Australia's National Science Agency

Developing a Darwin Heat Mitigation Strategy

A resource towards strategy development for the Northern Territory Government and City of Darwin

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Australian Government

NORTHERN TERRITORY GOVERNMENT

CITY OF DARWIN

About

This report was delivered as part of the work of the Darwin Living Lab. The Darwin Living Lab was established to foster improvements in the liveability, sustainability and resilience of the city. The Darwin Living Lab is an initiative under the Darwin City Deal and is a 10-year collaboration between CSIRO and the partners of the Darwin City Deal: the Australian and Northern Territory governments and the City of Darwin. The City Deal was signed in November 2018 by the Prime Minister of Australia, Chief Minister of the Northern Territory and Lord Mayor of the City of Darwin.

More information and contacts available at: https://research.csiro.au/darwinlivinglab/

Acknowledgement

We acknowledge the Traditional Owners of the greater Darwin region, the Larrakia people, and recognise their culture, history and connection to this land and water. We pay our respects to their Elders past, present and emerging.

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Glossary

Albedo

A dimensionless parameter that ranges between 0 (low reflectance – black body that absorbs all incident radiation) and 1 (high reflectance – white body that reflects all incident radiation). It is a measure of how much light that hits a surface is reflected without being absorbed.

Ambient temperature

The temperature of the surrounding atmospheric air measured in a sheltered environment away from the sun and wind. Ambient air temperature can affect the operation of process equipment, instruments and control. It is sometimes referred to as room temperature.

Apparent temperature

The temperature of what it ‘feels like’ outside versus what it says on the thermometer (ambient temperature). Humidity and wind can affect how cool or hot the body feels when modelled with the ambient temperature.

Canopy cover

The proportion of the forest covered by the vertical projection of the tree crowns.

Ecosystem services

The benefits humankind derives from the workings of the natural world. These include, most obviously, the supply of food, fuels and materials, but also more basic processes such as the formation of soils and the control and purification of water, and intangible benefits such as amenity, recreation and aesthetics.

Evapotranspiration

The sum of evaporation from the land surface and transpiration from plants. Some definitions include evaporation from surface water bodies, even the oceans.

Green cool islands

The vegetated areas inside the city that, due to their thermal characteristics, remain cooler in comparison to the surrounding non-vegetated urban area.

Greenhouse gas

A gas that traps heat in the atmosphere. Carbon dioxide and chlorofluorocarbons are examples of greenhouse gases.

Microclimate

A microclimate is defined as any area where the climate differs from the surrounding area. They occur naturally, as well as in the built environment. Microclimates can be small through to the scale of a city.

Nature-based solutions

The sustainable management and use of nature for tackling a wide variety of complex socio-environmental challenges. This includes the use of vegetation and urban green infrastructure to provide a sustainable way to increase a city’s resilience to climate change and deliver multiple benefits to people and communities.

Passive cooling systems

Design techniques to adapt buildings to local environmental conditions (e.g. climate and site context) using natural (non-mechanical) processes. Local examples in Darwin include breezeways, verandas and louvres.

Representative Concentration Pathways (RCPs)

Developed for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, the RCPs reflect plausible trajectories of future greenhouse gas and aerosol concentrations to the year 2100 and represent a range of economic, technological, demographic, policy and institutional futures.

Street/urban canyons

The space above the street and between the buildings. The measurement of the street canyon provides basic information regarding the building height to street width ratio. When its ratio falls below 0.5 it is referred to as a shallow, whereas a ratio of 2.0 signifies a deep street canyon.

Surface runoff

The flow across the land surface of water that accumulates on the surface when the rainfall rate exceeds the infiltration capacity of the soil.

Thermal comfort

The human satisfactory perception of the thermal environment. It ranges from very uncomfortable to very comfortable and depends not only on the thermal environment and physiological parameters, but also on adaptation and expectation, as well as recent thermal exposure.

Urban climate

The climatic conditions in an urban area that differ from neighbouring rural areas and are attributable to urban development. The effect is produced by the whole urban area. The science that studies this issue is called urban climatology. Generally, this concept refers to the mesoscale, but it could refer to the microscale, since variables have a high spatial variation (mainly air temperature, relative humidity, wind speed, radiation). Also, air pollution is frequently included in the concept of ‘urban climate’.

Urban heat island (UHI)

The urban area that is significantly warmer than its surrounding rural areas due to development and urban activities occurring inside the urban area. The main cause is the modification of land surfaces. Urban surface accumulates heat and thus air temperature tends to increase in the urban area.

Executive summary

One of the key commitments of the Darwin City Deal, announced in November 2018, is to improve Darwin's liveability by cooling the city. As part of the City Deal, the Northern Territory Government is responsible for developing a Darwin Heat Mitigation Strategy that will help mitigate present and future challenges associated with the regional climate.

The purpose of this report is to outline the latest science and information around urban heat mitigation, providing support to the Northern Territory Government and the City of Darwin, and informing the development of the strategy. In order to develop this report, a researcher workshop was conducted in August 2019 to create a set of potential strategies and actions for consideration in the Darwin region. Based on the discussed strategies, a literature review was conducted to examine options being considered and implemented in other cities, with a particular focus on cities with a similar wet-dry tropical climate. This literature review encompassed both scientific research papers as well as grey literature with the goal that Darwin can take advantage of the learnings from other locales. The results of this review are presented in this report.

The report is split into six sections:

- **Section 1**: Introduction to the report and outline of the methods and approaches used.
- **Section 2**: Summary of the current and future climate of Darwin to set the climatic context.
- **Section 3**: Background and science of the urban heat island effect and how it develops.
- **Section 4**: A report on potential strategies and actions that could be tested in future trials and pilots in Darwin. Five strategies are discussed: cool buildings, water sensitive urban design and water features, urban green infrastructure, cool roads and paths, and education and awareness.
- **Section 5**: Overview of relevant case studies from other cities with a similar climate to Darwin.
- **Section 6**: Conclusions and potential next steps.

Section summaries

Current and future climate of Darwin

Darwin has a tropical savanna climate with distinct wet and dry seasons, as represented by the Köppen-Geiger climate classification Aw (Every et al., 2020). In Darwin, January and February are the heart of the wet season, when monsoonal weather dumps heavy afternoon and overnight rain on the city, and average daily temperatures range between 24.6 °C and 31.9 °C. In March and April, the rains begin to subside. May marks the beginning of the dry season, which extends through to September. The humidity is at its lowest during this season and the nights can become relatively cool, with average daily temperatures ranging between 19.3 °C and 32.6 °C. October to December is the pre-monsoon period (locally referred to as the 'build-up') when it becomes increasingly humid with occasional rain. The hottest month is November, just before the onset of the main rain season, where the average daily maximum temperature is 34 °C. At this time, the apparent temperature, which is adjusted for humidity, provides a better measure of human thermal comfort and will sometimes rise above 45 °C.

Temperatures are projected to increase for all Australian cities. In Darwin the change may be significant, with very high confidence in continued substantial increases in projected mean, maximum and minimum temperatures based on modelled projection of increased greenhouse gas concentrations. The annual average number of days with maximum temperatures above 35 °C is projected to increase from 11 days in 1995 to between 141 and 308 days in 2070, under a high emission scenario (RCP8.5). By late this century, summer rainfall changes are projected to be between –15% and +10% under an intermediate emission scenario (RCP4.5) and between –25% and +20% under a high emission scenario (RCP8.5). There is high confidence that there will be an increase in the intensity of extreme rainfall events in the future.

Darwin and the urban heat island effect

The urban heat island effect is well documented in hundreds of cities around the world – including major cities in Australia – and will be amplified by global climate change and projected increases in background temperatures that will increase the heat load within a city (Zhao et al., 2014).

The urban heat island effect occurs when urban areas exhibit higher temperatures than surrounding rural or suburban areas (Oke, 1982). Urban development generally leads to natural land surfaces and vegetation being replaced by built infrastructure such as roads, footpaths, car parks and buildings (Yuan and Bauer, 2007). This built infrastructure often comprises materials, such as concrete and asphalt, which absorb and hold heat. A high density of nonporous and non-reflective surfaces in an urban area, such as roof tiles, concrete and asphalt, can trap the absorbed heat so that temperatures cool more slowly at night, providing limited respite from the daytime heat. Thus, the urban heat island effect is usually most evident at night (Arnfield, 2003).

As Darwin grows, it will increasingly experience urban heat island effects. Darwin already exhibits an urban heat island effect of 2–3 °C in the Darwin Central Business District, meaning the CBD is between 2 °C and 3 °C warmer than the surrounding suburbs, as measured in previous research from the University of New South Wales (Santamouris et al., 2017b).

Potential strategies and actions that could be tested in future trials and pilots

Cities around the world are developing and testing strategies to combat urban heat island and climate warming; however, only some will be relevant for Darwin’s climatic context. We review strategies and actions, drawn from both the scientific and grey literature, found to be effective in dealing with high temperatures. We especially focus on strategies and actions conducted for cities facing similar problems around heat. We review strategies and actions in these five areas:

- ***Cool buildings***: Designing buildings to reduce temperatures and increase cooling will be important as Darwin’s urban temperatures increase through urban development and climate change. Large-scale adaptation of buildings and cities are being considered by local governments and city planners to mitigate the effects of urban heat and to prevent heat-related illness. This section examines the utility of passive cooling, cool roofs, air conditioning, and district cooling and explores how these strategies could be implemented in Darwin. These strategies can be applied in new buildings as well as retrofit into older infrastructure in order to maximise cooling.
- ***Water sensitive urban design and water features***: Water sensitive urban design seeks to replace the traditional engineering approach to urban water management and promote the integration of urban planning with the management, protection and conservation of the urban

water cycle. Additionally, integrating water features and water management into city design can provide options for mitigating heat in urban environments. This section examines the potential for integrating suitable water designs and features in Darwin such as water spraying/misting systems; artificial wetlands, ponds, and fountains; and integrated green and blue spaces.

- ***Urban green infrastructure***: Green infrastructure incorporates a range of green space forms and types such as green walls and roof gardens, and green spaces such as parks, community gardens and natural areas. Worldwide, vegetation has been used extensively as an urban heat mitigation strategy. Sometimes known as 'nature-based solutions', the use of vegetation and urban green infrastructure may provide sustainable and multi-beneficial ways to increase a city's resilience to climate change. This section examines the potential to incorporate green roofs, vertical greenery and facades into the built environment, and increasing the urban forest across the Darwin CBD.
- ***Cool roads and paths***: There are multiple ways to support the development of cooler roads and paths. Technologies used to decrease the temperature of pavements in urban areas may include permeable pavement systems such as water retentive and porous pavements to reduce surface temperatures. Using alternative materials can increase the albedo (solar reflectance) of urban surfaces. Surfaces stay cooler by releasing less heat into the ambient air, providing an effective cooling option for urban areas. This section examines the potential of creating well-ventilated walkways and streetscapes, using cool and permeable pavements, and increasing tree cover along footpaths and streets to increase cool options for mobility and transport in Darwin.
- ***Education and awareness***: In many cases, education and communication will be required to initiate social change and promote end user buy-in for any new initiatives. Education and awareness strategies must consider the varying extents to which different groups of people within the community understand and desire to make changes. Due to the increase in hot days expected in Darwin, it is important the community is informed of how to deal with heat events. Behavioural change will be key towards keeping communities safe, and diverse messaging and actions may be necessary. This section examines how social campaigns and heat management plans can be used to increase awareness around heat prevention measures. This section also examines how changes in vehicle use can be encouraged through behavioural change.

A summary table (Table 3) of these strategies, outlining the pros, cons, and potential actions that could be implemented in Darwin is provided in Section 4. This table may be helpful in evaluating how the options compare and which options may be more effective for different parts of the city.

Relevant case studies from other cities with a similar climate to Darwin

Several case studies are presented to highlight experiences in other tropical cities that have implemented heat mitigation measures in response to the climate and local character of that city. These cases can provide insights for Darwin on different approaches to improve liveability and thermal comfort in a tropical wet-dry climate. Even in cases where tropical cities have an analogous climate to Darwin, the appropriate response to improve liveability and thermal comfort will emerge from the unique context of each city. In Darwin, a place-based approach to tropical urbanism is needed to not only consider the climate but the cultural heritage, values, community lifestyle expectations and local environment. The examples are from cities of the same climate classification (Köppen-Geiger climate classification *Aw*) as well as similar climate classifications (*Af*, *As* and *Am* classifications) as they will provide the most similar climate context for Darwin. The case study examples, and their Köppen-Geiger climate classifications, are:

- Cairns, QLD (*Am)*
- Singapore (*Af)*
- Bangalore, India (*Aw)*
- Miami, Florida, USA (*Am)*
- Enugu City, Nigeria (*Aw*).

Conclusions

There are few examples of heat mitigation activities from cities with an analogous climate to Darwin. Nevertheless, this presents an opportunity for Darwin to become a world leader in the science and innovation of heat mitigation among cities characterised by wet-dry tropical climates.

This report provides information to assist with developing strategies and prioritising actions for mitigating urban heat impacts in Darwin. The suggested next steps are as follows:

Short-term actions for long-term gain

The literature review findings demonstrate that urban heat can be mitigated through the strategic use of cool building design and materials, water sensitive urban design and water features, increasing vegetation cover, creating cool roads and paths, and increasing education and awareness about behavioural change to reduce heat. The following actions can be taken now:

- Use the maps of land surface temperature and information on population vulnerability to identify the priority areas for targeted urban heat mitigation actions.
- Examine opportunities to incorporate low-cost actions to retrofit current building types.
- Implement trials for cool and permeable pavements, tree shading, water retention and misting, and path placement to test the effect of these various changes on the cooling effect on these important transport corridors – for both roads as well as in the design of active transport corridors through Darwin.
- Consider current heat warning plans and social media campaigns in their effectiveness to inform Darwin communities about heat protective behaviours.

Engaging with stakeholders to obtain more information

Although the ultimate actions within the Darwin Heat Mitigation Strategy will have to be socialised across different levels of government, a wider engagement strategy across the general Darwin community will be needed, with a specific focus on vulnerable groups. This broader engagement strategy may take the form of:

- Research surveys, to systematically survey a representative population of Darwin LGA residents in order to garner specific understanding of vulnerabilities and needs within the community.
- Interviews or focus groups, conducted to socialise and discuss various strategies and actions to be piloted.
- Specific actions, to elicit ideas and opinions from vulnerable groups, which may require additional outreach and engagement to increase involvement.

Thinking through long-term changes for transformation

Transformational change will require long-term strategic engagement. This will require collaboration across sectors and stakeholders to develop a plan of action that will take into account the needs and desires currently and into the future.

Opportunities to support long-term strategic planning for transformational change include:

- Developing a multi-stakeholder reference group and process that can address various viewpoints on urban heat impact and comment on future planning.
- Modelling the costs and benefits at city scale of different treatment options through time and in different combinations that take into account different scenarios of change.
- Researching policy levers that allow for changes to occur at the city level, through multiple nodes of influence.

1 Introduction

Like much of the world, cities in Australia are experiencing unprecedented changes in urban heat, and Darwin is no exception. The Darwin City Deal, announced in November 2018, has a goal, as one of its key commitments, to improve Darwin's liveability by cooling the city for its community. As part of the Darwin City Deal, the Northern Territory Government is developing a Darwin Heat Mitigation Strategy that provides a plan towards decreasing temperatures across the CBD.

The IPCC Special Report *Global Warming of 1.5°C* (IPCC, 2018) warns of the vulnerability of cities to the impacts of climate change and emphasises the need to change the way we design, build and live in cities in order to mitigate or adapt to these impacts (Dasgupta, 2018). Besides the climate change impacts of rising temperature, more frequent, intense and longer lasting periods of hot weather are exacerbated by the urban heat island (UHI) effect. Such patterns of increasing urban temperatures have environmental, economic and social impacts on built infrastructure and urban communities (US EPA, 2019).

The purpose of this report is to outline the latest science and information around heat mitigation, providing support to the Northern Territory Government to inform the development of their strategy document.

1.1 Methods and approach

Before CSIRO embarked on developing this literature review report, CSIRO ran two processes to engage with stakeholders.

In August 2019, a workshop was conducted with researchers working in urban cooling in Darwin. This workshop helped to establish a baseline understanding of the types of research already being conducted in Darwin around urban cooling. This workshop brought together researchers from UNSW, CDU and CSIRO to discuss available data, current lines of inquiry, and areas of interest that researchers would like to see applied in Darwin. This workshop helped generate several ideas for future work in Darwin. A short report of this workshop was submitted to the Darwin Living Lab Management Committee.

Discussions were conducted with Northern Territory Government on preferred heat mitigation strategies and desired information to include in the strategy. Five heat mitigation strategies with different end goals, levels of detail, and sets of information were presented. Through subsequent discussions, a prototype strategy was developed with level of detail and type of information for each section specified. This conversation helped guide the literature review to provide decision makers with current scientific knowledge on heat mitigation approaches that could help inform the Darwin Heat Mitigation Strategy.

