Urban Heat Island Techniques for Residential Buildings in the Mediterranean Region. *Energy and Buildings*, 55(0), 66-76. doi: <http://dx.doi.org/10.1016/j.enbuild.2011.09.024>

APPENDIX 1

Scoping the UHI effect – some technical background

Three types of UHI are recognised - surface layer (related to surface materials), canopy layer (below the canopy of trees/skyline of buildings) and boundary layer (dome of hot air over urban areas).

The UHI effect is characterised by the urban surface layer, canopy layer and boundary layer, each with specific characteristics, contributing elements and sub-layers

Investigation of the surface UHI focuses on the urban 'skin'. The UHI effect is highly dependent on the thermal behaviour of materials and surfaces and their exposure to solar radiation. Building envelope materials (rooftops and façades) and open space surface covers (paving, vegetation) vary widely in their physical and thermal properties (specific heat, density, mass, albedo, emissivity and thermal diffusivity), and of course exposure time to the sunlight also varies.

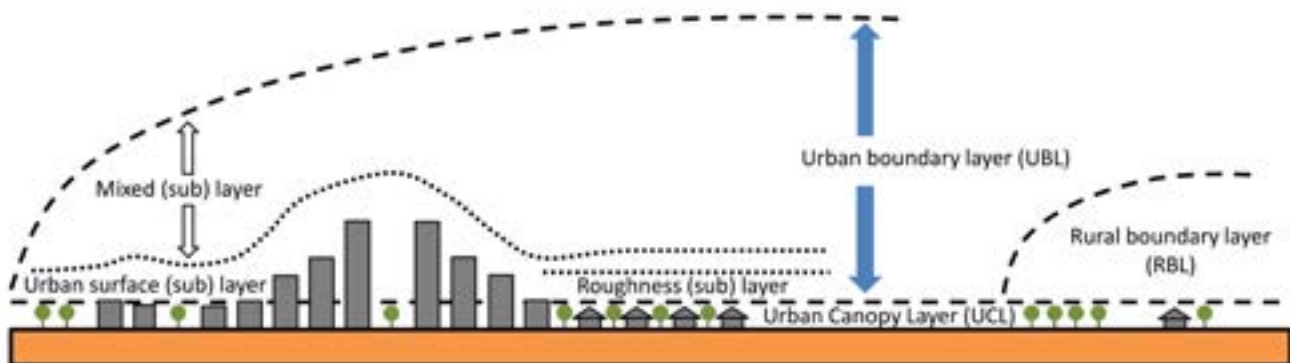
While any isolated material has a complex heat exchange with its surrounding environment, any combination of materials in an urban setting makes the system even more complex. In general, however, the surface UHI effect tends to maximise under a clear sky in the early afternoon.

Heat emitted from urban surfaces affects the air temperature above the surface layer. The space between the surface and the tree canopy or building roofline is known as the urban canopy layer. The thermal characteristics of the canopy layer are directly affected by the surface materials' thermal flux, and are also highly dependent on the air turbulence patterns in the built environment.

The geometry and orientation of urban canyons (linear open spaces such as streets), the aspect (height to width) ratio, land cover features such as asphalt, turf, water and trees, and local wind flow affect the **urban canopy layer**. The canopy layer UHI effect tends to maximise in calm and clear weather especially in the late afternoon and early night.

Turbulent mixing in and above the urban canopy creates a dome of warm air over urban areas which is referred to as the **urban boundary layer**. The height of such a relatively warm air dome can reach up to 1500 metres above the urban surfaces at midnight while it is normally around 500 metres in rural areas in the early morning.

Three sub-layers are detectable in the boundary layer (and above the canopy layer). The first of these, the **roughness sub-layer** is affected by local wind flow at an elevation of four to five times average building height. The second sub-layer is referred to as the inertial surface sub-layer or **urban surface sub-layer**. Here the air temperature is not affected by individual surface materials, but it is affected by the built form configuration and land cover typologies. The third sub-layer is known as the **mixed sub-layer**, which is formed above the inertial surface sub-layer.



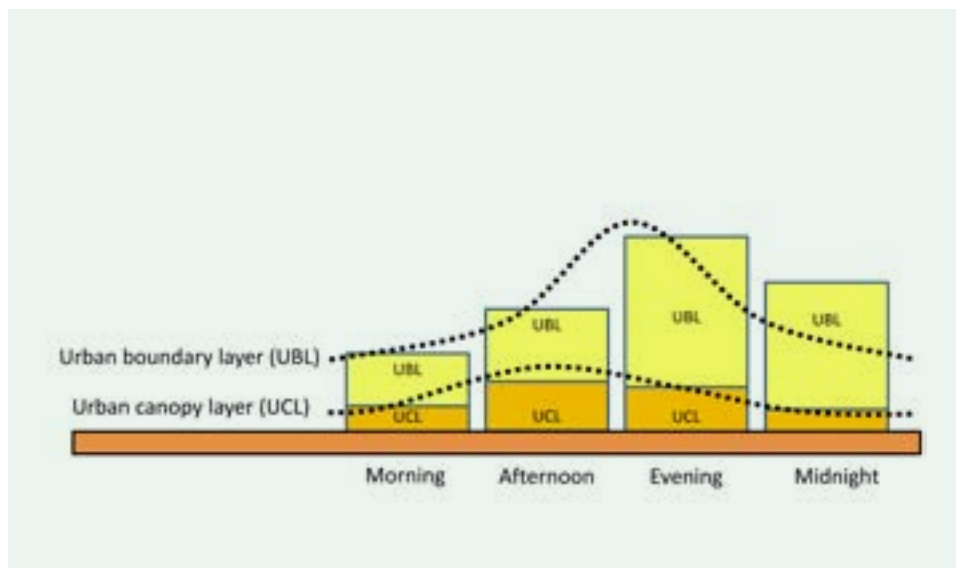
(Image adapted from Sailor, 2015, p. 272).

