
EXECUTIVE SUMMARY

**Heat Mitigation Program
Darwin, Northern Territory**



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Introduction

The urban heat island (UHI) effect in which urban areas exhibit higher temperatures than the surrounding rural or suburban areas is well documented in hundreds of cities around the world including major cities in Australia. High urban temperatures are further exacerbated by the global temperature rise due to climate change. This urban overheating has serious consequences on thermal comfort, energy consumption, health and the economy and thus affects negatively the sustainability and livability of cities.

Advanced mitigation strategies like cool roofs and pavements, green roofs and urban greenery, shading and the use of evaporative systems (e.g. water sprinklers, fountains) when properly implemented in urban areas contribute to decrease the ambient temperature and counterbalance the impact of urban heat islands.

In this framework, the NT Government has launched a project called "Heat Mitigation Program Darwin, NT" in collaboration with the Bureau of Meteorology, the CSIRO, the Charles Darwin University and the University of New South Wales aiming at reducing urban overheating of the city of Darwin through the implementation of appropriate UHI mitigation technologies and solutions. This report summarizes the efforts of the Faculty of the Built Environment of the University of New South Wales to investigate the characteristics of the urban heat island of Darwin, NT, identify hot spots in the city, develop and evaluate appropriate UHI mitigation scenarios and propose optimum UHI mitigation solutions tailored for the city of Darwin.

Methodology

The following activities have been carried out:

- Collection and statistical analysis of existing climatic data in order to explain the main climate characteristics of the Darwin area.
- Experimental campaign involving aerial infrared monitoring using drone technologies and terrestrial monitoring of meteorological parameters in order to investigate the specific characteristics of the UHI in Darwin CBD.
- Identification of the hot spots in the city and development of appropriate mitigation scenarios
- Climatic evaluation of the developed mitigation scenarios compared to the existing situation in Darwin CBD, using advanced simulation techniques and proposal for the optimum mitigation solution to be Implemented

The climate of Darwin

Meteorological data including hourly values of the ambient temperature, relative humidity, wind speed and wind direction, collected at the Darwin airport for 2006-2016, have been analyzed using advanced statistical techniques. The main characteristics of the Darwin climate which are summarized below have been used to assess qualitatively the potential of various technologies, systems and design solutions to mitigate urban overheating and prepare the basis for developing the appropriate UHI mitigation scenarios.

- When the wind flows from **North Western Directions**, the **highest levels of the average ambient temperature** are observed in the city with values close to 29.4°C and maximum ones to 37°C. The average relative humidity is close to 67% and the maximum is almost 100%. The average wind speed, during this period, is 4.7m/sec and the maximum speed exceeding 15m/sec. These synoptic conditions correspond to a time period equal to the 24% of the whole year.
- When the wind flows from **southern and southwestern directions**, **high ambient temperature and humidity levels** are observed in the city with average values equal to 27.7°C and 77% respectively. The average wind speed, during this period is 4.1m/sec. These synoptic conditions correspond to a time period equal to the 22% of the whole year.
- When the wind flows from **northern and North Eastern directions**, **average ambient temperature and humidity levels** are observed in the city with an average ambient temperature equal to 27°C and an average relative humidity of 71%. The corresponding maximum values are 36°C and 100 % respectively. The average wind speed, during this period, of 3.4m/sec. During this period a weak sea breeze is developed consisting the dominant cooling mechanism in the city. These synoptic conditions correspond to a time period equal to the 24% of the whole year.
- When the wind flows from **South East and South directions**, **minimum ambient temperature and humidity levels** are observed in the city, as advected air is highly influenced, cooled, by the national parks located in the southeastern parts of the city. The average ambient temperature is 25.3°C and the maximum close to 37°C. The average relative humidity is 66 % and the maximum one is close to the saturation conditions. The average wind speed is 4,1m/sec. These are the prevailing synoptic conditions and correspond to a time period equal to the 30% of the whole year.

It is evident that Darwin suffers from poor outdoor thermal comfort conditions for the most part of the year as ambient temperatures are high (reaching even 37°C) and the relative humidity is also very high.

Terrestrial and aerial monitoring campaign of Darwin CBD

A three-day monitoring campaign was conducted from the 23rd to the 25th of March 2017, during the wet season of Darwin, involving aerial infrared (IR) monitoring using drone technologies and terrestrial monitoring of meteorological parameters in order to investigate the specific characteristics of the UHI in Darwin CBD. The database coming out of this monitoring campaign represents the scientific basis for planning and assessing optimized strategies to counteract and mitigate the UHI phenomenon.

a. Aerial IR monitoring

The main objective of the aerial IR survey was to investigate and record the surface temperatures of the different materials of the urban fabric of Darwin CBD. In order to perform the survey, an Unmanned Aerial Vehicle (UAV=drone) equipped with a thermal camera was employed. The areas surveyed via UAV are summarized in Figure 1A. The output of the survey consisted of thermal images and videos that were processed using appropriate software in order to represent surface temperatures. It was found that:

- Streets and parking lots present high surface temperature values ranging from 55°C -62°C for streets and 45°C-67°C for parking lots.
- Roofs and pavements exhibit also very high temperatures ranging from 48°C -66°C for roofs and from 49°C -56°C for pavements.
- Trees and greenery were found to exhibit lower surface temperatures ranging from 28°C -38°C for trees and from 32°C -46°C for greenery.
- The shading effect from trees and greenery was found to be very effective in lowering the surface temperatures of streets and pavements with values ranging from 10°C -23°C

It is evident that the use of dark materials on roofs, streets and pavements that absorb solar radiation results in elevated surface temperatures and the overheating of the urban fabric. On the contrary, trees and greenery play a significant role in the reduction of urban surface temperatures since the areas around the harbour, the City Council and the Supreme Court (which are rich in vegetation) are the ones showing the lowest values.