This report provides a synthesis of the science around urban heat mitigation strategies used around the world, using a lens to focus on strategies and actions that may be more suitable for Darwin. These strategies and actions are drawn from the scientific literature as well as grey literature – particularly from other reviews conducted for cities facing similar problems around heat (e.g. Cooling Singapore Strategy) as well as previous work conducted in Darwin (e.g. The Heat Mitigation Program (Santamouris et al., 2017b)). This report provides an understanding of what strategies and actions have been considered and posits potential ways these could be applied in Darwin.

The report contains the following sections:

- Section 2: Current and future climate of Darwin.
- Section 3: Introduction to the urban heat island effect.
- Section 4: Potential strategies and actions that could be tested in future trials and pilots.
- Section 5: Relevant case studies from other cities with a similar climate to Darwin.
- Section 6: Conclusions and potential next steps.

2 Darwin’s climate

2.1 Current climate

The Köppen-Geiger climate classification is widely used to describe the various climates of the world. Darwin has a tropical savanna climate with distinct wet and dry seasons, as represented by the Köppen-Geiger climate classification *Aw* (Every et al., 2020). *Aw* climates often feature tree-studded grasslands with the widespread occurrence of tall, coarse grass (called savanna) which has led to *Aw* climates often being referred to as tropical savanna (McKnight and Hess, 2000). The native plants and animals in these climates have adapted to the seasonal wet and dry conditions.

Aw climates occur in the far north of Australia, as well as across several other regions around the world (Figure 1). These regions, and the cities they comprise, are analogues of the weather experienced in Darwin and may have climate mitigation and adaptation solutions that are also relevant to Darwin’s climate. In the southern hemisphere, the tropical savanna climate occurs across Sudan and eastern Africa (e.g. Accra, Ghana; Bamako, Mali), parts of south-central Brazil and adjacent parts of Bolivia and Paraguay (e.g. Brasilia, Brazil), as well as parts of south and south-east Asia (e.g. Dhaka, Mumbai, Bangkok and Ho Chi Minh City). In the northern hemisphere, the tropical savanna climate occurs north of the Amazon in Venezuela and Colombia (e.g. Cali, Colombia; Caracas, Venezuela), as well as parts of western Central America (e.g. Cancun, Mexico; Guatemala City, Guatemala), western Cuba (Havana, Cuba), and the southern part of Florida (e.g. Key West and Naples, Florida) in the United States (Peel et al., 2007).

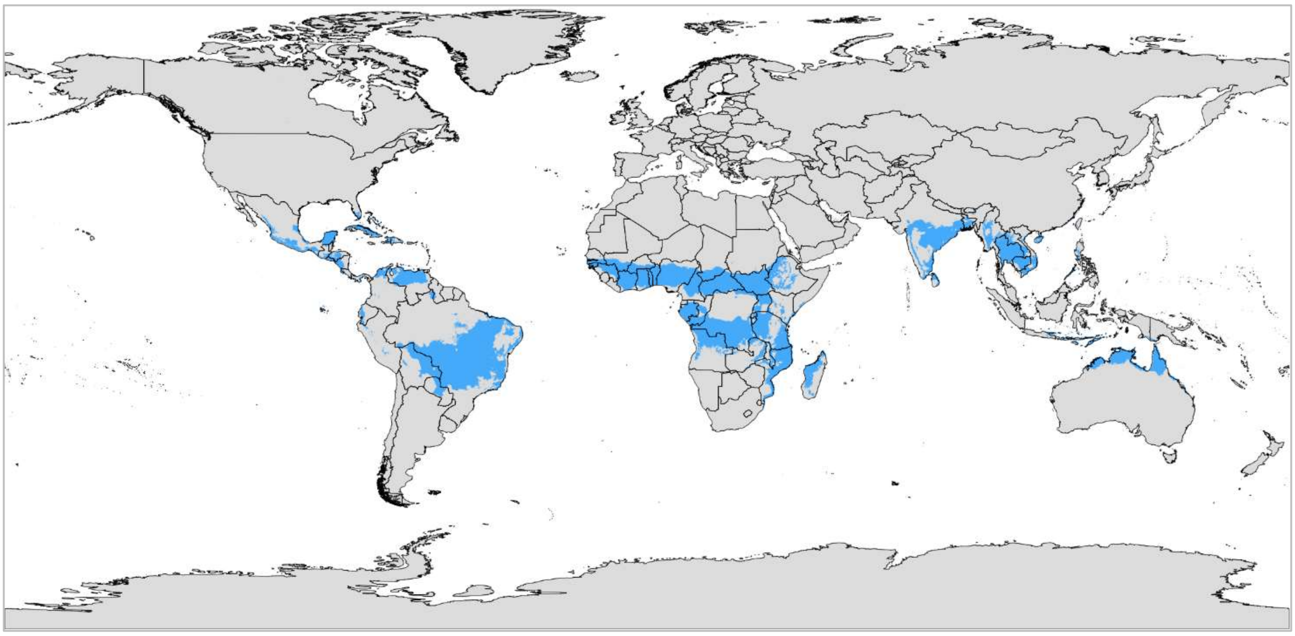

Figure 1. Global map of regions that fit the Köppen-Geiger climate classification *Aw* (1980–2016).

Source: Beck et al. (2018)

In Darwin, the heart of the wet season is in January and February, when monsoonal weather dumps heavy afternoon and overnight rain on the city, and average daily temperatures range between 24.6 °C minimum and 31.9 °C maximum. The rains begin to subside in March and April. May marks the beginning of the dry season, which extends through to September. The humidity is at its lowest during this season and the nights can become relatively cool, with average daily temperatures ranging between 19.3 °C and 32.6 °C. October to December is the pre-monsoon period (locally referred to as the 'build-up'), when it becomes increasingly humid with occasional rain. The hottest month is November, just before the onset of the main rain season, where the average daily maximum temperature is 34 °C (Figure 2). At this time, the apparent temperature, which is adjusted for humidity, provides a better measure of human thermal comfort and will sometimes rise above 45 °C.

The ***apparent temperature*** is what it 'feels like' versus what it says in the thermometer, called ambient temperature. By considering wind and humidity, the apparent temperature indicates what level of discomfort a person would feel, taking into account how much heat the wind would remove or if humidity levels were high enough that sweat could not evaporate and cool the skin.

For more information see: http://media.bom.gov.au/social/blog/1153/apparent-feels-like-temperature/ .

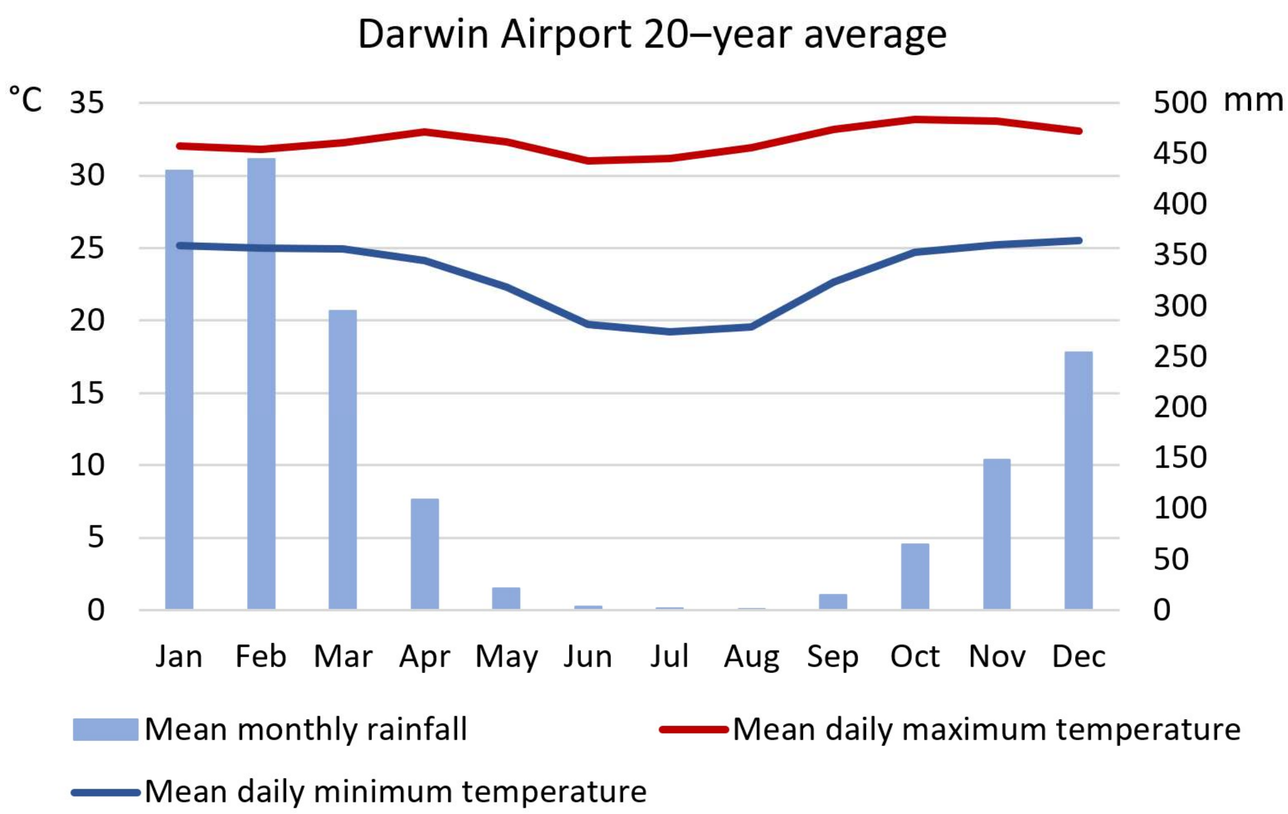

Figure 2. Monthly average temperature and rainfall measurements for Darwin Airport based on Bureau of Meteorology data for a 20-year period (Sep 1999 to Aug 2019).

The average annual temperature is 27.4 °C, and average annual rainfall is 1731mm. Average daily temperatures are highest on average in November, at around 29.2 °C, and lowest in July, when it is around 24.4 °C.
Figure created by Jacqui Meyers, CSIRO using data from the Bureau of Meteorology (Bureau of Meteorology, 2019a).

The 2019 wet season smashed records, with the Northern Territory experiencing its hottest season on record and the driest in 27 years. The extraordinary season made headlines for extreme heat in some communities and is consistent with the story of climate change affecting the region based on Bureau of Meteorology projections (Davidson, 2019). During the 2019 wet season, the Northern Territory's total rainfall was just two-thirds of the average, with several weather observation sites, including the Darwin River Dam and Tennant Creek, recording their lowest ever rainfall.

2.2 Larrakia calendar and seasonality

Gulumoerrgin is the Indigenous language for Darwin and the surrounding regions of Cox Peninsula and Gunn Point in the Northern Territory (Williams et al., 2012). The Gulumoerrgin (Larrakia) worked with CSIRO in 2012 to create a calendar using their seasonal knowledge, identifying seven main seasons that are delineated by rainfall as well as the bush foods that are available in that season.

The Gulumoerrgin seasons are defined as:

- Balnba (rainy season)
- Dalay (monsoon season)
- Mayilema (spear grass, magpie goose egg and knock 'em down season)
- Damibila (barramundi and bush fruit time)
- Dinidjanggama (heavy dew time)
- Gurrulwa (big wind time)
- Dalirrgang (build-up).

The Larrakia calendar may be relevant for certain strategies and actions as certain activities may be seasonal. More information can be found on CSIRO's website with access to visual representations of the various seasons (https://www.csiro.au/en/Research/Environment/Land-management/Indigenous/Indigenous-calendars/Gulumoerrgin).

2.3 Future climate

Climate projections for Darwin are based on the climate projections work found in *Climate Change in Australia for the Monsoonal North* (Moise et al., 2015). The projections are based on the outputs of a set of 40 global climate models (GCMs) developed by Australian and international scientists. Climate models are based on established laws of physics and are rigorously tested for their ability to reproduce past climate. These projections draw on the full breadth of available data and peer-reviewed literature to provide a robust assessment of the potential future climate.

Projections are based on four Representative Concentration Pathways (RCPs) underpinned by emission scenarios. The RCPs reflect plausible trajectories of future greenhouse gas and aerosol concentrations to the year 2100 and represent a range of economic, technological, demographic, policy and institutional futures. More information on climate models and RCPs can be found on the Climate Change in Australia website (www.climatechangeinaustralia.gov.au).

2.3.1 Temperature

Temperatures are projected to increase for all Australian cities. In Darwin, mean temperature increased between 1910 and 2013 by around 0.9 °C (CSIRO, 2016). Future changes to temperature may be significant, with very high confidence in continued substantial increases in projected mean, maximum and minimum temperatures based on modelled projection of increased greenhouse gas concentrations. The annual average number of days with maximum temperatures above 35°C is projected to increase from 11 days in 1995 to between 141 and 308 days in 2070, under a high emission scenario (RCP8.5), which reflects the world's current trajectory (CSIRO, 2016) (Table 1).

For the near future (2030), the annual average warming across all emission scenarios is projected to be between 0.5 °C and 1.3 °C above the climate of 1986–2005. By late in the century (2090), under a high emission scenario (RCP8.5), the projected range of warming is 2.8–5.1°C, while under an intermediate emission scenario (RCP4.5) the projected warming is 1.3–2.8 °C. Average temperatures will continue to increase in all seasons.

The year 2019 set records for extreme heat in Darwin. The Bureau of Meteorology's weather station at Darwin Airport recorded 45 days of 35 °C or above in 2019 (exceeding 29 such days in 2013), including a record run of 11 days in a row in December (www.bom.gov.au/climate/current/annual/nt/summary.shtml). This already exceeds the projected average for 2030 under RCP4.5 (Table 1).

Table 1. How will the frequency of hot days change in Darwin? Current average annual number of days (for the 30-year period 1981–2010) above 35 °C and 40 °C based on data collected from Darwin Airport.

Estimates for the future are calculated using the median CMIP5 project model warming for 2030 and 2090, and within brackets the 10th and 90th percentile CMIP5 warming for these periods, applied to the 30-year ACORN-SAT station series. Refer to the Climate Change in Australia technical report for the Wet Tropics Cluster for more information (Moise et al., 2015).

		Darwin Future Projected Days with T_{max} Greater Than Threshold			
Threshold	1995 baseline	2030 RCP4.5	2090 RCP2.6	2090 RCP4.5	2090 RCP8.5
Over 35 °C	11	43 (25–74)	52 (24–118)	111 (54–211)	265 (180–322)
Over 40 °C	0	0 (0–0)	0 (0–0)	0 (0–0.2)	1.3 (0.2–11)

2.3.2 Rainfall

Providing confident rainfall projections for the Darwin region is difficult because global climate models offer diverse results based on the modelled data from the Climate Change in Australia website (Table 2). Natural climate variability is projected to remain the major driver of rainfall changes in the next few decades. By late this century, summer rainfall changes are projected to be between –15% and +10% under an intermediate emission scenario (RCP4.5) and between –25% and +20% under a high emission scenario (RCP8.5).

Despite uncertainty in future projections of total rainfall for the Darwin region, an understanding of the physical processes that cause extreme rainfall coupled with modelled projections, indicate with high confidence that extreme rainfall events will become more intense. However, the magnitude of that increase in intensity cannot be confidently projected.

Table 2. Annual values of maximum temperature, rainfall and drought factor for the 1995 baseline and projections for 2030 and 2090 under RCP4.5 and RCP8.5 emission scenarios.

Values were calculated from three climate models from the Darwin Monsoonal North West Station (Moise et al., 2015).

Annual Maximum	1995 Baseline	2030 RCP4.5			2030 RCP8.5			2090 RCP4.5			2090 RCP8.5		
		Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Temp (°C)	32.2	33.1	33.7	33.1	33.4	33.7	33.2	34.5	34.2	34.1	36.3	36.2	35.2
Rainfall (mm)	1702	1805	1525	1842	1764	1670	1964	1849	1798	1936	1898	1561	1967
DF (drought factor)	6.4	6.4	6.8	6.3	6.4	6.5	6.3	6.4	6.5	6.4	6.4	6.8	6.3

Model 1: CESM (Community Earth Systems Model) developed by UCAR.
Model 2: GFDL (Geophysical Fluid Dynamics Laboratory) developed by NOAA.
Model 3: MIROC (Model for Interdisciplinary Research on Climate) developed by the University of Tokyo.

2.3.3 Other variables of interest

There are some additional variables of interest to Darwin that were explored within the Climate Change in Australia project. Humidity changes may have a large impact on the heat mitigation strategy, due to their effect on apparent temperature and thermal comfort. The other variables may be of interest when considering which strategies and actions to implement.

Tropical cyclones: Tropical cyclones are projected to become less frequent, but the proportion of the most intense storms is projected to increase.

