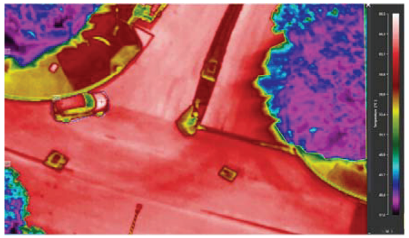
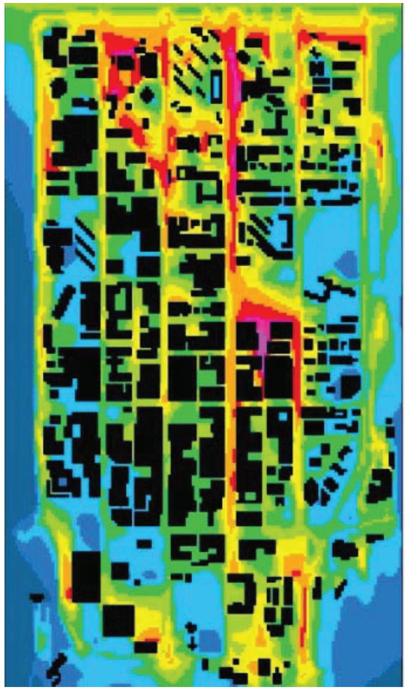
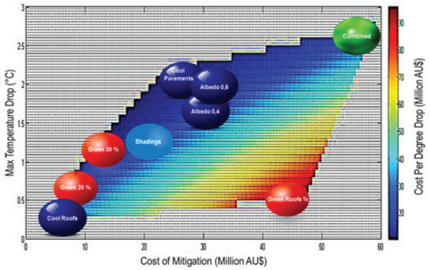




Heat Mitigation Program

Darwin, NT



Final Report

UNSW

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Heat Mitigation Program
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Contents and Acknowledgements

This document presents the mitigation study for the CBD area of Darwin, performed by the High Performance Architecture Group of UNSW, Faculty of Built Environment.

The first part of the report includes the methods and the results of the terrestrial and aerial monitoring campaign, the evaluation of the magnitude of the Urban Heat Island (UHI) and finally the main conclusions on the climatic context characterized with the monitoring.

The second part presents initially an introduction to the various available mitigation technologies, and then the methodology and the results of the considered mitigation scenarios. In total, thirteen mitigation scenarios have been developed and evaluated in details. In parallel, the existing thermal environment has been fully evaluated for comparison reasons. Advanced simulation techniques have been used and the distribution of the ambient temperature, surface temperature and wind speed have been fully calculated. The air temperature has been normalized to standard pressure conditions (referred to as potential temperature), so as to allow comparisons between the conditions at different elevations and in different scenarios. The spatial distribution of the potential temperature decrease has been calculated for each scenario. A gross estimation of the cost associated with each scenario, is provided.

The last part of the document includes the proposed specifications for each of the mitigation scenarios, as well as the conclusions of the study.

We thankfully acknowledge the Northern Territory Government for funding this research activity and the technical and logistic support offered during the monitoring campaign. We are particularly grateful to the Chief Minister Michael Gunner and Government Architect Professor Lawrence Nield for supporting the overall project. We would like to express our thankfulness to the Manager of Weather Services Todd Smith and Climatologist Greg Browning, of the Northern Territory Bureau of Meteorology, for helping with the planning of the monitoring campaign and for releasing Darwin Airport station weather data. We are also grateful to Aaron Emmett (National Drones) and to the Akron Group NT - Traffic Control Services for conducting and managing the aerial survey.

EXECUTIVE SUMMARY

Heat Mitigation Program
Darwin, Northern Territory

Built Environment

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Executive Summary

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 soar 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.

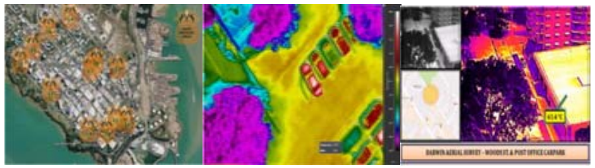

Figure 1: Locations of the aerial survey (A), thermal image of a high surface temperature parking lot (b), screen shot of a thermal video presenting high roof surface temperature

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 (unobstracted 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.

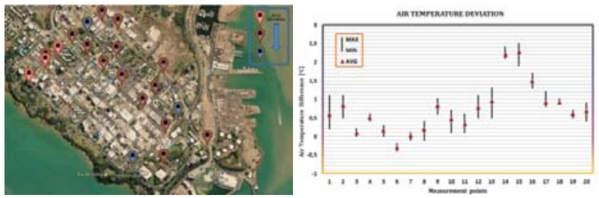

Figure 2: Locations of the terrestrial survey (A) –average air temperature difference spatial distribution is also shown on the map. Air temperature differences between the measurement locations and the reference stations (B).

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.

UHI 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 pavements Albedo=0.2, Loamy soil Albedo=0.15, 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 open space
3	Global albedo 0.6	Global Albedo=0.6. Greenery < 10 % of the total pavements and open space
4	Cool pavement	Albedo of streets and pavements=0.5, Greenery < 10 % of the total pavements and open space
5	Shading	Albedo of streets (Asphalt)=0.34, Albedo of concrete pavement=0.44, Greenery < 10 % of the total pavements and open 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 open space
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 cool pavements (albedo of 0.5) on Smith street, Chan 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 across the mall
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.

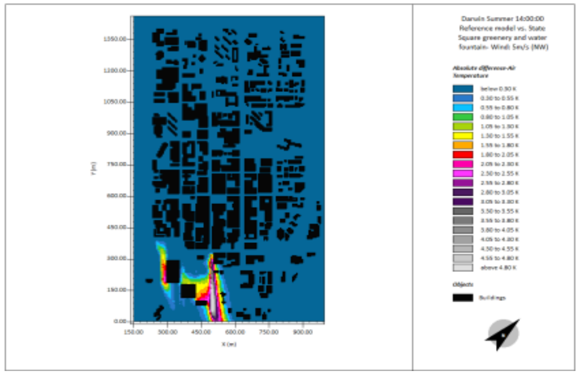

Figure 3.Distribution of the ambient temperature drop in the State Square zone of Darwin, NW wind direction, 5 m/sec.

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.

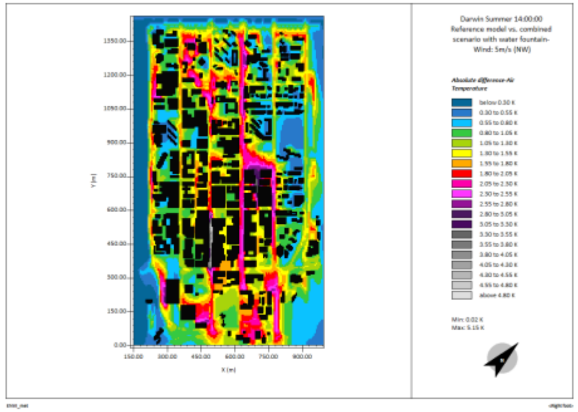

Figure 4: Simulated ambient temperature reduction distribution for the combined scenario in Darwin

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.

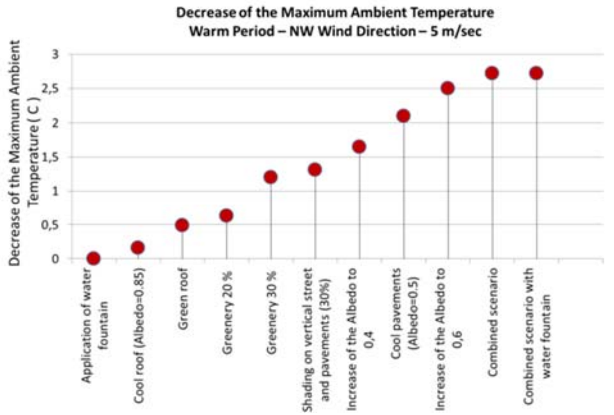

Figure 5 Decrease of the maximum ambient temperature achieved by the various considered mitigation scenarios

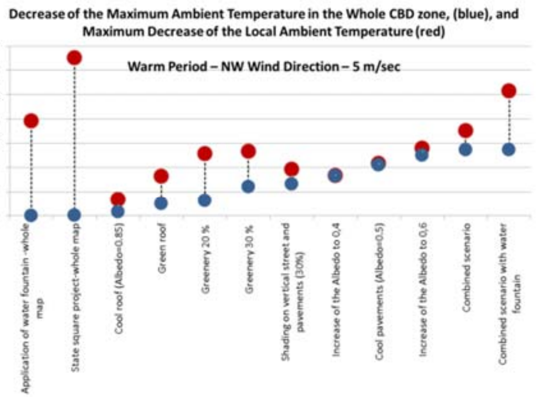

Figure 6.Decreased of the maximum temperature in the whole CBD area, (blue), and the corresponding maximum decrease of the local temperatures.

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.

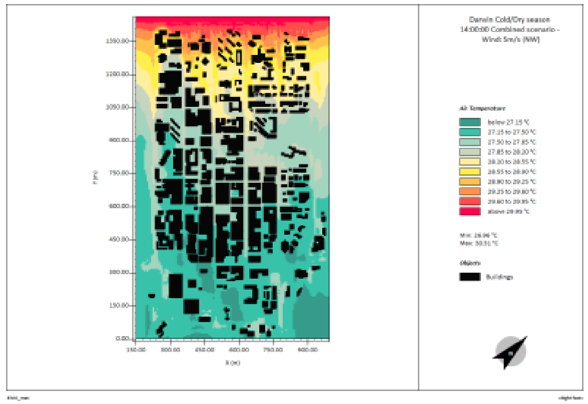

Figure 7.Air temperature distribution in the CBD area during the dry period. The graph refers to NW wind directions and 5 m/sec wind speed.

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.

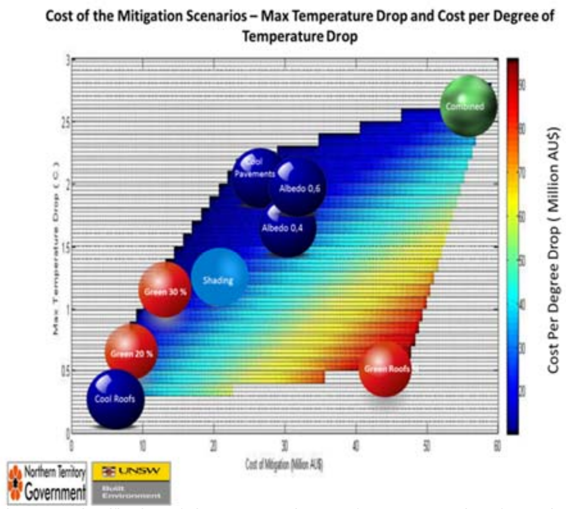

Figure 8. Classification of the cost per degree of temperature drop for each of the considered mitigation technology.

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.

DARWIN CBD MONITORING CAMPAIGN

23rd-25th March 2017

REPORT

Heat Mitigation Program Darwin, Northern Territory

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Introduction

The Urban Heat Island (UHI) is a very well documented climatic phenomenon. It refers to the occurrence of higher ambient temperature in cities compared to the rural or suburban adjacent areas. Higher urban temperatures are the result of the positive thermal balance of cities caused mainly by the increased absorption of solar radiation and heat storage, high anthropogenic heat and reduced heat losses. Higher urban temperatures have a serious impact on city life and in particular on energy consumption for cooling, outdoor comfort, health and the local economy. Higher urban temperatures are due to the positive thermal balance of urban areas caused by the important release of anthropogenic heat, the excess storage of solar radiation by the city structures, the lack of green spaces and cool sinks, the non-circulation of air in urban canyons and the reduced ability of the emitted infrared radiation to escape in the atmosphere.

To fully access the heat island amplitude and characteristics of the urban heat island in the CBD area of Darwin, specific experiments have been carried out in the whole central area of the city. In parallel, a drone using an infrared camera was used to measure the surface temperature in the area.

The report presents and discusses the main experiments performed and the main results and conclusions.

Preliminaries

A three-day ground and aerial survey was conducted in order to get real time thermal and meteorological data useful to recreate the contingent Urban Heat Island amplitude and characteristics. The main goals were:

* collecting metereological data all along the hot spots of Darwin CBD;

* capturing aerial thermographic shots of the pavements, streets, buildings facades and roof surfaces by utilizing a Remotely Piloted Aircraft.

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.

AERIAL SURVEY – PILOT AARON EMMETT (NT NATIONAL DRONES)

TERRESTRIAL SURVEY – UNSW BUILT ENVIRONMENT FACULTY PHD STUDENTS (ULPIANI GIULIA, JONATHAN FOX)

Plan

According to the initial assessment performed, a roadmap of the crucial points to be investigated was conceived in order to proceed following a structured battle plan based on priority targets, which are summarized as follows:

1) MAIN VERTICAL STREETS:
· Cavenagh St. – length 1.5 m - from Daly St. to Bennett St.
· Woods St. - from Daly St. to Bennett St.
· Michelle St. (mainly Daly st.side)
· Smith St. (mainly Daly st. side)
· Esplanade (mainly Daly st.side)
2) PARKING LOTS:
· P1 (Cavenagh St. parking lot next to Australian Post Office)
· P2 (all the area parking lots between Michelle St. and Cavenagh St., 260mX133m area in front of the petroleum stations)
· P3.1 (130mx240m area between Woods and McMinn St.s, Daly St. as superior boundary)
· P3.2 (parking lot along McMinn St. in front of McLachlan St.)
· P3.3 (parking lot along McMinn St. in front of Manton St.)
· P4 (parking lots in front of Supreme Court of the NT, Darwin City Library and NT Local Court)
3) MAIN HORIZONTAL STREETS:
· Daly St. (length 800m)
· McLachlan St.
· Lindsey St.
· Knuckey St.
· Bennett St.

PRIORITIES IN DATA COLLECTION:

* surface temperatures and meteo data along the streets
* surface temperatures of the pavements
* surface temperatures and meteo data of parking lots (and asphaltic areas)
* surface temperatures of the roofs (where compatible with the risk assessment and mitigation strategy)

Against the above battle plan, UNSW and National Drones managed the monitoring campaign respecting priorities and weather favourable conditions.

Aerial Survey – Instruments & Methods

The main interest behind the conduction of the aerial survey is to detect the surface temperatures of the different urban materials composing Darwin's CBD landscape.

In order to perform the measurements, an Unmanned Aerial Vehicle (UAV=drone) equipped with a thermal camera was employed: a DJI INSPIRE 1 fitted with a DJI FLIR Zenmuse XT Thermal Camera.

Technical specs are displayed in the following tables (table 1 and table 2):

DRONE - DJI INSPIRE 1	
GENERAL SPECS	
Model	T600
Weight	6.27 lbs (2845 g, including propellers and battery, without gimbal and camera) 6.76 lbs (3090 g, including propellers, battery and Zenmuse XT)
GPS Hovering Accuracy	Vertical: ±1.64 feet (0.5 m) Horizontal: ±8.20 feet (2.5 m)
Max Angular Velocity	Pitch: 300°/s Yaw: 150°/s
Max Tilt Angle	35°
Max Ascent Speed	16.4 ft/s (5 m/s)
Max Descent Speed	13.1 ft/s (4 m/s)
Max Speed	49 mph or 79 kph (ATTI mode, no wind)
Max Wind Speed Resistance	10 m/s
Max Flight Time	Approx. 18 min
Motor Model	DJI 3510H
Propeller Model	DJI 1345T
Max Takeoff Weight	7.71 lbs(3500 g)
BATTERY TECHNICAL DETAILS	
Name	Intelligent Flight Battery
Model	TB47
Capacity	4500 mAh
Voltage	22.2 V
Battery Type	LiPo 6S
Energy	99.9 Wh
Net Weight	570 g

TABLE 1. DJI INSPIRE 1 UAV SPECIFICATIONS

THERMAL CAMERA - ZENMUSE XT	
GENERAL SPECS	
Dimensions	103 mm x 74 mm x 102 mm
Weight	270 g
Thermal Imager	Uncooled VOx Microbolometer
FPA/Digital Video	640 × 512
Display Formats	336 × 256
Analog Video Display Formats	720 × 480 (NTSC); 720 × 576 (PAL)
Pixel Pitch	17 μm
Spectral Band	7.5 - 13.5 μm
Full Frame Rates	640 × 512 : 30 Hz (NTSC) 25 Hz (PAL) 336 × 256 : 30 Hz (NTSC) 25 Hz (PAL)
Exportable Frame Rates	7.5 Hz NTSC; 8.3 Hz PAL
Sensi ivity (NEdT)	<50 mK at f/1.0
Scene Range (High Gain)	640 × 512 : -13° to 275°F (-25° to 135°C) 336 × 256 : -13° to 212°F (-25° to 100°C)
Scene Range (Low Gain)	-40° to 1022°F (-40° to 550°C)
Spot Meter	Temperatures measured in central 4×4
File Storage	Mic o SD Card
Photo Format	JPEG, TIFF
Video Format	MP4

ENVIRONMENTAL SPECS	
Operating Temperature Range	14° to 104°F (-10° to 40°C)
Non-Operating Temperature Range	-22° to 158°F (-30° to 70°C)
Temperature Shock	5°C/min
Humidity	5% to 95%
GIMBAL TECHNICAL DETAILS	
Angular Vibration Range	±0.03
Mount	Detachable
Controllable Range	Tilt：+35° to -90°; Pan：±320°; Roll：±15°
Mechanical Range	Tilt：+45° to -135° Pan：±320° Roll：±45°
Max Controllable Speed	120°/s
IMAGE PROCESSING & DYSPLAY CONTROLS	
NTSC/PAL (field switchable)	yes
Image Optimization	yes
Digital Detail Enhancement	yes
Polarity Control (black hot/white hot)	yes
Color & Monochrome Palettes (LUTs)	yes
Digital Zoom	*640 × 512：2x, 4x, 8x* *336 × 256：2x, 4x*

TABLE 2. ZENMUSE XT THERMAL CAMERA SPECIFICATIONS

Aerial Survey – Measurement Campaign

In order to run the aerial survey in the safest possible conditions several and redundant precautions were taken to mitigate the risk.

First of all we requested an acknowledged drone operator to conduct UAV flights. Therefore, that delicate task was assigned to the pilot Aaron Emmett, National Drones Franchisee/Director in the Northern Territory, boasting a standard area approval to operate within 3nm of Darwin International Airport.

We addressed the main issues in regards to meeting CASA's populous area and hazardous operation rules (min 30m distance from peoples not involved with the operation, CAST 101.055 prohibitions), through traffic management, temporary closing of footpaths with spotters and conducting works around times of low vehicular and pedestrian traffic etc.

Indeed, the drone operations took place straight over uninhabited bordering areas and mainly hovering over parking lots, secured ex ante. Oblique views of the main streets were captured as well in order to help recreating the thermographic scene in between take–off points.

The areas patrolled via UAV are summarized and codified in figure 1.

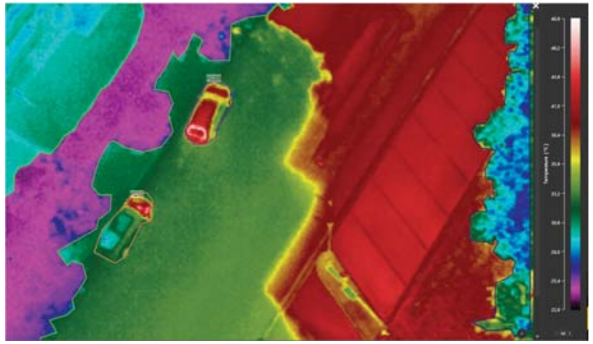
FIGURE 1. DARWIN AERIAL MONITORING CAMPAIGN – STRATEGIC MAP

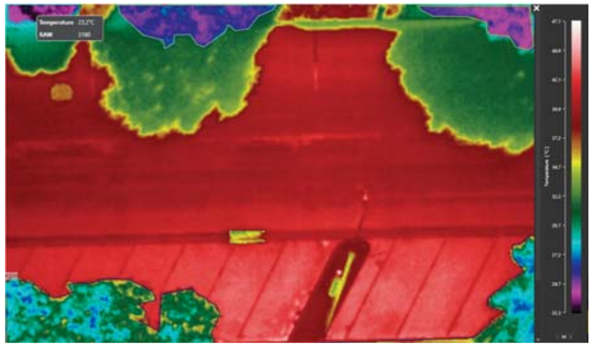
Aerial Survey – Thermal shots

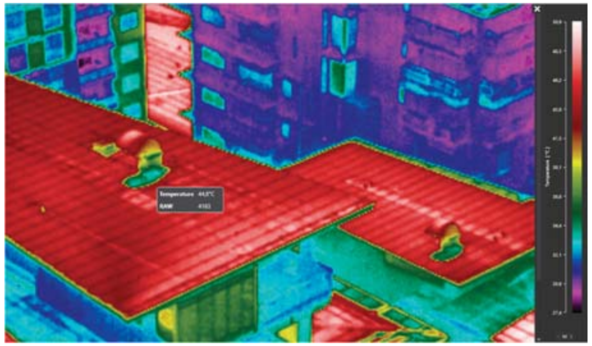
The thermocamera measurement via Unmanned Aerial Vehicle (drone) took place on the 23rd of March (all the day long) and during the morning of the 24th of March.The radiometric images captured by the DJI FLIR Zenmuse XT were corrected to compensate the deviation from the ideal behaviour of "black bodies" according to the most accredited emissivity values defined in various previous studies [see Low Carbon Cities – transforming urban systems, S. Lehmann, 2015].

The following tables (tables 3-14) display the main results:

ESPLANADE - DALY STREET CROSSING							
AREA CODE	1.1	**DAY**	23rd March	**TIME SLOT**	11:00 – 11:20		







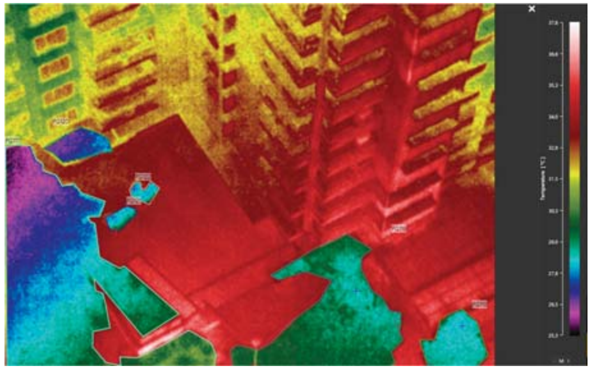
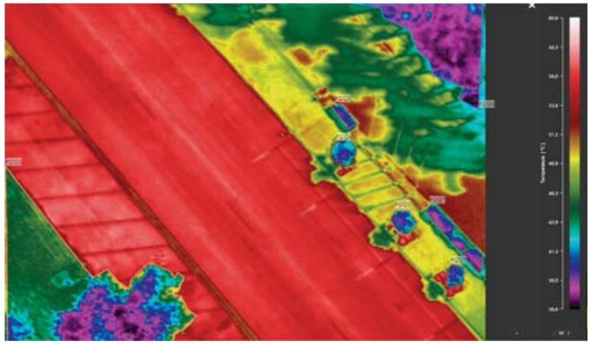
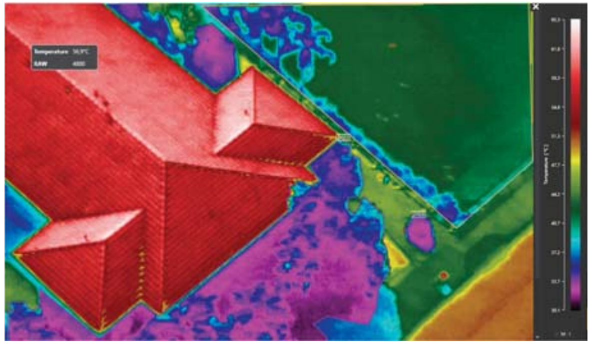


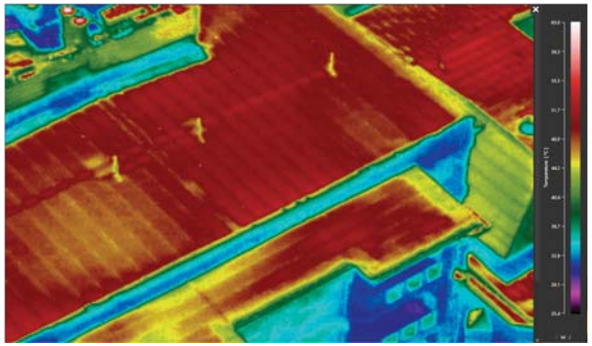
TABLE 3. ESPLANADE –DALY STREET CROSSING THERMAL IMAGES

ESPLANADE - PEEL STREET CROSSING

AREA CODE	1.2	DAY	23rd March	TIME SLOT	11:26 – 11:40







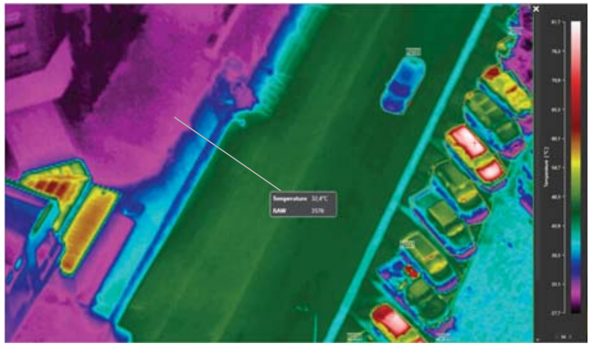
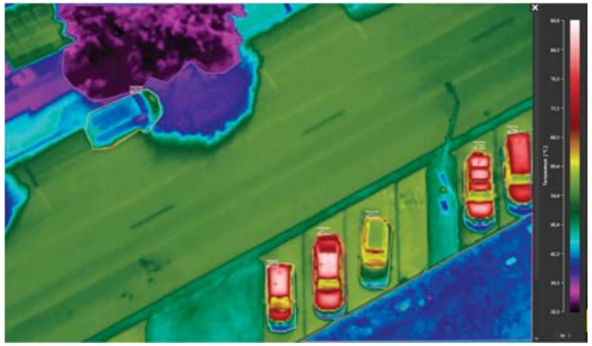
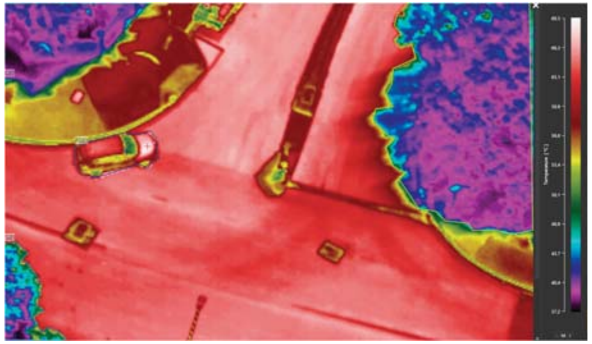


TABLE 4. ESPLANADE –PEEL STREET CROSSING THERMAL IMAGES

ESPLANADE – BENNETT STREET CROSSING

AREA CODE	1.3	DAY	23rd March	TIME SLOT	11:58 – 12:19





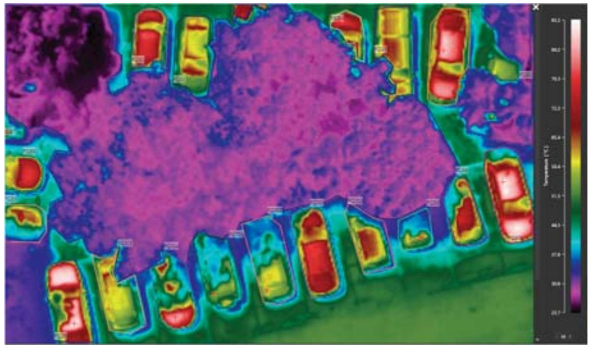
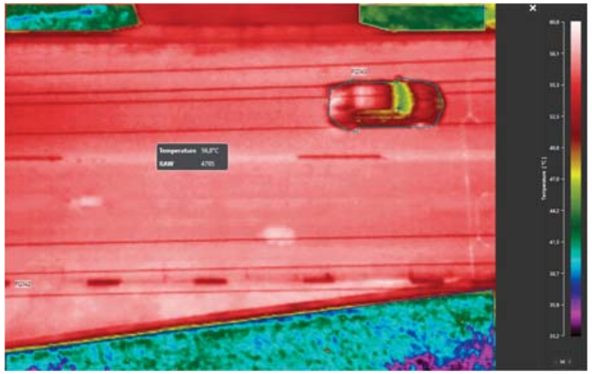
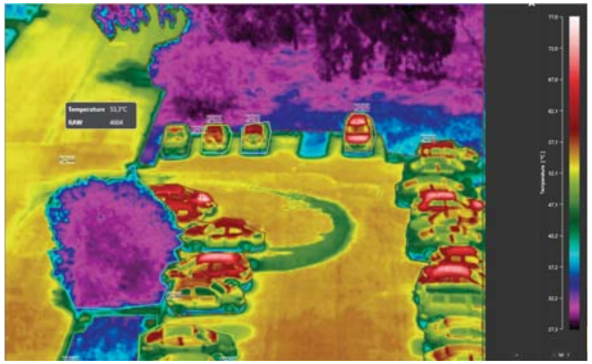