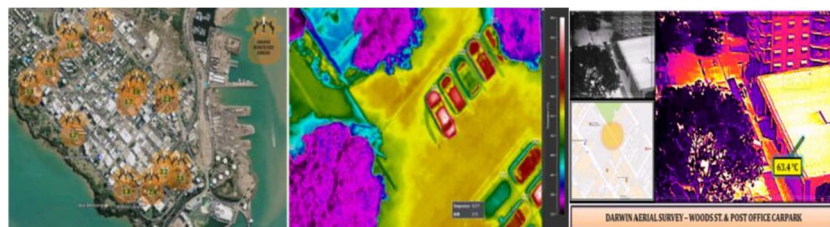


Figure 1: Locations of the aerial survey (A), thermal image of a high surface temperature parking lot (b), screen shot of a thermal video presenting high roof surface temperature

b. Terrestrial monitoring

The objective of the terrestrial survey was to investigate the magnitude and specific characteristics of the UHI in Darwin. Different meteorological parameters including air temperature, relative humidity, wind speed and direction, solar radiation and heat flux have been measured using a professional weather station equipped with the appropriate sensors and a net radiometer. The measurement locations displayed in Figure 2A were selected based on the analysis of the climatic characteristics of Darwin and preliminary observations indicating the areas of interest in terms of microclimate monitoring. Measurements of air temperature, wind speed and relative humidity taken at Darwin CBD were compared with the corresponding ones recorded at the same time at the Darwin airport meteorological station which was considered as the reference station. The average air temperature differences between the measurement locations and the reference stations, indicating the UHI, are presented in Figure 2B. Minimum and maximum values are also displayed. The analysis of the results showed that:

- The UHI magnitude observed in Darwin CBD is 2°C - 3°C and it is mainly due to the high surface temperatures of the urban fabric that release heat in the ambient air, reduced wind speeds and the lack of sea breeze that is not formed due to the high temperature of the water and the anthropogenic heat.
- Significant differences in the spatial distribution of ambient temperature have been recorded. Higher ambient temperatures (reaching 33°C) are observed in the north-west side of the CBD, which represents the entry door for the hot western winds. Lower values are recorded in the harbour area where the building density is much lower, the greenery is more widely spread and evaporation phenomena are emphasized. Relative humidity presents a high value in all locations which always higher than 75%.
- In the CBD the wind speed is much lower compared to the reference station (unobstructed environment) because of the physical barrier created by the urban morphology which blocks the air flow so that warmer air remains within the canopy for a longer time.

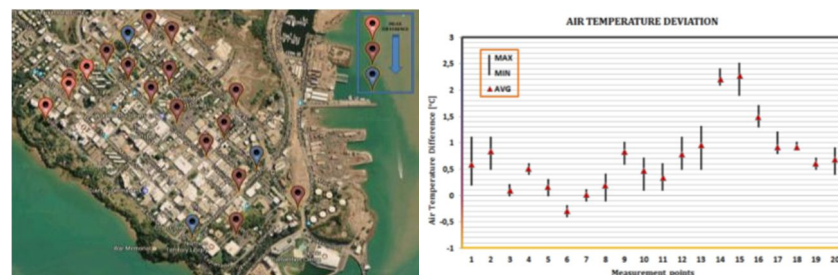


Figure 2: Locations of the terrestrial survey (A) –average air temperature difference spatial distribution is also shown on the map. Air temperature differences between the measurement locations and the reference stations (B).

UHI mitigation strategies

The analysis of the data collected during the aerial and terrestrial monitoring campaign has shown the specific microclimate characteristics of Darwin that contribute to the overheating of the CBD. The specific UHI characteristics, sources and magnitude have been investigated and the hot spots in the city have been identified. The results of the experimental campaign will lead to the development of appropriate mitigation strategies tailored to address the specific problems detected. Moreover, the collected data will be used to validate the microclimate models that will be developed in order to evaluate the proposed mitigation strategies.

In an effort to reduce urban overheating and mitigate the consequences of the urban heat island effect like thermal discomfort in outdoor and indoor non AC spaces, increased energy consumption for cooling and peak loads, increased air pollution and emission of GHG, increased rates of heat related mortality and morbidity and of course increased related expenses, urban heat island mitigation strategies have been proposed. Some of the most successful and applied technologies are outlined below.

Cool roofs and pavements increase the albedo (solar reflectance) of urban surfaces preventing solar radiation from being absorbed. Surfaces stay cooler under the sun releasing less heat into the ambient air.