Humidity: There is little change projected in relative humidity until later in the century under a high emission scenario (RCP8.5), where a decrease in relative humidity is projected. Relative humidity measures how much moisture is in the air relative to saturation point (Bureau of Meteorology, 2017). The moisture content of the air influences human thermal comfort, as it determines how effectively the body can evaporatively cool through sweating. Warmer air can hold more moisture than cooler air, therefore as temperature rises the relative humidity falls but the amount of moisture in the air has remained the same. The moisture in the dew point temperature reflects the temperature at which condensation will start to occur, which measures the amount of moisture in the air – this may provide a more robust measure of heat stress risk (Bureau of Meteorology, 2017).

Marine and coastal projections: There is very high confidence in future sea level rise. By 2030 the projected range of sea level rise is 0.06–0.17 m above the 1986–2005 level, with only minor differences between emission scenarios. Sea surface temperature is projected to increase in the range of 2.2–4.1 °C by 2090 under a high emission scenario (RCP8.5). The sea will also become more acidic, with acidification proportional to emissions growth. Impacts of sea level rise in Darwin include increased risk of coastal flooding and erosion (Moise et al., 2015). The occurrence of extreme sea level events are influenced by tides, wind direction and storm surges (in Darwin, storm surges are often caused by tropical cyclones). Sea level rise might also result in changes to coastal vegetation around Darwin Harbour, such as reduced area of mangrove ecosystems (Heenkenda and Bartolo, 2016).

3 Urban heat island effect

The urban heat island (UHI) effect is well documented in hundreds of cities around the world, including major cities in Australia, and will be amplified by global climate change and projected increases in background temperatures that will increase the heat load within a city (Zhao et al., 2014).

The UHI effect occurs when urban areas exhibit higher temperatures than surrounding rural or suburban areas (Oke, 1982). Urban development generally leads to natural land surfaces and vegetation being replaced by built infrastructure such as roads, footpaths, car parks and buildings (Yuan and Bauer, 2007). Because vegetation is often removed to make way for built structures, there are fewer trees and plants in the urban landscape to provide shade and the cooling benefits of evapotranspiration that lower the local temperature (Yuan and Bauer, 2007).

This built infrastructure often comprises materials such as concrete and asphalt, which absorb and hold heat. A high density of nonporous and non-reflective surfaces, such as roof tiles, concrete and asphalt in an urban area can trap the absorbed heat so that temperatures cool more slowly at night, providing limited respite from the daytime heat. Thus, the UHI effect is usually most evident at night (Arnfield, 2003). Rainfall tends to run off paved surfaces, providing fewer opportunities for retention in the landscape and infiltration into the soil where evaporation can contribute to further cooling.

Although rural areas typically cool down quickly at night, in urban areas, solar radiation and heat absorbed during the day by building materials and hard paved surfaces is released slowly back into the environment at night. Tall buildings also tend to prevent heat from dissipating and reduce air flow – although they may provide shade to urban surfaces during the day, which can prevent heat build-up (Mohajerani et al., 2017). Night-time cooling can also be reduced if the layout and design of buildings and streets trap warm air for longer at night (Arnfield, 2003). Other sources of heat, such as waste heat from air conditioners used to cool buildings or heat generated from the engines of vehicles can also be trapped and absorbed in cities and contribute to the UHI effect (US EPA, 2019).

Research from Melbourne also shows that the UHI effect can affect seasonality with summer weather spreading into early autumn (Sachindra et al., 2016). However, based on multi-year measurements in Sydney, data show that the magnitude of the UHI effect varies depending on prevailing weather conditions (Santamouris et al., 2017a).

As Darwin grows, it will increasingly experience UHI effects. Darwin already exhibits a UHI effect of 2–3 °C in its CBD. This means the CBD is between 2–3 °C warmer than the surrounding suburbs, as measured in previous research from the University of New South Wales (Santamouris et al., 2017b).

Urban overheating has serious consequences on thermal comfort, energy consumption, health and the economy and thus negatively affects the sustainability and liveability of cities (Corburn, 2009).

4 Potential strategies and actions

Cities around the world are developing and testing strategies to combat urban heat and climate warming through a combination of adaptation and mitigation options. However, only some will be relevant for Darwin's climatic context or will be able to provide greater cooling potential and may have different effects depending on the season. In this section, we highlight strategies and actions that have been found to be effective in dealing with high temperature based on a literature review of successful heat mitigation strategies.

When possible, this report highlights examples specific to Australia or international cities with similar climate characteristics to Darwin. Importantly, there are few examples of experimental data and reports regarding heat mitigation strategies in cities with similar climate characteristics to Darwin. We present examples from *Aw* (tropical savanna climate with dry-winter characteristics) specific cities, as well as cities that are similar (e.g. *As* (tropical savanna climate with dry-summer characteristics)*, Af* (tropical rainforest climate)*, Am* (tropical monsoon climate)). Specific case studies are provided in Section 5 that highlight *Aw* cities as well as similar climates.

4.1 Cool buildings

Designing buildings to reduce temperatures and increase passive cooling will be important as Darwin's urban temperatures increase through the growth of urban development as well as climatic change. Large-scale adaptation of buildings and cities are currently being considered by local governments and city planners to mitigate the effects of urban heat and to prevent heat-related illness (Wilhelmi and Hayden, 2010). Options such as the adoption of different building materials or the implementation of more efficient cooling systems are also being considered. These strategies may need to be applied in new construction as well as retrofit into older buildings in order to maximise cooling in buildings across the city. Also, it is important to investigate the different physical properties that characterise the surfaces of the paving and building envelope because different urban surfaces, in their interactions with the local microclimate, will affect the outdoor thermal comfort for communities (Doulos et al., 2004).

Historically in Darwin, homes were characterised by raised lightweight construction, which were designed to maximise cooling by cross-ventilation. These lightweight homes were extensively damaged during Tropical Cyclone Tracey in 1974 (Leicester and Reardon, 1976; Safarova et al., 2018). The homes built after this event were designed to withstand future tropical cyclones (Schofield et al., 2010). The Darwin Office of the Federal Department of Construction (1975–1978) introduced a new housing type: single-storey dwellings on a concrete slab that had concrete or brick walls, which required air conditioning to maintain thermal comfort and insulation for energy efficiency (Szokolay, 1976). Housing stock in Darwin can be broadly divided into the following (Safarova et al., 2018):

- Naturally ventilated – houses that often have low thermal mass to prevent heat retention and are designed to manage thermal comfort through cross-ventilation.
- Air-conditioned – houses that provide thermal comfort through air conditioning and are often designed with high thermal mass or insulation to improve efficiency of air conditioning.

- Mixed mode – houses that combine both zones with a mix of high and low thermal mass, providing thermal comfort through both air conditioning and cross-ventilation.

Most homes in Darwin operate in mixed mode, where air conditioning is used to provide thermal comfort at least some of the time. A survey by the ABS found that more than 90% of households in the Northern Territory have some air conditioning installed (ABS, 2014). Passive design approaches can help to improve the thermal comfort in buildings while reducing energy demand and associated greenhouse gas emissions (Daniel, 2018). Passive design uses building approaches that are responsive to the local climate and site context, which reduces the energy needed to maintain a comfortable temperature in the building. Figure 3 highlights a selection of house designs in Darwin that includes some passive design approaches, such as shading/awnings, use of reflective material and cross-ventilation.

Figure 3. Selection of houses in Darwin that use passive design.
Source: CSIRO.

4.1.1 Passive cooling

Changes in building design may include changing the building layout or the location of urban elements within a precinct to improve the thermal performance of the urban area. Good urban planning is crucial to take advantage of the regional climate and air flow and develop suitable flow paths for wind to remove the accumulated urban heat (Omer, 2008). Previous research has shown that suboptimal lot orientation can decrease energy efficiency by 10–32% (Miller and Ambrose, 2005).

Passive cooling systems are design techniques that prevent heat from entering a building or promote heat removal from the building envelope through open spaces or natural cooling. Local examples in Darwin include breezeways, verandas and louvres. Passive cooling systems may be a cost-effective method to cool buildings as it emphasises design, orientation and arrangement of the building to take advantage of natural processes (Santamouris and Asimakopoulos, 1996).

Passively cooled buildings can be more energy efficient than those that reply solely upon air conditioning to maintain thermal comfort. An energy efficiency assessment of a cool roof (highly reflective material) found that improvements, when compared to a typical ceramic-tiled roof, were higher in a tropical savanna climate of Colombia (*As*) when compared to a Mediterranean climate of southern Spain (*Csa*) (Domínguez Torres and Domínguez Delgado, 2017). The energy efficiency improvements from building design features that enable passive cooling, such as cross-ventilation, are influenced by the surrounding urban microclimate (Geros et al., 2005).

Building porosity can be achieved by generating adequate openings or gaps in buildings, either in a horizontal or vertical direction to allow for natural ventilation. By maximising the air permeability of the urban area, urban regions can also take advantage of wind flow to remove heat from building canyons and built materials and surfaces (Cooling Singapore, 2017). Increasing variation in building density and height to create spaces between may be more important as a city becomes more developed as building canyons (ratio of building height to street width, see also Glossary) can also affect wind speed. For example, the *Hong Kong Urban Design Standard and Guidelines* have incorporated building porosity analysis into their policies which affect the design of any new building developments (Ng, 2012)[1]. In Darwin, guidelines for building porosity may have to take into account the wind direction of the sea breezes to channel the wind appropriately for cooling, as developed in the work of Santamouris and colleagues in 2017 (Santamouris et al., 2017b).

Breezes Muirhead is a subdivision in Darwin designed to maximise the cross-ventilation cooling potential for each dwelling (Safarova et al., 2018). The subdivision layout increases exposure to the cooling breezes, which come from the south-east in the dry season and the north-west in the wet season (Figure 4). To reduce the build-up of heat radiation during the day the development includes extensive areas of green open space and the blocks are staggered to enable the movement of cooling breeze through the subdivision. Houses must be setback at least 4 m from the street and have 6 m between houses to enable each dwelling to access cooling breezes for cross-ventilation (Defence Housing Australia & Oliver Hume, 2016). The design guide[2] for Breezes Muirhead sets out the requirements that need to be achieved by developers for each lot, which include ensuring living areas have parallel windows that are exposed to the cooling breezes; large roof eaves to shield walls and windows from direct sun; use of light-coloured roofing and paving materials; and covered outdoor living areas with a ceiling fan (Defence Housing Australia & Oliver Hume, 2016). The design guide also specifies planting requirements for shade trees in breezeways, with all plants to be selected from the planting list (Defence Housing Australia & Oliver Hume, 2016). There is a detailed post-implementation assessment of Breezes Muirhead under way to determine how the design approach improved thermal comfort while reducing energy consumption (Safarova et al., 2018). The assessment tried to account for the complex interrelationships between local climate, subdivision design, housing design and occupant behaviour.

[1] https://www.pland.gov.hk/pland_en/tech_doc/hkpsg/full/pdf/ch11.pdf

[2] https://www.breezesmuirhead.com.au/assets/uploads/2018/05/Breezes_Design_Guidelinesweb.pdf

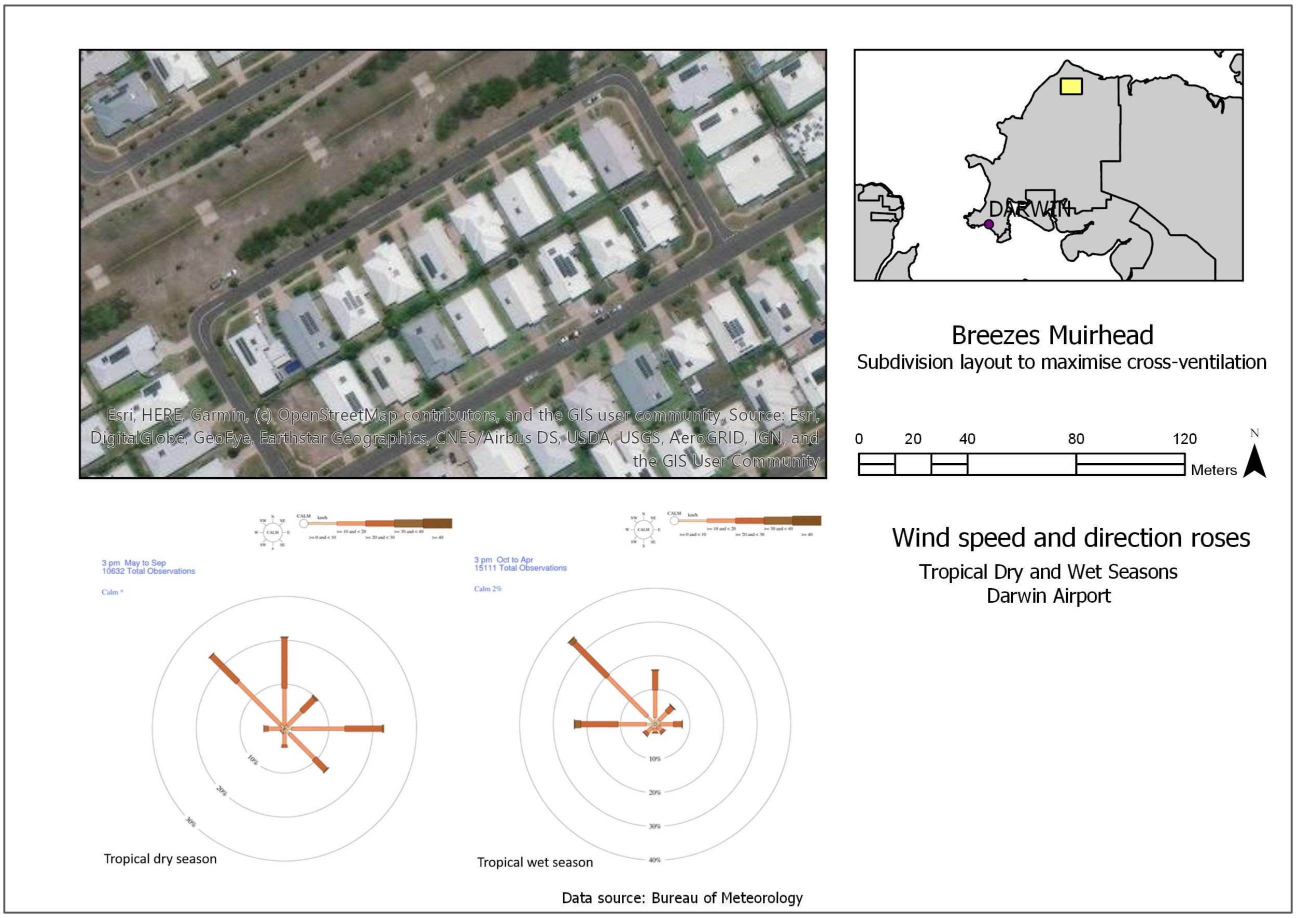

Figure 4. Climate-responsive subdivision design to maximise cross-ventilation for Breezes Muirhead, based on Bureau of Meteorology wind rose data.

In the tropics, a decrease in wind speed from 1.0–0.3 m/s was found to increase temperatures by 1.9 °C; outdoor thermal comfort under typical summer conditions requires 1.6 m/s wind speed (Yuan and Ng, 2012). Therefore, building setbacks and building permeability are helpful in improving the pedestrian level wind environment. Fluid dynamic modelling of wind flow at the pedestrian level indicates that larger building porosity sizes generally result in improved outdoor thermal comfort (Du et al., 2018).

Mechanical systems such as air conditioners or chillers are often used for improving indoor thermal comfort; however, a passive cooling strategy would have fewer adverse impacts on UHI effect and outdoor thermal comfort as they do not require more energy for cooling. Furthermore, a passive cooling strategy could be more accessible for people in lower socio-economic circumstances as it reduces the need for costly mechanical air conditioning. Passive cooling can be particularly important for tropical cities such as Darwin where the hot and humid climate is offset through either natural ventilation or mechanical cooling. Kane et al. (2009) undertook an analysis of passive design approaches to improve thermal comfort in Darwin using two typical dwelling types – 1) a lightweight elevated house, 2) house built on a concrete slab with precast concrete walls (150 mm thick). This demonstrated that ventilation and increased shading were the most beneficial passive design approaches in improving thermal comfort. However, the high overnight temperature and humidity in Darwin's wet season means that air conditioning is still likely to be required to improve thermal comfort to acceptable levels in both types of house. Both effective passive design approaches and energy efficient air-conditioning are important as together they provide thermal comfort while simultaneously reducing the negative impacts on the environment.

Figure 5. Passive cooling design for a house from Los Angeles, California. Wood slats provide shade while allowing for air flow.

Source: Photo by Jeremy Levine from Flickr (CC BY 2.0).