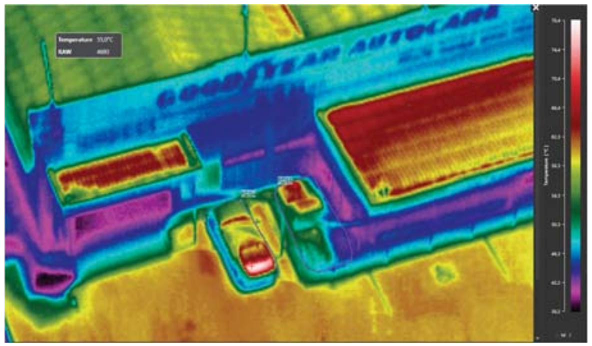
TABLE 5. ESPLANADE –BENNETT STREET CROSSING THERMAL IMAGES

MCMINN STREET - DALY STREET CROSSING

AREA CODE	1.4	DAY	23rd March	TIME SLOT	13:49 – 14:03







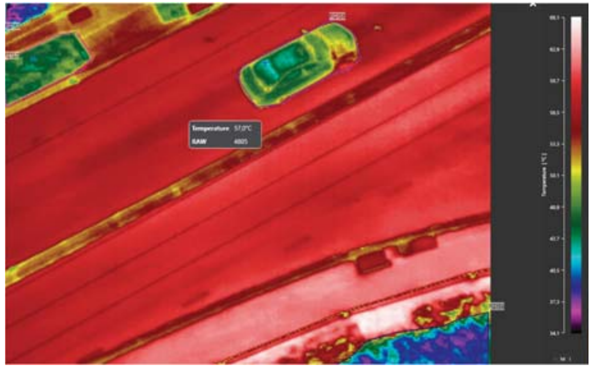
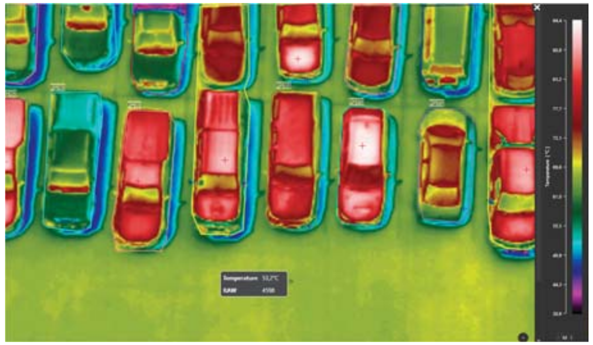
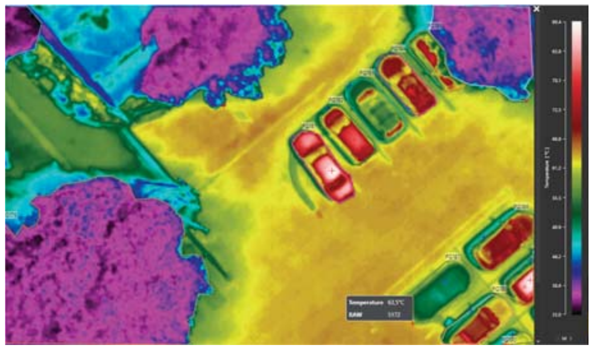


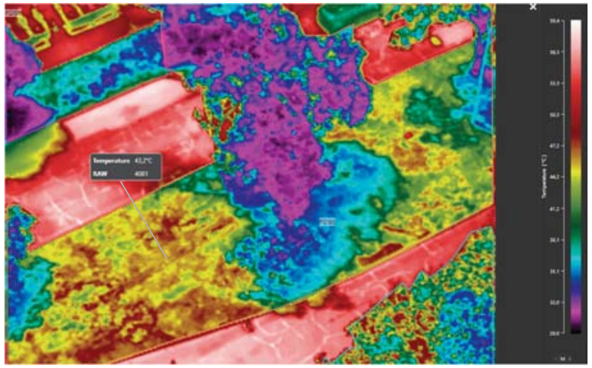
TABLE 6. MCMINN STREET – DALY STREET CROSSING THERMAL IMAGES

UNITED PETROLEUM DARWIN CARPARK

AREA CODE	1.5	DAY	23rd March	TIME SLOT	14:22 – 14:28







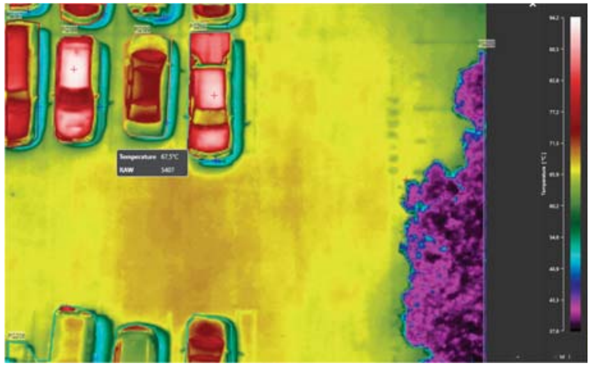
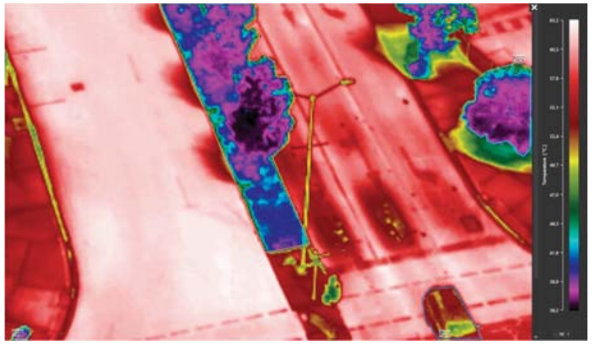
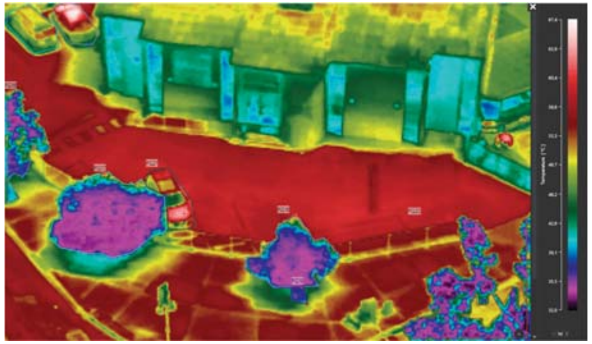
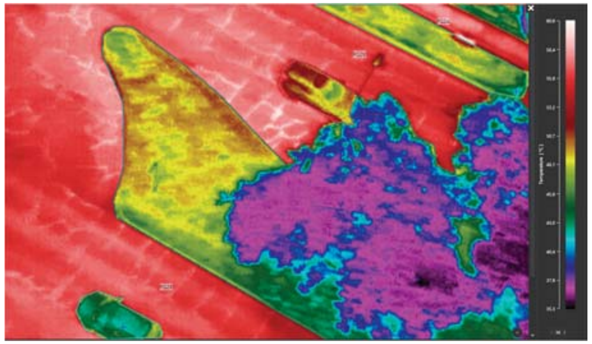


TABLE 7. UNITED PETROLEUM DARWIN CARPARK THERMAL IMAGES

CAVENAGH STREET - DALY STREET CROSSING					
AREA CODE	1.6	DAY	23rd March	TIME SLOT	14:50 – 15:02







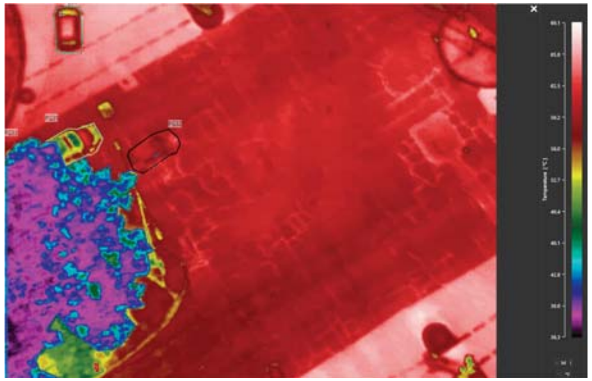
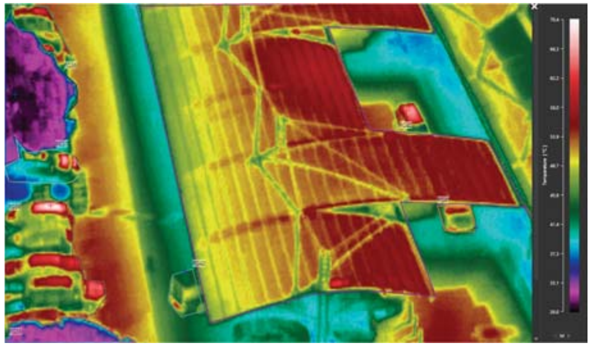
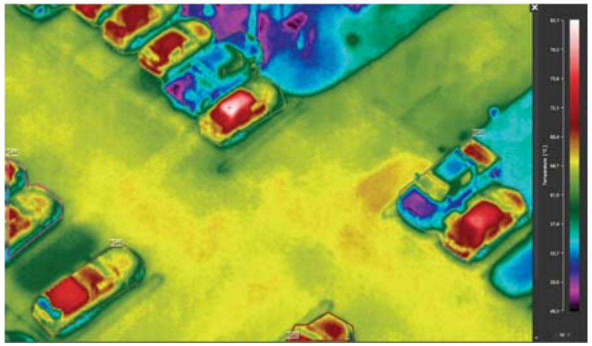
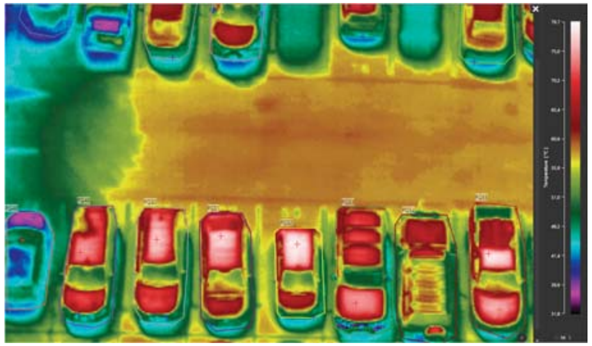


TABLE 8. CAVENAGH STREET – DALY STREET CROSSING THERMAL IMAGES

DARWIN GPO POSTSHOP CARPARK					
AREA CODE	1.7	DAY	23rd March	TIME SLOT	15:27 – 15:31







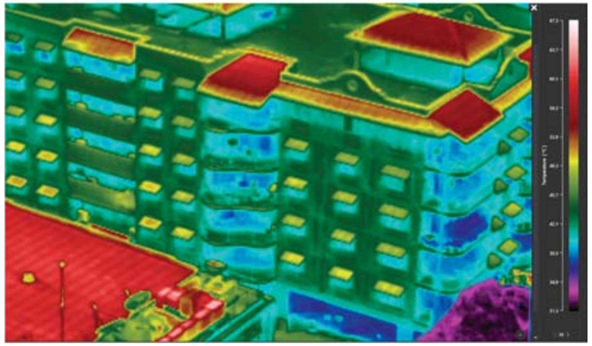
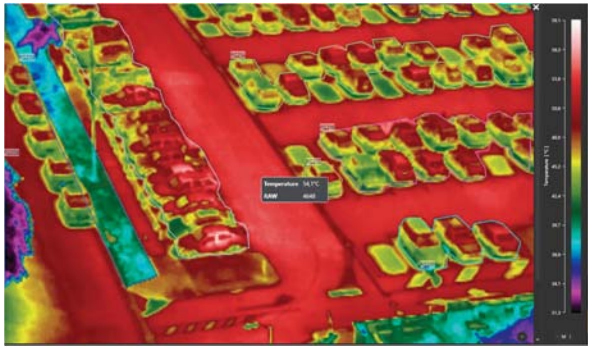
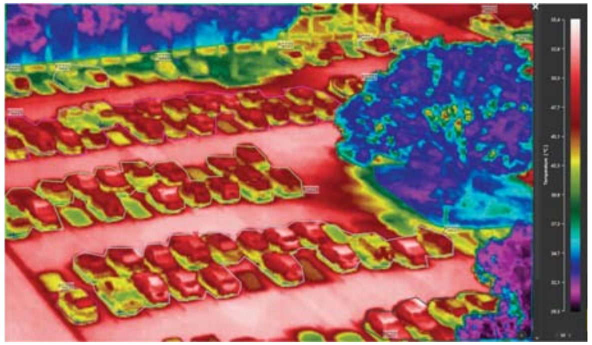
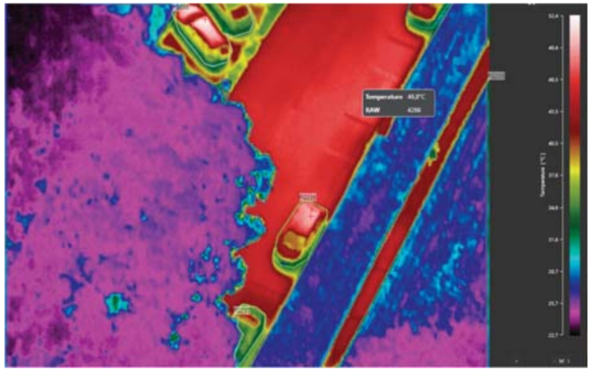


TABLE 9. DARWIN GPO POSTSHOP CARPARK THERMAL IMAGES

WOODS STREET – SAINT FRED HOLLOW					
AREA CODE	1.8	DAY	23rd March	TIME SLOT	16:03 – 16:09







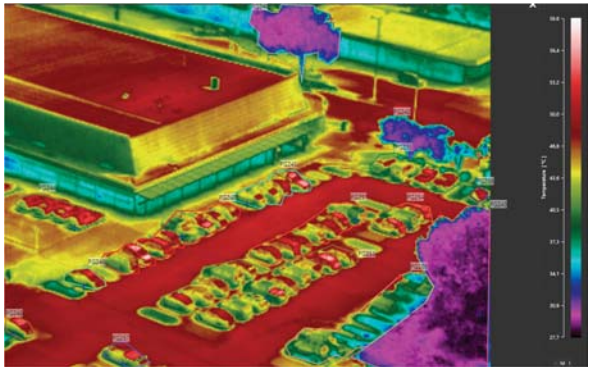
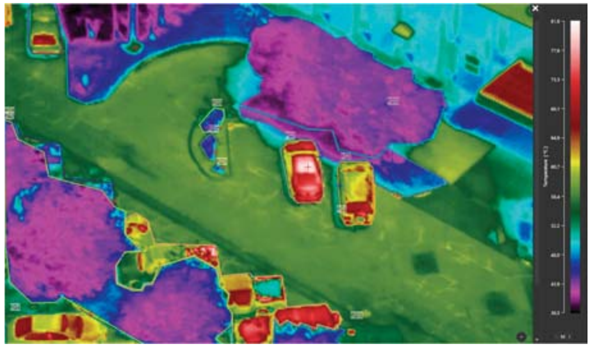
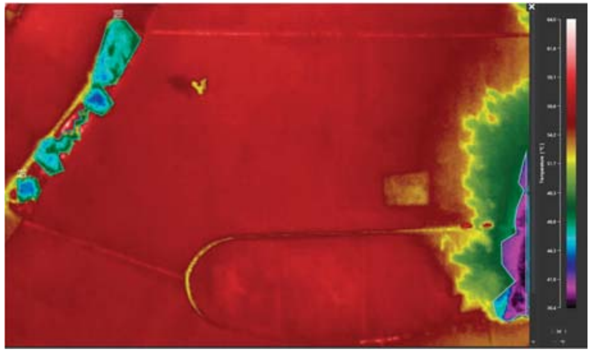
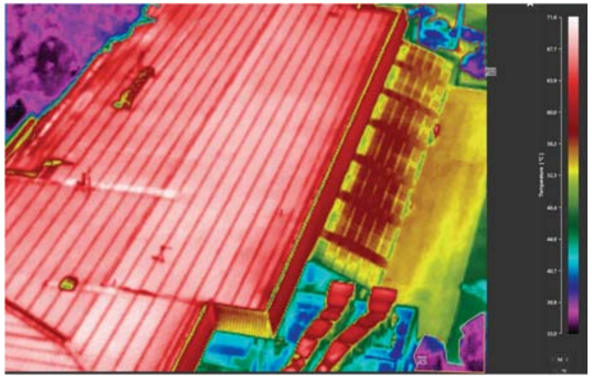


TABLE 10. WOODS STREET – SAINT FRED HOLLOW THERMAL IMAGES

DARWIN CITY COUNCIL					
AREA CODE	2.1	DAY	24th March	TIME SLOT	10:41 – 10:44







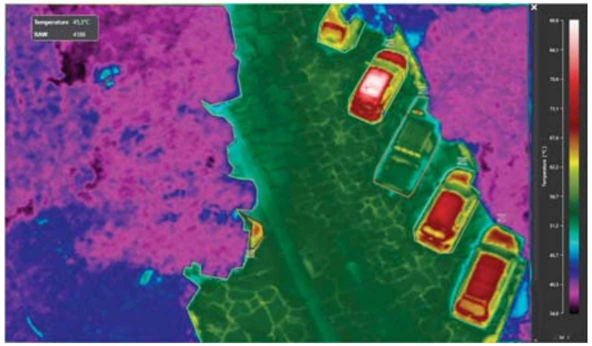
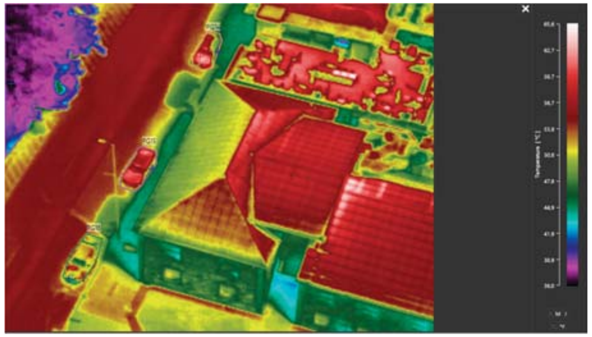
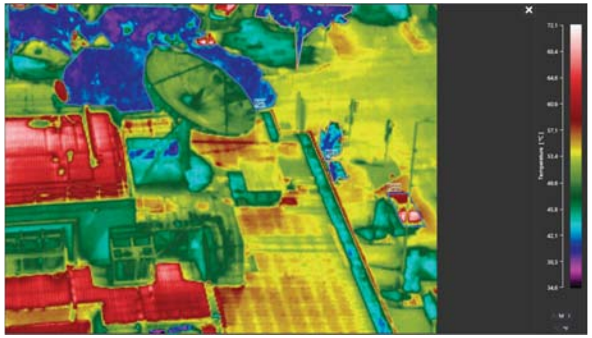
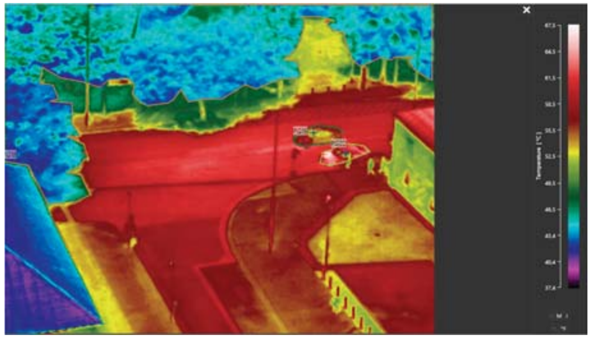


TABLE 11. DARWIN CITY COUNCIL THERMAL IMAGES

BUS INTERCHANGE – PARLIAMENT HOUSE					
AREA CODE	2.2	DAY	24th March	TIME SLOT	11:00 – 11:06







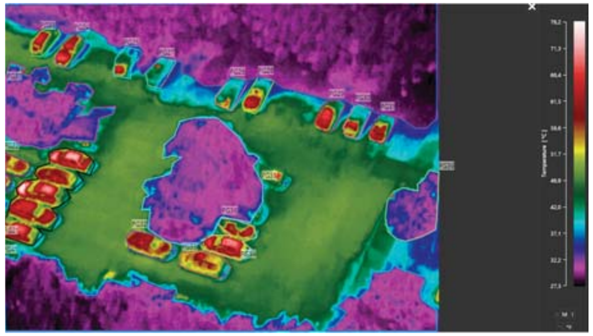
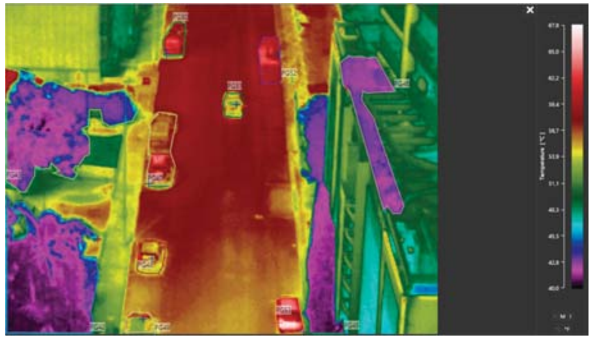
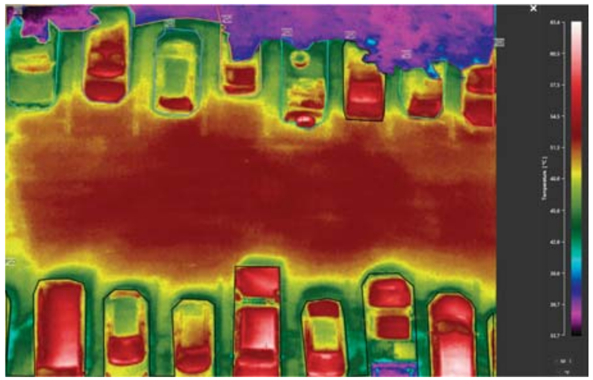
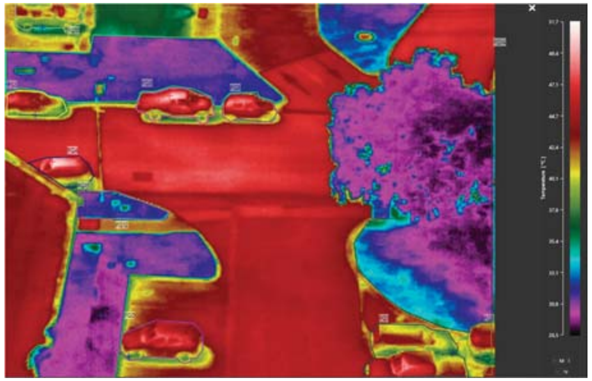


TABLE 12. BUS INTERCHANGE – PARLIAMENT HOUSE THERMAL IMAGES

CNR MCMINN STREET – KNUCKEY STREET					
AREA CODE	2.3	DAY	24th March	TIME SLOT	11:29 – 11:33







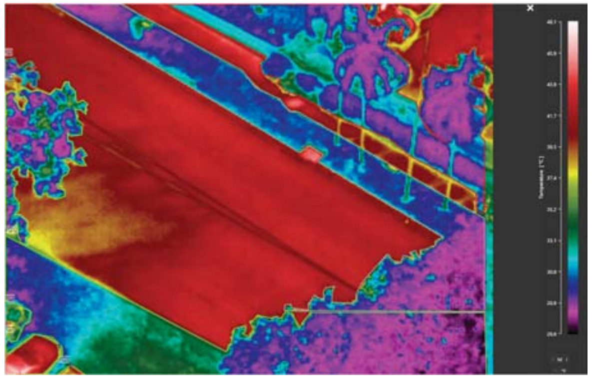
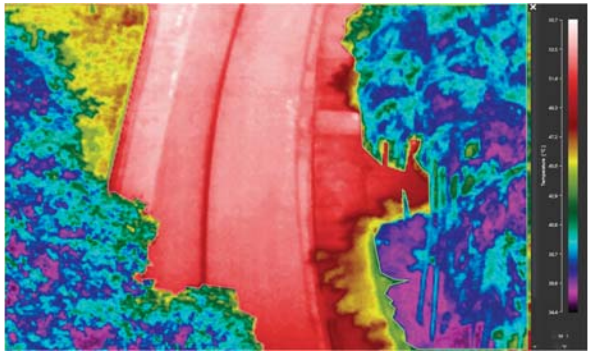
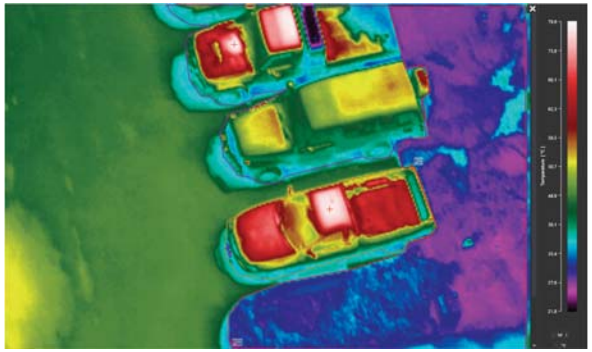
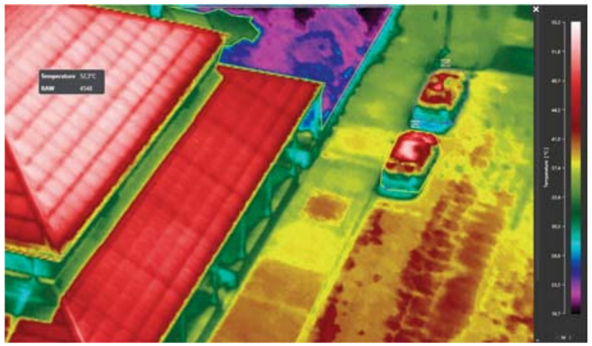


TABLE 13. CNR MCMINN STREET – KNUCKEY STREET THERMAL IMAGES

DARWIN SUPREME COURT					
AREA CODE	2.4	DAY	24th March	TIME SLOT	11:50 – 11:57







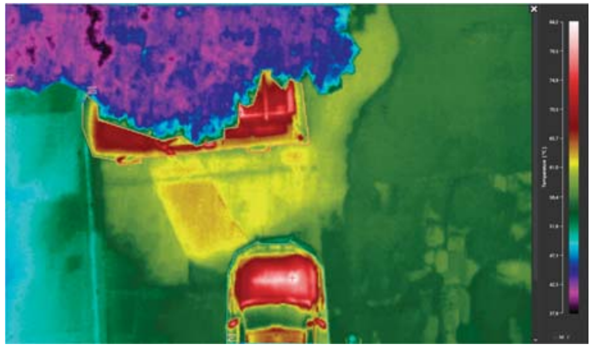


TABLE 14. DARWIN SUPREME COURT THERMAL IMAGES

Aerial Survey – Thermal Videos

As an integral part of the aerial survey, thermal videos were recorded over almost all the same areas mapped through thermal shots in order to provide a powerful and immediate means of summarizing information.
The raw videos returned by the Zenmuse XT camera have been post-processed and detailed as follows:

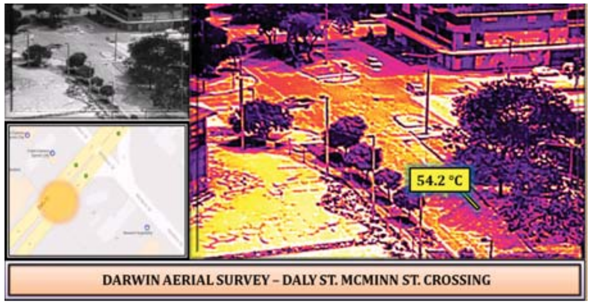
- each videos has been cut into 100 frames and reassembled in both thermo-chromatic scale and radiometric greyscale in order to manipulate the time intervals between the shots and make it easier to locate and analyse each point of interest;
- specific temperature indications have been added in synch with the videos in order to flash out reference values of the surface temperature of the city landscape components playing a major role in the UHI phenomenon. The values are obtained by comparing the videos with the correspondent emissivity-adjusted thermal shots;
- Darwin terrain maps have been additionally provided alongside the video and supplemented by a moving viewer pane to retrace the drone's path and to ease the association between the series of time-lapse images and the target objects.

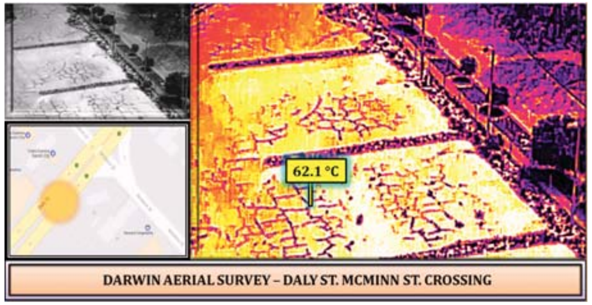
By overlapping all these pieces of information it is possible to get the feeling of the overall situation at a glance. Therefore such re-shaped thermal videos are effective tools for kickstarting the mitigation strategy design process.

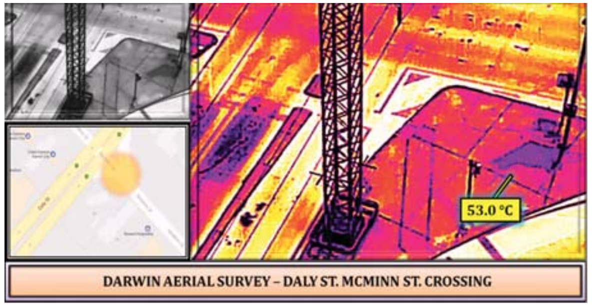
Figure 2 shows a graphical overview of the roadmap, while the following tables (table 15 to table 24) collect the information about covered area, date and original duration of the footage plus some screenshots to recreate the path and get reference temperature values.