Street shading reduces solar radiation from reaching the street level providing a cooler environment.

Trees, Greenery and green roofs can significantly improve thermal comfort conditions as water evaporating from the soil and the leaves of plants uses heat in the air, thereby decreasing local ambient temperatures.

Fountains, ponds and sprinklers provide improved thermal comfort by cooling the air through the evaporation process of water and by using water bodies as heat sinks.

These UHI mitigation strategies when properly designed and installed in the built environment contribute significantly in lowering ambient air temperatures and improving thermal comfort conditions. The existing knowledge acquired through monitored applications, show that it is possible to decrease the peak temperature of the cities up to 2.5°C. In this sense, they have the potential to reduce the UHI effect and its negative consequences improving the sustainability and livability of cities. More information on the benefits and impacts of the proposed UHI mitigation strategies as well as specifications and design recommendations are included in the respective sections of this report.

Climatic evaluation of the mitigation potential of the proposed strategies for Darwin

Based on specific climatic characteristics and the identified overheating and thermal comfort problems in Darwin, fourteen mitigation scenarios have been designed aiming to decrease the ambient temperature in the Darwin area (Table 1). Advanced simulation techniques involving 3D microclimate modeling, have been used in order to quantitatively evaluate the impact of the developed mitigation scenarios in terms of reducing ambient temperatures in comparison with the reference case which represents the actual situation. The spatial distribution of the ambient temperature in the whole CBD area, as well as the distribution of the surface temperature, and of the wind speed and direction have also been calculated in detail for each scenario. Simulations have been performed for two synoptic conditions, NW and SE wind direction, and for low and high wind speeds, (1 and 5 m/sec). Also, the final combined scenario has been simulated under the climatic conditions of the cold (dry) period. In total 54 scenarios have been simulated.

Table 1: Description of the defined mitigation scenarios

No	Description of scenarios	
1	Reference Model	Albedo of walls and roofs=0.2, Asphalts Albedo=0.05, Concrete pav Greenery < 10 % of the total pavements and open space
2	Global albedo 0.4	Global Albedo=0.4, Greenery < 10 % of the total pavements and op
3	Global albedo 0.6	Global Albedo=0.6, Greenery < 10 % of the total pavements and op
4	Cool pavement	Albedo of streets and pavements=0.5, Greenery < 10 % of the total
5	Shading	Albedo of streets (Asphalt)=0.34, Albedo of concrete pavement=0.4, space
6	Greenery 20%	Greenery 20% of the total pavements and open spaces
7	Greenery 30%	Greenery 30% of the total pavements and open spaces
8	Cool roof	Albedo of roof=0.85, Greenery < 10 % of the total pavements and op
9	Green roof	Green roof in all buildings
10	Water fountain	Application of water fountain on The Mall
11	State square changes	increase of greenery by 30%, application of water fountain, use of c building is removed
12	Combined scenario	Global albedo=0.6, Greenery 30%, and Shading
13	Combined scenario with water fountain	Global albedo=0.6, Greenery 30%, Shading, and water fountain acr
14	Combined scenario cold/dry season	Global albedo=0.6, Greenery 30%, and Shading

The main results for each scenario are outlined below, while Tables 2 and 3 give the minimum and maximum ambient temperatures, reduction of the maximum and minimum temperatures, and the local maximum temperature drop achieved in all scenarios:

Reference scenario: The ambient temperature varies between 32°C - 36.4°C and about 32.8°C - 36°C in the CBD area for wind speeds of 5m/s and 1m/s respectively. The maximum surface temperature of asphalt pavements (parking area) is above 55°C for both wind speeds.

Increase of the reflectivity of the city to a global albedo of 0.4: results in a local maximum temperature drop in the CBD area of about 1.7°C for the 5 m/s wind speed and 1.3°C for the 1m/s wind speed for NW wind directions with somewhat lower reduction for the SE wind. The ambient temperature ranges from 31.9°C to 34.8°C (NW wind, 5m/s). The maximum surface temperature drops by 8.9°C reaching a value of about 47°C for both wind speeds.

Increase of the reflectivity of the city to a global albedo of 0.6: results in a local maximum temperature drop in the CBD area of about 2.5°C for the 5 m/s wind speed and 1.9°C for the 1m/s wind speed for NW wind directions with somewhat lower reduction for the SE wind.

The ambient temperature ranges from 31.9°C to 33.9°C (NW wind, 5m/s). The maximum surface temperature drops by 12°C reaching a value of about 44°C for both wind speeds.

Use of cool pavements: Increasing the albedo of streets and pavements to 0.5, results in a local maximum temperature drop in the CBD area of about 2.1°C for the 5 m/s wind speed and 1.7°C for the 1m/s wind speed for NW wind directions with somewhat lower reduction for the SE wind. The ambient temperature ranges from 31.9°C to 34.3°C (NW wind, 5m/s). The maximum surface temperature drops by 11°C reaching a value of about 44.5°C for both wind speeds.