4.1.2 Cool roofs

Increasing the albedo (reflectance of light, see Glossary) of rooftops to reflect energy rather than absorb it is another passive solution that can help mitigate urban heat (Prado and Ferreira, 2005). Strategies may include painting roofs and buildings white or light colours, using materials (e.g. especially designed tiles) that reflect light, or creating walls and rooftops with vegetation (living walls/green roofs) (Corburn, 2009; Levinson et al., 2007; Pauleit et al., 2019) (see Section 4.3 for more on green infrastructure). Cool roofs are characterised by high solar reflectance (roof material reduces the heat gain from the sun), but also by high thermal emittance (roof material rapidly emits any absorbed heat). These positive effects reduce building energy consumption for cooling due to their ability to increase thermal losses and decrease corresponding heat gains on hot days (Akbari and Matthews, 2012).

Using building materials with cool or reflective surfaces can also prevent the build-up of heat within building materials, with cool materials lowering the surface temperatures that affect the thermal exchanges with the air. For example, in California (*Csb*) and Florida (*Am*), applying high-albedo coatings to the lee (downwind) side of residential buildings led to cooling energy savings of between 10% and 70% (Bretz and Akbari, 1997).

A study from Brazil (*Cfa*) examined multiple materials with a range of colours and concluded that lighter coloured and uncoated roof materials exhibited higher albedo; however, this diminished with time as roofs aged (Prado and Ferreira, 2005). Another example from Melbourne (*Cfb*) suggested that cool roofs, combined with insulation, provide the greatest overall benefit in terms of urban heat mitigation and energy transfer into buildings. The high albedo of cool roofs substantially reduced net radiation, leaving less energy available at the surface for heat absorption during the day (Coutts et al., 2013a).

Single-storey 'warehouse' type buildings may especially benefit from cool roof technology as their heat load predominantly comes through the roof. Results show that the application of cool roof technology to a warehouse type building in a subtropical environment increases the energy efficiency and reduces cooling energy demand. Application of cool roof technology across Australia indicates energy savings can be achieved in all broad Australian climate zones, with the greatest energy reduction associated with tropical, subtropical and arid environments (Seifhashemi et al., 2018).

Figure 6. Example of a cool roof from Bermuda.

Source: Photo by Acroterion on Wikimedia Commons (CC BY-SA 3.0).

4.1.3 Air conditioning

Air-conditioning is often used in hot and humid climates to maintain thermal comfort (Nguyen et al., 2012). In the Northern Territory, refrigerated air conditioning systems are most commonly used to cool homes (ABS, 2014). In hot and humid areas, such as Darwin, it is projected that there will be a significant increase in the future total energy consumption for both existing and new houses (Ren et al., 2011). Home air conditioning has been found to be a 'protective' factor for health during heatwaves, with a greater call for increased access (Klinenberg, 2015; O'Neill et al., 2005; Semenza et al., 1996), and especially for those in vulnerable groups such as young children or the elderly (Lundgren and Kjellstrom, 2013). However, relying on air-conditioning to reduce heat stress risks and provide thermal comfort can exacerbate existing inequities for vulnerable population groups due to the energy running costs (Farbotko and Waitt, 2011). Population groups vulnerable to heat stress include the very young, the elderly, and those with pre-existing medical conditions. In Darwin, it is likely that Indigenous people are more likely to be vulnerable to heat stress (Oppermann et al., 2017).

As space cooling is a large proportion of energy demand in buildings, improvement in the efficiency of these systems leads to significant cost savings. Installation of a new energy efficient air conditioner can achieve a 20–30% reduction in energy consumption compared to the same cooling provided by a 10-year old air conditioner. In Malaysia (*Af*), modelled studies to implement an energy efficiency standard for room air conditioners showed reduced electricity consumption as well as reduced carbon emissions from power plants (Mahlia et al., 2001). This study highlighted that implementing an energy efficiency standard for new air conditioners, along with ensuring adequate insulation, could reduce energy demand for cooling by up to 50% in Malaysia (Mahlia et al., 2001). New air conditioning designs that take advantage of cooling towers to remove heat from buildings and reduce indoor temperature may also increase the utility of air conditioners (Dhakal and Hanaki, 2002).

In most cases, energy demand for cooling is reduced if building occupants can tolerate a broad range of acceptable indoor temperatures. Research by CSIRO demonstrated that, for a lightweight construction house in Darwin, relaxing the acceptable thermal comfort benchmark from the current 90% in the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard to 70% can significantly reduce energy demand for cooling and improve energy efficiency star rating of the home (Figure 7) (Ren and Chen, 2018). The authors suggest that the 90% acceptability standard may be too strict, especially in a warming future climate, and that there is the need to consider how building occupants might adjust their thermal comfort through approaches other than air conditioning such as use of fans, cross-ventilation and changing clothes (Ren and Chen, 2018)

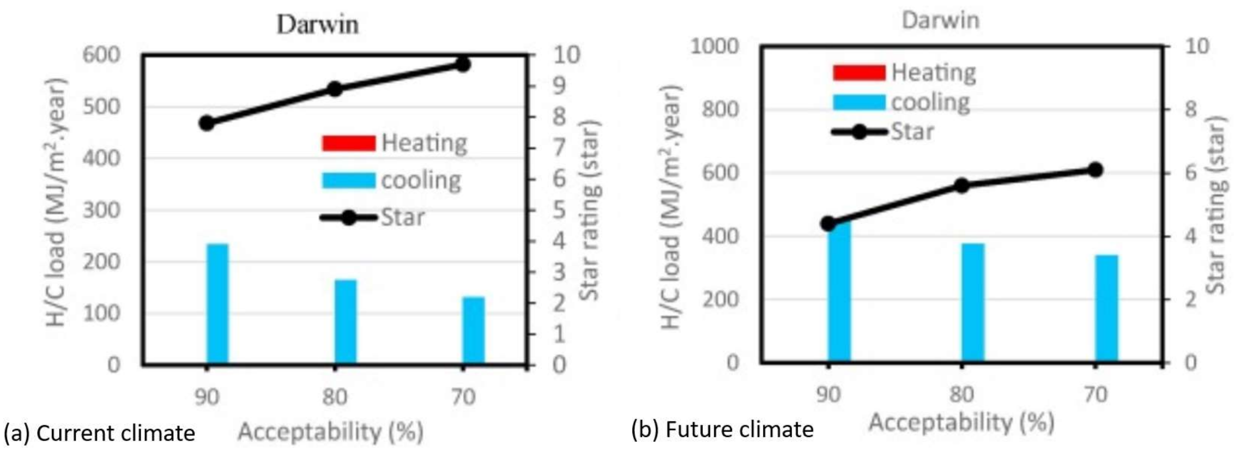

Figure 7. Sensitivity of space cooling loads and star rating in lightweight building to indoor thermal acceptability limits under (a) current and (b) projected future climate.

Source: https://research.csiro.au/energyrating/new-science/2018-march-impact-analysis-of-thermal-comfort-on-residential-energy-use/.

4.1.4 District cooling

District cooling is a system for distributing chilled water generated in a centralised location to cool buildings (both residential and commercial), especially in areas with a high density of buildings (Gang et al., 2016). District cooling uses chilled water to remove heat from buildings and reduce indoor temperature. This can provides higher efficiencies compared to multiple localised chillers and helps to reduce carbon emissions, particularly when it is integrated with local renewable energy resources (Gang et al., 2016). District cooling can improve outdoor thermal comfort by placing cooling units in strategic locations to reduce the impact of waste heat exhaust on local air temperatures (Cooling Singapore, 2017). District cooling provides a good alternative to the existing system of air conditioners, having higher efficiencies and consuming less energy for the same cooling load.

Globally, there is low uptake and awareness of district cooling systems; however, more efforts are required to identify, assess and implement these systems in order to determine their potential benefits (Werner, 2017). The technology may be most suitable for new urban development where there is greater freedom in system design and construction (Chow et al., 2004).

Seawater District Cooling (SDC) is one technology that has been used to provide district cooling that reduces energy demand (Looney and Oney, 2007). A SDC system uses cold ocean water to provide cooling for the chiller water. It is estimated that SDC can reduce energy demand for cooling by up to 85% when compared to conventional systems (Looney and Oney, 2007). While SDC has been used in tropical locations, there is the need for proximity to cold water. In the tropics cold water of 10 °C or less can be accessed in water depths of 700 m or more. The Barangaroo South development, on the edge of the Sydney CBD, uses seawater from the Sydney Harbour as a heat rejection source as part of a district cooling plant (Lend Lease, 2012). The use of seawater for heat rejection is part of an approach to maximise energy efficiency and reduce life-cycle costs in the commercial precinct. The warm and relatively shallow waters surrounding Darwin may limit the potential for SDC. In the Darwin Harbour, monitoring data shows there is some thermal stratification but that even at depths of 35 m the water temperature remains above 27 °C in winter[3]. The cost effectiveness of SDC is influenced by distance to deep, cold water; total air conditioning load; and local cost of electricity (Looney and Oney, 2007).

4.2 Water sensitive urban design and water features

Water sensitive urban design (WSUD) seeks to replace the traditional engineering approach to urban water management and promote 'the integration of urban planning with the management, protection and conservation of the urban water cycle, that ensures urban water management is sensitive to natural hydrological and ecological processes' (National Water Commission, 2004). The implementation of water management and water sensitive urban design into the planning and design of cities can deliver a series of ecosystem services such as rainwater storage for vegetation management, biofiltration systems, water quality regulation, stormwater retention and flood control (Berland et al., 2017; Fletcher et al., 2015; Masi et al., 2018; Van Roon and Rigold, 2016). Wong (2006) highlighted the value of incorporating the sustainable management of water within the urban design process.

WSUD approaches will depend on the specific constraints and opportunities of each development, but can include rainwater harvesting, rain gardens, bio-retention systems, green roofs, pervious pavements, aquifer storage and recovery, wastewater recycling, gross pollutant traps, swales, constructed wetlands and demand management (Cook et al., 2019). WSUD approaches can provide integrated options for mitigating heat in urban environments. WSUD helps to improve outdoor thermal comfort in urban areas and supports climate sensitive urban design (CSUD) (Coutts et al., 2013b). WSUD provides a mechanism for retaining water in the urban landscape through stormwater harvesting and reuse while also reducing urban temperatures through enhanced evapotranspiration and surface cooling (Coutts et al., 2013b). Hodo-Abalo et al. (2012) found that green roofs can provide an effective passive cooling approach for buildings in the hot-

[3] http://data.aims.gov.au/

humid tropics. The increase in leaf area increased evapotranspiration, reduced solar heat gains and stabilised indoor temperatures. Tan et al. (2015) found that increased evapotranspiration rate and the albedo effect of green roofs reduced the outdoor temperature in Singapore's tropical environment.

Water and 'green infrastructure', such as parks and trees, provide cooler areas to escape to on hot days and encourage outdoor recreation across a network of high-quality open spaces (CRC for Water Sensitive Cities, 2016). Because of these benefits, landholders and residents are willing to pay a premium for land close to WSUD spaces (CRC for Water Sensitive Cities, 2016).

Energy is transferred from the urban surface to the atmosphere through the evaporation of water, thereby linking the urban energy balance to the hydrological cycle (Oke, 1988). Water can cool the ambient temperature of urban areas by decreasing the heat in the atmosphere through evaporative cooling. There are many ways to incorporate the cooling properties of water into cities, and these ideally go hand in hand with the implementation of green infrastructure. Together they can influence air temperature, surface temperature and humidity, which all influence thermal comfort (Cooling Singapore, 2017). The hot-dry climate of Darwin presents challenges for managing WSUD features, such as wetlands, due to the lack of water available during the long dry season. Additionally, more humid conditions during the build-up and wet seasons can reduce evapotranspiration rates and limit the potential for evaporative cooling from water bodies (Huang and Lin, 2013; Wong et al., 2012).

Figure 8. Example of a water sensitive urban design feature to protect water and provide natural cooling in the Netherlands. The project combines natural systems and technical integrated waste and energy systems.
Source: Photo by Lamiot on Wikimedia Commons (CC BY 4.0).

WSUD can provide a source of water across urban environments for landscape irrigation and soil moisture replenishment to maximise the urban climatic benefits of existing vegetation and green spaces. WSUD could be implemented strategically into the urban landscape, targeting areas of high heat exposure, with many distributed WSUD features at regular intervals to promote infiltration and evapotranspiration, and maintain tree health.

Examples of WSUD ideas for the Darwin region presented by the CRC for Water Sensitive Cities include the implementation of high-flow drainage channels in new housing estates in Palmerston and channels of permanent pools that capture water after rainfall events (CRC for Water Sensitive Cities, 2016). While there is presently no mandatory provision for WSUD in Darwin, local governments have provided recommendations and guidelines for developers to include WSUD approaches in their subdivisions that reduce adverse environmental impacts of stormwater, particularly on the water quality in Darwin Harbour (Tjandraatmadja, 2019) (e.g. see City of Palmerston development guidelines[4]). Increased uptake of WSUD approaches in Darwin is likely to require more detailed understanding of the performance and life-cycle costs of different WSUD approaches in the wet-dry tropics (Saunders and Peirson, 2013).

4.2.1 Water spraying/misting systems

A water spraying system is an energy-efficient, economical and environmentally friendly method for improving thermal comfort in urban environments and is an effective local countermeasure to provide relief on hot days. The water spray system is widely used to reduce air temperatures in urban canyons in residential–commercial mixed-use areas and night markets in South Asian cities (e.g. Taipei, Köppen-Geiger climate classification, *Cfa*) (Lee et al., 2018). In an example from Iran, water spraying systems located near buildings decreased indoor temperatures by about 8%, but increased indoor relative humidity by about 17%, while outdoor relativity humidity remained relatively similar (Rabani et al., 2015).

A modelled example from Rotterdam, the Netherlands (*Cfb*), showed that during a heatwave period in 2006, water spraying at a 1.75-m height could have been an effective measure for improving outdoor thermal comfort by reducing maximum air temperatures by 5–7 °C. Thermal comfort for pedestrians was also improved up to 5 m away from the spray system (Montazeri et al., 2017). These results are supported by experimental research in Shanghai, which demonstrated that a water spray system reduced temperatures by 5–7 °C under an ambient temperature of 35 °C and a relative humidity of 45% (Huang et al., 2011). A modelling study based on Taipei climate conditions showed that the most effective cooling area was the area just under the spray nozzles. However, in a narrow street canyon, people in the middle of the street may feel the cooling effect because of the dispersion and accumulation of the cooled air. The results also suggest that under drier conditions the water spray systems will have higher cooling performance. Furthermore, using large water droplets created a wider cooling area in the middle of the street canyon (Lee et al., 2018).

Spray misting already exists in many restaurants at the Darwin Waterfront, allowing diners a chance to sit outside to enjoy the view while staying cool. The use of misting fans needs to manage the potential health risks. In Singapore it was found that increased use of misting fans, when poorly maintained, could provide a public health risk due to *Legionella,* which if inhaled can

[4] https://www.palmerston.nt.gov.au/operations/planning/development-guidelines

result in Legionnaires' disease (Lim et al., 2011). *Legionella* was detected in 14.2% of the mist fans sampled in Singapore (Lim et al., 2011). This highlights the importance of ensuring adequate maintenance of misting systems in Darwin.

Figure 9. Darwin Waterfront.
Source: CSIRO.

4.2.2 Artificial wetlands, ponds and fountains

Bodies of water in urban areas, such as artificial wetlands, or ponds, can potentially combat high temperatures in urban environments. Water play areas in Darwin, such as the Smith Street Mall Fountains or the interactive water playground at the Casuarina Square Shopping Centre, assist in cooling larger plazas and squares and provide a space for families to cool down while children play.

Studies indicate that the thermal environment inside an urban canyon with a pond is better than that without a pond, particularly during the day. For water bodies in urban areas, lower air temperatures were recorded downwind from the pond. However, this effect is accompanied by an increase in the absolute humidity, which may negatively influence outdoor thermal comfort (Syafii et al., 2017). In Darwin, this increase in humidity may decrease thermal comfort, especially if there is already high humidity in the air and cooling breezes are absent.

A water body's cooling potential is heavily dependent on its characteristics. Large water masses can absorb thermal energy from the incoming solar radiation due to its heat capacity. Also, water evaporation is a sink for sun-radiated energy. Thus, extending water-covered areas can increase the non-heated surfaces and hence contribute to reducing urban heat and improving outdoor thermal comfort (Cooling Singapore, 2017). Ponds in different configurations have different effects on the surrounding thermal environment; those with larger surface areas show increased evaporation and therefore a greater cooling effect (Syafii et al., 2017).

The mitigating potential of water-based techniques has been thoroughly investigated by studies analysing the temperature patterns in cities surrounded by lakes, rivers and other water reservoirs. However, the suitability of this technique requires further analysis given the likelihood of water stress due to the climate characteristics of Darwin. The adoption of WSUD approaches, such as urban wetlands, can provide optimal conditions for mosquitoes, presenting a public health risk due to mosquito-borne diseases (Crocker et al., 2017). Adaptive management frameworks that include monitoring of mosquito population and ecosystem health can help to promote best practice (Crocker et al., 2017). A sustainable approach to managing this risk is planting aquatic vegetation that encourages predator access to mosquito larvae (Hanford et al., 2020).