FIGURE 2. DARWIN AERIAL MONITORING CAMPAIGN – THERMAL VIDEOS REFERENTIAL AREAS

DALY STREET – MCMINN STREET CROSSING					
AREA CODE	1.1	**DAY**	23rd March	**DURATION**	3mins 17secs







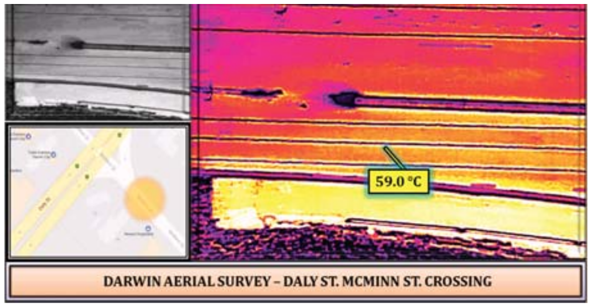
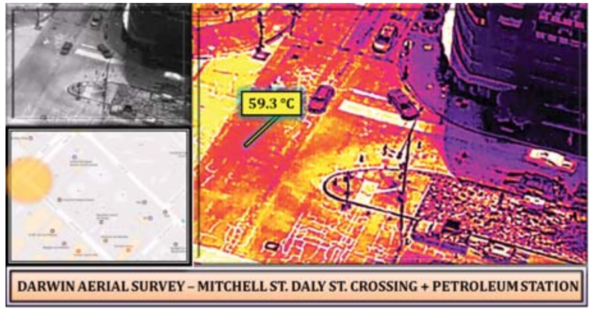
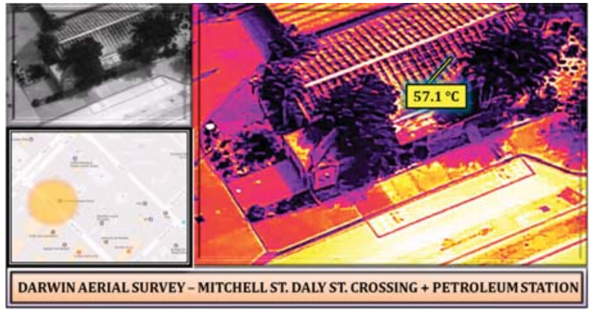
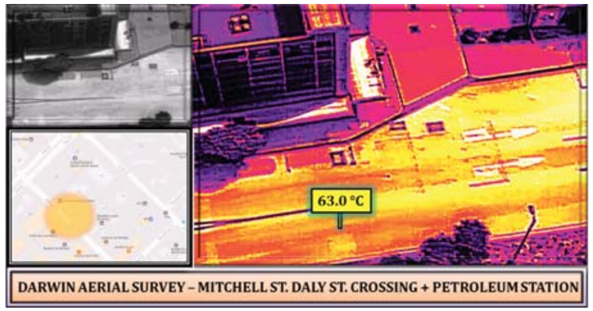


TABLE 15. DALY STREET – MCMINN STREET CROSSING THERMAL VIDEOS

MITCHELL STREET – DALY STREET CROSSING & PETROLEUM STATION CARPARK					
AREA CODE	1.2	**DAY**	23rd March	**DURATION**	3mins 8secs







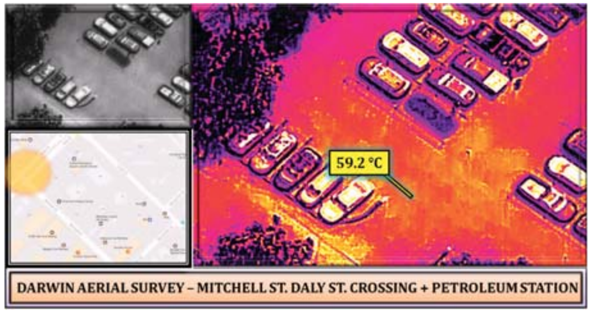
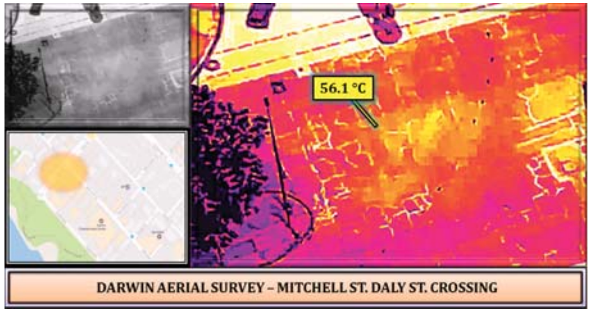
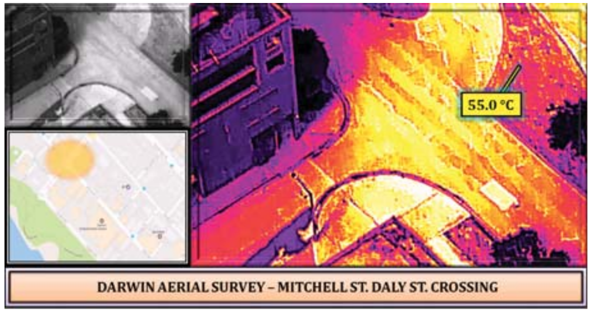


TABLE 16. MITCHELL STREET – DALY STREET CROSSING & PETROLEUM STATION CARPARK THERMAL VIDEOS

MITCHELL STREET – DALY STREET CROSSING					
AREA CODE	1.3	DAY	23rd March	DURATION	1min 01sec





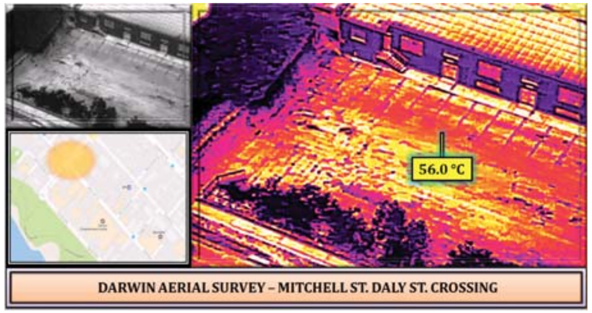
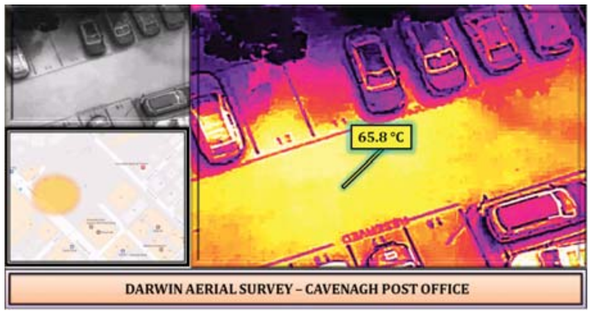
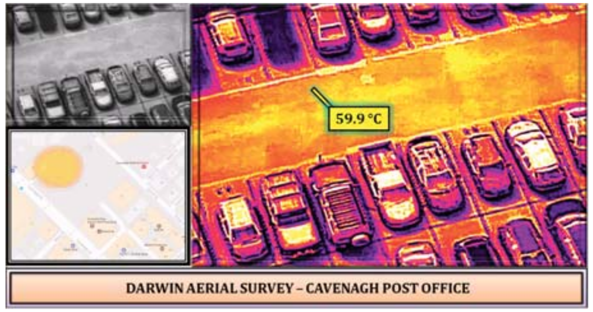
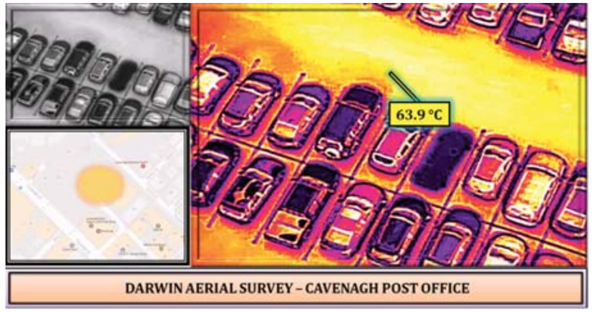


TABLE 17. MITCHELL STREET – DALY STREET CROSSING THERMAL VIDEOS

POST OFFICE CARPARK					
AREA CODE	1.4	DAY	23rd March	DURATION	1min 34secs







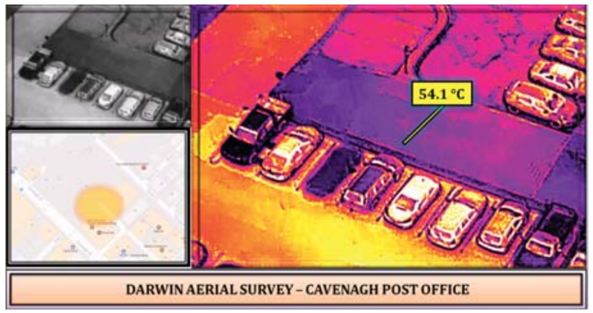
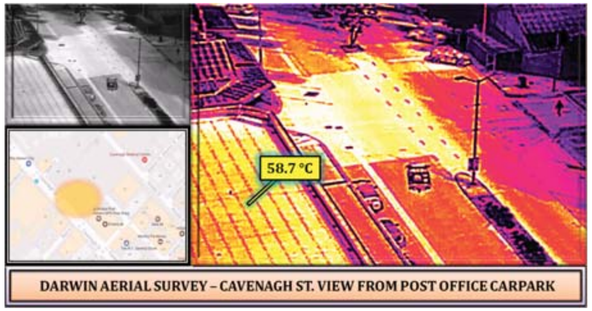
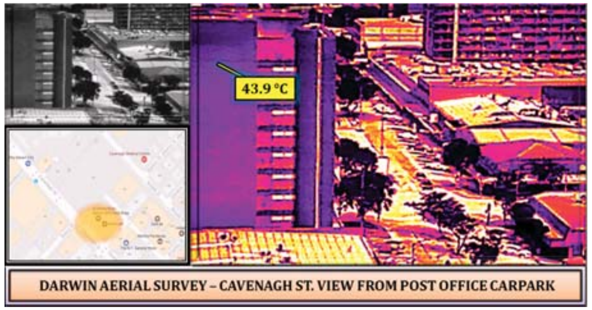


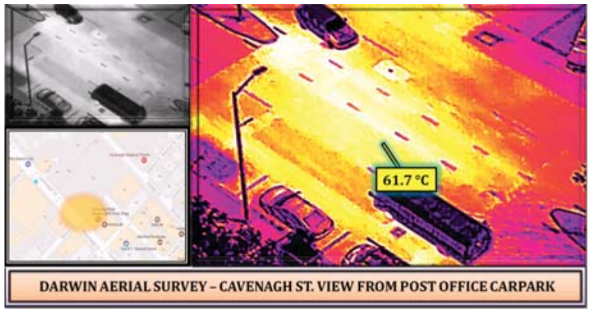
TABLE 18. POST OFFICE CARPARK THERMAL VIDEOS

CAVENAGH STREET VIEW FROM POST OFFICE CARPARK

AREA CODE	1.5	DAY	23rd March	DURATION	2mins 47secs







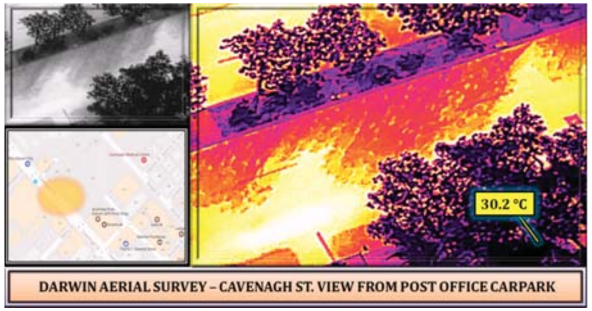
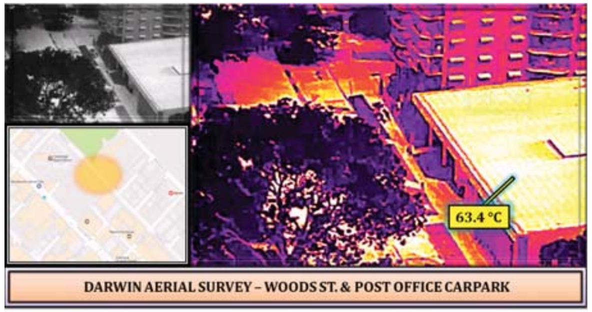
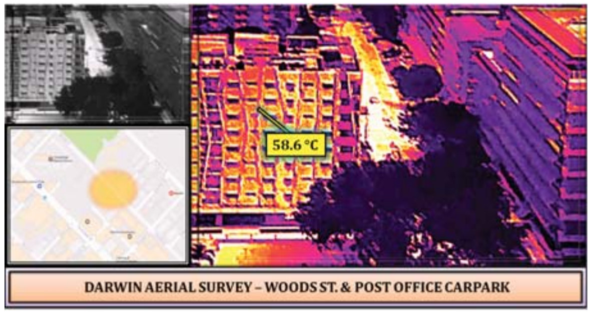


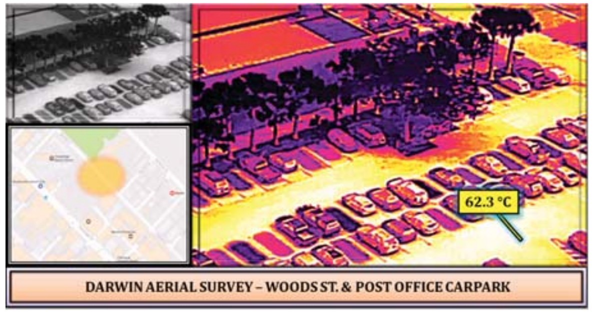
TABLE 19. CAVENAGH STREET VIEW FROM POST OFFICE CARPARK THERMAL VIDEOS

WOODS STREET AND POST OFFICE CARPARK

AREA CODE	1.6	DAY	23rd March	DURATION	3mins 57secs







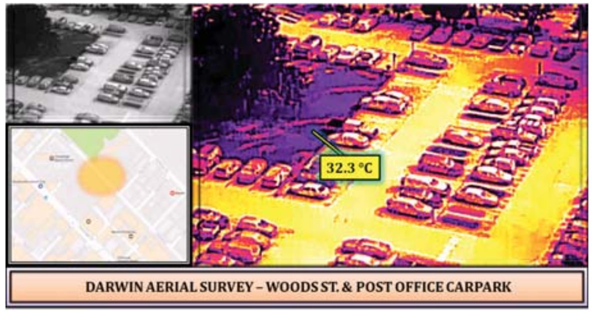
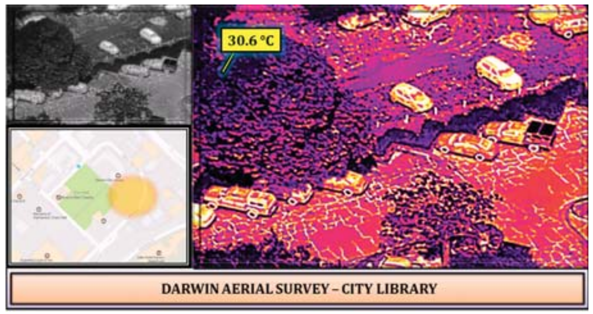
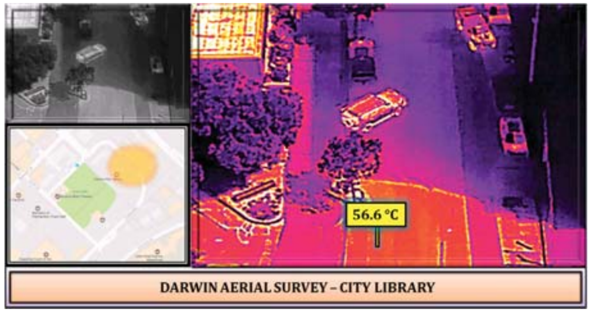


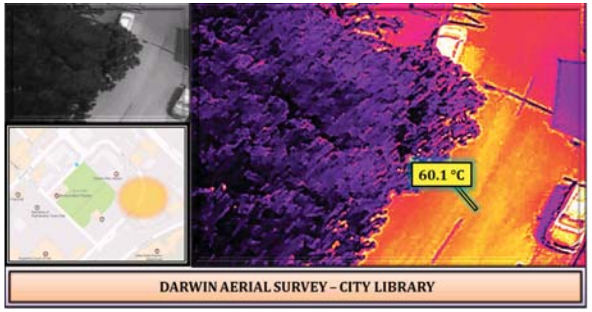
TABLE 20. WOODS STREET AND POST OFFICE CARPARK THERMAL VIDEOS

DARWIN CITY LIBRARY

AREA CODE	2.1	DAY	24th March	DURATION	3mins 30secs







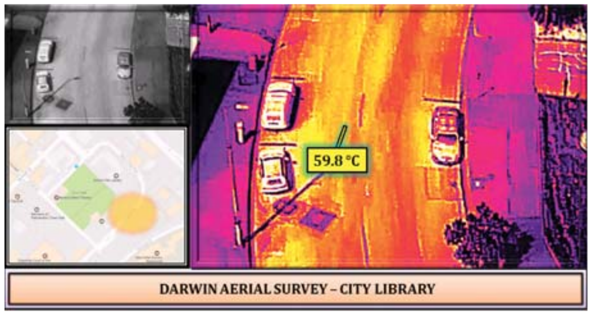
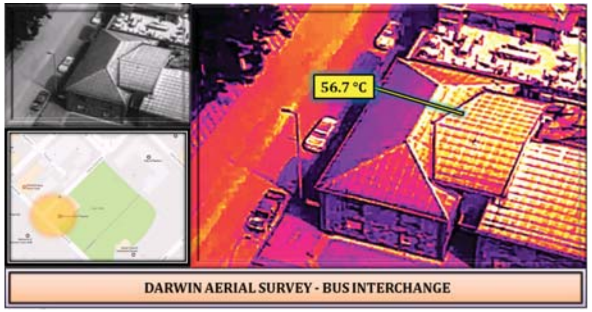
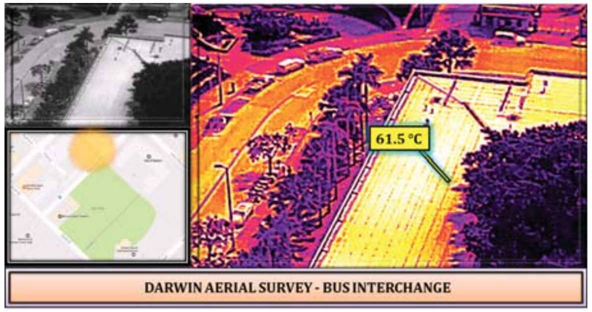
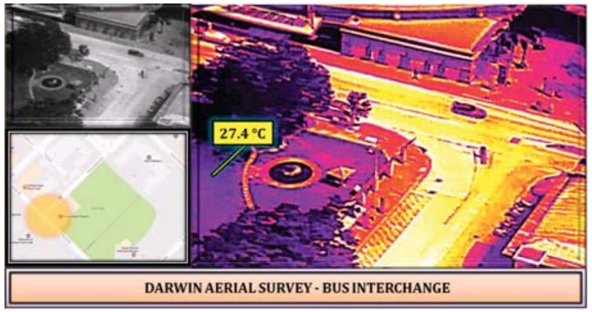


TABLE 21. DARWIN CITY LIBRARY THERMAL VIDEOS

BUS INTERCHANGE – CITY OF DARWIN					
AREA CODE	2.2	**DAY**	24th March	**DURATION**	3mins 10secs







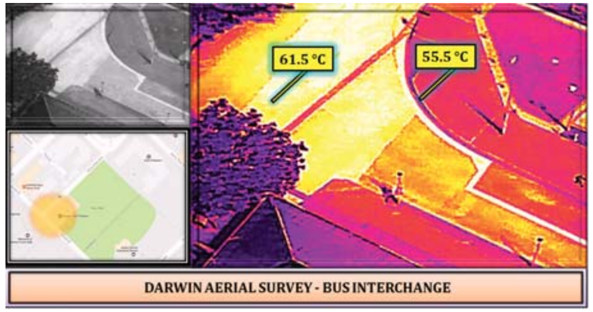
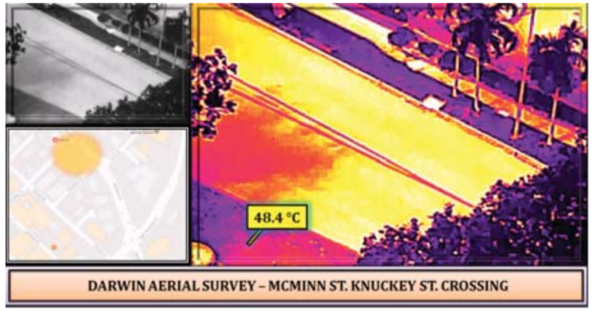
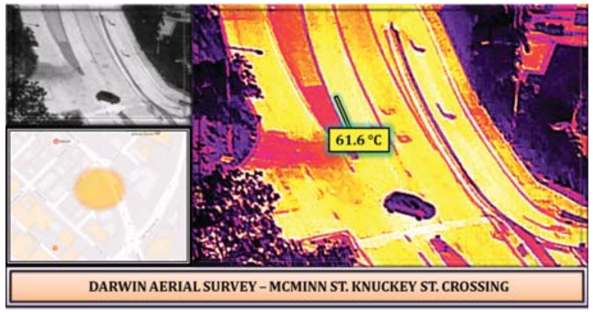
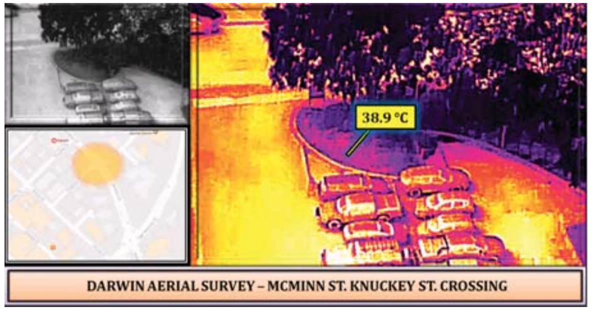


TABLE 22. BUS INTERCHANGE–CITY OF DARWIN THERMAL VIDEOS

MCMINN STREET – KNUCKEY STREET CROSSING					
AREA CODE	2.3	**DAY**	24th March	**DURATION**	3mins 01sec







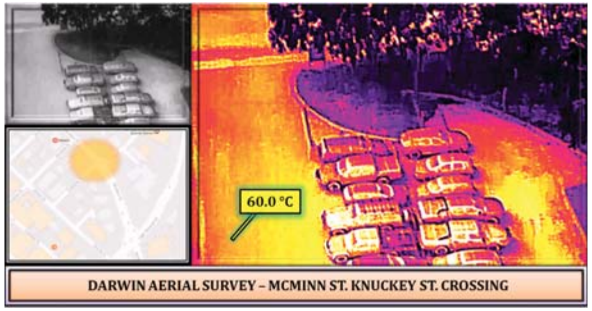
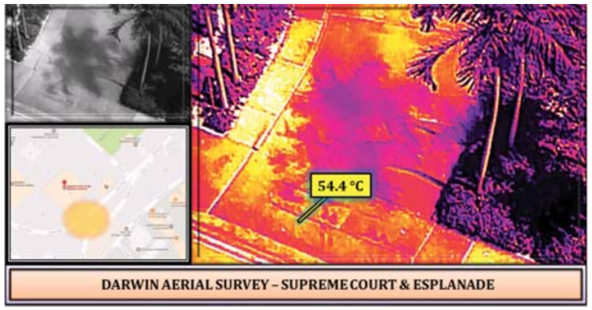
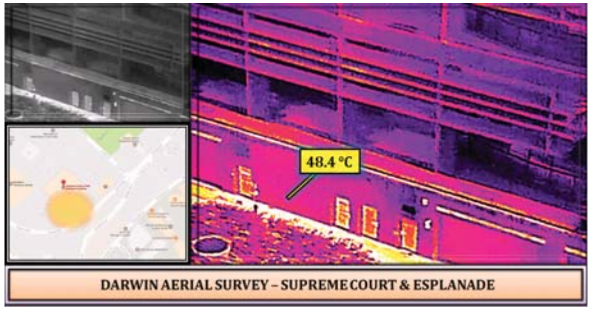
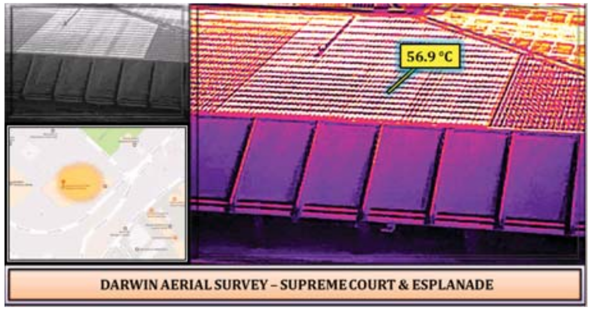


TABLE 23. MCMINN STREET – KNUCKEY STREET CROSSING THERMAL VIDEOS

SUPREME COURT - ESPLANADE					
AREA CODE	2.4	DAY	24th March	DURATION	2mins 54secs







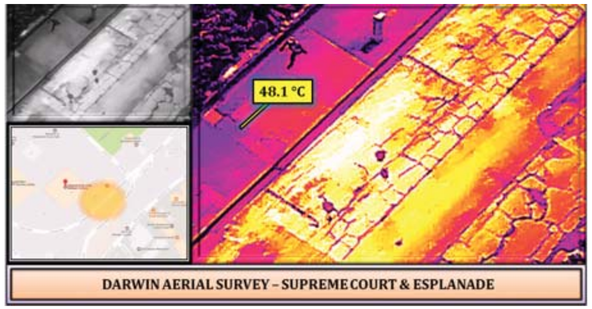


TABLE 24. SUPREME COURT AND ESPLANADE THERMAL VIDEOS

Aerial Survey – Conclusions

The heat absorbed, released, entrapped, generated within the boundaries of the urban landscape is related to diverse factors, some competing, others mutual-empowering, some environmental, others anthropogenic. In this extremely complex energy scenario, the temperatures reached by the surfaces act as a spy of the contribution given by urban materials and Sun exposure.

Thus, the thermal images captured during the aerial survey detected the "visible side" of the UHI.

Some conclusions can be drawn according to the information retrieved by analysing the post-processed thermal shots and privileging the least oblique views:

- The minimum average surface temperature of the streets is 55,4°C recorded at the crossing between Esplanade and Bennett Street. The maximum is 63,2°C (Cavenagh Street – Daly street crossing).
- The minimum average surface temperature of the parking lots is 44,9°C recorded in front of Darwin Supreme Court. The maximum is 65,7°C (Darwin GPO Postshop carpark).
- The minimum average surface temperature of shadowed street portions is 34,7°C recorded in front of Darwin Supreme Court. The maximum is 54,6°C (Darwin GPO Postshop carpark).
- The minimum average surface temperature of the trees is 27,6°C recorded in front of Darwin Supreme Court. The maximum is 38,5°C (Darwin City Council).
- The minimum average surface temperature of the greenery is 32,3C recorded in McMinn Street (near the crossing with Knuckey Street). The maximum is 46,1°C (Darwin Supreme Court).
- The minimum average surface temperature of the roofs is 48,0°C recorded at the crossing between Esplanade and Peel Street. The maximum is 66,0°C (McMinn Street – Daly Street crossing).
- The minimum average surface temperature of the pavements is 49,2°C recorded at the crossing between Esplanade and Peel Street. The maximum is 56,4°C (Darwin City Council).

- The minimum difference between streets and pavements surface temperatures is 0,2°C recorded in the area of Darwin City Council. The maximum is 7,3°C (Cavenagh Street – Daly street crossing).
- The minimum difference between streets and shadowed portions surface temperatures is 9,3°C recorded in the area of the United Petroleum Darwin carpark. The maximum is 22,7°C (Bus Interchange – Parliament House).
- The minimum positive difference between streets and parking lots surface temperatures is 1,7°C recorded in McMinn Street (near the crossing with Knuckey Street). The maximum is 11,2°C (Bus Interchange – Parliament House).
- The minimum negative difference between streets and parking lots surface temperatures is -2,7°C recorded at the crossing between McMinn Street and Daly Street. The maximum is -8,2°C (United Petroleum carpark).
- The minimum difference between pavements and greenery surface temperatures is 7,0°C recorded in front of Darwin Supreme Court.. The maximum is 21,2°C (McMinn Street, near Knuckey Street crossing).

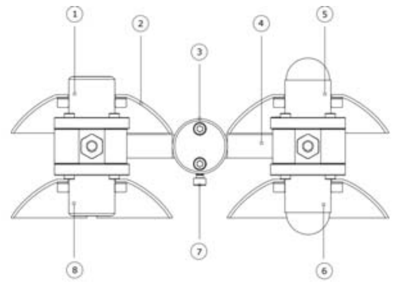
Apparently, the abundance of trees and greenery play a significant role in the reduction of urban elements temperatures since the areas around the harbour, the City Council and the Supreme Court (which are rich in vegetation) are the ones showing the lowest values.
The shadows (from the trees mainly) exert an effective refreshing effect (minimum temperature reduction close to 10°C) avoiding excessive overheating of the pavements and streets surfaces thus mitigating the radiant emissions of the unlit areas below.
The pavements' surface temperature is just slightly different from the one of the streets, while the parking lots' surface temperature can overtake the one of the nearest streets by more than 8°C. Some parking lots show a cooler thermal profile compared to the adjacent streets: this happens when the green cover of the trees is extensive.
Finally, when greenery replaces the concrete of the pavements the difference can rise up to 22°C thus reinforcing the evidence of the positive effect played by green areas in the urban landscape.

Terrestrial Survey – Instruments & Methods

The terrestrial survey has been conceived to map the meteorological conditions characterizing Darwin CBD in terms of air temperature, relative humidity, wind speed and direction, solar radiation and heat flux.
The data coming out of the measurement campaign will be compared to the BoM ones simoultaneously detected by the meteo station located near Darwin's airport (the "undisturbed" baseline). The discrepancies in the recorded values will reveal the magnitude of the Urban Heat Island affecting the Capital of the Northern Territory and will be used to doublecheck the outputs of the simulation model.
In order to collect all necessary information, two main measuring instruments were adopted:

- Hukseflux NR01 net radiometer: its four separate components measure the different terms of the surface radiation balance. The downward and upward solar radiation is measured by two pyranometers, while the longwave radiation is detected by two pyrgeometers. From these 4 separate components the net radiation is derived. Pyranometers output is used to quantify the albedo too, while pyrgeometers output is properly corrected to get sky and surface temperatures. In order to compensate for irradiated heat by the pyrgeometers themselves (Stefan-Boltzmann law) a Pt100 temperature sensor is included in NR01's body. Hukseflux probe technical specs are summarized in table 25. The height of measurement was set to 50cm to minimize the interefence from the mounting mast, vehicles, pedestrians…
- Gill Instrument MetPak Pro: professional weather station capable of monitoring up to six weather parameters (barometric pressure, air temperature, humidity, dew point, wind speed and wind direction). External sensors are connected directly to the weather station via a junction box. Technical data are presented in table 26. The height of measurement was set to 110cm as representative of the centre of gravity of people standing in an upright position, like pedestrians [see Mayer H, Hoppe P. 1987. Thermal comfort of man in different urban environments. Theoretical and Applied Climatology 38: 43–49].

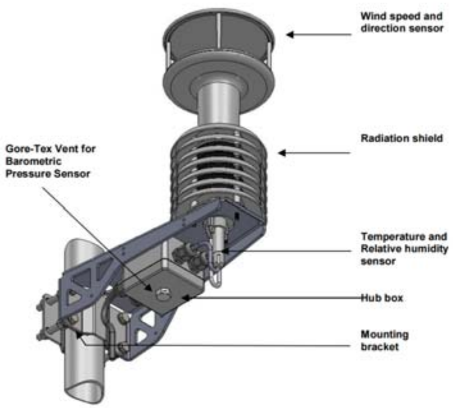
The acquisition of the probes outputs was performed via Lontek datalogger dataTaker DT85 (specs in table 27).
Finally the visualization and the post-processing were developed in G-language via the software LabVIEW by National Instruments: block diagram snapshots are provided in figures 3-5.