Solar Control of the Main Streets in Darwin: Reducing incident solar radiation on streets and car parks by 30% via shading, results in a maximum temperature drop in the CBD area of about 1.3°C for the 5 m/s wind speed and 0.5°C for the 1m/s wind speed for NW with similar results for SE winds. The ambient temperature ranges from 31.7°C to 35.1°C (NW wind, 5m/s). The maximum surface temperature drops by 10-12°C reaching values of about 40 -42°C for both wind speeds.

Increase the Greenery to cover 20 % of the CBD Area: This scenario results in a maximum temperature drop in the CBD area of about 0.6°C and 0.2°C for the 5 m/s wind speed for NW and SE winds respectively and negligible effect for the 1m/s wind speed for both wind directions. The ambient temperature ranges from 31.9°C to 35.8°C (NW wind, 5m/s). The local effect of greenery results in a maximum temperature drop that reaches 2.6°C (NW/5m/s). The maximum surface temperature drops by 11°C reaching values of about 31 -33°C for both wind speeds. If the local effect of adding trees is also considered, surface temperature reduction may reach values of 23°C and 26°C for 5 m/s wind speed and for NW and SE winds respectively.

Increase the Greenery to cover 30 % of the CBD Area: This scenario results in a maximum temperature drop in the CBD area of about 1.2°C and 0.5°C for the 5 m/s wind speed for NW and SE winds respectively and negligible effect for the 1m/s wind speed for both wind directions. The ambient temperature ranges from 31.9°C to 35.2°C (NW wind, 5m/s). The local effect of greenery results in a maximum temperature drop of 2.7°C (NW/5m/s). The maximum surface temperature reduction is about 26 -27°C for both wind speeds and directions. If the local effect of adding trees is also considered, surface temperature reduction may reach values of 23°C and 26°C for 5 m/s wind speed and for NW and SE winds respectively,

Use of cool roofs: Increasing the albedo of roofs to 0.85, results in a maximum temperature drop in the CBD area of about 0.16°C and 0.25°C for the 5 m/s wind speed for NW and SE winds respectively and negligible effect for the 1m/s wind speed for both wind directions. The ambient temperature ranges from 32°C to 36.3°C (NW wind, 5m/s). The local effect of cool roofs results in a maximum temperature drop of 0.7°C (NW/5m/s). The maximum surface temperature at the surface level does not present a significant reduction (about 1°C) compared to the reference case.

Use of green roofs: Implementing green roofs in all buildings, results in a maximum temperature drop in the CBD area of about 0.49°C for the 5 m/s wind speed and 0.21°C for the 1m/s wind speed for NW and

about 0.53°C for the 5 m/s wind speed and 0.25°C for the 1m/s wind speed for SE winds. The ambient temperature ranges between 31.7-36°C. The local effect of green roofs results in a maximum temperature drop of 1.99°C (SE/5m/s). The maximum surface temperature drops by 1-2°C reaching values of about 51-55°C for both wind speeds. The maximum reduction of the surface temperature is about 21-22°C in some locations.

Use of Water- Evaporative Cooling: The application of 10 water fountains at the Mall, results in a local maximum temperature drop of 3.9 and 5.8°C for the 5 m/s wind speed and 5.5 and 6.7°C for the 1m/s wind speed for NW and SE wind directions respectively. The temperature reduction effect in the whole CBD area for this mitigation strategy is almost negligible. The maximum surface temperature at the Mall drops by 2.2°C reaching values of about 40-42°C for the 5 m/s wind speed while for the 1m/s wind speed the maximum surface temperature drops by 3°C reaching values of about 44-46.5°C.

State square changes: The increase of greenery by 30%, the application of water fountain and use of cool pavements (albedo of 0.5), results in a maximum ambient temperature drop for the whole area of 2.4°C (NW/ 5m/s) (Figure 3). The maximum temperature drop in the southern part of Darwin (local impact) was about 6.5°C and 8°C for the wind speed of 5 m/s and directions of NW and SE winds, respectively and 8°C for 1m/s and for both directions. The ambient temperature ranges between 27-34°C at the State Square. The maximum surface temperature reduction achieved at the State Square is 25.3°C when wind speed is taken as 5m/s and 26-26.7°C when wind speed is taken as 1m/s for both wind directions. Local effects at the points where mitigation measures are applied are significantly higher.

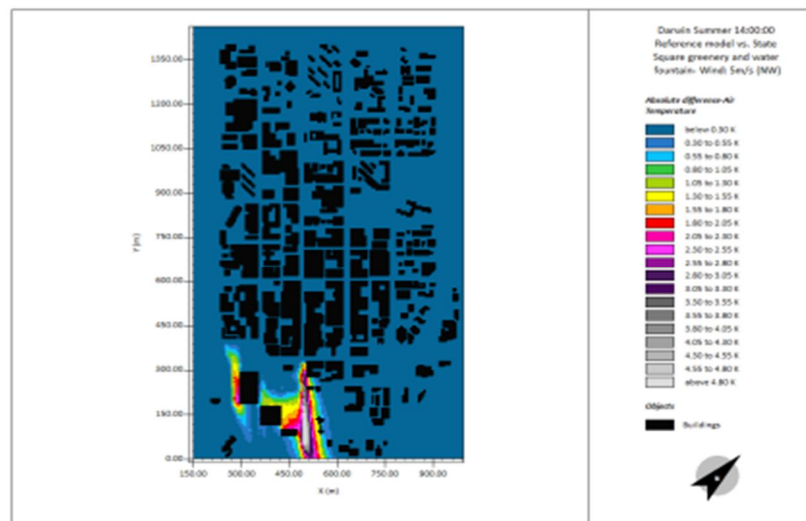


Figure 3. Distribution of the ambient temperature drop in the State Square zone of Darwin, NW wind direction, 5 m/sec.