Figure 10. Water feature at Jingili Water Gardens, Jingili, Northern Territory.

Source: Photo by Grant Williamson on Flickr (CC BY-SA 2.0).

4.2.3 Integrated green and blue spaces

Cities typically contain less vegetation and bodies of water than rural areas, and existing green and blue space is often under threat from increasing population densities (Gunawardena et al., 2017). However, combining green and blue mitigation strategies in urban areas can bring about integrated solutions that lead to a multitude of benefits. To increase urban resilience to extreme weather cycles, it is essential to enhance storage capacity during the rainy season to increase water availability during dry periods. Integrated blue-green spaces may assist with this (Voskamp and Van de Ven, 2015). The George Brown Darwin Botanic Gardens provides a good example of a space near the CBD that integrates green and blue spaces.

Integrated green and blue space strategies and actions will contribute most to climate adaptation when they are implemented at different spatial scales and establish hydrologic connectivity (Voskamp and Van de Ven, 2015). Some innovative methods have been developed to take advantage of evaporative cooling in green spaces. In a study from Hong Kong (*Cfa*), researchers showed that implementing a rooftop rainwater harvesting garden showed a temperature drop of 1.3 °C due to the rainwater layer in the rain garden (An et al., 2015).

Case simulations show that the cooling effect of green and blue infrastructure is dependent on building type, time of the day and, in the case of blue infrastructure, water temperature. Temperature reduction and size of the cooled surface are largest in densely built-up environments. A real-case simulation for Vienna (*Cfb*) showed that in order to gain substantial cooling at the city scale, a combination of minor measures had the greatest effect, such as a 10% decrease in building density, a 20% decrease in pavement and a 20% enlargement in green or water spaces. The modelling results showed that heat load mitigation efficiency depended on the context of the location (e.g. prevailing meteorological conditions or land-use characteristics) (Žuvela-Aloise et al., 2016).

4.3 Urban green infrastructure

Green Infrastructure incorporates a range of green space forms and types (Tzoulas et al., 2007). This can be represented as elements associated with the built environment, such as green walls and roof gardens; and green spaces, such as parks and plazas, community gardens and natural areas.

Vegetation has already been used extensively as an urban heat mitigation strategy worldwide. Sometimes known as 'nature-based solutions', the use of vegetation and urban green infrastructure may provide sustainable and multi-beneficial ways to increase a city's resilience to climate change (Cohen-Shacham et al., 2016; Kabisch et al., 2016; Norton et al., 2015; Scott et al., 2016; Solecki et al., 2005). Temperature in urban centres can be reduced through increasing vegetation. Plants mitigate heat because they have high albedos, low heat admittance and regulate air movement and heat exchange through shade provision and plant evapotranspiration (Cameron et al., 2014; Crawford et al., 2012).

For Darwin CBD, research showed that shading from vegetation reduced street and pavement temperatures by 10–23 °C (Santamouris et al., 2017b). In Bangalore (similarly, *Aw*), street trees reduce ambient air temperature by as much as 5.6 °C, and road asphalt surface temperatures by as much as 27.5 °C, decreasing urban heat substantially (Vailshery et al., 2013). Other regions of the world have shown evidence of the significant role of urban greening for heat mitigation. A recent study of Glasgow (*Cfb*) indicated that a 20% increase in greenspace could eliminate between one-third and one-half of the city's expected UHI effect in 2050 (Emmanuel and Loconsole, 2015). Chow et al. (2013) showed that for every 0.5 °C rise in temperature, cooling load in a typical office building in Hangzhou, China (*Cfa)* increased by 10.8%; however, this could be reduced by shading.

Research from Australia has shown that the greatest thermal benefits of urban green infrastructure are achieved in climates with hot, dry conditions; however, there is comparatively little information available for urban planners and managers to determine an appropriate strategy for green infrastructure implementation under these climatic conditions (Norton et al., 2015). Thus, piloting and testing various methods will be necessary to determine the methods towards implementing green infrastructure for heat mitigation. Within Darwin, there are several examples of urban green infrastructure currently being implemented, such as the pilot shade structure on

Cavanagh Street as well as the changes in green space planning at State Square, Civic Square, and the Esplanade (Nield, 2018). To continue to reduce the temperature in the Darwin CBD, further greening of open spaces and built environment facades could be implemented.

Figure 11. Rainforest Gully in the George Brown Darwin Botanical Gardens.
Source: Flickr and Wikimedia Commons by Kathryn Greenhill (CC BY-SA 2.0).

4.3.1 Green roofs

Green roofs, sometimes referred to as 'rooftop gardens' or 'eco roofs', involve placing a vegetative layer such as plants, shrubs, grass and/or trees on building rooftops. Green roofs can be installed as a thin layer (around 5 cm) of groundcover up to a thick layer (around 1 m) of intensive vegetation and trees. The thickness depends on several components including vegetation, substrate, filter fabric, drainage material, root barrier and insulation (Cooling Singapore, 2017). The type of each green roof component depends on the geographic location in the topography and the directionality of the roof as some roofs may be exposed to conditions that are not amenable to green roofs (Vijayaraghavan, 2016). Green roofs reduce accumulated urban heat, lowering the temperature of roof surfaces by providing an insulating layer, as well as ensuring the loss of heat through evapotranspiration.

Green roofs can mitigate the heat effect of an urban environment; as they keep surface temperature closer to ambient temperature when compared to surfaces such as concrete and bituminised surfaces, which absorb solar energy and re-emit it as sensible heat, which increases the surrounding air temperature (Gaffin et al., 2009). They can reduce building energy demand by decreasing the amount of solar energy that is conducted into a building, and potentially improve the quality of stormwater runoff coming from the roof (Corburn, 2009). Green roofs can reduce the energy required for cooling during summer by up to 40% (Spala et al., 2008). At Columbia

University (New York City) green roofs were adopted to improve building thermal performance, which have reduced the energy required to heat or cool buildings (Rugh, 2013).

An example from southern Brazil (*Aw*) examining the impact of green roofs on thermal condition showed that during a warm period, green roofs reduced heat gain by 92–97% in comparison to ceramic and metallic roofs, respectively (Parizotto and Lamberts, 2011). Chicago's Department of Buildings has developed an incentive program, known as the Green Permit Program, that encourages developers to incorporate environmentally conscious design elements, including green roofs on new buildings. The benefits of this program include mitigation of climate change through reduced need for heating and cooling in buildings with green roofs, enhancing the image of the city and the emergence of businesses specialising in green roof installation (Kazmierczak and Carter, 2010).

There are several barriers to implementing green roofs (Vijayaraghavan, 2016; Williams et al., 2010). Depending on the type of green roof, there can be extensive maintenance in terms of fertilisation, watering and weeding. Green roofs with thick substrate to support trees and shrubs have higher capital costs due to increased maintenance and the additional roof support that will be needed for the added weight. Green roofs designed with grasses, mosses and succulents may require much less maintenance and will not require extra roof supports. Different types of green roofs may need to be tested in Darwin in order to better understand water demand during the dry season as little scientific data is available for the local conditions. Previous research initiated by the Northern Territory Government undertook modelling of heat mitigation techniques for the Darwin CBD (Santamouris et al., 2017b). This research showed that green roofs were not considered suitable for heat mitigation in the Darwin CBD when compared to approaches, such as increasing the tree canopy, as the local cooling impact of green roofs is less likely to reduce air temperature at the street level.

4.3.2 Vertical greenery or facades

Vertical greenery is defined as the growing of vegetative elements on the external facade of the building envelope. There are two kinds of systems: support systems that allows plants to climb through or around them, and carrier systems where plants can settle and develop. Green facades are vegetative layers such as small plants, grass and/or moss attached to external building facades. They are also called 'living walls' and 'vertical gardens' (Cooling Singapore, 2017). Green facades can be considered as an alternative to insulating construction materials and reduce indoor overheating. However, the range and extent of benefits can vary with green wall typology.

The strategy reduces the temperature of facades, especially those exposed to intense sun radiation. Consequently, the temperature inside the building can remain more stable and thus reduce the energy consumption required for cooling indoors. Similarly, nearby air temperature is also reduced, providing benefits of thermal comfort for pedestrians.

In a study in Reading, UK (*Cfb*), researchers found that during periods of high solar irradiance outdoors, the presence of live shrubs placed against walls significantly reduced air and surface temperatures compared to blank walls. The largest temperature differentials were recorded mid to late afternoon, where air adjacent to vegetated walls was 3 °C cooler than non-vegetated walls. Testing across various species showed that species varied in their cooling capacity. Plant physiology and leaf area/morphology should be considered when selecting species to maximise cooling in green wall applications (Cameron et al., 2014).

Under local conditions in Darwin, there may be substantial gains to reducing air temperatures; however, similar to the green roofs, maintenance and water usage during the dry season will have to be studied to gauge the efficacy and cost effectiveness of this strategy.

Figure 12. Green roof from residential building in Vancouver, Canada.

Source: Photo by NNECAPA Photo Library on Flickr (CC BY 2.0).

4.3.3 Increasing the urban forest

Large-scale urban greening involves the increase of vegetation in big urban parks, forests and natural reservoirs. They can be located at the edge or in central areas of the city and have different effects on the local climate (Chen et al., 2014). A 2017 study showed that since 2009, tree canopy cover in the City of Darwin declined by 3.8% while urban hard surfaces increased by 7.1% (Amati et al., 2017). In 2018 Tropical Cyclone Marcus caused widespread damage in Darwin with the loss of thousands of trees in public spaces (Clark et al., 2018). This loss of urban forest may impact the cooling benefits of vegetation to the city.

A meta-analysis of the benefits of green spaces suggests that the evapotranspiration-based cooling depends on the size, spread and geometry of green and blue spaces (Gunawardena et al., 2017). Areas such as forests and green belts do not only assure better thermal performance inside them, but can also provide coolness to nearby urban areas, thus helping to regulate the accumulation of heat in the whole urban area. Additionally, the positioning of green spaces in relation to the urban centre and prevailing wind directions may be important. A study of the Frankfurt (*Cfb*) greenbelt highlighted the greenbelt as providing a beneficial cooling of 3–3.5 °C between the greenbelt and the city core (Bernatzky, 2012). Locations such as the community orchard at Jingili Water Gardens is an example of a multifunctional urban forest space that serves the Darwin public.

Nature-based solutions, such as those provided by urban forests and WSUD, can be effectively implemented to control urban stormwater and flooding at the local and city-wide scale (Berland et al., 2017). While parks and forests may contribute to regulating air temperature and pollution, bioswales along streets or constructed wetlands in newly built neighbourhoods are increasingly used to regulate vertical and horizontal water flows created by heavy rainfall events or local flooding (Haase, 2015; Pauleit et al., 2019; Sommer et al., 2009). This is a role that the mangrove forests along the Darwin coast may also be fulfilling.

A changing climate will likely mean that a different set of flora species will have to be selected to survive future temperature and precipitation regimes (Churkina et al., 2015). With the loss of urban trees in Cyclone Marcus, the City of Darwin has developed a report assessing 219 tree species against several attributes that contribute to cyclone resilience. There is currently a preferred tree list for Darwin containing 194 species, as well as a list of 25 species that are not recommended for planting in Darwin. The goal is to plant trees of varying age, characteristics and size with a mix of Australian and Northern Territory natives and tropical exotic species (City of Darwin, 2018). The benefits of increased tree cover in Darwin has been recognised, but there is the need to consider the best location and position for trees that can maximise their value for the community.

4.4 Cool roads and paths

There are multiple ways to support the development of cooler roads and paths. The materials conventionally used to build roads and paths in urban areas absorb 80–95% of sunlight, increasing their temperature and the temperature of the urban environment (Cooling Singapore, 2017). Technologies used to decrease the temperature of pavements in urban areas may include permeable pavement systems such as water retentive and porous pavements.

Using alternative materials and providing shading along streets can increase the albedo (solar reflectance) of urban surfaces. Surfaces stay cooler releasing less heat into the ambient air, providing an effective cooling option for urban areas. Street shading also reduces solar radiation from reaching street level, contributing to a cooler environment (Tsiros, 2010).

Modelling of heat mitigation techniques for the Darwin CBD showed that increasing the reflectivity of the city as a whole could reduce the temperature in Darwin CBD by between 1.3–2.5 °C (depending on the level of reflectivity achieved). Increasing the albedo of streets and pavements would contribute to this cooling by reducing the temperature in Darwin CBD by between 1.7–2 °C. Reducing solar radiation on the main streets in Darwin through shading results in cooling of between 0.5–1.3 °C (Santamouris et al., 2017).

Figure 13. A shaded bike path in New South Wales.
Source: Photo by Nick-D on Wikimedia Commons (CC BY-SA 3.0).

4.4.1 Well-ventilated walkways and streetscapes

Like well-ventilated buildings, well-ventilated walkways can also increase cooling in Darwin's CBD. Well-ventilated pedestrian walkways can be achieved by aligning them parallel to the prevailing winds and positioning them in adequate locations. Choosing the appropriate geometry and the orientation of street canyon can improve the permeability to airflow for urban ventilation, and the potential for cooling of the whole urban system, thereby increasing outdoor thermal comfort. Walkway spaces such as sidewalks, skywalks and overpasses can be orientated to the wind flow patterns (Cooling Singapore, 2017). However, to make the most of natural ventilation, there must also be an understanding of how to protect walkways and streetscapes from solar radiation and control for other factors that may impact on the microclimate condition and the pathways (Akubue, 2019). This may require that street trees or buildings (e.g. the addition of awnings) are designed to provide shade to the streetscape.

Another method to increase ventilation is to widen the streets to increase air flow and exchange in street canyons. Increased air movement inside a street canyon will lead to a greater release of urban heat accumulation, thereby reducing the UHI effect and building energy demand (Cooling Singapore, 2017). In the redesign of Havana, Cuba (*Aw*) architects and planners recognised the need to design new buildings and streetscapes through gaps and airflow parameters to take advantage of breezes essential to achieve thermal comfort (Tablada et al., 2009). In Enugu, Nigeria (*Aw*) a schematic analysis of airflow regimes was conducted to identify the behaviours of flow in the street configurations relative to the height and width ratios of the street canyon. Results showed that wider streets provided better mixing of air and consequently better airflow in the urban street canyon. Because there are high-density residential settlements in Enugu, new street dimensions and configurations may be needed to take advantage of natural ventilation (Akubue, 2019). Although tall, narrow canyons are often shaded by buildings, shallow street canyons will require tree shading to increase the outdoor thermal comfort of streets. Species selection, placement and density in relation to meteorological conditions must be considered (Coutts et al., 2016). For more information, see Section 4.4.3.

4.4.2 Cool or permeable pavement

Cool pavements are made of materials that reduce their surface temperature by reflecting a significant percentage of solar radiation and releasing thermal heat into the environment. These surfaces are usually white or a light colour (Taleghani and Berardi, 2018). Dark materials store solar radiation during the day and re-radiate it overnight (Cooling Singapore, 2017). In Toronto, simulation models of a change in albedo during a heatwave showed that when the albedo of the ground pavement was increased from 0.1 to 0.5, the air temperature at the height of 1.0 m was reduced up to 0.66 °C and the pedestrian thermal comfort was reduced by 4.7 °C (Li et al., 2013). Switching from asphalt to cement concrete roads can also have positive effects on heat generation because the albedo of concrete is much greater and thus absorbs less solar radiation (Guan, 2011). Consequently, this reduces urban heat accumulation, especially in hot climates.

Permeable pavements remain cooler than conventional pavements, providing thermal comfort by reducing the surface temperature of the pavements due to water evaporation. Water retentive and porous pavement systems, which include additional voids compared to conventional pavements, allow water to flow into the ground or into water-holding fillers where evaporative cooling can occur (Cooling Singapore, 2017).

The high-albedo paint at the corner of Cavanagh Street and Knuckey Street in the Darwin CBD is a current local trial of a cool pavement. If changes in pavement colour and albedo can be changed on a large scale, there may be a large contribution towards reducing UHI effect, and with permeable pavements, a lower flood risk. Additionally, such changes can have multiple benefits as they can contribute to pollution control from surface runoff from roads and parking areas and help with noise reduction (Li et al., 2013).

4.4.3 Tree cover along transport corridors

Increasing vegetation along transport corridors and pedestrian walkways can provide shade to people and surfaces. Opportunities for creating new areas of green space within cities are often limited and tree planting initiatives may be constrained to kerbside locations (Salmond et al., 2016).

The effect of vegetation on cooling can vary depending on the density, height and species of the vegetation. Additionally, it is important to have strategies that combine the reduction of incoming solar radiation with the natural ventilation capacity of these spaces. Vegetation can absorb incoming solar radiation and thus reduce heat accumulation in urban materials. At the same time, it provides shade (in the case of trees). For Darwin, increasing the number of trees makes sense to reduce direct solar radiation, improving outdoor thermal comfort. However, transport corridors are often open spaces that can be used as ventilation paths to introduce fresh air into the urban area and/or help remove the accumulation of heat (Cooling Singapore, 2017). To have the greatest impact, trees need to be strategically placed along roads and paths through trial and testing (as discussed in Section 4.1.1). An example from Athens, Greece (*Cfa*) during an exceptionally hot weather period in 2007 showed an average cooling effect of 0.5–1.6 °C (at 1400 h) and 0.4–2.2 °C (at 1700 h). The highest cooling effect of 2.2 °C was found in high tree-shaded areas with minimal traffic load (Tsiros, 2010).