(1) upfacing pyrgeometer model IR01
(2) sun screens
(3,4) levelling assembly for x- and y-axis
(5) upfacing pyranometer model SR01
(6) downfacing pyranometer model IR01
(7) 4 x hex bolts for levelling adjustment
(8) downfacing pyrgeometer model IR02

HUKSEFLUX NR01 NET RADIOMETER	
GENERAL SPECS	
Product type	4-component net radiometer
Included sensors	2 x identical ISO 9060 second class pyranometer (see separate specification table for model SR01) 2 x identical pyrgeometer with 150 ° field of view angle (see separate specification table for model IR01)
Zero offset b (response to 5 K/h change in ambient temperature)	< ± 4 W/m2
Non-stability	< ± 1 % change per year
Non-linearity	< ± 1 % (100 to 1000 W/m2)
Directional response	< ± 25 W/m2
Spectral selectivity	< ± 5 % (0.35 to 1.5 x 10-6 m)
Temperature response	< ± 3 % (-10 to +40 °C)
Tilt response	< ± 2 % (0 to 90 ° at 1000 W/m2)
SPECIFICATIONS OF IR01 PYRGEOMETER	
Spectral range	4.5 to 40 x 10-6 m
Solar offset	< 15 W/m2 (at 1000 W/m2 global horizontal irradiance on the window)
Field of view angle	150 °
Response time (95 %)	18 s
Sensitivity (nominal)	15 x 10-6 V/(W/m2)
Sensitivity range	5 to 15 x 10-6 V/(W/m2)
Temperature dependence	< ± 3 % (-10 to +40 °C)
Required sensor power	zero (passive sensor)
Zero offset b (response to 5 K/h change in ambient temperature)	< ± 4 W/m2
Non-stability	< ± 1 % change per year
Non-linearity	< ± 2.5 % (100 to 300 W/m2, relative to 200 W/m2 sensor to source exchange)
Spectral range solar	285 to 3000 x 10-9 m
Spectral range longwave	4.5 to 40 x 10-6 m
Levelling	Bubble level and a levelling assembly for x- and yaxis are included
Required sensor power	zero (passive sensor)
Temperature sensor	Pt100
Heater on pyrgeometer	12 VDC, 1.5 W
Rated operating temperature range	-40 to +80 °C
Rated operating relative humidity range	0 to 100 %
Required readout	4 x differential voltage channel or 4 x single ended voltage channel, input resistance; 1 x temperature channel for Pt100
SPECIFICATIONS OF SR01 PYRANOMETER	
ISO classification (ISO 9060: 1990)	second class pyranometer
Response time (95 %)	18 s
Zero offset a (response to 200 W/m2 net thermal radiation)	< ± 15 W/m2 unventilated
Measurement range	-300 to +300 W/m2 (sensor to source exchange: U/S)
Tilt dependence	< ± 2 % (0 to 90° at 300 W/m2)

TABLE 25. HUKSEFLUX NR01 NET RADIOMETER SPECIFICATIONS



GILL INSTRUMENT METPAK PRO METEOROLOGICAL STATION

WIND MEASUREMENT	
Parameters	Wind speed and direction
Wind Speed Range	0-60m/s
Wind Speed Accuracy	±2% @12m/s
Wind Speed Resolution	0.01m/s
Wind Direction Range	0 to 359º - No dead band
Wind Direction Accuracy	±3º @12m/s
Wind Direction Resolution	1º

AIR TEMPERATURE	
Air Temperature	Pt100 1/3 Class B
Range	-50ºC to +100ºC
Accuracy	±0.1ºC
Resolution	0.1ºC (0.1ºF)
Units of measure	ºC or ºF
BAROMETRIC PRESSURE	
Range	600-1100hPa
Accuracy	±0.5hPa
Resolution	0.1hPa
Units of measure	hPa, mbar, mmHg, inHg
Compensated for temperature dependency	**-30ºC to +70ºC**
DEW POINT	
Resolution	0.1ºC (0.1ºF)
Units of measure	ºC or ºF
Accuracy	±0.15ºC (23ºC ambient temp @20ºC dew point)
OUTPUT	
Digital	**SDI-12** V1.3

TABLE 26. GILL INSTRUMENT METAPAK PRO METEOROLOGICAL STATION SPECIFICATIONS

LONTEK DATATAKER DT85 DATALOGGER

FEATURES	
• USB memory for easy data & program transfer	• Expandable to 800 analog inputs
• Dual Channel Isolation Technology	• 12 Flexible Digital channels
• 2x Serial 'Smart Sensor' ports	• USB memory for easy data & program transfer
• User Definable allocation of memory size & mode	• Dual Channel Isolation Technology
• Web Interface	• 2x Serial 'Smart Sensor' ports
• FTP for automatic data transfer	• User Definable allocation of memory size & mode
• Modbus for sensors and SCADA connection	• Web Interface
• SDI-12 (multiple networks)	• Expandable to 800 analog inputs
• Up to 48 Analog (± 30V) sensor inputs	• 12 Flexible Digital channels

TABLE 27. LONTEK DATATAKER DT85 DATALOGGER SPECIFICATIONS

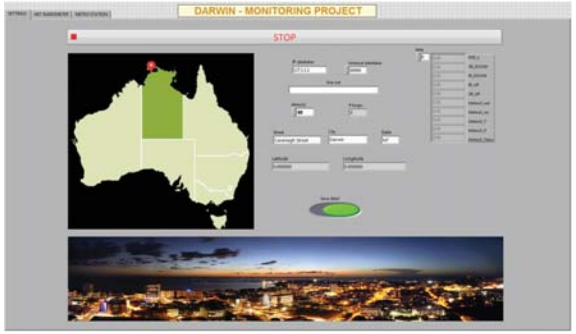


FIGURE 3. LABVIEW FRONT PANEL - SETTING SCREEN: COMMUNICATION WITH THE DATATAKER, DT85 AND GEOGRAPHIC DATA RETRIEVAL.

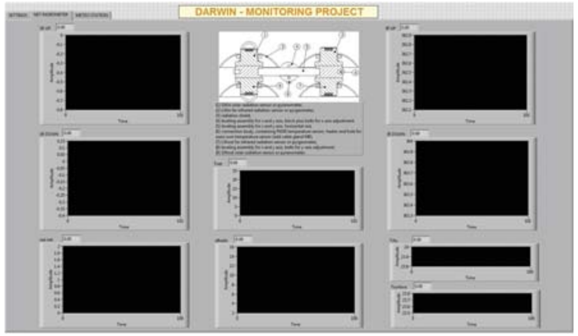


FIGURE 4. LABVIEW FRONT PANEL – GRAPHICAL VISUALIZATION OF NET RADIOMETER OUTPUT TIME TRENDS.

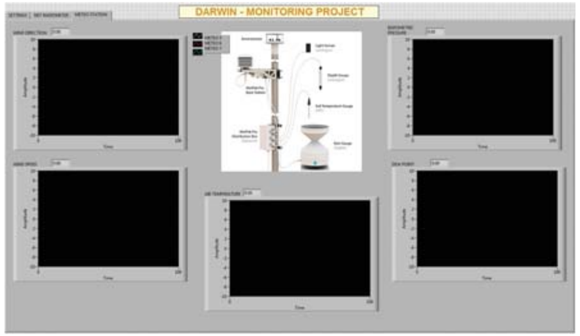


FIGURE 5. LABVIEW FRONT PANEL – GRAPHICAL VISUALIZATION OF METEO STATION OUTPUT TIME TRENDS.

Terrestrial Survey – Measurement Campaign

In order to run the terrestrial survey in the most efficient way (in consideration of the weather instabilities during the wet season in Darwin) a careful study of the simulations output was conducted prior to the on-site operations to outline the hot spots to detect and the "tricky" points to investigate.

The selected locations are summarized and displayed in figure 6. They were chosen in undisturbed areas in the parking lots or at the crossing of the main streets. In order to clarify the role played by the wind in the UHI phenomenon multiple points were aligned along Daly Street as it actually represents the "entry door" for the incoming wind and gusts.

FIGURE 6. DARWIN TERRESTRIAL MONITORING CAMPAIGN – STRATEGIC MAP

Terrestrial Survey – Data Collection

The following charts (figures 7-26) sum up the outputs of the monitoring activity (fully tabled in Appendix): air, surface and sky temperatures are displayed on the primary vertical axis; reative humidity (espressed in decimals) and wind speed are plotted on the secondary vertical axis. 20 recordings were taken per point (one each 30 seconds making a total of 10 minutes per point).

24TH MARCH 2017

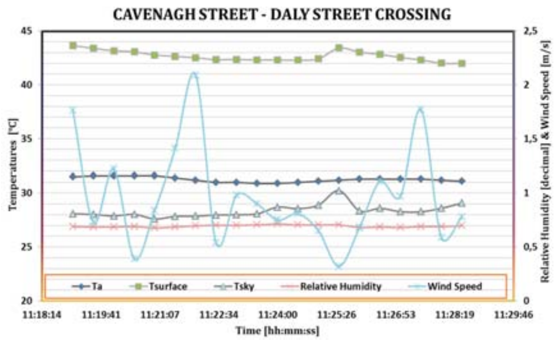


FIGURE 7. CAVENAGH STREET – DALY STREET CROSSING METEOROLOGICAL TIME TRENDS.

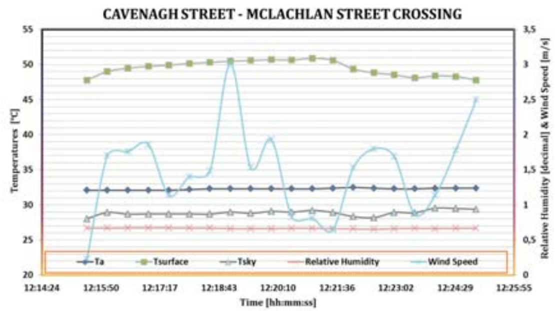


FIGURE 8. CAVENAGH STREET – MCLACHLAN STREET CROSSING METEOROLOGICAL TIME TRENDS.

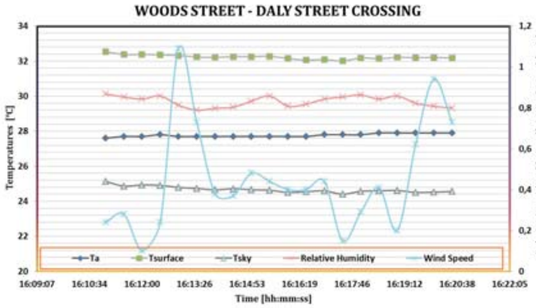


FIGURE 9. WOODS STREET – DALY STREET CROSSING METEOROLOGICAL TIME TRENDS.

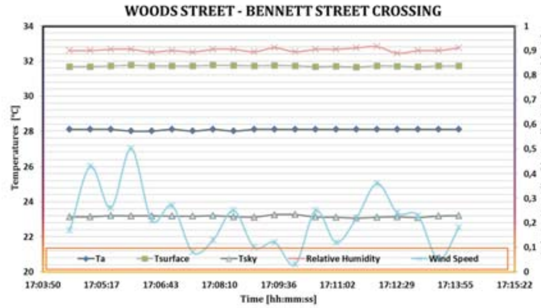


FIGURE 10. WOODS STREET – LINDSEY STREET CROSSING METEOROLOGICAL TIME TRENDS.

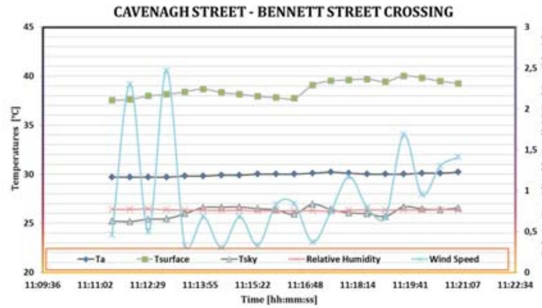


FIGURE 11. WOODS STREET – KNUCKEY STREET CROSSING METEOROLOGICAL TIME TRENDS.

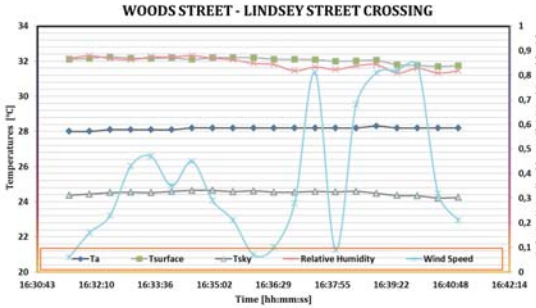


FIGURE 12. WOODS STREET – BENNETT STREET CROSSING METEOROLOGICAL TIME TRENDS.

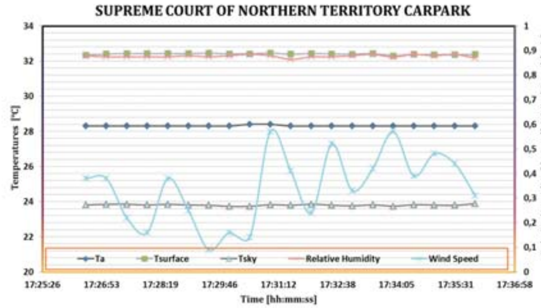


FIGURE 13. SUPREME COURT OF NORTHERN TERRITORY CARPARK METEOROLOGICAL TIME TRENDS.

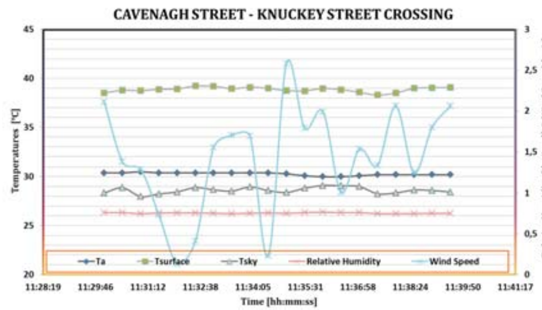


FIGURE 14. NORTHERN TERRITORY LIBRARY CARPARK METEOROLOGICAL TIME TRENDS.

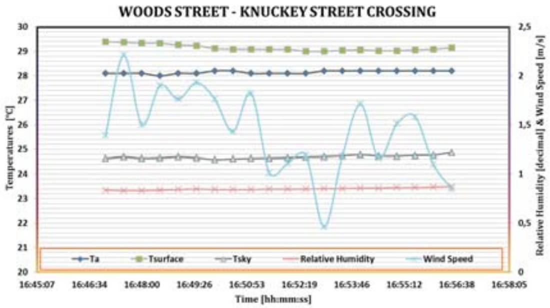


FIGURE 15. CAVENAGH STREET – BENNETT STREET CROSSING METEOROLOGICAL TIME TRENDS.

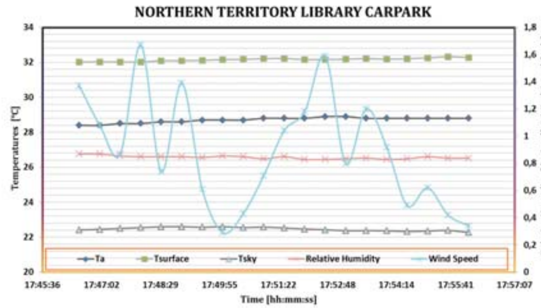


FIGURE 16. CAVENAGH STREET – KNUCKEY STREET CROSSING METEOROLOGICAL TIME TRENDS.

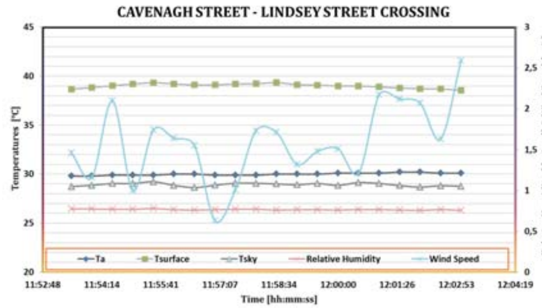


FIGURE 17. CAVENAGH STREET – LINDSEY STREET CROSSING METEOROLOGICAL TIME TRENDS.

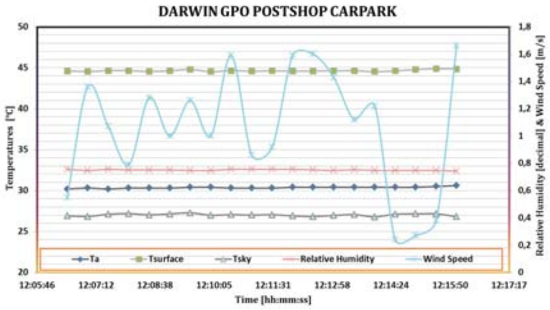


FIGURE 18. DARWIN GPO POSTSHOP CARPARK METEOROLOGICAL TIME TRENDS.

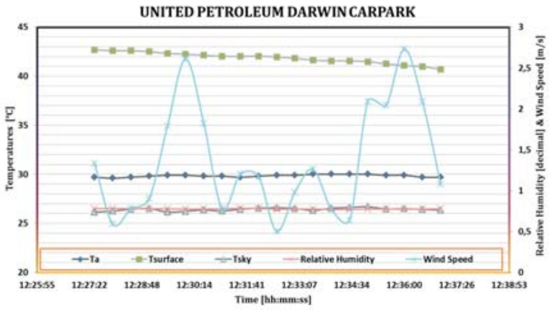


FIGURE 19. UNITED PETROLEUM DARWIN CARPARK METEOROLOGICAL TIME TRENDS.

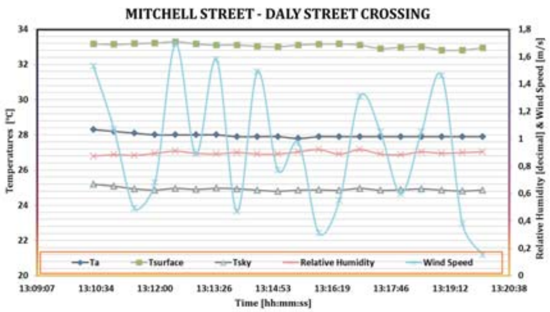


FIGURE 20. MITCHELL STREET – DALY STREET CROSSING METEOROLOGICAL TIME TRENDS.

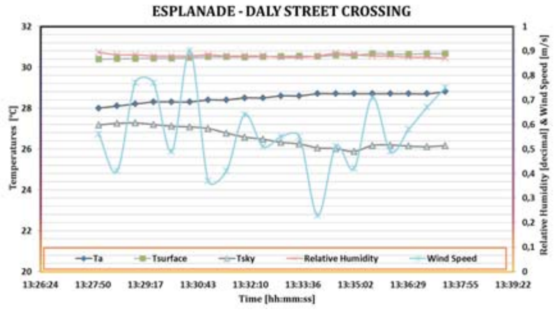


FIGURE 21. ESPLANADE – DALY STREET CROSSING METEOROLOGICAL TIME TRENDS.

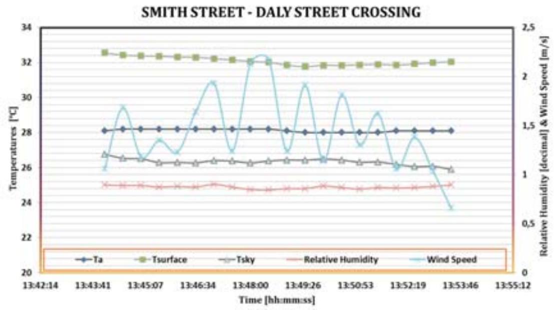


FIGURE 22. SMITH STREET – DALY STREET CROSSING METEOROLOGICAL TIME TRENDS.

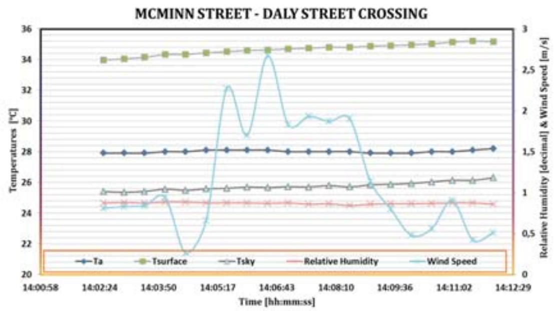


FIGURE 23. MCMINN STREET – DALY STREET CROSSING METEOROLOGICAL TIME TRENDS.

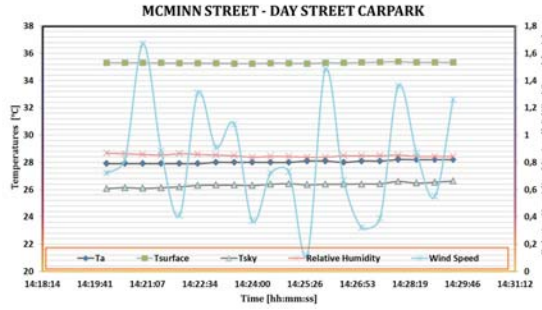


FIGURE 24. MCMINN STREET – DAY STREET CARPARK METEOROLOGICAL TIME TRENDS.

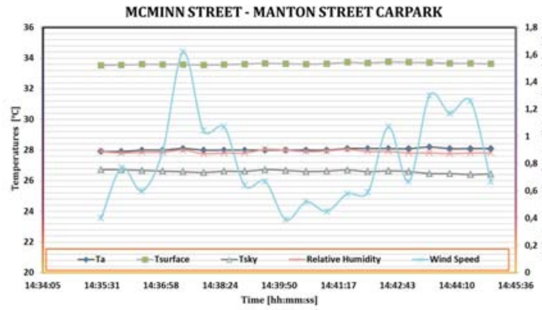


FIGURE 25. MCMINN STREET – MANTON STREET CARPARK METEOROLOGICAL TIME TRENDS.

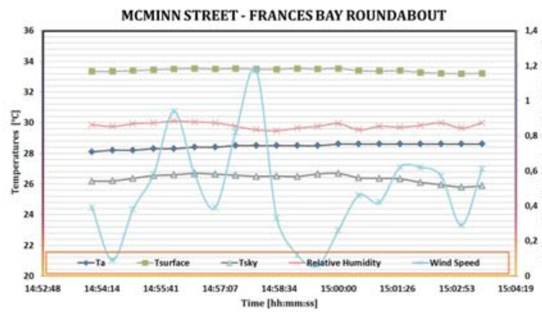


FIGURE 26. MCMINN STREET – FRANCES BAY ROUNDABOUT METEOROLOGICAL TIME TRENDS.

Terrestrial Survey – Data Analysis

Running meteorological monitoring campaign during the wet season in a tropical climate presents diverse peculiar challenges: the intermittent, but steady occurrence of short, sharp downpours of torrential rain and scattered thunder showers inevitably lead to a strong lack of coherence and continuity in the readings thus returning raw data which need to be treated in order to provide meaningful information.

Nevertheless, each of the above charts (figures 7-26) represents an all-inclusive meteorological frame of the strategic points of Darwin CBD investigated during the terrestrial survey.

Indeed, some conclusions and observations can be drawn focusing on the relative values rather than the absolute ones in order to depict thermo-hygrometric profiles of the main urban areas of interest (as listed in the “Plan” paragraph).

The following pictures (figures …..) display the difference in averaged air temperature (ΔTa) and relative humidity (ΔRH) moving from a point to another of the main roads. Such analyses were performed just among recordings collected within a time slot of around one hour (undisturbed by invasive weather phenomena) in order to select comparable values.

FIGURE 27. THERMOHYGROMETRIC DIFFERENCES ALONG WOODS STREET

FIGURE 28. THERMOHYGROMETRIC DIFFERENCES ALONG CAVENAGH STREET

FIGURE 29. THERMOHYGROMETRIC DIFFERENCES ALONG DALY STREET

On the other hand, the frequency of rainfalls (from drizzles to squally storms) allows to investigate:

- the average increase in relative humidity after a storm (+16,5%);
- the average decrease in air temperature after a storm (-4,52°C);
- the transient response of the asphaltic surfaces in terms of temperature variation after a rainfall: in the 10-minute-time slot in which each spot measurement occurred surface temperature of the streets were found to increase by more than 1°C (peaking at 2,49°C at the crossing between Cavenagh Street and Bennett Street), while surface temperature of the parking lots reached an high of +1,7°C (United Petroleum Darwin carpark).

Further analyses on meteorological data are presented in the following paragraph.

UHI Investigation – Data Analysis

Urban Heat Island is actually "the result of the positive thermal balance of cities caused mainly by the increased absorption of solar radiation and heat storage, high anthropogenic heat and reduced heat losses."
As it refers to the increased ambient temperature of cities compared to rural settings, its investigation implies the identification of an "undisturbed" environment serving as reference case for comparison.
With the precious collaboration of the Bureau of Meteorology the baseline values were collected from the Darwin airport meteo station for the same days and a time step of 1 minute.
Concomitant measurements of air temperature, wind speed and relative humidity were compared and analysed in order to get the magnitude and the specific peculiarities of the UHI phenomenon affecting Darwin CBD.
The results are presented as follows:

- Figures 30, 31 and 32 plot – respectively - the air temperature, wind speed and relative humidity differences obtained by subtracting the reference values to the ones simultaneously measured in each point of investigation with the CBD terrestrial survey sensor network (listed in table 28). Maximum, Minimum and average levels are graphically displayed. These graphs help defining the microclimates that the urban landscape locally creates as a function of the urban pattern, of the population density, of the proximity to the sea,…
- Each figure is followed by the related table listing each monitoring point in order of decreasing average values. These tables (tables 29-31) help identifying where the UHI is emphasized and check if it possible to strike any correlation with the specific wind and relative humidity conditions. The first three locations are red highlighted while the last three locations are blue highlighted. A satellite map of the CBD is added at the bottom of each table to help interpret the data distributions.

The results are discussed in the following paragraph.

TERRESTRIAL SURVEY LEGEND	
X-AXIS INDICES	**MEASUREMENT POINT**
1	CAVENAGH STREET – DALY STREET CROSSING
2	CAVENAGH STREET – MCLACHLAN STREET CROSSING
3	WOODS STREET – DALY STREET CROSSING
4	WOODS STREET – LINDSEY STREET CROSSING
5	WOODS STREET – KNUCKEY STREET CROSSING
6	WOODS STREET – BENNETT STREET CROSSING
7	SUPREME COURT OF NORTHERN TERRITORY CARPARK
8	NORTHERN TERRITORY LIBRARY CARPARK
9	CAVENAGH STREET – BENNETT STREET CROSSING
10	CAVENAGH STREET – KNUCKEY STREET CROSSING
11	CAVENAGH STREET – LINDSEY STREET CROSSING
12	DARWIN GPO POSTSHOP CARPARK
13	UNITED PETROLEUM DARWIN CARPARK
14	MITCHELL STREET – DALY STREET CROSSING
15	ESPLANADE – DALY STREET CROSSING
16	SMITH STREET – DALY STREET CROSSING
17	MCMINN STREET – DALY STREET CROSSING
18	MCMINN STREET – DAY STREET CARPARK
19	MCMINN STREET – MANTON STREET CARPARK
20	MCMINN STREET – FRANCES BAY ROUNDABOUT

TABLE 28. LIST OF THE TERRESTRIAL SURVEY MONITORING POINTS AND THEIR INDEXING

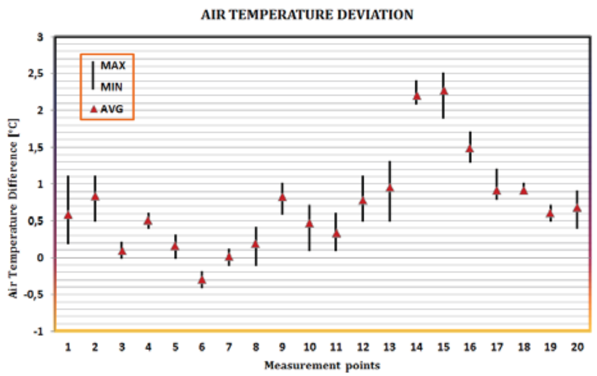


FIGURE 30. DARWIN CBD AIR TEMPERATURE DIFFERENCES DISTRIBUTION – MAXIMUM, MINIMUM AND AVERAGE VALUES DISPLAYED PER EACH MONITORING LOCATION.

AIR TEMPERATURE DIFFERENCES IN ORDER OF DECREASING RANKING			
LOCATION INDEX	**MAX_ΔT [°C]**	**MIN_ΔT [°C]**	**AVG_ΔT [°C]**
15	2,5	1,9	2,27
14	2,4	2,1	2,21
16	1,7	1,3	1,49
13	1,3	0,5	0,95
18	1	0,9	0,92
17	1,2	0,8	0,92
2	1,1	0,5	0,84
9	1	0,6	0,83
12	1,1	0,5	0,78
20	0,9	0,4	0,69
19	0,7	0,5	0,61
1	1,1	0,2	0,59
4	0,6	0,4	0,5
10	0,7	0,1	0,47
11	0,6	0,1	0,33
8	0,4	-0,1	0,19
5	0,3	0	0,16
3	0,2	0	0,09
7	0,1	-0,1	0,01
6	-0,2	-0,4	-0,3

TABLE 29. LIST OF THE TERRESTRIAL SURVEY MONITORING POINTS IN ORDER OF DECREASING AVERAGE UHI MAGNITUDE – MAXIMUM AND MINIMUM VALUES ADDITIONALLY SHOWED.

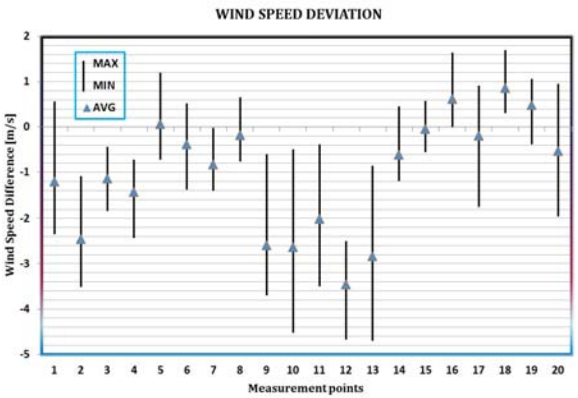


FIGURE 31. DARWIN CBD WIND SPEED DIFFERENCES DISTRIBUTION – MAXIMUM, MINIMUM AND AVERAGE VALUES DISPLAYED PER EACH MONITORING LOCATION.

WIND SPEED DIFFERENCES IN ORDER OF DECREASING RANKING			
LOCATION INDEX	MAX_Δws [m/s]	MIN_ Δws [m/s]	AVG_ Δws [m/s]
3	1,67	0,32	0,85
8	1,62	0,01	0,61
7	1,04	-0,36	0,47
18	1,18	-0,69	0,06
11	0,55	-0,54	-0,05
9	0,64	-0,74	-0,18
5	0,90	-1,74	-0,20
17	0,50	-1,36	-0,38
6	0,94	-1,94	-0,53
10	0,43	-1,17	-0,62
2	-0,03	-1,38	-0,84
16	-0,45	-1,82	-1,14
15	0,55	-2,34	-1,21
13	-0,73	-2,41	-1,45
19	-0,40	-3,49	-2,02
14	-1,11	-3,49	-2,46
12	-0,62	-3,68	-2,60
20	-0,51	-4,50	-2,65
4	-0,87	-4,68	-2,85
1	-2,53	-4,66	-3,46

TABLE 30. LIST OF THE TERRESTRIAL SURVEY MONITORING POINTS IN ORDER OF DECREASING AVERAGE WIND SPEED DIFFERENCE – MAXIMUM AND MINIMUM VALUES ADDITIONALLY SHOWED.