Combined scenario: The use of reflective materials for roofs and pavements (global albedo to 0.6), the application of shading in specific zones of the city and a 30% increase of the urban greenery of open spaces, results in a maximum temperature drop in the CBD area of approximately 2.7 °C (Figure 4) and 1.9°C for the wind speed of 5m/s

and 1 m/s, respectively for NW winds with quite similar results for the SE direction. The ambient temperature ranges between 32-33.7°C (NW/ 5m/s). The surface temperature of the major asphalt parking areas shows a reduction of 10-15°C from the reference case, ranging from 33.3°C to a maximum of 37.7°C for 5m/s wind speed. The surface temperature is mainly reduced to the range of 24.5°C to 28.9°C when trees were used in the green area. Similar reduction was calculated for the 1m/s wind speed.

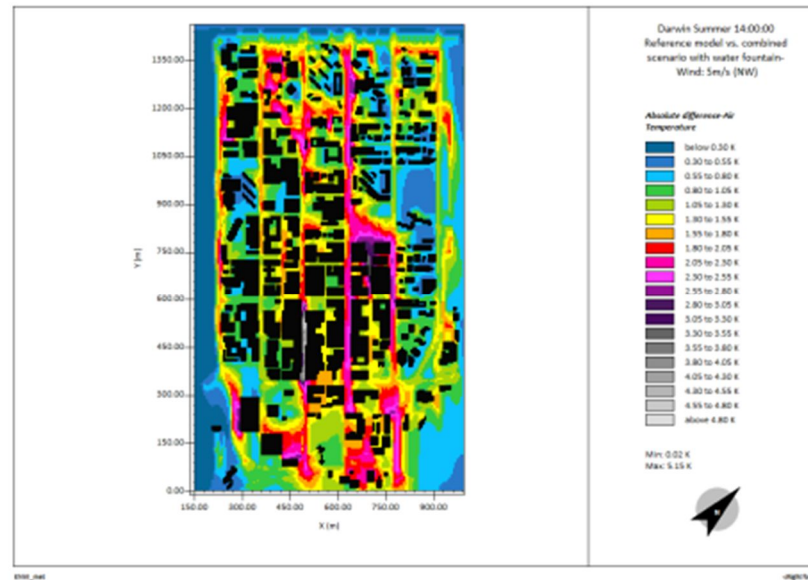


Figure 4: Simulated ambient temperature reduction distribution for the combined scenario in Darwin

Combined scenario with water: The use of reflective materials for roofs and pavements (global albedo to 0.6), the application of shading in specific zones of the city and a 30% increase of the urban greenery of open spaces, and the application of water fountain results in a maximum temperature drop in the CBD area of approximately 2.7 °C and 1.9°C for the wind speed of 5m/s and 1 m/s, respectively for NW winds with lower values for the SE direction. The local maximum temperature reduction of is 7°C for all wind speeds and directions except for the simulation with North westerly wind at the speed of 5m/s which is over 5 °C. The ambient temperature ranges between 28.8-32.7°C (NW/ 5m/s). The maximum surface temperature varies between 19.9°C and 43.6°C when the combined scenario is used in the simulations. The surface temperature reduction is in the range of approximately 10-15°C but significantly higher reductions are observed at local level where specific mitigation technologies were applied. Figure 5 presents the decrease of the maximum ambient temperature achieved by the various considered mitigation scenarios. It was found that the achieved maximum ambient temperature decrease for the whole CBD area is close to 2.8°C and corresponds to the combination scenario.

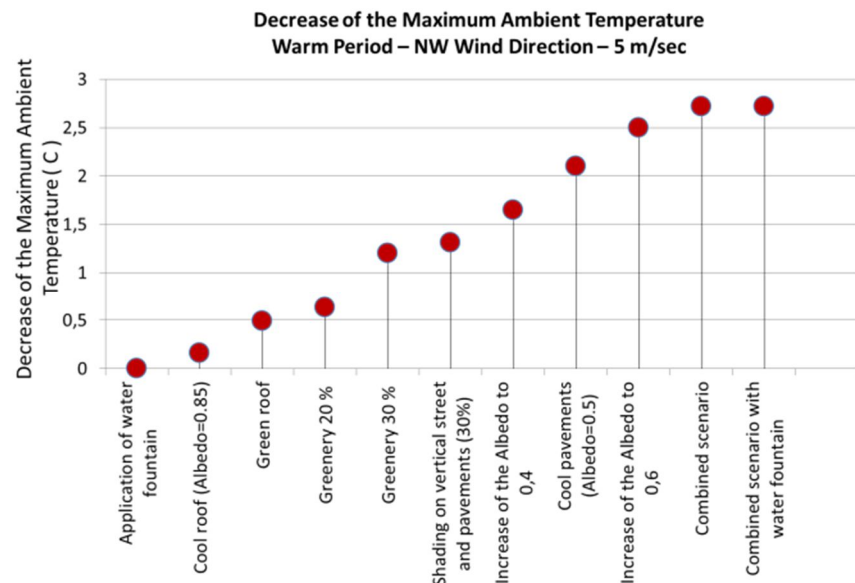


Figure 5 Decrease of the maximum ambient temperature achieved by the various considered mitigation scenarios