Increasing tree cover along street corridors may also require consultation with residents and end users about the look and feel of the street. In Australia, Blacktown City Council's Cool Streets urban heat project increased the number of street trees in order to reduce temperatures in western Sydney. In order to ensure community buy-in, the council engaged residents through community events to promote the benefits of street trees and enabled resident participation. The council developed and trialled street tree designs that maximised temperature reductions and lowered residential energy consumption, which could potentially increase property prices.[5]

Tree plantings, such as those on Garramilla Boulevard, will provide a shaded tropical boulevard to Darwin's CBD. Similar initiatives could be trialled across street types to discover optimal designs for end users.

Figure 14. Street tree in the main street in Kuranda, Queensland.

Source: Photo by denisbin on Flickr (CC BY-ND 2.0).

[5] https://www.coolstreets.com.au/

4.5 Education and awareness

In many cases, education and communication will be required to initiate social change and promote community buy-in for any new initiatives proposed. In any education and awareness strategy, it is important to note that different groups of people within the community will understand and desire to make changes to different extents. Issues such as increasing inequality and changes in age structure within the population may lead to greater levels of vulnerable people (Haase et al., 2018). For example, researchers in the UK found that individuals with higher income or education levels were more likely to pursue personal heat protective measures (Khare et al., 2015), potentially because they have more access to information or resources. Even when certain protective measures are available (e.g. air conditioning), low income households may choose not to use them because of associated costs such as energy costs (Farbotko and Waitt, 2011). In Darwin, relying on air conditioning to reduce the risk of heat stress and provide thermal comfort can exacerbate existing inequities for vulnerable population groups. Population groups vulnerable to heat stress include the very young and the elderly, and those with underlying health conditions. Furthermore, in Darwin, it is likely that Indigenous people are more likely to have risk factors that make them vulnerable to heat stress (Oppermann et al., 2017). Others vulnerable to heat stress include those who are homeless or live in poor standard homes that do not provide adequate thermal comfort (Farbotko and Waitt, 2011). In Darwin, COOLmob[6] have developed guidance to help the public better design their homes to reduce energy bills and reliance on air conditioning (Beagley, 2011).

Due to the increase in hot days expected for Darwin, it is important that the community at large is informed on how to deal with heat events. Behavioural change will be key towards keeping communities safe, and diverse messaging and actions may be necessary.

4.5.1 Social awareness campaigns

Social awareness and communication campaigns (including through local pamphlets, newspapers, radios, tv) that help people learn how to stay cool during heatwaves can be very effective. This may require collaboration between the public and private sectors, grassroots campaigns, and scientific organisations to effectively and equitably carry out communication and education strategies (Harlan and Ruddell, 2011). Social agencies will also play a large role in the effective communication of heat-related illness (e.g. City of Phoenix[7]).

General social campaigns around heat management aim to promote easy and cost-effective solutions for people to adopt. This may be especially true for new arrivals to Darwin who are not acclimatised to the local climate. These include solutions such as (Becker and Stewart, 2011; White-Newsome et al., 2011):

- wearing loose fitting and light weight clothes
- staying in the shade

[6] https://www.coolmob.org/

[7] https://www.phoenix.gov/pio/summer/heat

- drinking lots of water
- avoiding the use of heat emitting appliances such as a stove or an oven
- submerging oneself in water for evaporative cooling
- wearing hats
- avoiding outdoor work
- going to an air-conditioned centre.

Social campaigns also aim to identify high risk groups that will benefit the most from targeted education campaigns (Michelozzi et al., 2010). In Darwin, there has been a particular focus in research on work practices for occupations that are primarily outdoors (Oppermann et al., 2017). Literature reviews on outdoor occupational health and safety show there is growing evidence that occupational sun-safety education is effective in increasing outdoor workers' sun-protection habits and presumably in decreasing sunburn rates (Reinau et al., 2013). Social networks are extremely important in the event of heatwaves as neighbouring residents will be able to identify vulnerable groups in the area and be able to provide support (Pelling and High, 2005) sometimes through the use of local communication strategies, such as bulletins and pamphlets (Michelozzi et al., 2010). However, other research has shown that strong bonding networks can also cause people to overestimate their resilience or cause people to perpetuate a narrative that heatwaves do not pose a significant risk to them personally, thus increasing vulnerability (Wolf et al., 2010).

Figure 15. Heat warning image developed by the Texas Military Department.

Source: Downloaded from Flickr (CC BY-ND 2.0).

4.5.2 Heat management plans

Heat management plans can help cities coordinate, prepare and respond to extreme heat events. In Darwin, heat management plans that address high heat and humidity during the build-up and wet season could be very useful for helping the Darwin community adapt to periods of low thermal comfort. These plans are often customised to suit local meteorological and demographic conditions and may include early alerts and advisories combined with emergency public health measures to mitigate the heat dangers. These plans may also be known as 'heat warning systems' (HWS) or 'heat health warning systems' (HHWS) (Lowe et al., 2011; O'Neill et al., 2010).

Although heat warning systems have been established in many cities, there is still little research on their efficacy. In a review of the existing research on the effectiveness of heat warning systems, researchers found varying results. Of the 15 epidemiological articles that were retrieved, HWS were associated with a reduction in ambulance use and six studies asserted that fewer people died of excessive heat after HWS implementation (Toloo et al., 2013). One study estimated the benefits of HWS in 1995 to 1998 to be US$468 million for saving 117 lives compared to the US$210,000 costs of running the system (Ebi et al., 2004). Eight studies showed that availability of HWS did not lead to behavioural changes; rather, perceived threat of heat dangers to self/others was the main factor related to heeding warnings and taking proper actions. However, costs and barriers associated with taking protective actions, such as costs of running air conditioners, were of significant concern, particularly to the poor (Toloo et al., 2013).

Indeed, commonly promoted behaviours such as using air conditioners and attending cooling centres are complex, and these resources are often inaccessible financially, physically, or culturally (Sampson et al., 2013). Heat management plans must be designed to reach vulnerable populations, especially isolated populations. To encourage changes in behaviour, heat health warning systems may need to be combined with specific actions. For example, providing transportation and services to help get people to cooling centres may also be necessary. In Japan, researchers investigated if the delivery of bottled water labelled with messages could be effective in improving the behaviours and knowledge of elderly people to prevent heat-related illness. When compared with the control group, which had no warnings, the heat health warning and water delivery groups showed improvements in night-time air-conditioner use, water intake, and reduced activities in the heat. An additional effect of household water delivery was increased water intake, indicating that home water delivery in addition to a heat health warning may be needed to raise awareness of the elderly (Takahashi et al., 2015).

4.5.3 Changing vehicle use in cities

Changes to energy use and vehicle use is another strategy that cities are adopting to reduce heat production from transport and mitigate greenhouse emissions (Cooling Singapore, 2017). Reducing the number of vehicles within the city centre can reduce the amount of heat, greenhouse gas emissions and pollution in the air (Buehler and Pucher, 2011). Switching to electric vehicles and public transport systems or providing infrastructure that promotes walking, cycling and use of scooter paths within cities can significantly reduce heat-producing vehicles in city centres (Sovacool and Brown, 2010).

The Northern Territory Government and the City of Darwin are contemplating ways to encourage people to use active transport to enter the CBD. Policies that can limit car use and encourage active transport can have multiple benefits for Darwin. Currently in Darwin, only 4% of dwellings have a public transport stop within 400 m with frequent service (at least every 30 minutes)[8]. This lack of access to public transport can reduce and discourage public transport use. Changes in transport and land-use policies in Freiburg, Germany (*Cfb*) over the last 40 years have encouraged more walking, bicycling and public transport use. Over the last three decades, the number of bicycle trips tripled, public transport ridership doubled, and car use declined from 38% to 32%. Per capita greenhouse gas emissions from transport have fallen—despite strong economic growth (Buehler and Pucher, 2011).

Another option is to encourage the adoption of cleaner, smarter cars that emit less greenhouse gas, such as through the adoption of electric cars. This may require additional charging stations to be located strategically around Darwin. Additionally, if public or active transport options become the norm, there may be advantages to reduce the amount of space in the CBD for parking in lieu of other socially desired spaces, such as green spaces or increasing shading through tree-lined

[8] https://theconversation.com/city-by-city-analysis-shows-our-capitals-arent-liveable-for-many-residents-85676

boulevards. The rising popularity of e-scooters and e-bikes provides another mobility option that can reduce reliance on cars. Several cities around the world have introduced shared e-scooters schemes as they can provide benefits such as reduced congestion and parking demand, extending mobility to those without cars and reducing emissions. E-scooters are also seen as an approach to activate a city by providing a flexible and enjoyable approach to getting around the city (Gössling, 2020). The City of Darwin is currently running a trial of e-scooters in the CBD, waterfront and Cullen Bay. This trial will be monitored and evaluated for the potential to expand the use of e-scooters in Darwin.

4.6 Summary of strategies and actions

Table 3 summarises the various strategies described in this section, outlining the pros, cons, and potential actions that could be implemented in Darwin. This table may clarify how the options compare to one another and which options may be more effective for different parts of the city.

Table 3 Summary table of the heat mitigation strategies and actions described this report and a brief description of the pros, cons, and potential actions that could be implemented in Darwin.

STRATEGIES AND ACTIONS	PROS	CONS	POTENTIAL APPLICATION TO DARWIN
Cool buildings			
Passive cooling	• Maximises natural ventilation through buildings to remove heat from surface • Can reduce reliance on air conditioning systems • Access to cooling across socially disadvantaged groups.	• The need to redesign or retrofit buildings to take advantage of natural breezes • Is less effective when there is no breeze, but the conditions are still hot and humid.	• Create new regulations for building design • Encourage retrofit design in established buildings. • Aligning buildings can capture ocean breezes. • Design integration with air conditioning.
Cool roofs	• Reduces building energy cooling due to increased heat losses and decreased heat gains.	• Few cons except the lack of resources to implement this action.	• Encourage all new builds to paint or install roofs with solar reflectance.
Air conditioning	• Energy efficient room air conditioners can reduce electricity consumption as well as reduce greenhouse gas emissions. • Education and awareness of reducing set points can reduce energy consumption considerably.	• Can be expensive to install and run (i.e. energy costs). • Will emit heat to outdoor areas. • Poor maintenance can lead to higher energy consumption.	• Implementing a minimum standard across the region can reduce electricity use, especially during heatwaves. • Energy efficiency education and awareness programs.
District cooling	• Can improve outdoor thermal comfort by placing cooling units in strategic locations to reduce their impact on local air temperatures.	• Little research has been conducted on this technology • Lack of awareness and understanding of how to implement it.	• District cooling may be suitable in specific locations within Darwin CBD to reduce energy and air conditioner use, particularly for new buildings and developments. • Test cost/benefits for Darwin in monitored trial/s.
Water sensitive urban design and water features			

STRATEGIES AND ACTIONS	PROS	CONS	POTENTIAL APPLICATION TO DARWIN
Water spraying/misting systems	• Effective local countermeasure to provide relief on hot, dry days.	• Cooling capacity may only reach a certain distance. • Will increase humidity. • Potential waterborne health risks.	• May have a greater impact during the dry season when there is low humidity. • Test cost/benefits for Darwin in monitored trials.
Artificial wetlands, ponds and fountains	• Water bodies lower temperature around and downwind of water source.	• Can increase absolute humidity, which may negatively influence pedestrian comfort. • Will require maintenance such as water availability, energy to run the pumps, filtration systems.	• Can be strategically designed to take advantage of the natural breezes. • Will be more difficult to maintain in dry season.
Integrated green and blue spaces	• Can enhance storage capacity during the rainy season to increase water availability during dry periods.	• Cooling effect of green and blue infrastructure very context specific – dependent on the building type, time of the day and, in the case of blue infrastructure, the water temperature.	• Increasing design of parks that integrate blue spaces for stormwater management and other co-benefits.
Urban green infrastructure			
Green roofs	• Can reflect sunlight and increase evapotranspiration, which reduces solar heat gain to increase indoor thermal comfort and reduce energy use.	• Difficult and sometimes expensive to maintain because of extra weight on roof and the need to weed, water and fertilize. • Water availability may be a challenge during dry season.	• Create incentive programs that encourages developers to incorporate climate appropriate design elements, including green roofs on new buildings. • Test cost/benefits for Darwin in monitored trials.
Vertical greenery or facades	• Can reflect sunlight and increase evapotranspiration that reduces solar heat gain to increase indoor thermal comfort and reduce energy use.	• Difficult and sometimes expensive to maintain; Water availability may be a challenge during the dry season.	• Create incentive program that encourages developers to incorporate climate appropriate design elements, including green walls on new buildings. • Test cost/benefits for Darwin in monitored trials.
Increasing the urban forest	• Can be effectively implemented to control heat, urban stormwater and flooding at the local and city-wide scale.	• Species selection will be important to prevent tree loss as was seen after Cyclone Marcus.	• Darwin already has a tree planting strategy, but may use the land surface temperature maps to target planting in high-priority heat areas.
Cool roads and paths			
Well-ventilated walkways and streetscapes	• Provides better paths for outdoor thermal comfort; introduces fresh air into the urban area.	• Ventilation of paths may be dependent on the structure of the buildings around the path and street canyon design.	• Creating paths that channel the natural ventilation; aligning them parallel to the prevailing winds and positioning them in adequate locations. • Wind modelling would assist to identify opportunities for this.

STRATEGIES AND ACTIONS	PROS	CONS	POTENTIAL APPLICATION TO DARWIN
Cool and permeable pavements	• Can reflect sunlight or increase evaporative cooling to increase indoor thermal comfort and reduce energy use.	• May have a greater impact if implemented widely across the city and region.	• Trialling different types of cool and permeable pavement throughout Darwin; monitor the results from the trial on Cavanagh Street. • Can switch from asphalt to concrete.
Increasing tree cover through transport corridors	• Provides better paths for outdoor thermal comfort. • Increases walkability of the CBD. • Improves air quality in the urban area. • Reduces road surface temperatures.	• Limited space – tree planting initiatives may be constrained to kerbside locations.	• Increased planting of trees along major roadways leading into and out of the CBD for visual and environmental benefits. • Provides shade to hot sidewalk and road surfaces.
Education and awareness			
Social awareness campaigns	• Protects health by providing simple behavioural changes – especially for vulnerable population groups.	• Sometimes the messages are not enough; there will need to be more social support provided to those with less access to information or resources.	• Existing campaigns could be built upon to include climate-savvy strategies. Encourage neighbourhood leaders and champions to craft community narratives to communicate with the diverse stakeholder groups. • Will need to be translated into multiple languages to reach communities.
Heat management plans	• Customised to local meteorological and demographic conditions; includes early alerts and advisories to mitigate heat dangers.	• Must be designed to reach vulnerable populations, especially isolated populations.	• Current plans may have to consider how they are reaching vulnerable population groups or if their messages are adequate to reach the desired community.
Changing vehicle use in cities	• Reducing the number of vehicles within the CBD can reduce the amount of heat and greenhouse gases: Switching to active transport in the last few kilometres into the CBD can significantly reduce heat-producing vehicles in city centres. • Reclaims parking for green space.	• Few cons, but there is a need to increase accessibility to public transport by increasing the number of stops close to homes and increasing frequency of transport.	• The Northern Territory Government and the City of Darwin are already considering options to increase active transport in the CBD. Free public transport days to encourage use, and 'car free' days have been used in international cities.

5 Case studies

The following case studies highlight experiences from other tropical cities that have implemented heat mitigation measures in response to the climate and local character of that city. These case studies can provide insights for Darwin on different approaches to improve liveability and thermal comfort in a tropical wet-dry climate. As stated in the previous section, much of the literature around heat mitigation strategies is concerned with temperate, desert or tropical climates with few examples about cities of the wet-dry tropics. However, even in cases where tropical cities have analogous climate to Darwin, the appropriate response to improve liveability and thermal comfort will emerge from the unique context of each city. There is the need for a place-based approach to tropical urbanism in Darwin that emerges not only from the climate but the cultural heritage, values, community lifestyle expectations and local environment. These case studies involve studies from cities of *Aw* as well as *Af, As*, and *Am* Köppen-Geiger climate classifications as they will provide the most similar climate context for Darwin.