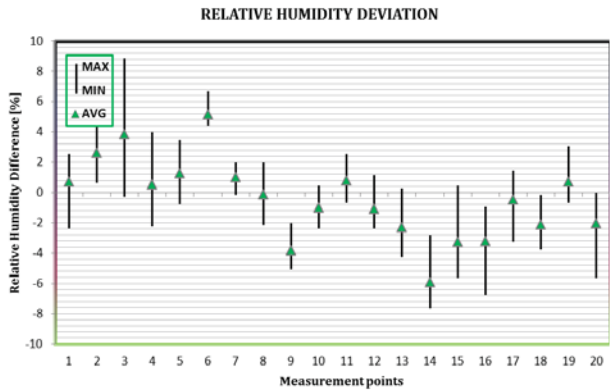


FIGURE 32. DARWIN CBD RELATIVE HUMIDITY DIFFERENCES DISTRIBUTION – MAXIMUM, MINIMUM AND AVERAGE VALUES DISPLAYED PER EACH MONITORING LOCATION.

RELATIVE HUMIDITY DIFFERENCES IN ORDER OF DECREASING RANKING			
LOCATION INDEX	MAX_ΔRH [%]	MIN_ ΔRH [%]	AVG_ ΔRH [%]
9	6,6	4,5	5,12
7	8,8	-0,2	3,85
8	4,4	0,7	2,59
11	3,4	-0,7	1,26
5	1,9	-0,1	1
2	2,5	-0,6	0,8
4	3	-0,6	0,71
3	2,5	-2,3	0,68
18	3,9	-2,2	0,53
17	1,9	-2,1	-0,15
12	1,4	-3,2	-0,49
10	0,4	-2,3	-1
16	1,1	-2,3	-1,08
1	-0,1	-5,6	-2,06
20	-0,2	-3,7	-2,15
15	0,2	-4,2	-2,3
14	-1	-6,7	-3,22
19	0,4	-5,6	-3,29
6	-2,1	-5	-3,85
13	-2,9	-7,6	-5,94

TABLE 31. LIST OF THE TERRESTRIAL SURVEY MONITORING POINTS IN ORDER OF DECREASING AVERAGE RELATIVE HUMIDITY DIFFERENCE – MAXIMUM AND MINIMUM VALUES ADDITIONALLY SHOWED.

UHI Investigation – Observations

By analysing the above presented results, some conclusions can be drawn:

- The maximum UHI magnitude, considered as the difference in air temperature figures, concentrates in the north-west side of the CBD, which represents the entry door for the hot western winds indeed. The proximity to the Ocean seems not to play a significant role in reducing the air temperature since no sea breeze is actually activated. In the same zone the wind speed difference (with the one recorded in the undisturbed environment) hits its negative maximum because of the physical barrier given by the urban morphology. This reduces the convective phenomena so that warmer air flows are stuck within the canopy for a longer time.
- The minimum UHI magnitude is recorded in the harbour area where the building density is much lower, the greenery is more widely spread and evaporation phenomena are emphasized. Accordingly, this urban block is the one with the highest positive relative humidity difference.

All things considered, the above described on-site measurement campaign has revealed the specific characteristics and reasons behind the formation of different microclimatic zones within Darwin CBD. Ad-hoc developed UHI mitigation strategies can now be tailored to each case.

Conclusions

This report presents the main results of the monitoring campaign run throughout Darwin CBD from the 23rd to the 25th of March 2017 via means of aerial and terrestrial investigation.

The data measured and here displayed and analysed have been used to move on to the next phase of Darwin Heat Mitigation program, represented by the design and the simulation of “corrective” scenarios.

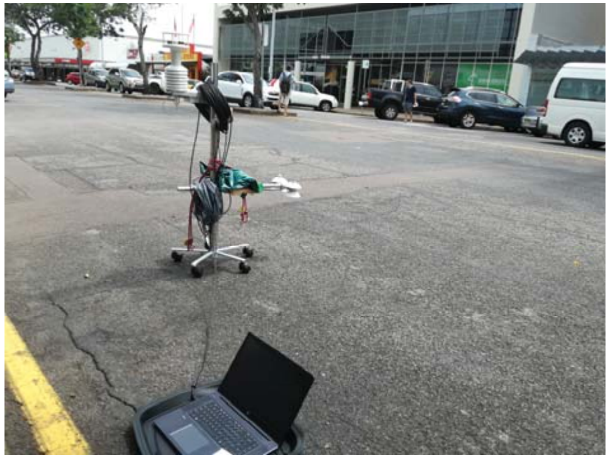
In particular, the analyses on the on-site collected datasets led to:

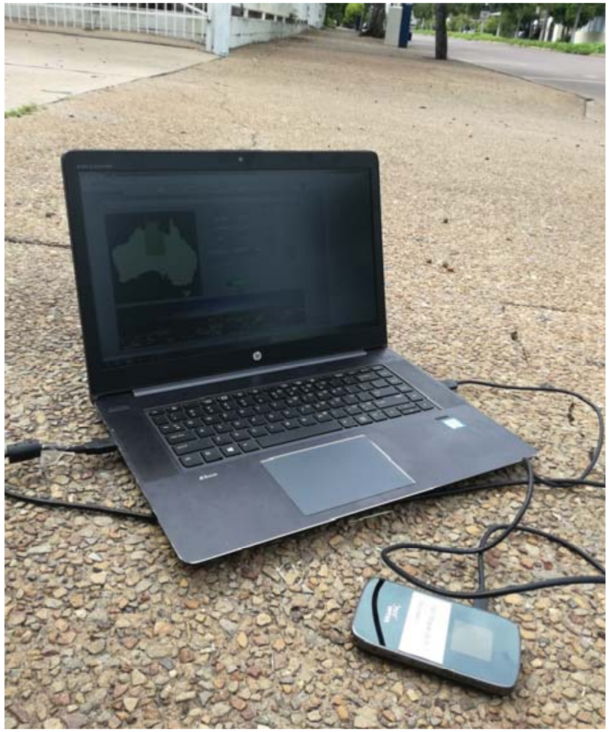
- the validation of the simulation model developed in ENVI-met. Indeed that is the closed loop that actually guarantees the truthfulness and reliability of the released information: interpret the output of the simulation model to conceive a proper monitoring plan and use the output of the on-site measurements to retro-feed the same model and check its effectiveness. Once the validity of the “as-is” simulations is demonstrated, the same model is manipulated to include single or combined mitigation strategies and investigate the way they alter the current situation. Finally, via multi-perspective, comparative analyses, the countermeasures showing highest positive momentum and promising potential are identified;
- the detection (and direct experience) of Darwin’s specific UHI characteristics, sources and magnitude in order to conceive the right corrective actions accordingly. Once the thermophysical phenomena leading to the creation of hot spots and abnormal microclimates are known, it is possible to address the mitigation strategies from an ad-hoc-developed and result-oriented perspective.

Appendix

The following tables (tables 32-51) show the data collection of the terrestrial monitoring activity. Refer to the following code to identify the parameters in the column fields:

- Wdir = Wind direction;
- Ws = Wind speed;
- Ta = Air temperature;
- P = Barometric pressure;
- Tdew = Dew-point;
- RH = Relative humidity
- θ↑PYR = Upfacing pyranometer;
- θ↓PYR = Downfacing pyranometer;
- θ↑PYRG = Upfacing pyrgeometer;
- θ↓PYRG = Downfacing pyrgeometer;
- Rnet = Net Radiation;
- α = Albedo;
- Tsrf = Surface Temperature (calculated from θ↓PYRG output);
- Tsky = Sky Temperature (calculated from θ↑PYRG output).





CAVENAGH STREET – DALY STREET CROSSING

DAY	START	LAT	-12,457005
24-mar	11:19:00	LONG	130,837579
	FINISH	DISTANCE FROM DALY STREET	40m
	11:29:00		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING					
Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
166	1,76	31,5	1006,6	25,1	68,9
73	0,73	31,6	1006,6	25,1	68,5
2	1,22	31,6	1006,6	25,1	68,5
193	0,39	31,6	1006,6	25,2	68,9
108	0,84	31,6	1006,6	24,9	67,7
126	1,41	31,4	1006,5	24,9	68,5
143	2,09	31,2	1006,5	25	69,7
309	0,54	31	1006,5	24,9	70,1
129	0,98	31	1006,5	24,9	70,1
128	0,9	30,9	1006,5	24,9	70,5
101	0,75	30,9	1006,4	25,1	71,3
103	0,81	31	1006,4	25	70,5
346	0,65	31,1	1006,4	25,1	70,5
238	0,32	31,2	1006,4	25,2	70,5
23	0,68	31,3	1006,4	24,7	68,1
63	1,11	31,3	1006,4	24,8	68,5
140	0,97	31,3	1006,4	24,7	68,1
139	1,77	31,3	1006,4	24,9	68,9
354	0,59	31,2	1006,4	24,8	68,9
87	0,78	31,1	1006,3	24,9	69,7

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
311,8543	33,0787	466,8850	571,0162
270,3542	29,2040	466,4639	569,3182
248,8249	26,5632	465,6376	567,5957
234,2557	24,4713	466,5490	566,9381
227,6869	24,3580	463,8693	564,7923
223,5517	22,5163	465 3647	563,9034
230,7368	22,79 4	465,4768	562,9871
231,1553	22,0664	466,1858	561,7241
247,5597	24,7716	466,3223	561,8807
260,2129	25,5984	466,8260	561,4696
262,3914	26,3123	470,6870	561,5936
284,1777	28,3272	469,8322	561,3831
379,3276	38,3059	471,9483	562,2623
1029,6680	109,0283	480,3535	569,4815
287,9147	29,1276	468,6143	566,7167
263,1056	26,5494	469,9868	565,2504
253,4118	23,6049	468,1083	563,1432
251,3688	24,0813	467,9973	561,5702
235,4839	22,3288	470,0642	559,3787
271,3747	27,5010	473,0093	559,2176
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
174,6444	0,1061	43,6363	28,0859
138,2958	0,1080	43,4005	28,0179
120,3036	0,1068	43,1608	27,8845
109,3953	0,1045	43,0691	28,0317
102,4060	0,1070	42,7695	27,5983
102,4966	0,1007	42,6451	27,8404
110,4351	0,0988	42,5168	27,8585
113,5506	0,0955	42,3396	27,9731
127,2296	0,1001	42,3616	27,9951
139,9709	0,0984	42,3038	28,0764
145,1725	0,1003	42,3212	28,6973
164,2996	0,0997	42,2917	28,5602
250,7076	0,1010	42,4151	28,8993
831,5117	0,1059	43,4232	30,2353
160,6848	0,1012	43,0383	28,3644
141,2927	0,1009	42,8335	28,5850
134,7720	0,0931	42,5386	28,2830
133,7147	0,0958	42,3179	28,2651
123,8406	0,0948	42,0097	28,5974
157,6654	0,1013	41,9870	29,0689

TABLE 32. CAVENAGH STREET – DALY STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

CAVENAGH STREET – MCLACHLAN STREET CROSSING

DAY	START		LAT	-12,458048
24-mar	12:15:30		LONG	130,838601
	FINISH		DISTANCE FROM MCLACHLAN ST.	30m
	12:25:30			
	TIMESTEP			
	30 s			

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
4	0,23	32,1	1005,3	25,2	67,0
349	1,7	32,1	1005,3	25,2	67,0
303	1,76	32,1	1005,3	25,3	67,4
317	1,86	32,1	1005,3	25,3	67,4
315	1,14	32,1	1005,3	25,3	67,4
351	1,4	32,2	1005,3	25,3	67,0
316	1,48	32,3	1005,3	25,4	67,1
310	3,01	32,3	1005,2	25,2	66,3
288	1,53	32,3	1005,2	25,2	66,3
309	1,93	32,3	1005,2	25,2	66,3
93	0,83	32,3	1005,2	25,3	66,7
8	0,81	32,3	1005,2	25,3	66,7
338	0,65	32,4	1005,2	25,3	66,3
330	1,53	32,5	1005,2	25,3	65,9
23	1,8	32,4	1005,2	25,1	65,5
328	1,69	32,3	1005,2	25,2	66,3
70	0,87	32,3	1005,1	25,3	66,7
282	1,14	32,4	1005,1	25,3	66,3
322	1,78	32,4	1005,1	25,4	66,7
328	2,5	32,4	1005,1	25,4	66,7

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
714,6666	59,5802	466,6728	601,6182
1193,3405	104,1052	472,2001	610,8690
1152,0026	100,3510	470,7024	614,4113
1134,6305	99,1937	470,8629	616,4487
1132,3263	97,9989	470,8815	617,6859
1143,8191	9 ,1816	470,8335	619,5622
1119,9911	97,0996	470,7157	620,7295
1156,1328	100,6464	472,5448	622,1528
1155,1486	100,6343	471,4588	622,7450
1156,4011	99,7971	473,1737	623,6820
1116,8572	95,6573	472,4815	623,2411
1076,1212	92,7459	474,0674	625,2636
460,8752	40,5348	472,1949	623,0549
314,0574	29,3905	468,5542	613,5316
326,5338	29,9158	467,6136	609,4383
340,1256	30,1534	472,1886	607,2497
357,0434	31,5286	471,9156	604,1720
552,4261	48,3490	476,0400	606,1859
510,9578	45,6422	475,7378	605,4934
290,3533	26,7749	475,0677	601,6356
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
520,1410	0,0834	47,7979	28,0517
950,5664	0,0872	49,0246	28,9396
907,9427	0,0871	49,4906	28,6998
889,8511	0,0874	49,7577	28,7255
887,5230	0,0865	49,9197	28,7285
895,9087	0,0867	50,1647	28,7280
872,8778	0,0867	50,3169	28,7019
905,8783	0,0871	50,5022	28,9947
903,2281	0,0871	50,5791	28,8210
906,0957	0,0863	50,7008	29,0952
870,4402	0,0856	50,6436	28,9846
832,1790	0,0862	50,9060	29,2378
269,4805	0,0880	50,6194	28,9388
139,6896	0,0936	49,3751	28,3548
154,7933	0,0916	48,8358	28,2034
174,9111	0,0887	48,5463	28,9377
193,2583	0,0883	48,1379	28,8941
373,9312	0,0875	48,4053	29,5519
335,5600	0,0893	48,3134	29,5038
137,0105	0,0922	47,8002	29,3972

TABLE 33. CAVENAGH STREET – MCLACHLAN STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

WOODS STREET – DALY STREET CROSSING

DAY	START	LAT	-12,458048
24-mar	16:11:00	LONG	130,838601
	FINISH	DISTANCE FROM MCLACHLAN ST.	30m
	16:21:00		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
263	0,24	27,6	1002,4	25,2	86,8
297	0,28	27,7	1002,4	25	85,3
90	0,1	27,7	1002,4	24,8	84,3
144	0,24	27,8	1002,4	25,2	85,8
150	1,09	27,7	1002,4	24,2	81,3
138	0,73	27,7	1002,3	23,7	78,9
138	0,38	27,7	1002,3	23,9	79,8
43	0,37	27,7	1002,3	24	80,3
352	0,48	27,7	1002,3	24,6	83,3
233	0,44	27,7	1002,3	25,1	85,8
288	0,4	27,7	1002,2	24,1	80,8
242	0,4	27,7	1002,2	24,3	81,8
3	0,44	27,8	1002,2	24,9	84,3
327	0,15	27,8	1002,2	25,1	85,3
281	0,29	27,8	1002,2	25,3	86,3
248	0,41	27,9	1002,1	25	84,3
259	0,2	27,9	1002,1	25,3	85,8
229	0,62	27,9	1002,1	24,6	82,3
191	0,94	27,9	1002,1	24,3	80,8
198	0,73	27,9	1002,1	24,1	79,9

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
134,3649	12,5624	448,8451	495,1009
134,9836	12,5998	447,2693	494,0932
135,4926	12,5371	447,6554	494,1021
136,1250	12,6124	447,4920	493,9887
136,7708	12, 251	446,7993	493,6837
136,0146	12,4864	446,4446	493,1408
136,3838	12,2741	445,9481	493,0197
137,1670	12,1730	446,3388	493,2677
138,1561	12,2362	445,9933	493,2554
138,9246	12,1609	445,8364	493,3843
140,1467	12,3115	445,1087	492,6488
141,1617	12,3616	445,3248	491,9689
142,6845	12,4243	445,6181	492,1849
145,2334	12,8264	444,4792	491,6743
146,0394	12,5497	445,4690	492,8039
147,3182	12,7131	445,6457	492,5389
151,1101	12,9766	445,7365	493,0366
152,6057	13,2027	445,1118	492,9011
153,7576	13,4788	445,1862	492,9645
145,2198	12,9265	445,4199	492,7953
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
75,5467	0,0935	32,5375	25,1329
75,5599	0,0933	32,3818	24,8707
76,5089	0,0925	32,3832	24,9350
77,0159	0,0927	32,3657	24,9078
77,2613	0,0923	32,3185	24,7924
76,8320	,0918	32,2345	24,7333
77,0380	0,0900	32,2157	24,6504
78,0652	0,0887	32,2541	24,7156
78,6578	0,0886	32,2522	24,6580
79,2159	0,0875	32,2722	24,6318
80,2950	0,0878	32,1583	24,5102
82,1560	0,0876	32,0529	24,5463
83,6933	0,0871	32,0864	24,5953
85,2119	0,0883	32,0072	24,4049
86,1548	0,0859	32,1823	24,5704
87,7118	0,0863	32,1413	24,5999
90,8335	0,0859	32,2184	24,6151
91,6138	0,0865	32,1974	24,5107
92,5005	0,0877	32,2072	24,5232
84,9178	0,0890	32,1810	24,5622

TABLE 34. WOODS STREET – DALY STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

WOODS STREET – LINDSEY STREET CROSSING

DAY	START	LAT	-12,458237
24-mar	16:31:30	LONG	130,840838
	FINISH	DISTANCE FROM PREVIOUS POINT	350m
	16:41:30		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
176	0,06	28	1002,1	25,6	86,8
73	0,16	28	1002,1	25,8	87,9
180	0,23	28,1	1002,1	25,7	86,8
167	0,43	28,1	1002,1	25,6	86,3
199	0,47	28,1	1002,1	25,8	87,4
181	0,35	28,1	1002,1	25,8	87,4
225	0,45	28,2	1002,1	26	87,9
134	0,29	28,2	1002,1	25,8	86,9
137	0,21	28,2	1002,1	25,7	86,3
176	0,07	28,2	1002,1	25,4	84,8
253	0,1	28,2	1002,1	25,3	84,3
231	0,28	28,2	1002,1	24,8	81,8
197	0,81	28,2	1002,1	25,1	83,3
133	0,09	28,2	1002,1	24,9	82,3
269	0,68	28,2	1002,1	25,2	83,8
194	0,81	28,3	1002,2	25,4	84,3
297	0,82	28,2	1002,2	24,6	80,9
201	0,84	28,2	1002,2	25	82,8
322	0,32	28,2	1002,2	24,6	80,9
189	0,21	28,2	1002,2	24,8	81,8

NET RADIOMETER MEASUREMENTS AND PROCESSING			
θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
125,2983	9,3720	444,2856	492,3175
124,2494	9,6360	444,6702	492,6648
123,2141	9,6987	445,1388	493,1928
122,3489	9,7240	445,2995	492,7445
121,6340	9,9375	445,1681	492,6208
120,8495	9,8242	445,5840	492,8298
120,4637	9,7614	445,9254	492,2463
120,8224	10,1635	445,9344	492,8678
121,3037	10,2895	445,5032	492,9225
121,2489	10,0882	445,7827	492,9410
121,0830	9,9628	445,3276	492,3587
120,7947	9,7988	445,3252	492,2587
119,7759	9,6107	445,5676	492,1705
118,6741	9,5227	445,4040	491,6197
117,1309	9,3846	445,6024	491,7158
115,6284	9,5354	444,9174	491,9583
113,4765	8,8313	444,1800	490,3092
111,8341	8,9699	444,0785	490,0828
110,1770	8,7686	443,3495	489,6605
108,2832	8,4792	443,5300	490,0191
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
67,8944	0,0748	32,1069	24,3725
66,6188	0,0776	32,1608	24,4369
65,4615	0,0787	32,2425	24,5152
65,1799	0,0795	32,1731	24,5421
64,2437	0,0817	32,1540	24,5201
63,7796	0,0813	32,1863	24,5896
64,3814	0,0810	32,0959	24,6466
63,7254	0,0841	32,1922	24,6481
63,5949	0,0848	32,2007	24,5761
64,0025	0,0832	32,2035	24,6228
64,0891	0,0823	32,1133	24,5468
64,0623	0,0811	32,0978	24,5464
63,5623	0,0802	32,0842	24,5869
62,9357	0,0802	31,9987	24,5596
61,6329	0,0801	32,0136	24,5927
59,0521	0,0825	32,0512	24,4782
58,5160	0,0778	31,7952	24,3548
56,8598	0,0802	31,7600	24,3378
55,0974	0,0796	31,6943	24,2156
53,3149	0,0783	31,7500	24,2459

TABLE 35. WOODS STREET – LINDSEY STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

WOODS STREET – KNUCKEY STREET CROSSING

DAY	START	LAT	-12,460901
24-mar	16:48:30	LONG	130,843583
	FINISH	DISTANCE FROM PREVIOUS POINT	400m
	16:58:30		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING					
Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
113	1,39	28,1	1001,8	25,1	83,8
119	2,21	28,1	1001,8	25	83,3
124	1,5	28,1	1001,8	25	83,3
98	1,9	28	1001,8	25	83,8
91	1,76	28,1	1001,9	25,2	84,3
106	1,93	28,1	1001,9	25,3	84,8
104	1,76	28,2	1001,9	25,3	84,3
122	1,43	28,2	1001,9	25,3	84,3
101	1,82	28,1	1001,9	25,2	84,3
142	1,01	28,1	1001,9	25,3	84,8
128	1,11	28,1	1001,9	25,3	84,8
121	1,19	28,1	1001,9	25,3	84,8
60	0,46	28,2	1001,9	25,5	85,3
115	1,18	28,2	1001,9	25,5	85,3
172	1,71	28,2	1001,9	25,6	85,8
141	1,16	28,2	1001,9	25,6	85,8
136	1,51	28,2	1001,9	25,7	86,3
107	1,58	28,2	1001,9	25,7	86,3
109	1,1	28,2	1001,9	25,8	86,9
163	0,85	28,2	1001,9	25,9	87,4

NET RADIOMETER MEASUREMENTS AND PROCESSING			
θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
72,7843	4,6200	445,8442	475,0614
72,0620	4,4946	446,2113	474,9043
71,7705	4,6200	445,8823	474,6810
71,2147	4,4693	445,9997	474,6765
70,6865	4,3565	446,2402	474,2147
70,8536	4,7327	445,9926	474,0287
70,4221	4,7074	445,5996	473,3020
70,1861	4,4440	445,7278	473,1266
69,6999	4,3065	445,8475	473,1268
69,8114	4,4319	445,9119	473,0871
69,8527	4,4566	446,0166	473,0736
69,6580	4,4693	446,1938	472,6077
69,4213	4,6074	446,2854	472,5953
69,3936	4,6074	446,4659	472,7989
68,8094	4,7074	446,7401	472,9359
69,5884	5,0089	446,4201	472,7225
69,8244	5,1216	446,3994	472,7450
69,1434	5,0463	446,5919	472,9449
69,5470	5,2718	446,6591	473,1084
69,6167	5,6354	447,2463	473,4837
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
38,9471	0,0635	29,3962	24,6331
38,8745	0,0624	29,3712	24,6944
38,3518	0,0644	29,3356	24,6394
38,0686	0,0628	29,3349	24,6590
38,3555	0,0616	29,2613	24,6992
38,0847	0,0668	29,2316	24,6579
38,0123	0,0668	29,1157	24,5922
38,3433	0,0633	29,0877	24,6136
38,1141	0,0618	29,0877	24,6336
38,2043	0,0635	29,0813	24,6444
38,3391	0,0638	29,0792	24,6619
38,7748	0,0642	29,0048	24,6914
38,5041	0,0664	29,0028	24,7067
38,4533	0,0664	29,0353	24,7368
37,9062	0,0684	29,0572	24,7826
38,2770	0,0720	29,0231	24,7292
38,3572	0,0734	29,0267	24,7257
37,7440	0,0730	29,0586	24,7578
37,8259	0,0758	29,0847	24,7691
37,7439	0,0809	29,1447	24,8669

TABLE 36. WOODS STREET – KNUCKEY STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

WOODS STREET – BENNETT STREET CROSSING

DAY	START	LAT	-12,460901
24-mar	17:04:30	LONG	130,845299
	FINISH	DISTANCE FROM PREVIOUS POINT	250m
	17:14:30		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
105	0,17	28,1	1002,6	26,3	90,0
153	0,43	28,1	1002,6	26,3	90,0
166	0,26	28,1	1002,6	26,4	90,5
157	0,5	28	1002,6	26,3	90,5
169	0,21	28	1002,6	26,1	89,4
150	0,27	28,1	1002,6	26,3	90,0
273	0,08	28	1002,6	26,1	89,4
169	0,13	28,1	1002,6	26,4	90,5
174	0,25	28	1002,6	26,3	90,5
216	0,1	28,1	1002,5	26,2	89,5
221	0,12	28,1	1002,5	26,5	91,1
131	0,03	28,1	1002,5	26,2	89,5
149	0,25	28,1	1002,5	26,4	90,5
17	0,12	28,1	1002,5	26,4	90,5
176	0,22	28,1	1002,5	26,5	91,1
154	0,36	28,1	1002,5	26,6	91,6
226	0,24	28,1	1002,5	26,1	88,9
184	0,23	28,1	1002,5	26,3	90,0
218	0,05	28,1	1002,5	26,3	90,0
235	0,18	28,1	1002,5	26,5	91,1

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
100,9620	6,6420	436,9914	489,6050
100,1989	6,8934	437,0002	489,6129
99,7183	7,1954	437,3446	489,7902
99,4422	7,4974	437,2890	490,0794
99,1791	7,7994	437,3060	489,8448
98,9449	8,0887	437,2302	489, 728
98,4753	8,1014	437,1864	489,8331
97,8258	8,2020	437,3203	490,0777
97,5903	8,3901	437,0419	490,0124
97,0517	8,3654	436,9048	489,8808
96,6363	8,3901	437,7169	490,0055
96,4157	8,4913	437,7285	489,8920
96,0385	8,4666	436,9198	489,5459
95,6792	8,3286	436,8254	489,6968
95,2639	8,1146	436,5482	489,4122
94,9737	8,2399	436,8467	489,8498
94,6279	8,2026	436,9387	489,7579
94,3371	8,1272	436,7527	489,5213
94,0055	7,9638	437,2337	489,7923
93,7146	7,9253	437,3746	489,7743

Rnet [W/ m²]	α	Tsrf [°C]	Tsky [°C]
41,7062	0,0658	31,6856	23,1437
40,6928	0,0688	31,6868	23,1452
40,0773	0,0722	31,7144	23,2036
39,1544	0,0754	31,7594	23,1942
38,8410	0,0786	31,7229	23,1970
38,2137	0,0817	31,7273	23,1842
37,7272	0,0823	31,7211	23,1768
36,8664	,0838	31,7592	23,1995
36,2296	0,0860	31,7490	23,1523
35,7102	0,0862	31,7285	23,1290
35,9576	0,0868	31,7479	23,2666
35,7609	0,0881	31,7303	23,2686
34,9458	0,0882	31,6764	23,1316
34,4793	0,0870	31,6999	23,1156
34,2854	0,0852	31,6556	23,0686
33,7306	0,0868	31,7237	23,1192
33,6062	0,0867	31,7094	23,1348
33,4413	0,0862	31,6726	23,1033
33,4830	0,0847	31,7148	23,1848
33,3896	0,0846	31,7120	23,2087

TABLE 37. WOODS STREET – BENNETT STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

SUPREME COURT OF NORTHERN TERRITORY CARPARK

DAY	START	LAT	-12,466174
24-mar	17:26:30	LONG	130,844299
	FINISH	DISTANCE FROM SMITH STREET	40m
	17:36:30		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
26	0,38	28,3	1001,9	26,1	87,9
26	0,38	28,3	1001,9	26	87,4
52	0,22	28,3	1001,9	26	87,4
84	0,16	28,3	1001,9	26	87,4
78	0,38	28,3	1001,9	26	87,4
101	0,25	28,3	1001,9	26,1	87,9
3	0,09	28,3	1001,9	26	87,4
354	0,16	28,3	1001,9	26,1	87,9
21	0,14	28,4	1001,9	26,3	88,4
92	0,57	28,4	1002	26,2	87,9
71	0,41	28,3	1002	25,8	86,4
82	0,24	28,3	1002	26	87,4
110	0,52	28,3	1002	26	87,4
91	0,33	28,3	1002	26,1	87,9
36	0,42	28,3	1002	26,2	88,4
55	0,57	28,3	1002	26	87,4
24	0,39	28,3	1002	26,2	88,4
84	0,48	28,3	1002	26,1	87,9
60	0,44	28,3	1002	26,2	88,4
53	0,31	28,3	1002	25,9	86,9

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
73,5750	4,9704	440,9515	493,7993
73,2280	5,1211	441,1587	494,1712
72,7837	5,2718	441,1739	494,3833
72,2556	5,3345	440,9397	494,3126
71,7138	5,3846	441,1587	494,3564
71,2830	5,3345	440,9290	494,35 9
70,7556	5,3593	440,8465	494,4799
70,2132	5,3846	440,4643	494,2642
69,7966	5,3846	440,4790	494,2922
69,3930	5,4093	441,0331	494,5027
68,8506	5,2465	440,8551	494,1482
68,3780	5,2339	441,1848	494,3842
67,8074	5,2965	440,8675	494,2453
67,2508	5,1585	440,6304	494,1284
66,5970	5,0958	440,9779	494,3242
66,0960	5,1084	440,5340	493,5410
65,4557	5,1337	441,0185	494,0099
64,9405	5,1585	440,9049	493,9570
64,3969	5,1585	440,8055	493,8605
63,0737	5,0084	441,3778	494,0332
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
15,7568	0,0676	32,3364	23,8127
15,0944	0,0699	32,3939	23,8476
14,3025	0,0724	32,4267	23,8502
13,5482	0,0738	32,4157	23,8107
13,1316	0,0751	32,4225	23,8476
12,5186	0,0748	32,4229	23,8089
11,7630	0,0757	32,4416	23,7950
11,0288	,0767	32,4083	23,7307
10,5989	0,0771	32,4126	23,7331
10,5141	0,0780	32,4451	23,8265
10,3111	0,0762	32,3903	23,7965
9,9448	0,0765	32,4268	23,8520
9,1330	0,0781	32,4053	23,7986
8,5943	0,0767	32,3873	23,7586
8,1549	0,0765	32,4175	23,8172
7,9805	0,0773	32,2964	23,7424
7,3305	0,0784	32,3689	23,8240
6,7299	0,0794	32,3608	23,8049
6,1835	0,0801	32,3458	23,7881
5,4100	0,0794	32,3725	23,8845