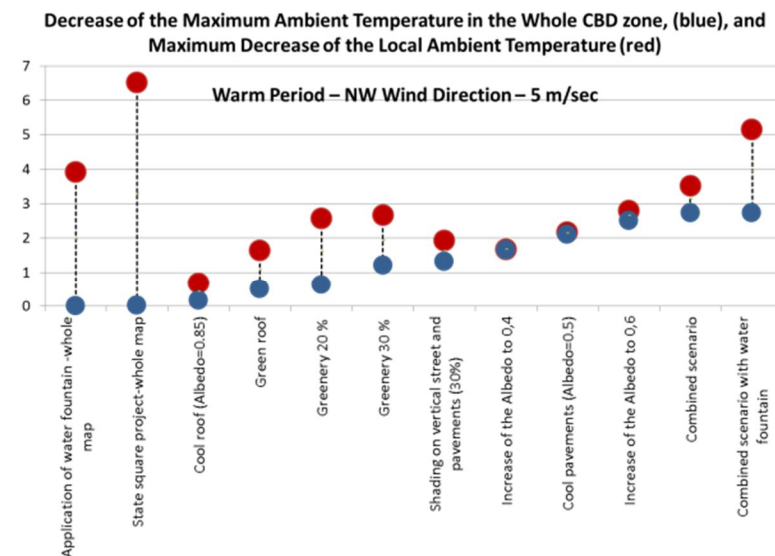


Figure 6. Decreased of the maximum temperature in the whole CBD area, (blue), and the corresponding maximum decrease of the local temperatures.

Combined scenario cold/dry season: The use of reflective materials for roofs and pavements (global albedo to 0.6), the application of shading in specific zones of the city and a 30% increase of the urban greenery of open spaces, when simulated for the cold/dry season results in a maximum temperature drop of approximately 6.1 °C and 5.5°C for the NW winds at a wind speed of 5m/s and 1 m/s. The ambient temperature ranges between 26.9-30.3°C (NW/ 5m/s). The local minimum ambient temperature difference between the combined scenarios during the cold/ dry and the warm seasons are 3.3°C and 3.5°C for the wind speed of 5m/s and 1 m/s, respectively. The maximum surface temperature varies between 39.9°C and 41.4°C when combined scenario during cold/dry season is used in the simulations. The results indicate that the proposed mitigation strategies will enhance thermal comfort conditions during the dry period.

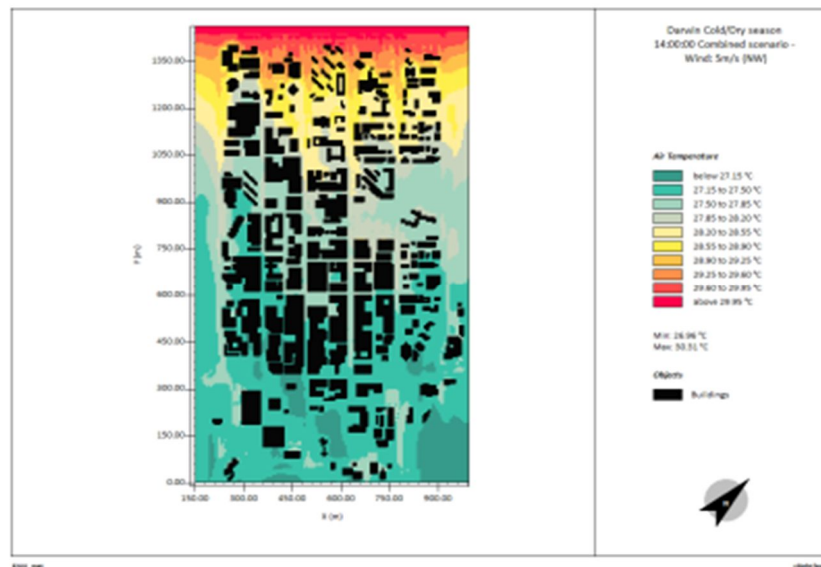


Figure 7. Air temperature distribution in the CBD area during the dry period. The graph refers to NW wind directions and 5 m/sec wind speed.