5.1 Tropical urbanism: Cairns

5.1.1 Overview

Cairns is in Far North Queensland and, as of 2018, has an urban population of 165,00 people (Cairns Regional Council, 2019d). Its climate is classified as a tropical monsoonal climate (*Am*). It has a distinct wet season from November to May, and then a relatively dry season from June to October; however, compared to Darwin, there are light rainfall events during this period. During the summer months, Cairns experiences hot and humid conditions, which impacts on thermal comfort both outdoors and indoors (Bureau of Meteorology, 2019b). The Cairns Regional Council has prepared several documents that can assist developers and homeowners in designing buildings that are responsive to Cairns' climate by keeping out the heat and maximising opportunities for passive cooling.

The specific guidelines include:

- *Sustainable tropical building design: Guidelines for commercial buildings* (Cairns Regional Council, 2019e)
- *Cool homes: Smart design for the tropics* (Cairns Regional Council, 2019c)
- *Cairns style design guide* (Cairns Regional Council, 2019b).

These guidelines provide general references that can assist builders and developers to incorporate tropical design approaches in designing, constructing and renovating commercial and residential buildings (Cairns Regional Council, 2019e). The intended outcomes are to design buildings that are more liveable through improving thermal comfort and more sustainable by reducing the energy demand for cooling. The *Cairns style design guide* has the overarching intent to encourage the development industry to provide streetscapes, housing and building design that retains and enhances a tropical design character that is responsive to the local climate, heritage and community expectations. Encouraging a distinct Cairns tropical design character will improve the amenity and liveability of the area.

5.1.2 Heat mitigation approaches

The *Cairns style design guide* highlights how effective planting arrangements on both public and private land can provide shading (Cairns Regional Council, 2019b). Using vegetation to shade outdoor living areas and houses from the summer sun can reduce the build-up of heat, while reducing the demand for air conditioning (Figure 16). A selection of tropical species native to Cairns is highlighted as an approach to enhance the local character and provide native bird habitat.

The style guide also provides passive design principles that can improve liveability and enhance Cairns' tropical character. This includes shading, cross-ventilation, building insulation and creating outdoor living spaces.

Figure 16. Cairns Central Business District.

Source: Downloaded from Flickr David Stanley (CC BY 2.0).

5.1.3 Implementation

Tropical design principles are included in the Cairns planning scheme with a policy on tropical urbanism[9]. This policy provides the context and guidance for how tropical urbanism should be

[9] https://www.cairns.qld.gov.au/__data/assets/pdf_file/0019/160039/SC6.16-Planning-scheme-policy-Tropical-urbanism.pdf

incorporated in the planning and design of landscaping and the built environment. The council can request supporting information from planning applicants that demonstrate how they are complying with the intent of the tropical urbanism policy. This assessment can include landscaping structure plans that detail both horizontal and vertical landscaping, which includes a list of plant species and plans of landscaping at different stages (installation, maturity and in-between). The site analysis can also demonstrate how the building design will be orientated to the sun and prevailing winds.

Community consultation was undertaken in 2018 as part of the master plan process for Cairns City Centre. A community survey found that, in the context of future planning of the city centre, maintaining and enhancing a tropical feel and character was one of the main priorities for respondents (Cairns Regional Council, 2019a).

5.1.4 Outcomes

Cairns has been the fastest growing city in northern Australia, with strong population growth of around 2% per year (Cairns Regional Council, 2019d). The ability of Cairns to attract new residents and economic growth has been attributed in part to its planning and development approach to enhance liveability in the tropical city based on climate-responsive and place-based design strategies. However, there is also a challenge for managing urban growth in a way that is reflective of the diversity of perspectives across the city (Jo Russell-Clarke, 2018).

5.2 Cooling Singapore

5.2.1 Overview

Singapore has become warmer in recent years due to increasing growth and densification, exacerbating the UHI effect. The challenges of managing the UHI effect is particularly relevant for Singapore as one of the most densely urbanised countries in the world with a population of 5.6 million living in an area of just 722 km^2 [10]. The increased temperatures from the UHI effect in addition to the high humidity experienced all year long leads to challenges for improving the thermal comfort for the city's residents. Singapore has a tropical rainforest climate (*Af*) that does not have distinct seasons but is characterised by mostly consistent temperatures of around 25–35 °C, high humidity and high rainfall.

These problems will most likely become more severe in the future, partly because of urban growth but also exacerbated by the impacts of climate change. Tackling such a complex issue will require a multidisciplinary set of stakeholders across government, industry, academia and the public.

The Cooling Singapore project (Cooling Singapore) was funded by Singapore's National Research Foundation to provide tools and approaches that can help support efforts to reduce the UHI effect and improve outdoor thermal comfort. The project partners span a wide range of scientific institutions including Singapore-ETH Centre (SEC), Singapore-MIT Alliance for Research and

[10] https://www.singstat.gov.sg/-/media/files/publications/reference/sif2019.pdf

Technology (SMART), TUMCREATE (Technical University Munich), National University of Singapore (NUS), Singapore Management University (SMU), and Agency for Science, Technology and Research (A*STAR).

The developed tools and approaches will help improve economic productivity while also improving the wellbeing of the population (Acero et al., 2017).

Cooling Singapore has the following objectives (Acero et al., 2017):

- Assess and measure the impact of different cooling strategies that might be relevant to Singapore's tropical climate.
- Develop a decision support tool that can help prioritise and evaluate benefits of different heat mitigation approaches.
- Design climate-responsive guidelines that can help the implementation of heat mitigation approaches in planning and design processes.

5.2.2 Heat mitigation approaches

To help reduce urban heat accumulation and improve outdoor thermal comfort, the use of vegetation has been explored in the project. This includes green roofs, vertical greenery and green facades, green pavements and carparks, and the use of green corridors along transport corridors. The project highlights that strategic planting of vegetation can improve the local outdoor thermal comfort while also reducing building energy demand for cooling. Furthermore, the use of vegetation along transport corridors can help improve thermal comfort for pedestrians, while also improving local air quality.

Urban geometry is also explored to improve liveability in Singapore. Urban form variables that can influence thermal comfort are identified at two spatial scales: (i) at the building scale, which involves consideration of building height and tree heights, variability in building heights, shading, street layout, building porosity (openings and gaps), and orientation; and (ii) at a coarser spatial scale, which involves the role of urban planning in enabling a more liveable city, considering urban density, ratio of green space, and ensuring there are open spaces along the seafront that enable cooling breezes to enter the city.

The use of water bodies and other water features is explored in providing heat mitigation benefits and increasing thermal comfort. Water bodies in Singapore can act as a heat sink. The use of evaporative cooling approaches, such as misting, can improve thermal comfort, but is limited due to the high humidity in Singapore.

Cooling Singapore also explores the potential effects of different urban materials and surfaces, focusing on their thermal properties, on urban climate and thermal comfort. The project investigates different materials and surfaces that limit the absorption of solar radiation through approaches, such as highly reflective surfaces, that mitigate UHI effect and can improve thermal comfort and reduce building energy demand.

5.2.3 Implementation

Cooling Singapore, funded by Singapore's National Research Foundation, was implemented in partnership with a range of organisations that included government agencies, universities and the private sector. The project recognised that mitigating urban heat is a complex issue and, due to implications across sectors, requires a whole-of-government approach. The project also plans to explore community perceptions of thermal comfort, their preferences for different strategies and their management strategies for adapting to heat stress (Acero et al., 2017).

The effectiveness of different approaches for improving outdoor thermal comfort and mitigating urban heat will be validated through monitoring studies and community surveys.

5.2.4 Outcomes

Cooling Singapore is an ongoing program to mitigate urban heat and improve thermal comfort. It is planned that findings from the research will be incorporated in design guidelines that encourage an approach to urban planning that is responsive to Singapore's climate.

5.3 Heat mitigation: Bangalore, India

5.3.1 Overview

Bangalore is one of the fastest growing cities in India, where the population has more than doubled over the period from 1991 to 2017 (TERI, 2017). This population increase has resulted in urban sprawl, resulting in loss of green space and natural water bodies that has exacerbated the challenges of managing urban heat. Bangalore has a tropical savanna climate (*Aw*) with distinct wet and dry seasons. The elevation of Bangalore (900 m) moderates the temperature throughout the year (TERI, 2017).

The Energy and Resources Institute (TERI) undertook a study to validate the UHI effect in different urban typologies and how different responses, such as cool roofs, might mitigate this effect (TERI, 2017). The study's purpose was to provide urban planners with information on how to mitigate UHI in new developments through land-use planning by retaining a mix of green spaces and water bodies as well as treatments for buildings and other urban surfaces that can improve the thermal comfort and liveability of Bangalore. Case study locations were selected for monitoring of UHI and validated the effectiveness of different heat mitigation approaches. The case study locations represented a range of urban contexts with varying levels of vegetation coverage and land-use typologies (residential and commercial)(TERI, 2017).

5.3.2 Heat mitigation approaches

The study monitored the UHI effect for different urban typologies based on urban geometry (especially ratio of building height to street width), land use (ratio of green space) and proximity to large water bodies.

The study also investigated the effectiveness of heat mitigation of green roofs (vegetated roofs), cool pavements (light-coloured and permeable pavements) and cool roofs (light-coloured reflective materials).

5.3.3 Implementation

The study explored the relationship between different urban planning characteristics with UHI effect across Bangalore. The understandings from this study were used to inform a more detailed assessment and selection of different heat mitigation options in different urban growth areas. The selected heat mitigation options will then be demonstrated in selected locations in Bangalore (TERI, 2017).

5.3.4 Findings

The study in Bangalore highlighted the following outcomes (TERI, 2017):

- Increasing green areas around commercial precincts can help to reduce start-up load for air conditioning in the morning as the green space will provide a heat sink to dissipate accumulated heat overnight.
- The design of new urban developments should prioritise the integration of green space and water bodies and incorporate a minimum of 14% of land use, which was found to be effective in reducing UHI effect.
- Cool roofs and green roofs, and the use of light-coloured exteriors for buildings can be effective in reducing the accumulation of heat during the day.

5.4 Million trees: Miami, Florida, United States

5.4.1 Overview

Miami-Dade County in Florida, United States implemented a Street Tree Master Plan that included the objective of reaching 30% tree canopy cover across the city by 2020 by planting at least one million trees across public and private land (Miami-Dade County, 2007). The Street Tree Master Plan was initiated following the loss of trees in hurricanes in 2005 (hurricanes Katrina, Rita and Wilma). These hurricanes exacerbated some of the existing pressure on the tree canopy from urban development. The program to improve the tree canopy was intended to provide a range of social, environmental and economic benefits to the community, which included mitigating the UHI effect in Miami and reducing the city’s energy demand (Miami-Dade County, 2007). Other co-benefits included reducing stormwater runoff and improving local air quality (Miami-Dade County, 2007).

Miami’s climate is classified as tropical monsoon (*Am*), with a hot and humid summer season while the winter is warm but relatively dry with less rainfall from November to April. Monitoring data across Miami-Dade County highlights how proximity to the ocean modifies temperature. The maximum temperature is higher at the airport, which is located 12 km inland, compared to the weather station data located on the coast (National Climatic Data Center - NOAA, 2019).

Figure 17. Typical street in Coconut Grove, south of downtown Miami, Florida, United States.
Source: Digital photo taken by Marc Averette, Wikimedia Commons (CC BY 3.0).

5.4.2 Heat mitigation approaches

The Street Tree Master Plan highlights the potential for increased tree canopy cover to reduce local air temperatures and mitigate the UHI effect. This is particularly the case in heavily urbanised parts of Miami, where temperatures are higher compared to the surrounding suburban areas due to the greater proportion of urban surfaces in the city covered in materials that absorb and store energy (Miami-Dade County, 2007). The Master Plan also promotes increasing tree canopy to reduce building energy use through tree shading and directing breezes to the urban areas (Miami-Dade County, 2007).

5.4.3 Implementation

The Street Tree Master Plan provides a framework for achieving the objective of a minimum of 30% tree canopy coverage by 2020, which includes (Miami-Dade County, 2007):

- Resources on recommended and prohibited tree species, with information on each of these species.
- Information on best management practices for planting and maintaining street trees.
- Encouraging partnerships and engagement through forming of working groups and community education programs.

5.4.4 Outcomes

A comprehensive assessment was undertaken of the Miami-Dade Million Tree Initiative in 2015 (Hochmair et al., 2015). This analysis of success found:

- Overall tree canopy coverage is currently around 20% with 42% of the tree canopy found on residential land use.
- Tree coverage and water bodies are associated with lower surface temperatures.
- Tree canopy coverage is positively correlated with median income, but negatively correlated with African American and Hispanic residents. This highlighted the need to ensure environmental equity by focusing efforts for tree planting in minority and lower income communities.
- Areas with tree cover were associated with lower overall hospitalisation numbers. However, this is not necessarily a causative relationship as better health outcomes might also be influenced by better opportunities for preventive health care in wealthier households (Hochmair et al., 2015).

5.5 Natural ventilation: Enugu city, Nigeria

5.5.1 Overview

Enugu city is located in the south-eastern part of Nigeria and is classified as tropical savanna (*Aw*). The city is 304.7 m above sea level, with a naturally humid climate that is regarded as oppressive between March and November. Its average maximum temperature stands at 34.9 °C, with average lows of about 22.3 °C and its annual mean temperature is about 26.7 °C.

Enugu experiences significant seasonal variations in windspeed over the course of a year. The windier part of the year lasts for 7 months (between March and September). The typical wind path comes from the west for an average of 10 months (termed the monsoon season), ranging from January to November. The wind direction changes to northerly for 2 months (termed the Harmattan season) from November to January.

5.5.2 Heat mitigation approaches

Because of the climate, passive cooling and natural ventilation are important aspects to cool the city. Thus, it is important to understand how the height of buildings and the width of streets take advantage of natural winds and ventilation for cooling.

Designers and planners of urban streets are faced with the complexity of integrating seasonal climatic factors in the configuration and orientation of streets and buildings. The major challenge is to design streetscapes that are protected from the sun yet allow for permeability of natural ventilation. The dual needs have influenced local designers to create shallower and compact street canyons.

5.5.3 Research

Most of Enugu streets are classified as high density, medium density and low density. The main goal of the research was to identify the extent of wind obstruction caused by existing street geometry on the airflow for natural ventilation in this city.

5.5.4 Outcomes

With high temperatures and humidity in Enugu, modelling shows that there needs to be a reduction of barriers that impede the airflow for natural ventilation; thus, encouraging passive cooling. Results indicate that for all three main street configurations, designing streets with wider widths (i.e. smaller height: width ratios) provides better mixing of air and consequently better airflow in the urban street canyon. Additionally, providing adequate openings between streets and courts and adopting different building heights in the streets could also improve air exchange within the urban canopy layer.

6 Conclusions and potential next steps

There are few examples of heat mitigation activities from cities with an analogous climate to Darwin. This presents an opportunity for Darwin to become a world leader in the science and innovation of heat mitigation among cities characterised by wet-dry tropical climates.

This report provides information to assist with developing strategies and prioritising actions for mitigating urban heat impacts in Darwin. This section describes the suggested next steps for developing the Darwin Heat Mitigation Strategy.

6.1 Short-term actions for long-term gain

The findings of this literature review demonstrate that urban heat can be mitigated through the strategic use of cool building design and materials, water sensitive urban design and water features, increasing vegetation cover, creating cool roads and paths, and increasing education and awareness regarding behavioural change to reduce heat.

Immediate actions that can be taken include:

- Use the maps of land surface temperature and information on population vulnerability (Meyers et al., 2020) to identify the priority areas for targeted urban heat mitigation actions.
- Examine opportunities to incorporate low-cost actions to retrofit current building types.
- Implement trials for cool and permeable pavements, tree shading, water retention and misting, and path placement to test the effect of these various changes on the cooling effect on these important transport corridors – for both roads as well as in the design of active transport corridors through Darwin.
- Consider current heat warning plans and social media campaigns in their effectiveness to inform Darwin communities about heat protective behaviours.

6.2 Engaging with stakeholders to obtain more information

While this literature review provides background information regarding the scientific validity of the heat mitigation strategies and actions, the symposium workshop around heat mitigation in December 2019 (information found in the Appendix as well as a separate report) revealed the enthusiasm stakeholders had for this topic. This workshop marked a starting point for gleaning ideas and opinions from potential stakeholders, which should be continued throughout the process of developing the heat mitigation strategy.

Although the ultimate actions within the Darwin Heat Mitigation Strategy will have to be socialised across the different levels of government, there will also need to be a wider engagement strategy across the general Darwin community, with a specific focus on vulnerable groups.

This broader engagement strategy may take the form of:

- Research surveys, to systematically survey a representative population of Darwin LGA residents in order to garner specific understanding of vulnerabilities and needs within the community.

- Interviews or focus groups, conducted to socialise and discuss various strategies and actions to be piloted.
- Specific actions, to elicit ideas and opinions from vulnerable groups, which may require additional outreach and engagement to increase involvement.

6.3 Thinking through long-term changes for transformation

Transformational change will require long-term strategic engagement. This will require collaboration across sectors and stakeholders to develop a plan of action that will take into account the needs and desires currently and into the future.