TABLE 38. – SUPREME COURT OF NORTHERN TERRITORY CARPARK (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

NORTHERN TERRITORY LIBRARY CARPARK

DAY	START	LAT	-12,466093
24-mar	17:46:30	LONG	130,841772
	FINISH	DISTANCE FROM ESPLANADE	40m
	17:56:30		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
60	1,37	28,4	1002	26	86,9
56	1,08	28,4	1002	26	86,9
67	0,87	28,5	1002	25,8	85,4
79	1,67	28,5	1002,1	25,7	84,9
128	0,74	28,6	1002,1	25,8	84,9
154	1,39	28,6	1002,1	25,8	84,9
121	0,61	28,7	1002,1	25,8	84,4
198	0,29	28,7	1002,1	26	85,4
110	0,43	28,7	1002,2	25,9	84,9
119	0,71	28,8	1002,2	25,7	83,4
70	1,04	28,8	1002,2	26	84,9
116	1,18	28,8	1002,2	25,6	82,9
86	1,59	28,9	1002,2	25,7	82,9
74	0,8	28,9	1002,3	25,8	83,4
78	1,2	28,8	1002,3	25,8	83,9
86	0,92	28,8	1002,3	25,6	82,9
52	0,49	28,8	1002,3	25,7	83,4
87	0,62	28,8	1002,3	26	84,9
92	0,42	28,8	1002,4	25,8	83,9
178	0,34	28,8	1002,4	25,8	83,9

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
65,9702	8,6541	432,7026	491,6993
64,8011	8,8802	432,9222	491,7985
63,7702	9,0942	433,2288	491,7462
62,6553	9,1822	433,4834	491,7511
61,6656	9,3588	433,7699	492,2024
60,5637	9,4716	433,8167	492,22 7
59,8667	9,7229	433,6321	492,3722
58,3309	9,7229	433,7784	492,6452
57,6050	9,7983	433,5352	492,6943
56,3207	9,7477	433,6520	492,9951
55,2725	9,7730	433,3709	493,0660
54,3499	9,6097	433,0370	492,6331
53,3571	9,5722	432,7786	492,6706
52,0500	9,2075	432,4733	492,7823
50,8514	9,0442	432,4725	493,0101
49,6385	8,8175	432,4315	492,7869
48,4386	8,6668	432,2245	492,9701
47,1272	8,4913	432,3654	493,2634
45,8984	8,4782	432,5437	493,6653
44,9629	8,4281	431,9136	493,3823
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
-1,6806	0,1312	32,0111	22,4140
-2,9554	0,1370	32,0265	22,4515
-3,8415	0,1426	32,0184	22,5039
-4,7946	0,1466	32,0191	22,5473
-6,1257	0,1518	32,0891	22,5961
-7,3138	0,1564	32,0922	22,6041
-8,5963	0,1624	32,1154	22,5727
-10,2588	0,1667	32,1577	22,5976
-11,3524	0,1701	32,1653	22,5561
-12,7702	0,1731	32,2119	22,5760
-14,1956	0,1768	32,2229	22,5281
-14,8559	0,1768	32,1559	22,4711
-16,1071	0,1794	32,1617	22,4270
-17,4665	0,1769	32,1790	22,3749
-18,7304	0,1779	32,2142	22,3748
-19,5343	0,1776	32,1797	22,3678
-20,9738	0,1789	32,2080	22,3324
-22,2621	0,1802	32,2535	22,3565
-23,7013	0,1847	32,3156	22,3869
-24,9339	0,1874	32,2719	22,2792

TABLE 39. –NORTHERN TERRITORY LIBRARY CARPARK (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

CAVENAGH STREET – BENNETT STREET CROSSING

DAY	START	LAT	-12,463854
25-mar	11:11:30	LONG	130,844378
	FINISH	DISTANCE FROM	
	11:22:30	WOODS STREET	170m
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
208	0,46	29,7	1005,3	25,2	76,9
269	2,3	29,7	1005,3	25,2	76,9
184	0,5	29,7	1005,3	25,3	77,3
339	2,47	29,7	1005,3	25,1	76,4
352	0,33	29,8	1005,2	25,1	76,0
341	0,68	29,8	1005,2	25,1	76,0
97	0,3	29,9	1005,2	25,1	75,5
318	0,68	29,9	1005,2	25,2	76,0
307	0,33	30	1005,2	25,1	75,1
264	0,83	30	1005,2	25,2	75,5
18	0,84	30	1005,2	25,1	75,1
217	0,37	30,1	1005,2	25,3	75,6
250	0,74	30,2	1005,2	25,2	74,7
271	1,17	30,1	1005,2	25,3	75,6
244	0,79	30	1005,2	25,4	76,4
347	0,67	30	1005,2	25,3	76,0
8	1,68	30	1005,2	25,4	76,4
348	0,95	30,1	1005,2	25,4	76,0
2	1,3	30,1	1005,2	25,5	76,5
7	1,41	30,2	1005,2	25,6	76,5

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
599,6288	60,6616	449,3339	528,2362
820,5590	82,5609	449,0764	528,8983
655,3705	66,6260	450,5702	531,2789
822,7535	82,7468	450,8167	532,3071
844,5934	84,0064	453,8360	534,1762
652,4236	65,2382	457 7321	536,1599
484,6077	46,9810	457,9436	533,6863
394,5162	39,2977	458,1366	532,5371
377,2989	37,9753	457,0203	530,9511
384,7717	38,7867	456,3188	530,1386
441,8178	44,4045	453,6571	529,5930
1122,6590	112,0454	459,7739	538,8346
1010,5725	98,2894	456,5740	541,7889
953,2220	93,7601	454,4453	542,5683
802,0932	78,2912	453,9261	543,1410
644,1379	61,6265	452,2718	541,3806
834,3616	81,3216	458,2134	545,3615
622,9993	59,0439	456,8550	543,9861
464,1217	43,9056	456,4524	541,6389
420,9435	39,7828	457,3908	539,9036

Rnet [W/ m²]	α	Tsrf [°C]	Tsky [°C]
460,0649	0,1012	37,5286	25,2141
658,1762	0,1006	37,6259	25,1713
508,0358	0,1017	37,9750	25,4191
658,5164	0,1006	38,1254	25,4599
680,2468	0,0995	38,3983	25,9587
508,7576	0,1000	38,6871	26,5985
361,8840	0, 969	38,3268	26,6332
280,8179	0,0996	38,1590	26,6647
265,3927	0,1007	37,9270	26,4819
272,1652	0,1008	37,8079	26,3669
321,4773	0,1005	37,7279	25,9292
931,5528	0,0998	39,0753	26,9322
827,0682	0,0973	39,5024	26,4088
771,3388	0,0984	39,6148	26,0590
634,5871	0,0976	39,6973	25,9735
493,4027	0,0957	39,4435	25,7006
665,8918	0,0975	40,0165	26,6773
476,8242	0,0948	39,8189	26,4548
335,0297	0,0946	39,4807	26,3888
298,6479	0,0945	39,2300	26,5426

TABLE 40. CAVENAGH STREET – BENNETT STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

CAVENAGH STREET – KNUCKEY STREET CROSSING

DAY	START	LAT	-12,461921
25-mar	11:30:00	LONG	130,842425
	FINISH	DISTANCE FROM	
	11:40:00	PREVIOUS POINT	350m
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
238	2,11	30,4	1005,3	25,7	76,0
265	1,38	30,4	1005,3	25,7	76,0
255	1,29	30,5	1005,3	25,5	74,7
278	0,73	30,4	1005,3	25,6	75,6
204	0,13	30,4	1005,3	25,6	75,6
243	0,41	30,4	1005,3	25,6	75,6
278	1,55	30,4	1005,3	25,5	75,2
277	1,7	30,4	1005,3	25,4	74,7
228	1,69	30,4	1005,3	25,5	75,2
333	0,23	30,4	1005,3	25,6	75,6
274	2,58	30,3	1005,3	25,4	75,1
259	1,79	30,1	1005,3	25,4	76,0
300	1,99	30	1005,3	25,4	76,4
232	1,01	30	1005,3	25,3	76,0
254	1,53	30,1	1005,3	25,4	76,0
250	1,34	30,2	1005,3	25,2	74,7
281	2,06	30,2	1005,3	25,2	74,7
264	1,25	30,2	1005,3	25,2	74,7
261	1,8	30,2	1005,3	25,3	75,1
238	2,06	30,2	1005,3	25,3	75,1

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m^2]	θ↓PYR [W/m^2]	θ↑PYRG [W/m^2]	θ↓PYRG [W/m^2]
491,9869	35,4286	468,4659	534,9521
855,9481	70,3813	471,7690	536,8017
718,0750	58,8805	466,2109	536,5217
686,7401	55,3255	467,8558	537,5103
876,2194	71,0502	469,1 19	537,7881
708,3042	56,8305	471,8873	539,8241
616,8018	49,5718	470,4868	539,5973
518,0876	40,5293	469,6657	538,0365
726,8225	58,7188	472,2872	538,9491
540,9768	41,9748	469,9884	538,1924
470,2622	36,6508	468,7676	536,5751
617,2788	48,2621	471,5058	536,4293
672,7484	52,5499	473,2178	538,0955
476,7108	36,4885	473,0065	537,2846
399,6380	30,1270	472,5550	535,3991
402,7297	31,5159	467,9516	533,4640
589,7587	46,9518	468,5063	534,9406
693,9105	55,6610	470,3401	538,1905
642,7931	51,2044	470,0585	538,6123
570,9471	45,2477	469,0669	538,7552

Rnet [W/ m^2]	α	Tsrf [°C]	Tsky [°C]
390,0721	0,0720	38,5114	28,3406
720,5341	0,0822	38,7804	28,8706
588,8836	0,0820	38,7397	27,9771
561,7600	0,0806	38,8833	28,2424
736,5230	0,0811	38,9236	28,4493
583,5370	0,08 2	39,2186	28,8896
498,1195	0,0804	39,1857	28,6652
409,1876	0,0782	38,9596	28,5334
601,4417	0,0808	39,0919	28,9535
430,7980	0,0776	38,9822	28,5852
365,8039	0,0779	38,7475	28,3891
504,0932	0,0782	38,7263	28,8285
555,3208	0,0781	38,9682	29,1022
375,9442	0,0765	38,8505	29,0685
306,6668	0,0754	38,5764	28,9963
305,7015	0,0783	38,2944	28,2578
476,3726	0,0796	38,5097	28,3471
570,3991	0,0802	38,9820	28,6417
523,0349	0,0797	39,0431	28,5965
456,0110	0,0793	39,0638	28,4372

TABLE 41. CAVENAGH STREET – KNUCKEY STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

CAVENAGH STREET – LINDSEY STREET CROSSING

DAY	START	LAT	-12,459434
25-mar	11:53:30	LONG	130,840056
	FINISH	DISTANCE FROM PREVIOUS POINT	400m
	12:03:30		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
292	1,46	29,8	1005,4	25,4	77,3
269	1,16	29,8	1005,4	25,4	77,3
293	2,1	29,9	1005,4	25,4	76,9
259	1	29,9	1005,4	25,4	76,9
283	1,74	29,9	1005,4	25,6	77,8
270	1,64	30	1005,4	25,4	76,4
292	1,55	30	1005,4	25,3	76,0
252	0,63	29,9	1005,3	25,3	76,4
309	1,01	29,9	1005,3	25,4	76,9
288	1,73	29,9	1005,3	25,4	76,9
285	1,71	30	1005,3	25,3	76,0
303	1,32	30	1005,3	25,4	76,4
259	1,48	30	1005,3	25,4	76,4
280	1,51	30,1	1005,3	25,4	76,0
291	1,21	30,1	1005,3	25,5	76,5
299	2,17	30,1	1005,3	25,5	76,5
277	2,12	30,2	1005,3	25,5	76,0
275	2,07	30,2	1005,3	25,4	75,6
273	1,63	30,1	1005,3	25,5	76,5
294	2,59	30,1	1005,3	25,3	75,6

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m^2]	θ↓PYR [W/m^2]	θ↑PYRG [W/m^2]	θ↓PYRG [W/m^2]
436,3040	33,2921	470,8959	535,9305
469,6244	36,0771	471,7376	537,2440
589,2977	45,3236	472,7901	538,4681
599,5749	46,5778	472,8300	539,6889
554,1689	43,5442	473,9699	540,5839
501,0836	39,9941	471,6962	539,7880
491,6212	39,0094	470,2290	538,9609
471,2760	36,4390	471,7458	538,9951
493,3011	38,5479	473,0325	539,7159
513,0142	40,2933	472,9747	539,8431
470,4225	37,6371	472,5617	540,6928
401,8430	32,1414	472,0628	539,1665
401,8170	32,1040	472,8586	538,8918
398,9767	32,6667	471,6786	538,3247
361,2111	29,2640	473,4438	538,2685
349,5724	28,6880	472,8358	537,6485
345,9943	28,4499	471,5440	536,8142
341,7624	28,4625	470,5395	536,3311
337,4183	27,6985	471,4329	536,1727
333,5044	27,5110	471,0137	535,2509

Rnet [W/ m^2]	α	Tsrf [°C]	Tsky [°C]
337,9773	0,0763	38,6538	28,7308
368,0410	0,0768	38,8446	28,8656
478,2960	0,0769	39,0222	29,0339
486,1381	0,0777	39,1990	29,0403
444,0107	0,0786	39,3284	29,2222
392,9977	0,0798	39,2133	28,8590
383,8798	0,0793	39,0936	28,6238
367,5878	0,0773	39,0986	28,8669
388,0696	0,0781	39,2029	29,0726
405,8526	0,0785	39,2213	29,0634
364,6543	0,0800	39,3441	28,9974
302,5980	0,0800	39,1234	28,9176
303,6798	0,0799	39,0836	29,0448
299,6638	0,0819	39,0014	28,8561
267,1225	0,0810	38,9933	29,1383
256,0716	0,0821	38,9033	29,0412
252,2742	0,0822	38,7822	28,8346
247,5083	0,0833	38,7120	28,6737
244,9801	0,0821	38,6890	28,8168
241,7562	0,0825	38,5549	28,7497

TABLE 42. CAVENAGH STREET – LINDSEY STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

DARWIN GPO POSTSHOP CARPARK

DAY	START		LAT	-12,459934
25-mar	12:06:30		LONG	130,841029
	FINISH		DISTANCE FROM	
	12:16:30		CAVENAGH ST.	35m
	TIMESTEP			
	30 s			

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
305	0,55	30,2	1005,2	25,4	75,6
228	1,36	30,3	1005,2	25,3	74,7
252	1,07	30,2	1005,2	25,4	75,6
115	0,79	30,3	1005,2	25,4	75,1
58	1,28	30,3	1005,2	25,4	75,1
79	1	30,3	1005,2	25,4	75,1
78	1,26	30,4	1005,2	25,4	74,7
72	1	30,4	1005,2	25,4	74,7
92	1,59	30,3	1005,1	25,5	75,6
59	0,86	30,3	1005,1	25,5	75,6
275	0,92	30,3	1005,1	25,5	75,6
264	1,59	30,4	1005,1	25,6	75,6
223	1,6	30,4	1005,1	25,5	75,2
222	1,43	30,4	1005	25,4	74,7
182	1,12	30,4	1005	25,5	75,2
200	1,22	30,4	1005	25,4	74,7
38	0,24	30,4	1005	25,4	74,7
185	0,27	30,4	1005	25,4	74,7
306	0,38	30,5	1005	25,5	74,7
266	1,66	30,6	1005	25,5	74,3

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
501,2768	50,5575	459,6713	578,0617
496,5072	50,5944	459,2020	577,5732
499,6961	50,6324	460,8549	578,3221
514,5225	52,1269	461,3100	578,2997
522,2687	53,2727	460,4082	577,5729
525,9512	53,4344	461,0806	578,1766
591,1924	59,7386	461,9195	579,3974
529,7946	54,3310	460,1268	577,4037
523,5737	52,3887	460,5406	578,3572
533,7855	53,6093	460,1979	577,8578
539,5368	54,5174	460,4812	578,1509
553,9147	56,2716	459,6507	577,9742
547,5206	54,9157	459,1450	577,9936
552,1115	55,1269	459,9380	578,1200
560,7238	55,7738	460,5660	578,2564
576,0526	57,1407	458,9173	577,3824
611,6910	59,7865	460,8904	578,1041
608,5031	59,7370	461,1145	579,2796
625,4671	61,6116	461,1424	580,0177
629,0929	62,7030	459,0076	579,8269
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
332,3288	0,1009	44,6089	26,9155
327,5415	0,1019	44,5418	26,8389
331,5965	0,1013	44,6447	27,1085
345,4060	0,1013	44,6416	27,1826
351,8313	0,1020	44,5418	27,0357
355,4208	0,1016	44,6247	27,1452
413,9759	0,1010	44,7923	27,2817
358,1867	0,1026	44,5185	26,9898
353,3683	0,1001	44,6496	27,0573
362,5163	0,1004	44,5809	27,0014
367,3497	0,1010	44,6212	27,0476
379,3196	0,1016	44,5969	26,9121
373,7563	0,1003	44,5996	26,8296
378,8026	0,0998	44,6170	26,9590
387,2597	0,0995	44,6357	27,0614
400,4467	0,0992	44,5156	26,7924
434,6907	0,0977	44,6148	27,1143
430,6010	0,0982	44,7762	27,1508
444,9802	0,0985	44,8774	27,1553
445,5707	0,0997	44,8512	26,8071

TABLE 43. DARWIN GPO POSTSHOP CARPARK (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

UNITED PETROLEUM DARWIN CARPARK

DAY	START		LAT	-12,458567
25-mar	12:27:30		LONG	130,835741
	FINISH		DISTANCE FROM	
	12:37:30		DALY ST.	20m
	TIMESTEP		MITCHELL E ST.	40m
	30 s			

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
300	1,33	29,7	1005,2	25,4	77,8
203	0,59	29,6	1005,2	25,4	78,2
273	0,78	29,7	1005,2	25,4	77,8
287	0,9	29,8	1005,2	25,5	77,8
294	1,79	29,9	1005,2	25,6	77,8
282	2,61	29,9	1005,2	25,5	77,3
325	1,82	29,8	1005,2	25,4	77,3
213	0,78	29,8	1005,2	25,5	77,8
251	1,2	29,7	1005,2	25,5	78,2
315	1,17	29,8	1005,1	25,6	78,2
281	0,5	29,9	1005,1	25,5	77,3
307	0,98	29,9	1005,1	25,5	77,3
295	1,26	30	1005,1	25,6	77,4
294	0,77	30	1005,1	25,5	76,9
241	0,64	30	1005,1	25,5	76,9
299	2,09	30	1005,1	25,6	77,4
274	2,04	29,9	1005,1	25,5	77,3
278	2,73	29,9	1005,1	25,5	77,3
274	2,09	29,7	1005,1	25,3	77,3
243	1,08	29,7	1005,1	25,4	77,8

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
364,8767	28,8877	454,9677	564,1102
354,2480	28,1616	455,6028	563,5075
344,2891	27,6611	456,7419	563,5015
335,9325	28,1116	457,1782	562, 583
327,5395	28,2623	454,9536	561,5634
318,9802	27,5731	455,4817	561,0036
310,3142	26,1820	456,2886	560,2150
300,9094	25,2942	455,6066	559,4353
292,5152	24,7826	456,7348	559,4110
284,9807	24,7320	457,4638	559,5941
276,7621	24,7947	457,6083	558,9670
270,2082	24,9570	457,1864	557,9541
262,4943	24,5197	455,9749	556,7087
252,9415	23,0081	457,3475	556,1382
244,7939	22,0581	457,8177	556,1530
235,4026	21,1704	458,2937	555,6113
230,3443	20,6324	456,9078	554,0130
222,1090	19,0559	457,0181	552,7804
213,9811	17,7159	456,6257	552,0052
207,5479	17,1394	456,2037	550,1200

Rnet [W/ m²]	α	Tsrf [°C]	Tsky [°C]
226,8465	0,0792	42,6741	26,1449
218,1817	0,0795	42,5897	26,2493
209,8685	0,0803	42,5888	26,4363
202,1408	0,0837	42,4987	26,5078
192,6674	0,0863	42,3170	26,1426
185,8852	0,0864	42,2383	26,2294
180,2058	0,0844	42,1275	26,3619
171,7866	0,0841	42,0177	26,2500
165,0563	0,0847	42,0143	26,4351
158,1183	0,0868	42,0401	26,5546
150,6086	0,0896	41,9517	26,5783
144,4835	0,0924	41,8089	26,5092
137,2409	0,0934	41,6330	26,3105
131,1427	0,0910	41,5523	26,5356
124,4004	0,0901	41,5544	26,6126
116,9146	0,0899	41,4777	26,6904
112,6067	0,0896	41,2512	26,4635
107,2909	0,0858	41,0762	26,4816
100,8857	0,0828	40,9660	26,4172
96,4922	0,0826	40,6974	26,3480

TABLE 44. UNITED PETROLEUM DARWIN CARPARK (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

MITCHELL STREET – DALY STREET CROSSING

DAY	START	LAT	-12,459649
25-mar	13:10:30	LONG	130,836267
	FINISH	DISTANCE FROM	
	13:20:30	DALY STREET	145m
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
116	1,53	28,3	1004,8	26	87,4
99	1,07	28,2	1004,8	26,1	88,4
130	0,49	28,1	1004,8	25,9	87,9
160	0,68	28	1004,8	26,1	89,4
115	1,69	28	1004,7	26,4	91,0
101	0,89	28	1004,7	26,1	89,4
126	1,58	28	1004,7	26	88,9
156	0,47	27,9	1004,7	26,1	90,0
116	1,49	27,9	1004,7	25,9	88,9
125	0,77	27,9	1004,6	25,9	88,9
106	0,97	27,8	1004,6	26,1	90,5
180	0,31	27,9	1004,6	26,5	92,1
164	0,55	27,9	1004,6	25,9	88,9
100	1,31	27,9	1004,6	26,5	92,1
120	1,05	27,9	1004,5	25,9	88,9
120	0,6	27,9	1004,5	25,8	88,4
176	1,05	27,9	1004,5	26,2	90,5
165	1,46	27,9	1004,5	26	89,4
179	0,38	27,9	1004,5	26,1	90,0
141	0,15	27,9	1004,4	26,2	90,5

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
105,3097	5,6101	449,2305	499,2683
106,1947	5,1712	448,5707	498,9967
107,0944	5,1464	447,6535	499,3133
108,1309	5,6601	447,2525	499,49 8
109,4578	6,0518	447,8319	500,0252
110,3563	6,2652	447,4394	499,1841
110,1074	6,3164	447,8518	498,7701
113,6416	6,2779	447,6925	498,8062
116,0142	6,9704	447,2018	498,3107
115,6143	6,3412	446,8444	498,1230
117,7645	6,9451	447,2142	498,8138
117,9438	6,8192	447,2980	499,0750
118,2883	7,2345	447,1636	499,2110
118,8527	7,4858	447,8104	498,7893
120,4225	7,5364	447,1647	497,4784
122,1701	7,3725	447,3384	497,9502
123,8630	7,6745	447,6273	498,1429
123,6973	7,8131	447,2382	496,9274
122,3069	7,6624	446,9115	496,9332
122,6761	7,9644	447,2586	497,7348

Rnet [W/ m²]	α	Tsrf [°C]	Tsky [°C]
49,6618	0,0533	33,1787	25,1969
50,5974	0,0487	33,1371	25,0873
50,2882	0,0481	33,1856	24,9347
50,2255	0,0523	33,2139	24,8680
51,2126	0,0553	33,2948	24,9644
52,3464	,0568	33,1658	24,8991
52,8726	0,0574	33,1023	24,9677
56,2500	0,0552	33,1078	24,9412
57,9349	0,0601	33,0317	24,8595
57,9946	0,0548	33,0029	24,8000
59,2198	0,0590	33,1090	24,8616
59,3476	0,0578	33,1491	24,8755
59,0065	0,0612	33,1699	24,8531
60,3880	0,0630	33,1052	24,9608
62,5724	0,0626	32,9038	24,8533
64,1858	0,0603	32,9763	24,8823
65,6729	0,0620	33,0060	24,9304
66,1949	0,0632	32,8190	24,8656
64,6228	0,0626	32,8199	24,8111
64,2356	0,0649	32,9432	24,8690

TABLE 45. MITCHELL STREET – DALY STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

ESPLANADE – DALY STREET CROSSING

DAY	START	LAT	-12,46
25-mar	13:28:00	LONG	130,834695
	FINISH	DISTANCE FROM DALY STREET	55m
	13:38:00		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
159	0,56	28	1003,8	26,1	89,4
124	0,41	28,1	1003,8	26	88,4
139	0,77	28,2	1003,8	26,1	88,4
106	0,77	28,3	1003,8	26,1	87,9
160	0,49	28,3	1003,8	26,1	87,9
120	0,9	28,3	1003,8	26,1	87,9
176	0,37	28,4	1003,8	26,3	88,4
139	0,41	28,4	1003,8	26,2	87,9
148	0,64	28,5	1003,8	26,3	87,9
139	0,51	28,5	1003,8	26,3	87,9
171	0,55	28,6	1003,8	26,3	87,4
176	0,55	28,6	1003,9	26,3	87,4
40	0,23	28,7	1003,9	26,5	87,9
39	0,51	28,7	1003,9	26,7	89,0
43	0,42	28,7	1003,9	26,6	88,5
126	0,71	28,7	1003,9	26,5	87,9
161	0,49	28,7	1003,9	26,5	87,9
117	0,58	28,7	1003,9	26,4	87,4
67	0,67	28,7	1003,9	26,4	87,4
143	0,75	28,8	1003,9	26,4	86,9

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
62,0563	5,6975	461,2700	481,3402
68,4477	6,3912	461,7680	481,4433
76,5842	7,5111	461,8812	481,5277
83,8155	8,2278	461,4074	481,6035
91,2921	9,1580	460,8838	48 ,6067
97,7530	9,7114	460,6678	481,8206
104,0914	10,7164	460,2263	482,0772
110,0802	11,4072	458,8254	482,0642
114,1802	12,0354	457,6339	482,0008
116,0142	12,3363	456,9984	482,1392
116,9103	12,3743	456,0640	482,2597
117,2961	12,4243	455,5675	482,3326
117,7232	12,6383	454,4346	482,2085
116,8548	12,0481	454,2001	482,5628
116,3865	12,0101	453,3658	482,4754
115,6556	11,6586	455,1403	483,1440
116,2620	12,1609	455,2684	482,9756
117,1167	12,3490	454,9384	482,8835
117,7368	12,6504	454,7680	483,0632
117,1309	12,4617	455,0855	483,0629
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
36,2885	0,0918	30,3909	27,1761
42,3812	0,0934	30,4072	27,2571
49,4267	0,0981	30,4205	27,2755
55,3916	0,0982	30,4324	27,1984
61,4112	0,1003	30,4329	27,1132
66,8889	0,0993	30,4666	27,0780
71,5241	0,1030	30,5071	27,0061
75,4342	0,1036	30,5050	26,7774
77,7778	0,1054	30,4950	26,5825
78,5372	0,1063	30,5168	26,4784
78,3404	0,1058	30,5358	26,3251
78,1067	0,1059	30,5473	26,2435
77,3110	0,1074	30,5277	26,0572
76,4441	0,1031	30,5835	26,0186
75,2667	0,1032	30,5698	25,8811
75,9933	0,1008	30,6749	26,1733
76,3939	0,1046	30,6484	26,1944
76,8226	0,1054	30,6340	26,1401
76,7911	0,1074	30,6622	26,1121
76,6918	0,1064	30,6622	26,1643

TABLE 46. ESPLANADE – DALY STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

SMITH STREET – DALY STREET CROSSING

DAY	START	LAT	-12,458041
25-mar	13:44:00	LONG	130,836567
	FINISH	DISTANCE FROM DALY STREET	40m
	13:54:00		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
75	1,06	28,1	1003,9	26,2	89,5
53	1,68	28,2	1003,9	26,2	88,9
84	1,18	28,2	1003,9	26,2	88,9
84	1,35	28,2	1003,9	25,9	87,4
115	1,23	28,2	1003,9	26	87,9
91	1,64	28,2	1003,9	25,9	87,4
75	1,93	28,2	1003,9	26,4	90,0
99	1,24	28,2	1003,9	25,9	87,4
32	2,13	28,2	1003,9	25,4	84,8
74	2,17	28,2	1003,9	25,3	84,3
81	1,24	28,1	1003,9	25,5	85,8
88	1,91	28	1003,9	25,4	85,8
48	1,14	28	1003,8	25,9	88,4
36	1,81	28	1003,8	25,6	86,8
110	1,3	28	1003,8	25,3	85,3
83	1,62	28	1003,8	25,6	86,8
16	1,06	28,1	1003,8	25,6	86,3
50	1,38	28,1	1003,8	25,7	86,8
66	1,04	28,1	1003,9	25,9	87,9
132	0,66	28,1	1003,9	26,2	89,5

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
123,0070	7,3598	458,7299	495,1720
131,0876	8,1531	457,3567	494,3627
136,0534	8,2158	457,1615	494,0868
138,2381	8,4919	455,8060	493,9458
136,5341	8,1652	455,8666	493,6483
133,8952	8,4165	455,7308	93,5317
130,4676	8,4666	456,5180	493,0539
126,8988	8,3918	456,3287	492,5858
124,3875	8,5425	455,7328	492,0183
122,9929	8,2405	456,3856	491,6743
124,8293	8,2784	456,7282	490,6672
129,5309	8,4165	456,6868	490,0991
137,2903	9,0706	457,0543	490,6102
146,3291	9,6867	456,7307	490,5487
155,8553	10,3022	455,9238	490,7723
164,8978	10,9430	456,0071	490,9240
174,4784	11,7714	455,1891	490,6661
182,8578	12,0607	454,4350	491,0900
190,2603	12,3363	454,5087	491,6020
196,6202	12,8891	453,4968	491,8369
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
79,2051	0,0598	32,5485	26,7618
85,9285	0,0622	32,4235	26,5371
90,9123	0,0604	32,3808	26,5051
91,6063	0,0614	32,3590	26,2827
90,5872	0,0598	32,3130	26,2927
87,6778	0,0629	32,2950	26,2704
85,4651	0,0649	32,2210	26,3996
82,2499	0,0661	32,1485	26,3685
79,5595	0,0687	32,0606	26,2707
79,4637	0,0670	32,0072	26,3779
82,6119	0,0663	31,8508	26,4341
87,7021	0,0650	31,7625	26,4273
94,6639	0,0661	31,8419	26,4875
102,8244	0,0662	31,8324	26,4345
110,7047	0,0661	31,8671	26,3021
119,0379	0,0664	31,8907	26,3157
127,2300	0,0675	31,8506	26,1813
134,1420	0,0660	31,9165	26,0573
140,8308	0,0648	31,9960	26,0694
145,3910	0,0656	32,0324	25,9027