Table 2: Statistical summary of the mitigation results – NW winds

Scenarios	Maximum ambient temperature (°C)		Minimum ambient temperature (°C)		Reduction of the maximum ambient temperature (K)		Reduction of the minimum ambient temperature (K)		Maximum temperature decrease (K) [*]	
	5m/s	1m/s	5m/s	1m/s	5m/s	1m/s	5m/s	1m/s	5m/s	1m/s
Reference Model	36.44	36.08	31.96	32.84	-	-	-	-	-	-
Global Albedo=0.4	34.79	34.78	31.92	32.61	1.65	1.30	0.04	0.23	1.67	1.30
Global Albedo=0.6	33.94	34.15	31.87	32.24	2.50	1.93	0.09	0.60	2.79	2.14
Cool pavements	34.34	34.42	31.9	32.55	2.10	1.66	0.06	0.29	2.16	1.71
Shading	35.13	35.60	31.72	32.58	1.31	0.48	0.24	0.26	1.93	1.46
Greenery 20 %	35.81	36.05	31.95	32.83	0.63	0.03	0.01	0.01	2.57	1.41
Greenery 30 %	35.24	35.99	31.94	32.79	1.20	0.09	0.02	0.05	2.66	1.60
Cool roof	36.28	36.08	31.96	32.70	0.16	0.00	0.00	0.14	0.67	0.49
Green roof	35.95	35.87	31.73	32.56	0.49	0.21	0.23	0.28	1.63	1.30
Water fountain ^{***}	34.48	33.52	30.10	28.20	1.96	2.56	1.86	4.64	3.92	5.46
State square ^{***}	34.02	34.76	28.12	27.07	2.42	1.32	3.84	5.77	6.52	8.18
Combined scenario	33.72	34.22	31.85	32.13	2.72	1.86	0.11	0.71	3.52	2.43
Combined scenario+water fountain	33.72	34.21	28.87	26.53	2.72	1.87	3.09	6.31	5.15	7.15
Combined scenario cold/dry	30.31	30.55	26.96	26.82	6.13	5.53	5.00	6.02	5.24^{**}	5.79^{**}

Note:

^{*}: Maximum temperature decrease achieved based on the scenarios compared to the reference model

^{**}: Maximum temperature decrease achieved based on the combined scenario cold/dry season compared to the combined scenario in the warm season

^{***}: Maximum temperature and reduction of the maximum ambient temperature (K) is given for the local scale where mitigation strategy was employed

Table 3: Statistical summary of the mitigation results – SE winds

Scenarios	Maximum ambient temperature (°C)		Minimum ambient temperature (°C)		Reduction of the maximum ambient temperature (K)		Reduction of the minimum ambient temperature (K)		Maximum temperature decrease (K) [*]	
	5m/s	1m/s	5m/s	1m/s	5m/s	1m/s	5m/s	1m/s	5m/s	1m/s
Reference Model	36.00	35.72	32.04	32.97	-	-	-	-	-	-
Global Albedo=0.4	34.54	34.77	31.94	32.74	1.46	0.95	0.10	0.23	1.57	1.25
Global Albedo=0.6	33.86	34.4	31.89	32.25	2.14	1.32	0.15	0.72	2.63	2.06
Cool pavements	34.18	34.55	31.91	32.59	1.82	1.17	0.13	0.38	1.99	1.64
Shading	34.73	35.23	31.75	32.48	1.27	0.49	0.29	0.49	2.30	1.95
Greenery 20 %	35.79	35.71	32.03	32.95	0.21	0.01	0.01	0.02	2.35	1.42
Greenery 30 %	35.48	35.7	32.02	32.94	0.52	0.02	0.02	0.03	2.41	1.45
Cool roof	35.75	35.7	32.01	32.74	0.25	0.02	0.03	0.23	0.70	0.59
Green roof	35.47	35.47	31.79	32.58	0.53	0.25	0.25	0.39	1.99	1.64
Water fountain ^{***}	35.13	34.49	28.62	27.20	0.87	1.23	3.42	5.77	5.83	6.67
State square ^{***}	34.44	35.10	27.24	27.03	1.56	0.62	4.80	5.94	8.02	8.13
Combined scenario	33.77	34.36	31.86	32.21	2.23	1.36	0.18	0.76	3.44	2.35
Combined scenario+water fountain	33.77	34.36	27.33	26.07	2.23	1.36	4.71	6.9	7.05	7.80
Combined scenario cold/dry[†]	30.34	30.71	27.03	26.89	-	-	-	-	-	-

Note:

^{*}: Maximum temperature decrease achieved based on the scenarios compared to the reference model

[†]: Statistics for Easterly winds

^{***}: Maximum temperature and reduction of the maximum ambient temperature (K) is given for the local scale where mitigation strategy was employed

Cost evaluation of the mitigation scenarios

The cost of the proposed mitigation scenarios has been evaluated using data received from various credible market sources. The calculated cost is realistic and logical and in agreement with the international practice and knowledge. The corresponding cost of each of the scenarios is analysed and given in the brochures. The required cost of all scenarios to decrease the ambient temperature by 1°C is calculated and then correlated against the maximum ambient temperature drop in the CBD area, and the corresponding total cost. The results are shown in Figure 8. The blue zone corresponds to the technologies, presenting a low specific cost per degree of temperature drop, while the red zone represents all technologies having a high relative cost. As shown, all considered mitigation technologies, except of the green roofs, are suitable for implementation in the Darwin CBD area.