SCALE	LAYER	TEMPERATURE FOCUS	URBAN ELEMENTS	DIMENSION RANGE
Micro-local	SURFACE	Surface Temperature	Open space surfaces Building rooftops Building façades	1-10 m
Micro-local	CANOPY	Air Temperature	Spaces between buildings Public open spaces Streetscapes Land cover feature classes Urban precincts	10-10 ³ m
Local	ROUGHNESS SUB-LAYER	Air Temperature	Warm waves of air over tall elements of a uniform surface	10 ² -10 ³ m
Local	INERTIAL SURFACE SUB-LAYER	Air Temperature	Blended warm air over uniform surfaces	10 ² -10 ³ m
Local	MIXED SUB-LAYER	Surface & Air Temperature	Land use classes Cities Urban regions	10 ³ -10 ⁵ m

Here the thermal characteristics of the air are no longer the direct result of the urban fabric below, but a mixture of thermal characteristics of the inertial surface sub-layers and local wind flows. As the scale increases, the UHI effect is moderated by air turbulence through convection.

Thus, UHI variability decreases with an increase in spatial scale. The depth of the UHI changes over the course of the day. The volume of warm air in the canopy layer reaches its maximum depth in the late afternoon, when the urban canopy has been exposed to the solar radiation for many hours.

The urban boundary layer, however, reaches its highest volume during the evening, when the warm air elevated through the lower atmosphere and forms the dome of warm air across the urban area.



APPENDIX 2

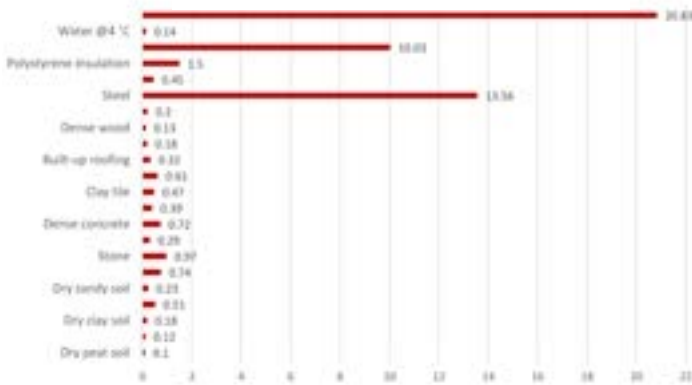
Cool surfaces – some technical information

Thermal diffusivity (thermal conductivity divided by heat capacity) indicates the extent of heat penetration and storage in a material. High values of thermal diffusivity signify that heat can reach deeper in the material volume and the resulting temperature increase can remain constant for a longer time. However, the complex interplay between heat capacity, thermal conductivity, and direct and diffuse radiation in the built environment

– influenced by urban fabrics, cloud cover and solar geometry – makes it vital to consider all thermal parameters of city surfaces to achieve heat-resilient environments. For example, whether or not surfaces are covered by significant shadow, are part of an assembly of different elements or open to the air will influence material selection to support cooling.

THERMAL DIFFUSIVITY OF COMMON BUILDING MATERIALS

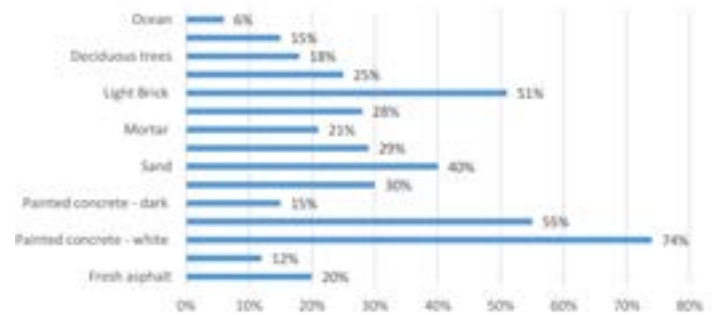
THERMAL DIFFUSIVITY



(Data source: Gartland, 2008)

ALBEDO (SOLAR REFLECTANCE) OF COMMON URBAN SURFACES

ALBEDO (%)



(Akbari & Muscio, 2015).

EMITTANCE OF COMMON URBAN SURFACES AT 300K (26.85 °C).

HEAT EMITTANCE





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