TABLE 47. SMITH STREET – DALY STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

MCMINN STREET – DALY STREET CROSSING

DAY	START	LAT	-12,455691
25-mar	14:02:30	LONG	130,839995
	FINISH	DISTANCE FROM DALY STREET	130m
	14:12:30		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
87	0,81	27,9	1004,6	25,6	87,3
67	0,83	27,9	1004,6	25,7	87,9
42	0,84	27,9	1004,6	25,6	87,3
141	0,94	28	1004,6	25,9	88,4
75	0,26	28	1004,6	25,9	88,4
76	0,66	28,1	1004,6	25,8	87,4
132	2,27	28,1	1004,6	25,8	87,4
123	1,7	28,1	1004,6	25,8	87,4
134	2,67	28,1	1004,6	25,7	86,8
90	1,83	28	1004,6	25,7	87,4
89	1,93	28	1004,6	25,4	85,8
115	1,87	28	1004,5	25,5	86,3
136	1,9	28	1004,5	25,1	84,3
114	1,14	27,9	1004,5	25,3	85,8
112	0,8	27,9	1004,5	25,4	86,3
97	0,48	27,9	1004,5	25,4	86,3
56	0,56	28	1004,5	25,6	86,8
100	0,9	28	1004,5	25,7	87,4
138	0,42	28,1	1004,5	25,8	87,4
20	0,51	28,2	1004,5	25,6	85,8

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
236,9260	20,7462	450,4947	504,4249
238,6232	21,5092	450,1642	504,9709
238,5160	22,0345	450,5192	505,5896
238,5695	22,4223	451,4054	506,7407
239,0792	23,0345	450,9497	506,8398
239,3226	23,3722	451 5182	507,4981
239,8496	23,6973	451,7433	508,0337
240,3364	23,6099	452,2190	508,5415
241,2146	23,7975	452,0566	508,7248
241,1061	23,3849	452,3392	509,2131
240,5527	23,2854	452,2605	509,4763
239,3769	23,0472	452,8053	509,9224
237,8424	22,7721	452,2722	509,8977
235,9153	22,2848	453,1045	510,3919
233,9605	22,1219	453,3494	510,6451
232,1931	22,3596	453,6647	510,9822
230,2086	22,3474	454,3023	511,3657
228,7900	22,4597	454,9084	512,1580
227,7898	22,8101	454,9085	512,5753
220,0464	22,4344	455,8949	512,3542
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
162,2496	0,0876	33,9666	25,4066
162,3073	0,0901	34,0497	25,3518
161,4112	0,0924	34,1438	25,4107
160,8120	0,0940	34,3185	25,5574
160,1545	0,0963	34,3336	25,4819
159,9705	0,0977	34,4334	25,5760
159,8619	0,098	34,5145	25,6132
160,4041	0,0982	34,5913	25,6919
160,7489	0,0987	34,6191	25,6650
160,8474	0,0970	34,6929	25,7117
160,0516	0,0968	34,7327	25,6987
159,2127	0,0963	34,8000	25,7887
157,4448	0,0957	34,7963	25,7007
156,3432	0,0945	34,8709	25,8381
154,5428	0,0946	34,9091	25,8784
152,5160	0,0963	34,9599	25,9304
150,7977	0,0971	35,0177	26,0354
149,0806	0,0982	35,1370	26,1352
147,3129	0,1001	35,1998	26,1352
141,1528	0,1020	35,1665	26,2973

TABLE 48. MCMINN STREET – DALY STREET CROSSING (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

MCMINN STREET – DAY STREET CARPARK

DAY	START		LAT	-12,456129
25-mar	14:20:00		LONG	130,841095
	FINISH		DISTANCE FROM	
	14:30:00		MC MINN ST.	30m
	TIMESTEP		DAY ST.	50m
	30 s			

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
23	0,72	27,9	1004,7	25,5	86,8
40	0,82	27,9	1004,7	25,4	86,3
95	1,67	27,9	1004,7	25,3	85,8
116	0,88	27,9	1004,7	25,2	85,3
83	0,41	27,9	1004,7	25,4	86,3
114	1,31	27,9	1004,7	25,3	85,8
69	0,91	28	1004,7	25,3	85,3
90	1,08	28	1004,7	25,2	84,8
9	0,37	28	1004,7	25	83,8
54	0,72	28	1004,6	25,1	84,3
46	0,73	28	1004,6	25,1	84,3
251	0,12	28,1	1004,6	25,1	83,8
112	1,48	28,1	1004,6	25,1	83,8
87	0,67	28	1004,6	25,2	84,8
112	0,32	28,1	1004,6	25,3	84,8
94	0,39	28,1	1004,5	25,3	84,8
123	1,36	28,2	1004,5	25,5	85,3
98	0,87	28,2	1004,5	25,3	84,3
88	0,55	28,2	1004,5	25,3	84,3
89	1,26	28,2	1004,5	25,3	84,3

NET RADIOMETER MEASUREMENTS AND PROCESSING

θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
176,0745	14,9964	454,5334	513,3007
172,9993	15,4480	454,9817	513,3007
171,1117	15,6108	454,6675	513,2939
169,0996	15,0338	454,9180	513,1828
167,3943	14,9084	455,3023	513,1320
165,7563	15 25 9	455,9507	513,1121
163,6530	14,9585	456,1021	513,1052
161,9718	15,0717	456,0789	512,9010
160,3578	14,7583	455,9199	512,8744
160,1797	15,1092	456,4963	513,1387
161,0006	15,4480	456,6876	513,0858
163,0244	15,8738	456,2638	512,9308
165,8519	16,3881	456,4713	513,3177
168,1036	15,9865	456,5315	513,1771
170,0985	15,9865	456,5642	513,4505
171,3169	16,4255	456,6871	513,6292
171,1252	16,6384	457,7160	513,8289
169,7836	16,4634	456,9940	513,4530
167,2988	15,7484	457,3898	513,5412
164,1583	15,1845	457,8906	513,4480
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
102,3107	0,0852	35,3088	26,0735
99,2322	0,0893	35,3088	26,1472
96,8744	0,0912	35,3078	26,0956
95,8010	0,0889	35,2911	26,1368
94,6563	0,0891	35,2835	26,1999
93,3350	0,0921	35,2805	26,3065
91,6914	0, 91	35,2795	26,3313
90,0780	0,0931	35,2488	26,3275
88,6451	0,0920	35,2448	26,3014
88,4282	0,0943	35,2845	26,3960
89,1543	0,0960	35,2765	26,4274
90,4836	0,0974	35,2532	26,3579
92,6174	0,0988	35,3114	26,3919
95,4715	0,0951	35,2903	26,4018
97,2257	0,0940	35,3313	26,4072
97,9493	0,0959	35,3582	26,4273
98,3740	0,0972	35,3881	26,5959
96,8611	0,0970	35,3317	26,4776
95,3990	0,0941	35,3449	26,5425
93,4164	0,0925	35,3309	26,6245

TABLE 49. MCMINN STREET – DAY STREET CARPARK (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

MCMINN STREET – MANTON STREET CARPARK

DAY	START		LAT	-12,459301
25-mar	14:35:30		LONG	130,844136
	FINISH		DISTANCE FROM	
	14:45:30		MC MINN ST.	25m
	TIMESTEP		MANTON ST.	60m
	30 s			

METEO STATION MEASUREMENTS AND PROCESSING

Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
211	0,4	27,9	1003,7	25,9	88,9
338	0,77	27,9	1003,7	25,7	87,9
219	0,6	28	1003,7	25,9	88,4
323	0,89	28	1003,7	25,9	88,4
278	1,62	28,1	1003,7	26,3	90,0
303	1,04	28	1003,7	25,7	87,4
290	1,07	28	1003,7	25,8	87,9
282	0,64	28	1003,7	25,8	87,9
280	0,67	28	1003,7	26,3	90,5
264	0,39	28	1003,7	26,2	90,0
291	0,52	28	1003,7	26	88,9
272	0,45	28	1003,7	26,1	89,4
183	0,58	28,1	1003,7	26,4	90,5
339	0,59	28,1	1003,7	26,1	88,9
266	1,07	28,1	1003,7	26,1	88,9
314	0,67	28,1	1003,7	25,9	87,9
305	1,3	28,2	1003,7	26	87,9
323	1,17	28,1	1003,7	25,8	87,4
291	1,26	28,1	1003,7	25,9	87,9
315	0,67	28,1	1003,7	25,9	87,9

NET RADIOMETER MEASUREMENTS AND PROCESSING			
θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
162,0402	12,0349	458,5183	501,6152
164,8825	12,7626	458,4669	501,7510
166,6031	13,1146	458,2181	501,9623
167,6267	13,4656	457,9041	501,9425
167,8720	13,3402	457,6980	501,9091
167,1078	13,3275	457 3976	501,6858
165,2238	12,9766	457,8920	501,8356
163,8033	12,9012	457,8071	502,1023
162,5048	12,9138	458,4986	502,3915
161,6594	12,8138	458,2287	502,2244
162,2066	13,1399	457,7514	502,0405
162,8488	13,2533	457,9113	502,2509
164,6119	13,5795	458,3767	502,8454
167,0418	14,2071	457,6889	502,5872
170,2390	14,4073	458,0376	503,0274
174,1782	14,7962	457,7448	502,8718
178,3306	15,2104	456,9546	502,7279
181,4410	15,4606	456,8953	502,4270
183,3489	15,0850	456,5708	502,3319
182,4085	14,7841	456,7940	502,1376
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
106,9085	0,0743	33,5381	26,7272
108,8358	0,0774	33,5588	26,7188
109,7443	0,0787	33,5911	26,6781
110,1226	0,0803	33,5881	26,6267
110,3208	0,0795	33,5830	26,5930
109,4920	0,0798	33,5489	26,5438
108,3036	0,078	33,5718	26,6247
106,6068	0,0788	33,6125	26,6108
105,6981	0,0795	33,6567	26,7240
104,8498	0,0793	33,6312	26,6798
104,7776	0,0810	33,6031	26,6017
105,2559	0,0814	33,6352	26,6279
106,5637	0,0825	33,7260	26,7040
107,9365	0,0851	33,6865	26,5915
110,8420	0,0846	33,7537	26,6485
114,2550	0,0849	33,7300	26,6006
117,3468	0,0853	33,7080	26,4712
120,4487	0,0852	33,6621	26,4615
122,5028	0,0823	33,6476	26,4082
122,2809	0,0810	33,6179	26,4448

TABLE 50. MCMINN STREET – MANTON STREET CARPARK (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

MCMINN STREET – FRANCES BAY ROUNDABOUT			
DAY	START	LAT	-12,46464
25-mar	14:54:00	LONG	130,847275
	FINISH		
	15:04:00		
	TIMESTEP		
	30 s		

METEO STATION MEASUREMENTS AND PROCESSING					
Wdir [°]	Ws [m/s]	Ta [°C]	P [hPa]	Tdew [°C]	RH [%]
221	0,39	28,1	1005	25,6	86,3
211	0,09	28,2	1005	25,5	85,3
116	0,38	28,2	1005	25,8	86,9
107	0,58	28,3	1005	26	87,4
247	0,94	28,3	1005	26,2	88,4
183	0,58	28,4	1005	26,2	87,9
77	0,39	28,4	1005	26,1	87,4
234	0,82	28,5	1005	25,8	85,4
192	1,17	28,5	1005	25,4	83,4
230	0,33	28,5	1005	25,3	82,9
312	0,12	28,5	1005	25,6	84,4
202	0,06	28,5	1005	25,8	85,4
237	0,26	28,6	1005	26,2	86,9
254	0,46	28,6	1005	25,5	83,4
253	0,42	28,6	1005	25,9	85,4
258	0,62	28,6	1005	25,8	84,9
256	0,62	28,6	1004,9	26	85,9
231	0,57	28,6	1004,9	26,3	87,4
108	0,29	28,6	1004,9	25,7	84,4
252	0,61	28,6	1004,9	26,3	87,4

NET RADIOMETER MEASUREMENTS AND PROCESSING			
θ↑PYR [W/m²]	θ↓PYR [W/m²]	θ↑PYRG [W/m²]	θ↓PYRG [W/m²]
173,9835	34,5413	455,2282	500,2764
170,0708	34,2910	455,2818	500,3478
167,0116	33,9286	456,3203	500,6261
164,3894	33,7162	457,4034	501,0190
162,4901	33,6409	457,7214	501,4038
160,9999	33,5413	458 3131	501,5053
160,3295	33,5413	457,9863	501,3047
160,8767	33,6661	457,5778	501,5475
162,3539	33,8790	457,1165	501,3143
165,5641	34,0660	457,2211	501,2492
170,6045	34,6161	457,0888	501,5468
176,7567	35,1777	458,0699	501,2912
183,9171	35,6277	458,2778	501,5821
190,6782	36,0898	456,5662	500,6581
196,8347	36,4522	456,3235	500,4541
202,6825	36,6392	456,1091	500,6319
208,3133	36,8884	454,7574	499,9249
212,9445	37,4627	453,7756	499,5492
216,5682	38,2487	452,7974	499,3100
219,9867	39,1844	453,3869	499,5722
Rnet [W/ m²]	**α**	**Tsrf [°C]**	**Tsky [°C]**
94,3941	0,1985	33,3332	26,1878
90,7139	0,2016	33,3442	26,1966
88,7773	0,2032	33,3868	26,3671
87,0576	0,2051	33,4469	26,5447
85,1668	0,2070	33,5058	26,5968
84,2664	0,2083	33,5213	26,6936
83,4697	0,2092	33,4960	26,6401
83,2410	0,2093	33,5277	26,5733
84,2770	0,2087	33,4921	26,4977
87,4699	0,2058	33,4821	26,5148
91,5304	0,2029	33,5276	26,4932
98,3577	0,1990	33,4886	26,6538
104,9852	0,1937	33,5330	26,6878
110,4966	0,1893	33,3917	26,4075
116,2519	0,1852	33,3605	26,3677
121,5205	0,1808	33,3877	26,3325
126,2574	0,1771	33,2794	26,1104
129,7082	0,1759	33,2218	25,9487
131,8068	0,1766	33,1851	25,7874
134,6170	0,1781	33,2253	25,8846

TABLE 51. MCMINN STREET – FRANCES BAY ROUNDABOUT (TIME AND SPACE DETAILS, TERRESTRIAL SENSOR NETWORK OUTPUTS AND PROCESSING).

INTRODUCTION TO MITIGATION TECHNOLOGIES

Heat Mitigation Program
Darwin, Northern Territory

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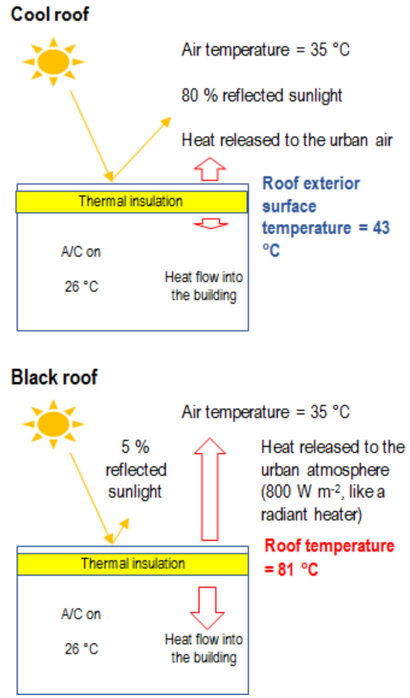
Introduction to mitigation technologies

Cool Roofs

What's a cool roof?
Nothing complicated. A cool roof (or reflective) is just a roof that reflects most of sunlight and, thus, does not overheat – stays cool – under the sun. It can be a white or a cool coloured surface. The latter looks like a traditional roof, but uses pigment that absorb less solar radiation, yielding to a lower surface temperature.



Direct benefits
- Save energy in air conditioned buildings
- It allows to downsize the air conditioning plants
- Improve indoor thermal comfort in unconditioned poorly insulated buildings (lower ceiling temperature and indoor air temperature)
- Reduce the heat released in the urban atmosphere → mitigate the local urban climate
- Delay global warming (10 tons of CO_2 offset by 100 m^2 white roof)
- Increase the service life of the roof (less thermal shocks and thermal cycles than for a traditional roof)

Indirect benefits
- Reduce demand at power plants (and their need)
- Reduce risk of black outs

- Reduce air pollution

By how much they mitigate urban heat islands?
The peak reduction of urban air temperature is, in average, of 1 °C with all roofs cool.

When a roof is cool?
A cool roof has high solar reflectance (or albedo, i.e., the ratio of reflected to incident solar radiation) and high thermal emittance (i.e., the ability of a surface to release thermal radiation). Even when aged, its solar reflectance shall be greater than 0.50 and its thermal emittance is about 0.90.

Is it complicated and risky new technology?
Cool surfaces have been used in the Mediterranean and Bahamas since centuries. New materials just offer better performance, but the principle is the same.

Cool Pavements

What's a cool pavement?
A cool pavement is a street pavement that absorbs less solar radiation of traditional dark asphalt concrete pavements. Thus, it heats less and releases less heat in the urban environment.
From measurements in the scientific literature, in peak summer conditions, a traditional dark asphalt concrete pavement, having albedo of 0.15 when aged, may exceed 60 °C. A cool pavement with albedo of 0.40, instead, in the same conditions, is cooler by even 8 °C.

Direct benefits
- Mitigate the local urban climate
- Reduce the generation of photochemical smog at street level
- Improve the thermal comfort
- Reduce the energy needs for street lighting

By how much they mitigate urban heat islands?
The peak reduction of urban air temperature is, in average, of 1.3 °C.

Street Shadings

What is street or urban canopy shading?

Canopy shading is reducing the solar radiation reaching the street level.

Direct benefits of canopy shading

- Mitigate urban heat islands increasing the albedo of urban canopies and reducing the sunlight reaching street pavements and vehicles and buildings

By how much they mitigate urban heat islands?

Their performance largely depends on design. Many real-world examples demonstrated that they can locally eliminate the heat stress risk.

Tree Planting

What is tree planting?

Tree planting is a conventional practice in urban landscaping. With suited design, the mitigation potential of urban trees can be maximized.

Direct benefits of urban trees

- Mitigate urban heat islands
- Provide shading without reducing air circulation
- Improve outdoor thermal comfort
- Reduce the sunlight reaching street pavements, vehicles and buildings

By how much they mitigate urban heat islands?

In average, the peak ambient temperature reduction is of 1.5 °C.

Greenery

What is urban greenery?

Urban greenery consists in exploiting available spots to increase the vegetative cover in urban areas, with grass or other vegetation, from bushes to trees.

Direct benefits of urban greenery

- Mitigate urban heat islands
- Improve the outdoor thermal comfort
- Absorb CO_2 and pollutants
- Reduce the storm-water runoff
- Large green spots create cool islands
- Perform as acoustic absorbers
- Help to safeguard biodiversity in urban areas
- Offer recreational areas

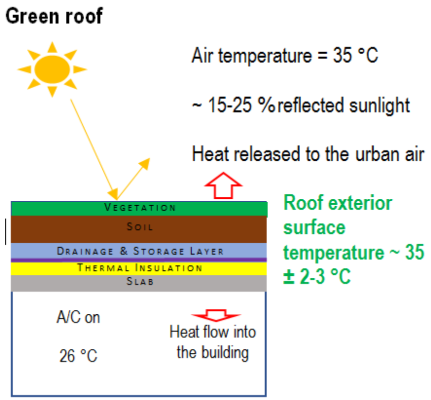
By how much they mitigate urban heat islands?

From the scientific literature, the peak reduction of urban air temperature is, in average, of 1 °C.

Green Roofs

What's a green roof (or eco-roof)?

Green roofs couple to a traditional roof assembly a root protection, storage and drainage layer, filtering layer, growing medium and vegetation. They can be intensive, light intensive or extensive. The first require intensive maintenance, with thick soil (usually more than 50 cm) and bushes or trees. Extensive green roofs need little maintenance, with 20 cm or less of lightweight and with succulent plants such as sedum, grass or light shrub.



Direct benefits of green roofs

- Reduce both heating and cooling energy needs of buildings and peak power demand
- Dump and shift in time the peak heat flow and surface temperatures
- Improve indoor thermal comfort in poorly insulated buildings
- Reduce the storm-water runoff
- Reduce the heat released in the urban atmosphere → mitigate the local urban climate
- Absorb CO_2 and pollutants
- Increase the service life of the roofing membrane
- Help to safeguard biodiversity in urban areas
- Offer rooftop recreational areas

By how much they mitigate urban heat islands?

The peak reduction of urban air temperature is, in average, of 0.6 °C with all roofs green.

What about design?

Green roofs require careful design. They can be installed only on buildings that can bear the additional load. Vegetation, maintenance and irrigation type and frequency shall be carefully selected for the climate context of application.

Water Sprinkling

What is water sprinkling?

Spraying water is an effective local countermeasure to provide relief during hot days, minimizing the thermal discomfort. Water is supplied directly into the air and evaporation takes place while the cool air is descending, providing comfort.

Direct benefits of water spraying

- Local mitigation of hot spots
- Improve the outdoor thermal comfort

By how much they mitigate local hot spots?

From the scientific literature, the peak reduction of air temperature is, in average, of 6.5 °C. Their efficiency depends largely on the type and size of nozzles and on the environmental conditions.

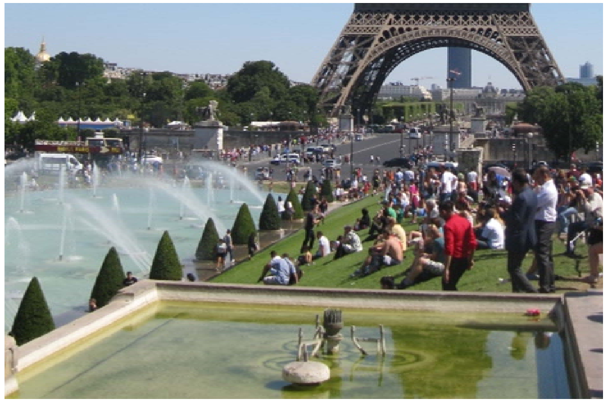
Fountains

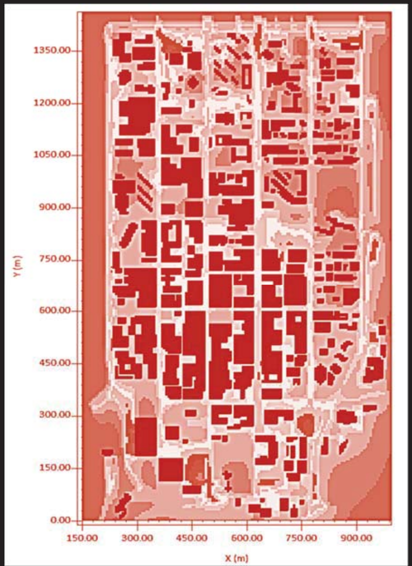
Aren't fountains just ornamental?
Fountains with a basin or a pond can effectively contribute to mitigate heat islands.

Direct benefits of water fountains

- Local mitigation of hot spots
- Improve the outdoor thermal comfort
- Recreational functions

By how much they mitigate local hot spots?
From the scientific literature, the peak reduction of air temperature is, in average, of 2.5 °C, naturally, depending on their size and local environmental conditions.





Heat Mitigation Program
Darwin, NT

INTRODUCTION AND REFERENCE SCENARIO

UNSW

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INTRODUCTION

To counterbalance the impact of urban overheating, mitigation techniques have to be designed and implemented at the city scale. The aim of the mitigation technologies is to decrease the heat gains and increase the heat losses in the city. Fourteen mitigation technologies and combination of technologies have been designed and evaluated. The technologies considered aimed to increase the reflectivity of the opaque surfaces in the city, like cool roofs and cool pavements, increase the greenery, apply solar control devices, and use of water for evaporative cooling. Several combinations of technologies are also studied. All scenarios are quantitively evaluated using detailed climatic simulation codes. The spatial distribution of the ambient temperature, wind speed and direction and surface temperature are calculated under representative climatic conditions. Details and characteristics of the scenarios are given in the following chapters. A reference scenario that reflects the current situation in the city has been also developed. The distribution of the main climatic parameters is calculated for the same climatic conditions as for the mitigation scenarios. The results of the reference scenario are used to evaluate the potential temperature decrease achieved when the proposed mitigation scenarios are applied. The present chapter, reports he main characteristics, assumptions, inputs ad results obtained for the reference climatic scenario.

.

ENVI-met Simulation

- Simulations have been carried out using the software ENVI-met V4.1.2 built from 07 March. This program is a three-dimensional microclimate model designed to simulate the surface, plant and air interactions in an urban environment. This computer program is an accurate tool to simulate the distribution of the main climatic parameters in the urban environment.

The urban zone of Darwin CBD (12.42°S, 130.89°E) shown in Figure 1 was selected for simulation. Simulations are performed for a representative warm summer day under various climatic conditions. The corresponding climatic data are taken from Darwin airport station based on the records of the last 10 years (elevation 30m above the sea level). Darwin airport is located approximately 6 km north-east from the CBD. The average maximum outdoor temperature for the representative warm summer day was taken as 34°C and the relative humidity was about 56%.

Figure 1. Map of the area selected for the simulation

Inputs and Assumptions of the simulation model

The prevailing wind is North-West with two different wind speed of approximately 5m/s and 1m/s. The simulation was performed at the hottest hour of the day (14:00:00). The model has been made applying the standard values of the urban environment in the city of Darwin, especially regarding radiative properties of buildings; the albedo of the building surface materials (roofs and walls) was selected as 0.2 in the actual (base case) scenario. The model has been created with the Area Input file editor of the ENVI-met® rotated of 45° counter clockwise, according to the main direction of development of the roads. The modelled area has the following dimensions: width 780 m and length 1390 m. The spatial resolution used in the simulations is 6 m horizontally. The area has been rendered with a 250 × 250 × 25 (x-y-z) cells, with the following size: dx = 6 m, dy = 6 m, and base dz = 0.5 m. The grid at the z axis is telescopic with a thicker cell near the ground, allowing a better accuracy for edge effects. The base height of dz is 0.5m and the telescoping grid increase factor is 20%. The telescoping effect allows to have the highest building height of 80 m in the model. The height of 3D model top is 179.68 m, which is at least twice the height of the tallest building in the model (Envi-met, 2017). For the modelling of the vegetation, two different plant types have been employed: tree 15m tall, very dense foliage, distinct crown layer, and grass with average density, 20 cm tall. The obtained results of the simulation are presented in the following sections (See Parts 2-14).

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 pavements Albedo=0.2, Loamy soil Albedo=0.15, 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 open space
3	Global albedo 0.6	Global Albedo=0.6. Greenery < 10 % of the total pavements and open space
4	Cool pavement	Albedo of streets and pavements=0.5, Greenery < 10 % of the total pavements and open space
5	Shading	Albedo of streets (Asphalt)=0.34, Albedo of concrete pavement=0.44, Greenery < 10 % of the total pavements and open 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 open space
9	Green roof	Green roof in all buildings
10	Water fountain	Application of water fountain on The Mall
11	State square	Replacing car parks with greenery, removing Chan building, application of water fountain in Smith street
11	Combined scenario	Global albedo=0.6, Greenery 30%, and Shading
12	Combined scenario with water fountain	Global albedo=0.6, Greenery 30%, Shading, and water fountain across the mall
14	Combined scenario-Cold and dry season	Global albedo=0.6, Greenery 30%, and Shading

Description of the Scenarios

For evaluating the urban microclimate effects, fourteen different mitigation scenarios, described in Table 1, have been considered in the model. The scenarios investigated the impact of cool pavements (Albedo of pavement =0.5), cool roofs (Albedo of roof =0.85), global increase of the albedo to 0.4 and 0.6, increase of the urban greenery to occupy 20% and 30% of the open spaces, providing shading use of green roofs, and a set of proposed changes in the State square. The global scenario investigated here refers to combination of increase of albedo to 0.6, application of shading on vertical streets and 40% greenery in open spaces (Albedo walls and roofs=0.6, albedo vertical pavements=0.72).

The simulation run for two prevailing wind directions: North westerly wind which corresponds to the highest levels of the average ambient temperature in the city and South easterly winds which refers to the lowest average ambient temperatures in the city. All simulation scenarios and climatic conditions were kept unchanged for the two prevailing wind directions. The ambient temperature, wind speed, and surface temperature are obtained and the absolute air temperature difference between each scenario and the base case scenario is derived and discussed in the following sections (see Part 2-14). The combined scenario was also simulated for the cold/dry season.

Reference model

- Simulation results for the base case model is presented in following section.