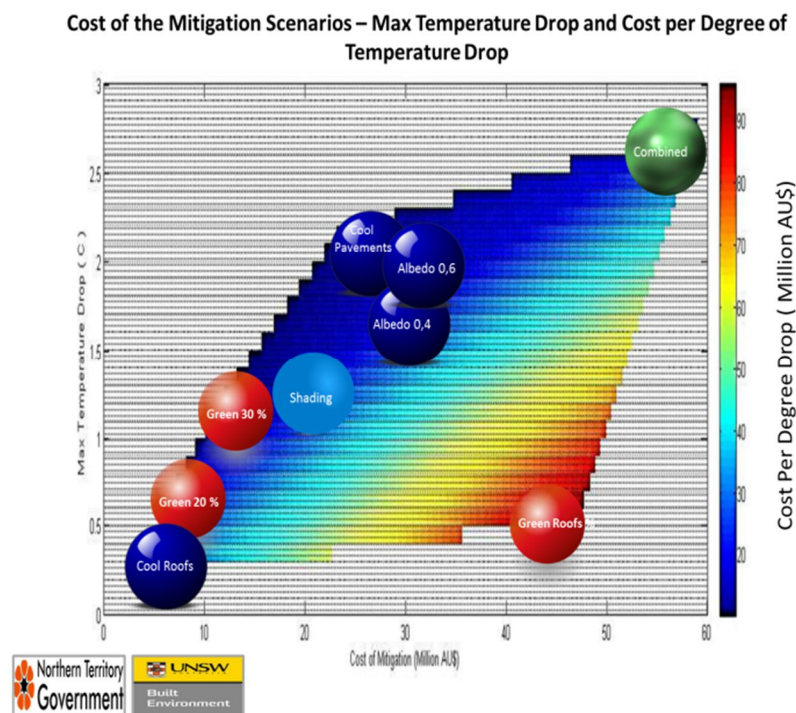


Figure 8. Classification of the cost per degree of temperature drop for each of the considered mitigation technology.

Conclusions

Darwin suffers from high ambient temperatures and low outdoor thermal comfort conditions. Ambient temperatures may exceed 37°C, while humidity easily exceeds 80 %. In parallel, because of the positive thermal balance, the CBD area presents about 2 – 3 °C, higher temperature than the airport area. This is mainly due to the high surface temperatures of the urban fabric (values exceeding 60°C have been recorded) that release heat in the ambient air, reduced wind speeds and the lack of the cooling effect of the sea breeze, and the increased anthropogenic heat.

Fourteen mitigation scenarios involving UHI mitigation strategies such as cool roofs and pavements, street shading, green roofs, greenery and evaporative systems have been designed aiming to decrease the ambient temperature in the Darwin area. Advanced simulation

techniques have been used to quantitatively evaluate their UHI mitigation impact. The results have shown that the proposed mitigation technologies can decrease the maximum ambient temperature from 36.5 °C to 33.7°C. In parallel, the minimum ambient temperature in the area can decrease from 31.2 °C to 28.9°C. The achieved decrease of the maximum ambient temperature is close to 2.8°C, while the corresponding decrease of the minimum temperature is close to 3.1° C compared to the reference scenario representing the actual situation. The maximum temperature drop is achieved through the combination of the various mitigation technologies, while the minimum performance corresponds to the use of only cool roofs. Some of the considered mitigation scenarios (mainly evaporative systems and greenery), which are implemented in specific zones and not in the whole CBD area, were shown to have a significant local maximum temperature reduction, although their mitigation impact for the whole CBD area is very low or even zero.

The potential of the considered scenarios to decrease the ambient temperature varies considerably as a function of the synoptic weather conditions and in particular of the wind direction and wind speed. Increase of the wind speed has a positive impact on the mitigation potential of all scenarios related to reflective surfaces (increase of the albedo, cool roofs and cool pavements), shading and greenery mitigation. On the contrary, higher wind speeds decrease the mitigation potential of the evaporative water based systems. Regarding the impact of wind direction, it was found that the mitigation potential of the greenery scenarios is reduced to about 40-50 % under SE wind compared to NW synoptic conditions and the same applies for the evaporative technologies. The rest of the technologies are not significantly affected

The results of the simulation for the combined scenario during the cold /dry season validate the assumption that the proposed mitigation techniques will enhance thermal comfort conditions during the dry period and will improve the local climatic conditions.

The considered mitigation technologies contribute to decrease considerably the surface temperature in the CBD area. The maximum surface temperature reduction found to vary between 1°C to 15° C. The lower surface temperature reduction corresponds to mitigation technologies applied in roofs, cool or green roofs, 1-2°C, while the maximum drop is achieved when shading, greenery and cool pavement technologies, are implemented. It should be pointed out that the local reduction of the surface temperature caused by these technologies may exceed 20-25°C. Lower surface temperatures correspond to improved thermal comfort levels as the emitted infrared radiation and the convected heat from the opaque surfaces is significantly reduced.

Finally, the cost analysis of the various mitigation scenarios examined based on process obtained by Australian market actors, indicate that all considered mitigation technologies, except of the green roofs, are suitable for implementation in the Darwin CBD area.