Opportunities to support long-term strategic planning for transformational change include:

- Developing a multi-stakeholder reference group and process that can address various viewpoints on urban heat impact and comment on future planning.
- Modelling the costs and benefits at city scale of different treatment options through time and in different combinations that take into account different scenarios of change.
- Researching policy levers that allow for changes to occur at the city level, through multiple nodes of influence.

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Appendix: Symposium workshop results: Conversation maps

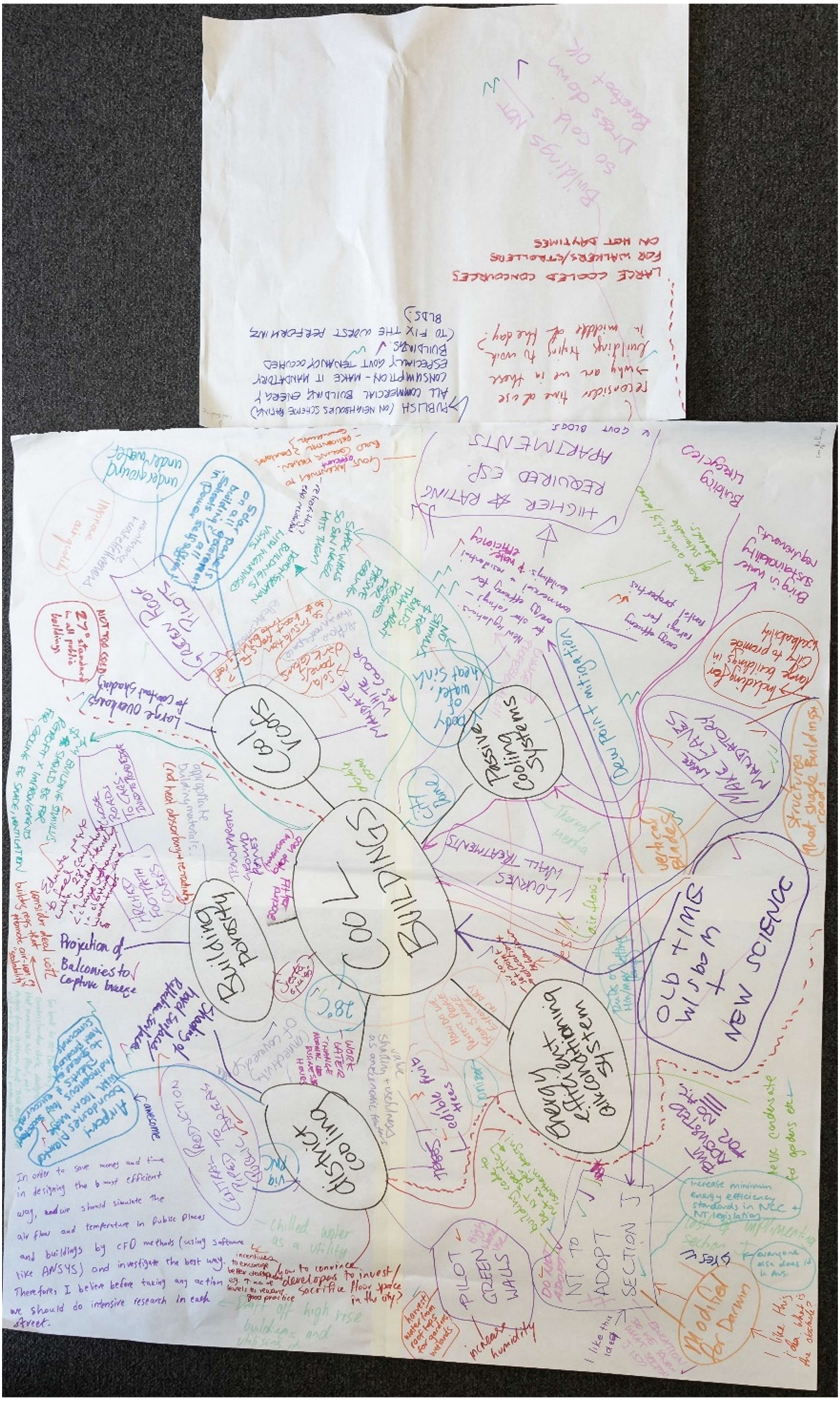
On December 13th, 2019 a deep-dive workshop was run as part of the Darwin Living Lab Inaugural Science Symposium. This symposium was developed to socialise the strategies and actions from Section 4 with the practitioners and community of Darwin.

Symposium participants (about 45 people) engaged in a conversation mapping exercise to further develop the strategies and actions outlined in Section 4 providing ideas on the types of actions they would like to see implemented. The participants split up into five groups and rotated across all five tables throughout the workshop period. Some participants preferred to work silently while others engaged in conversation to develop ideas.

The conversation mapping process allowed participants to build upon each other's ideas and to refine potential future projects as they moved through the tables. Once all participants had visited all five tables, they were given time to roam across the various maps to read through the various ideas. They were then asked to vote (using check marks as a sign of support) for the ideas that they felt were most important for Darwin to trial. These project ideas should be considered in the development of the Darwin Heat Mitigation Strategy.

The findings from the five conversation maps are summarised in the following sections.

A.1 Cool buildings



Summary

The main themes resulting from the cooling buildings maps showed that participants wanted buildings to be designed with higher resource use efficiency. For example:

- Mandating energy efficiency.
- Making sure that there was a minimum start rating for energy and water efficiency.
- Making sure new buildings are designed to achieve energy efficient targets.

Some of the discussion also centred on participants believing there were simple options that could be implemented to mitigate heat in the design of the building that also would affect overall cooling. For example:

- Retrofit buildings for better cooling and ventilation.
- Implement white roofs and surfaces.
- Shade hard surfaces or make them reflective.
- Balconies designed to catch breezes.
- Awnings to help with shading.

Lastly, the idea of increasing the indoor temperature of buildings to save energy was considered to be important – and probably ties closely to some of the discussions had within the education and awareness map.

- Making sure that air conditioning in buildings is set to a higher temperature to reduce energy use.
- Pairing the practice of increased air conditioning in buildings with relaxed rules around business wear (e.g. allowing people to wear shorts and sandals at work).

A.2 Water sensitive urban design / Water features

Summary

Many of the suggestions within the water sensitive urban design map focused on the development of water features that considered natural systems and sought to develop and protect natural creeks or connections between salt and freshwater systems for cooling. These included:

- Supporting natural features such as creeks within the city area – as long as it is flowing and does not allow for mosquitoes.
- Connecting saltwater to freshwater through the topography of the city.

There was also a set of ideas around harvesting stormwater to use – most likely for greenery – or to test out the possibilities of using grey or recycled water in maintaining water features within the city. For example:

- Using grey water – testing the opportunity of using it to maintain greenery in the city.
- Harvesting stormwater for use.
- Designing buildings that can be part of the water cycle in terms of harvesting water and using it for indoor water features.

Finally, there was a strong acknowledgment that participants would like to see some placemaking activities around water, where water features would be used to encourage people to gather and spend time in public spaces.

- Use water to help with placemaking of public centres (e.g. attracting people to spend time in these places through gathering around water).

A.3 Urban green infrastructure / Vegetation

Summary

Discussion around urban green space and vegetation centred on where green space is needed and what type of green space participants wanted.

A strong theme was for green space to be developed within Darwin that takes advantage and showcases the native vegetation and biodiversity. This also expanded into ideas of how to encourage the use of bush tucker in green spaces, especially in urban farming systems. This includes ideas like:

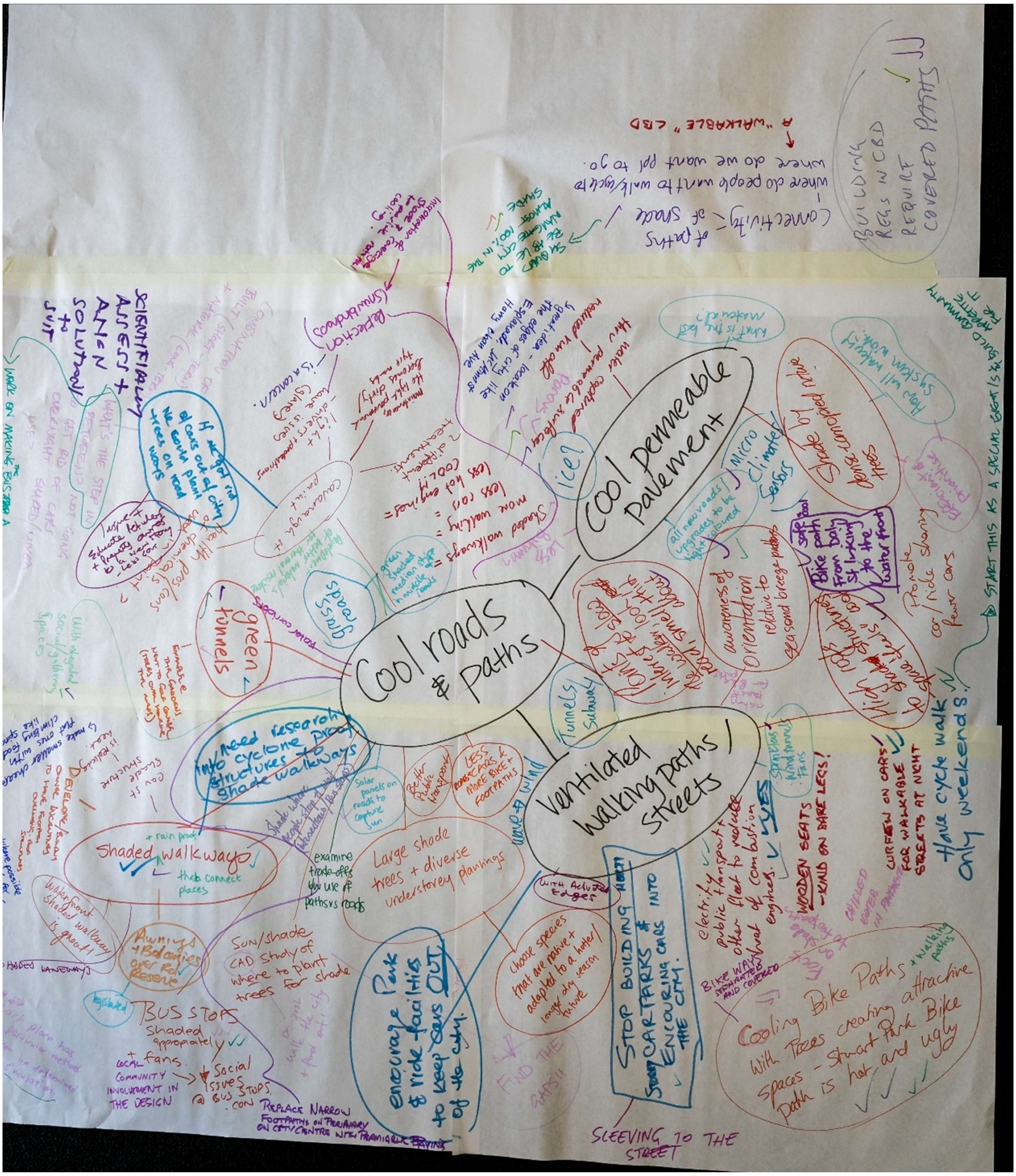
- Considering Darwin’s unique ecosystem and biodiversity when designing complex green space.
- Increasing the education and knowledge sharing around how to protect and expand native vegetation across the city.
- Providing educational opportunities for people to engage with native plants – this can include in nature spaces, but also native foods.
- Considering farming the city and linking the greening with food initiatives – urban orchards and gardens.

Greening the road corridors was also a major conversation point in the maps. Participants were very supportive of trees within transport corridors, suggesting two specific areas:

- Greening the road corridor from the airport to the CBD.
- Creating vegetated road medians especially in residential streets.

There was a discussion about greening in buildings, and ideas such as balcony gardens and growing trees indoors was encouraged. Although participants liked the idea of green roofs and green facades, they also recognised that they may be expensive and difficult to maintain.

A.4 Cool roads and paths

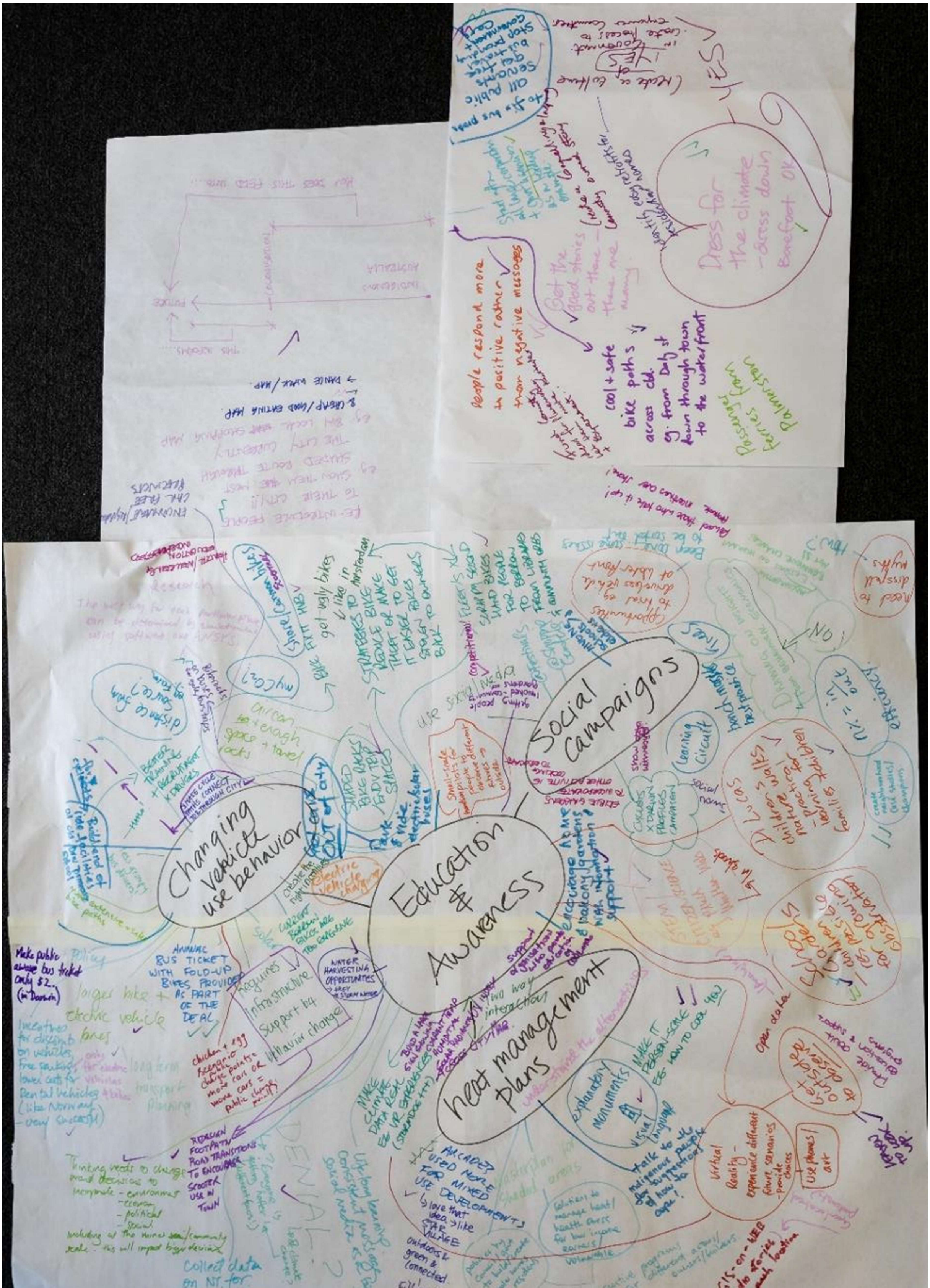


Summary

Participants expressed a desire for cooler pathways for walking and cycling to and through the CBD. Several suggestions were made:

- Green tunnels to provide shaded walkways.
- Better bike paths that are shaded with shaded bike parking for people to keep their bikes.
- Bus stops need to be shaded properly for people to take public transport.
- Make CBD only cycle accessible or walkable on the weekend to encourage active transport.
- Change building and development policy in the CBD to require shade on the paths.
- Implementation of permeable pathways to absorb water to increase cooling – could also help with stormwater harvesting (as considered in the water features map).
- Orient roads to incorporate sea breezes.

A.5 Education and awareness



Summary

The education and awareness map not only discussed what education topics people would like to see, but also how to provide the message to the community. Specifically:

- People respond better to positive messages rather than negative messages.
- Need to get the good stories out there.
- Need to create a community-owned story/narrative.
- Create neighbourhood case studies and champions.

There were several other ideas that gained traction across the group, ranging from changing indoor air conditioning to helping people better understand climate change.

- Changing behaviours to dress appropriately for the climate – in line with changing indoor air-conditioner use.
- Give people free public transport into the city to incentivise public transport use.
- Create heat management plans at the person/individual scale – how to cool yourself.
- Educate people about the changing climate and provide access to the climate data.

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