Ambient temperature (◦C)

NW winds

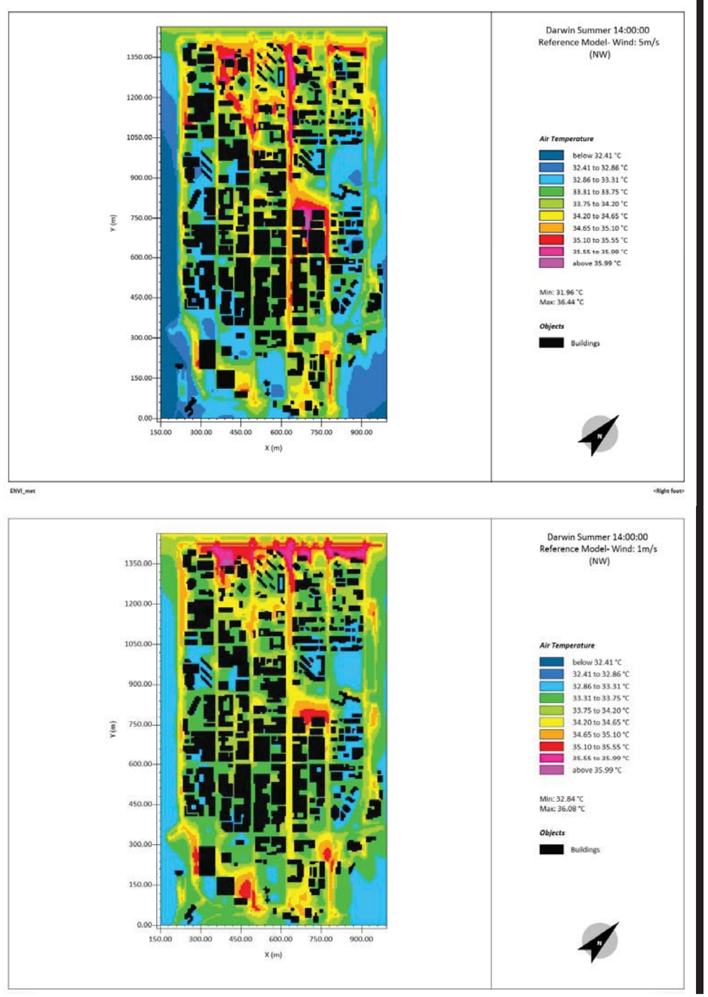

Figure 2. Reference Case: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

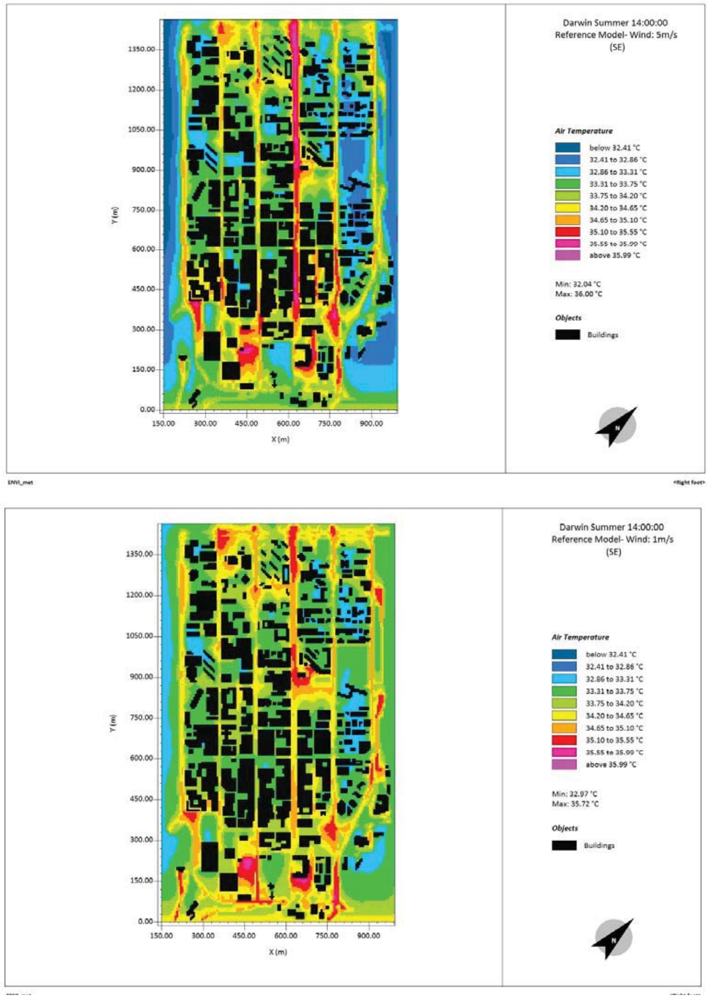

Figure 3. Reference Case: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The model has been made by applying standard values of the urban environment in Darwin. Radiative properties of buildings and pavements include: Albedo roofs = 0.2, Albedo walls = 0.2, Asphalts Albedo=0.05, Concrete pavements Albedo=0.2, Loamy soil Albedo=0.15. Grass is employed for the greenery in the simulation of the base case scenario. The simulated distribution of the ambient temperature in the reference scenario is given in Figure 2 and 3. Thermal maps of the analyzed area are shown, considering the warmest moment of the day (14:00:00 PM). The ambient temperature at the street level of the open spaces (1.46 m above the ground) ranges between 31.9°C to 36.4°C in the reference model. The maximum temperature is obtained with North westerly winds at the speed of 5m/s. Comparison of the 5m/s and 1m/s maps highlights the effects of convection in the study area. Tables 2 and 3 summaries the minimum and maximum temperatures in the reference scenario (whole area) for North westerly and South easterly winds.

Table 2. Statistical summery of the mitigation results – North westerly 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	-	-	-	-	-	-

Table 3. Statistical summery of the mitigation results – South easterly 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	-	-	-	-	-	-

Surface temperature (°C)

NW winds

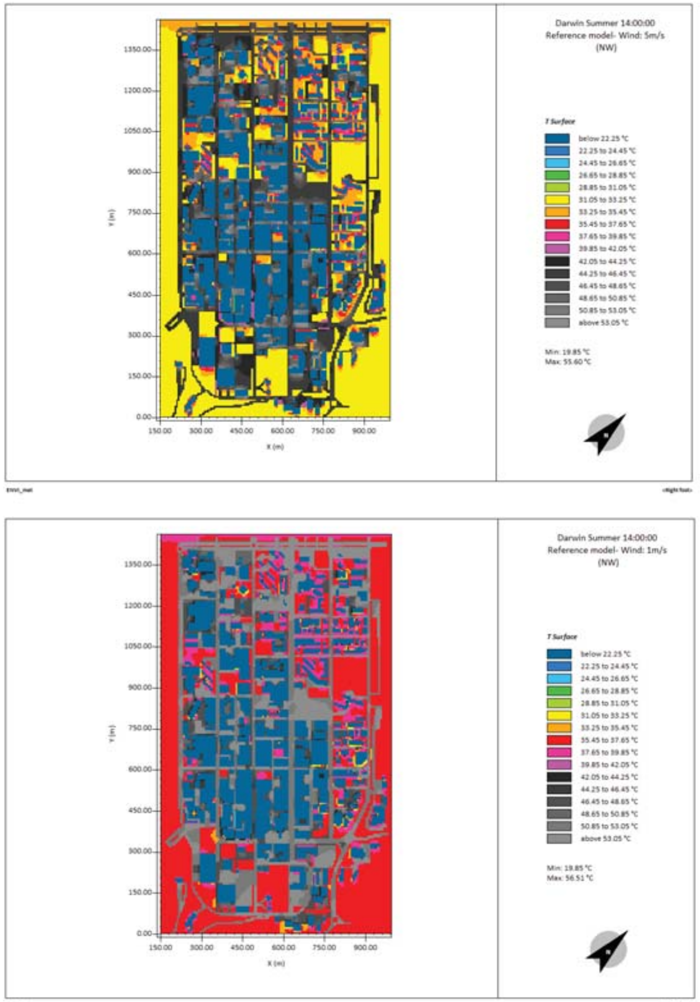

Figure 4. Reference Case: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

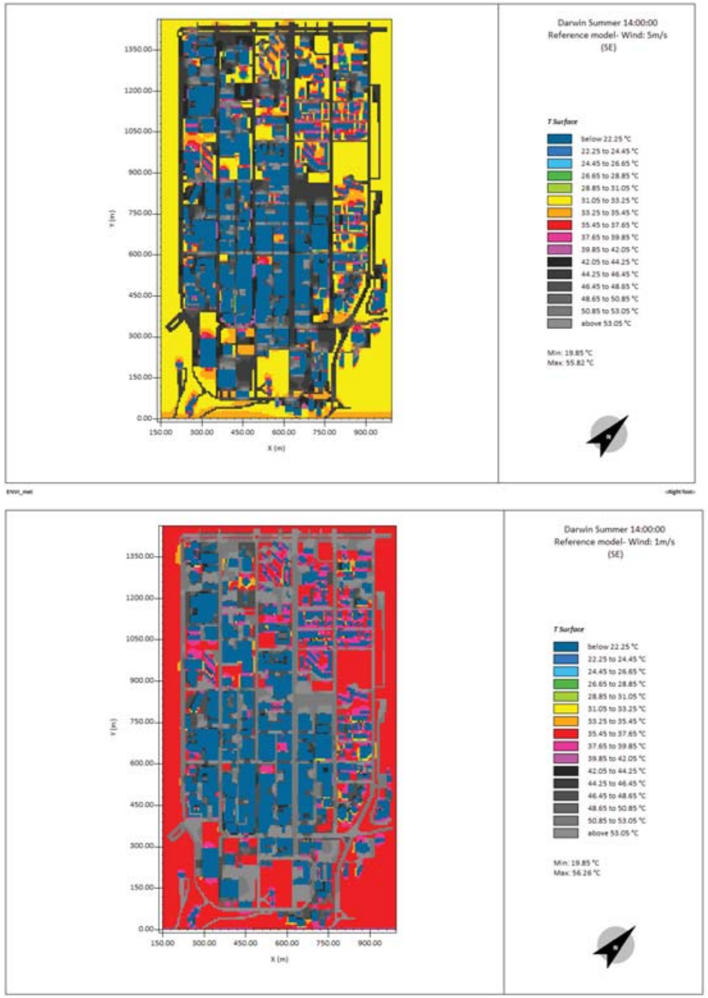

Figure 5. Reference Case: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature at 14:00:00 in the reference scenario is given in Figure 4 and 5 for North westerly and South easterly winds and for the speed of 1m/s and 5m/s.

It is shown that the surface temperature reaches to 56.5°C in the asphalt car parks and pavements in the reference model when the air speed is 1m/s and wind direction is from North west. Figure 4 and 5 illustrates that the main streets and car parks have highest surface temperature because of a longer period of direct exposure and the asphalt material used. The surface temperature is generally lower in case of the higher wind speed (5 m/s) compared to that when wind speed is 1 m/s in the refernce scenario. The maximum and minimum surface temperature ranges from 19.85°C to 55.60°C for the North westerly winds at the speed of 5m/s. The maximum surface temperature for the same wind speed from South east reaches to 55.82°C. The maximum surface temperature when the wind speed is taken as 1m/s is 56.51°C and 56.26°C for North westerly and South easterly winds, respectively.

Wind speed (m/s)

NW winds

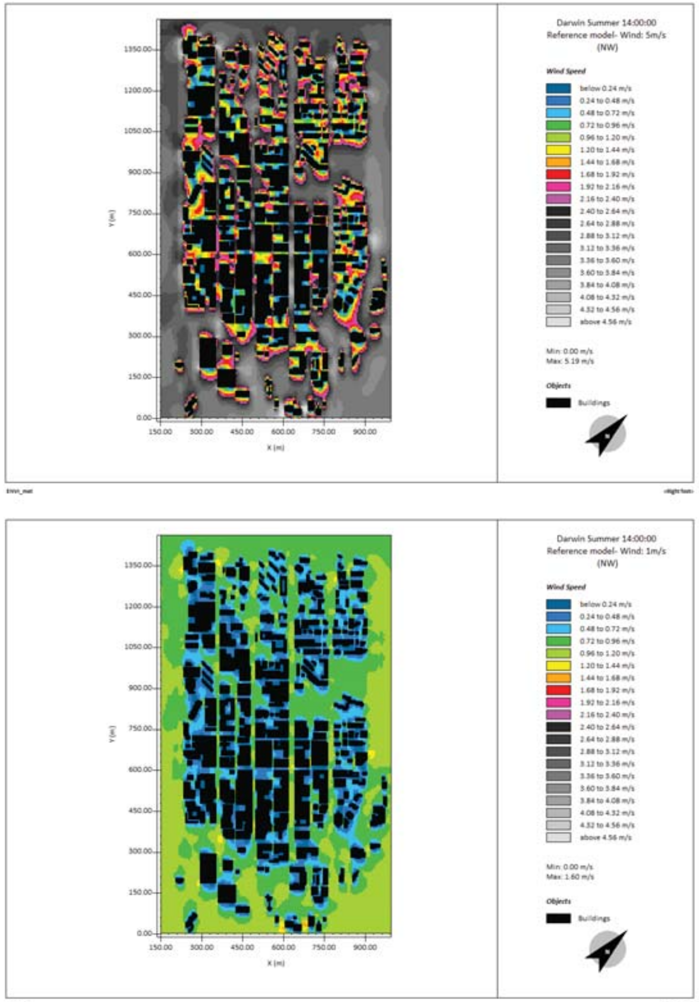

Figure 6. Reference Case: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

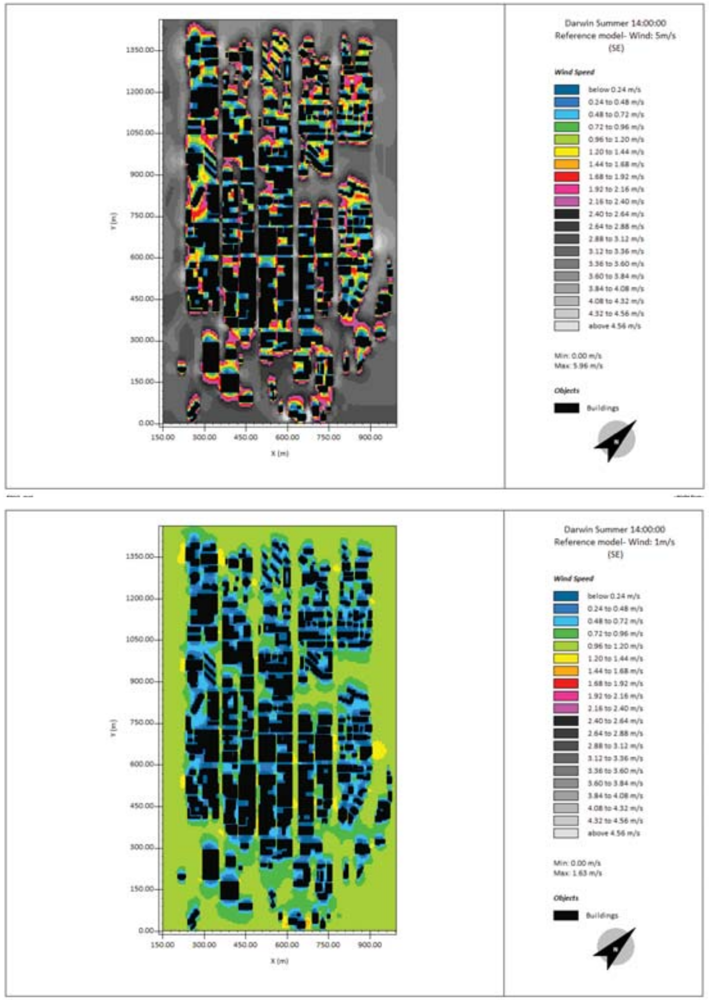

Figure 7. Reference Case: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 6 and 7 show the wind speed distribution in the simulation of the reference model. The maximum wind speed observed when the model was simulated for the South easterly winds is higher than that for the North westerly winds. It has been shown that the wind speed in open spaces and major car parks of the CBD is mostly above 2.40 m/s and 0.72 m/s in the reference scenario with 5m/s and 1m/s winds, respectively. The maximum wind speed in all conditions occurs in a number of locations, mainly in the Central part of MacMinn street, northern and southern part of Esplanade street, and central part of the Cavenagh street.

Concluding remarks

The reference scenario investigated here, reflects the current situation in the city of Darwin under two wind speeds and prevailing wind directions during summer. The results of the reference scenario are used to evaluate the potential temperature decrease achieved when the proposed mitigation scenarios are applied. The results of the reference scenario indicate that ambient temperature varies between about 32.00°C to about 36.40°C in urban areas when wind speed is taken as 5m/s. The ambient temperature falls within a range of about 32.80°C to about 36.00°C for the wind speed of 1m/s in the refernce scenario.The maximum surface temperature of asphalt pavements (parking area) reaches to above 55.00°C and 56.00°C with the wind speed of 5m/s and 1m/s, respectively.

Heat Mitigation Program
Darwin, NT

MITIGATION SCENARIO 1: Use of Cool Roofs

UNSW

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[redacted]

Reflective or cool materials present a very high reflectance to solar radiation together with a high emissivity coefficient. Lower absorption of solar radiation and increased infrared emission keep the surface temperature of the materials, low and decrease substantially the released sensible heat to the atmosphere. Reflective materials applied to the roof of buildings are white and may be single ply or liquids. Typical single ply products are EPDM, (Ethylene Propylenediene Tetrolymer Membrane), CPE, (Chlorinated Polyethylene), PVC (Polyvinyl Chloride), TPO, (Thermoplastic Polyolefin), and CPSE, (Chlorosulfonated Polyethylene), Liquid products are usually white paints, elastomeric, acrylic or polyurethane coatings. Four classes of reflective materials are identified: (a) Natural materials presenting a high reflectivity to solar radiation like white marbles, etc., very reflective white artificial coatings developed the recent period, colored coatings with a high reflectivity in the infrared part of the solar spectrum , and intelligent coatings doped with nanotechnological additives like thermochromics paints and PCM materials that present enhanced optical and thermal properties, The mitigation potential of reflective roofs depends on several parameters like the local climate and in particular the solar radiation intensity, the ambient temperature and humidity, wind speed and cloud cover, optical parameters like the reflectivity of the roof to solar radiation and the emissivity factor, thermal parameters like the thermal capacity and the U value of the roof, and technical parameters defining the ageing process of the reflective roofs. The present mitigation scenario investigates the climatic potential of cool roofs the CBT area of Darwin. Advanced simulation techniques have been used and the outcomes of the simulation have been compared against the corresponding results of the reference scenario to calculate the potential temperature decrease.

Ambient temperature (◦C)-NW winds

NW winds

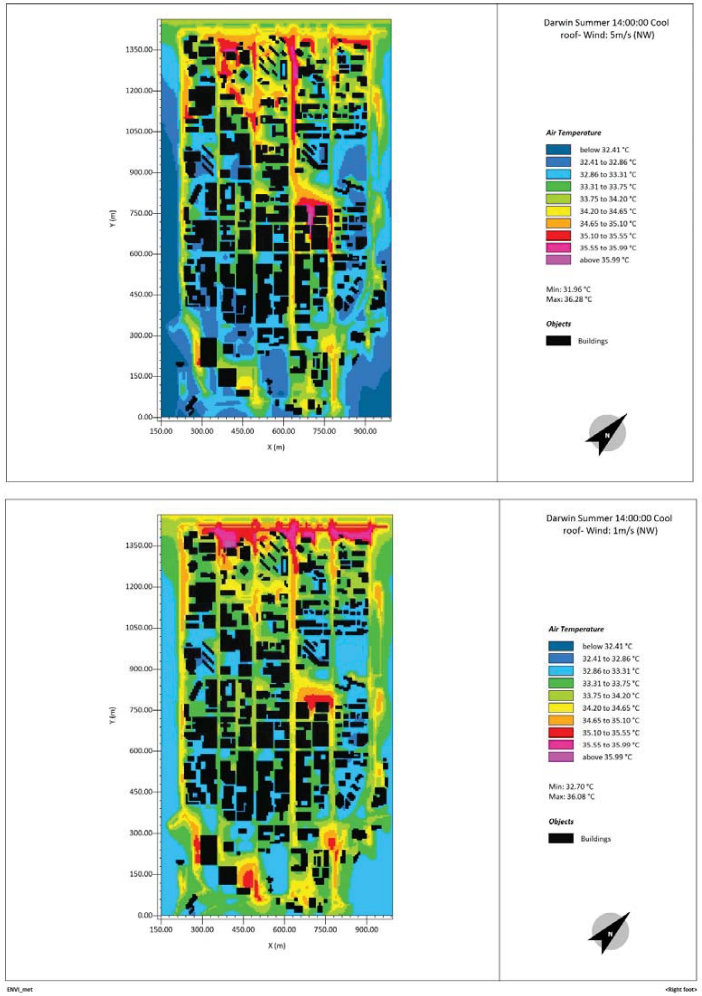


Figure 1. Cool roof: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

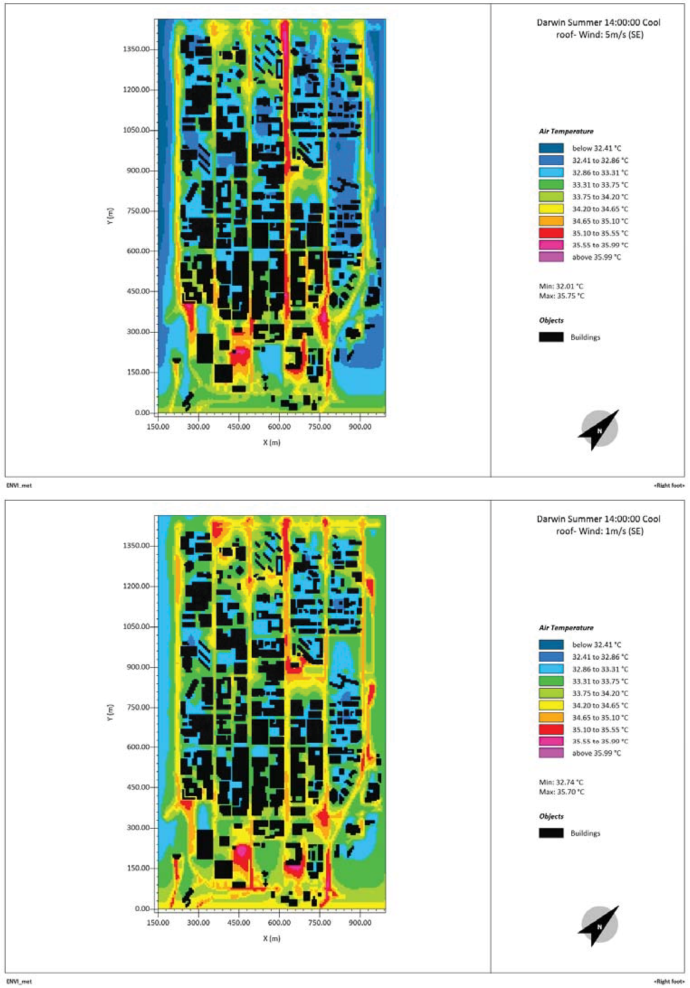


Figure 2. Cool roof: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The model was simulated for the scenario of the cool roof. The Albedo of all building roofs was taken as 0.85. The total roof area in the model is 314272 m^2.

Figure 1 and 2 show the simulated distribution of the ambient temperature when cool roofs are used in the study area. The results of simulation for wind speeds of 5m/s and 1m/s and North westerly and South easterly directions are presented. It has been shown that the ambient temperature in the study area at 14:00:00 ranges between about 31.96°C to 36.08°C at the street level of the open spaces (1.46 m above the ground level) when cool roof was employed. The minimum and maximum ambient temperatures with the wind speed of 5m/s are lower and higher than those at the speed of 1m/s. Tables 1 and 2 summaries the minimum and maximum temperatures, reduction of the maximum and minimum temperatures, and the local maximum temperature drop achieved in this scenario.

Table 1. Statistical summery of the mitigation results – North westerly 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	-	-	-	-	-	-
Cool roof	36.28	36.08	31.96	32.70	0.16	0.00	0.00	0.14	0.67	0.49

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Table 2. Statistical summery of the mitigation results – South easterly 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	-	-	-	-	-	-
Cool roof	35.75	35.7	32.01	32.74	0.25	0.02	0.03	0.23	0.70	0.59

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Air temperature difference (K)

NW winds

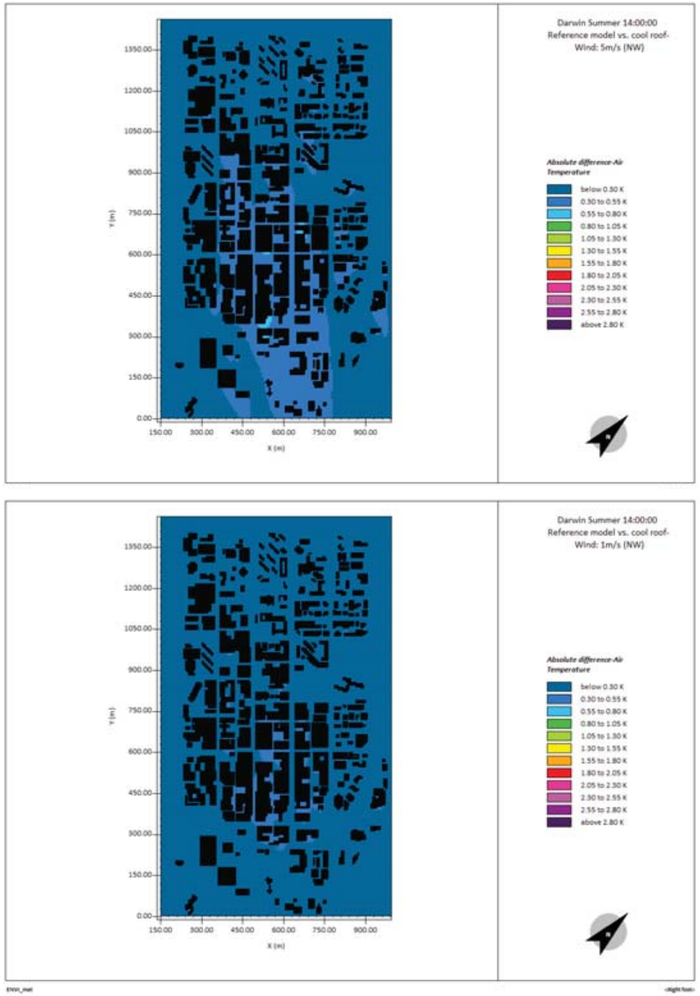


Figure 3. Cool roof: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

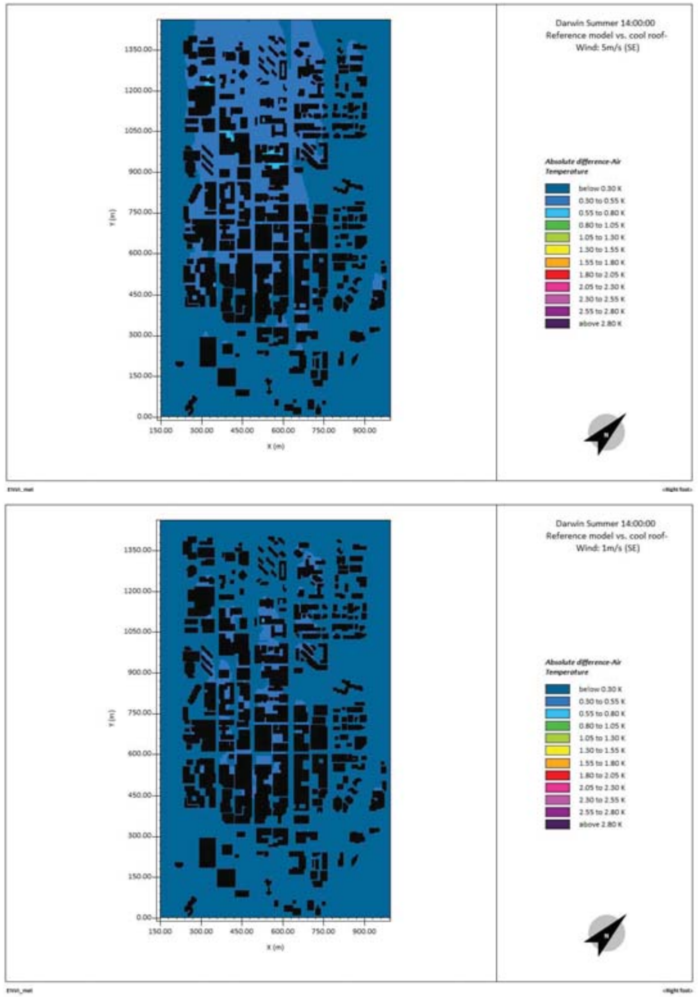


Figure 4. Cool roof: Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares the scenario of cool roof (albedo of 0.85) with the base case model. The temperature reduction distribution is given in Figures 3-4.

The absolute local maximum temperature drop achieved, when cool roof technologies (with the albedo of 0.85) are used, is 0.67(K) and 0.70 (K) for the wind speed of 5m/s and directions of North westerly and South easterly winds, respectively. The local maximum temperature reduction, when wind speed is 1m/s, is 0.49 (K) and 0.59 (K) for North westerly and South easterly winds, respectively.

Cool roofs seem to present a lower mitigation potential than cool pavements. That is mainly because "reflective roofs are located at a certain distance from the ground and cool the air above the roof. Their cooling potential at ground level depends on the capacity of the cool air to reach ground level. The taller the building the less the cooling potential of cool roofs" (Santamouris et al., 2016).

Surface temperature (°C)

NW winds

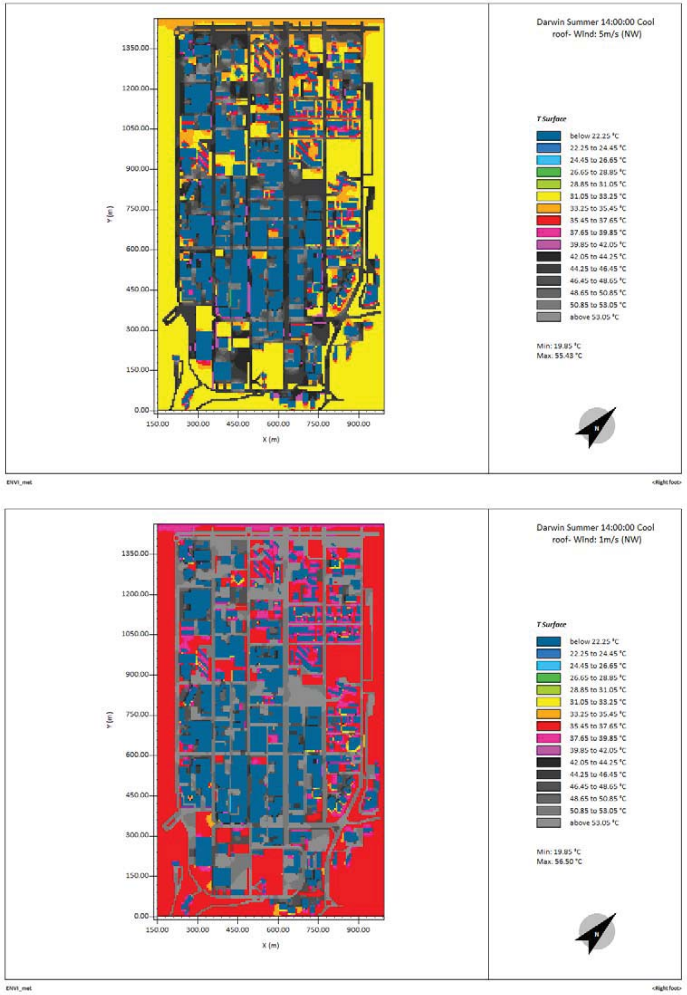


Figure 5. Cool roof: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

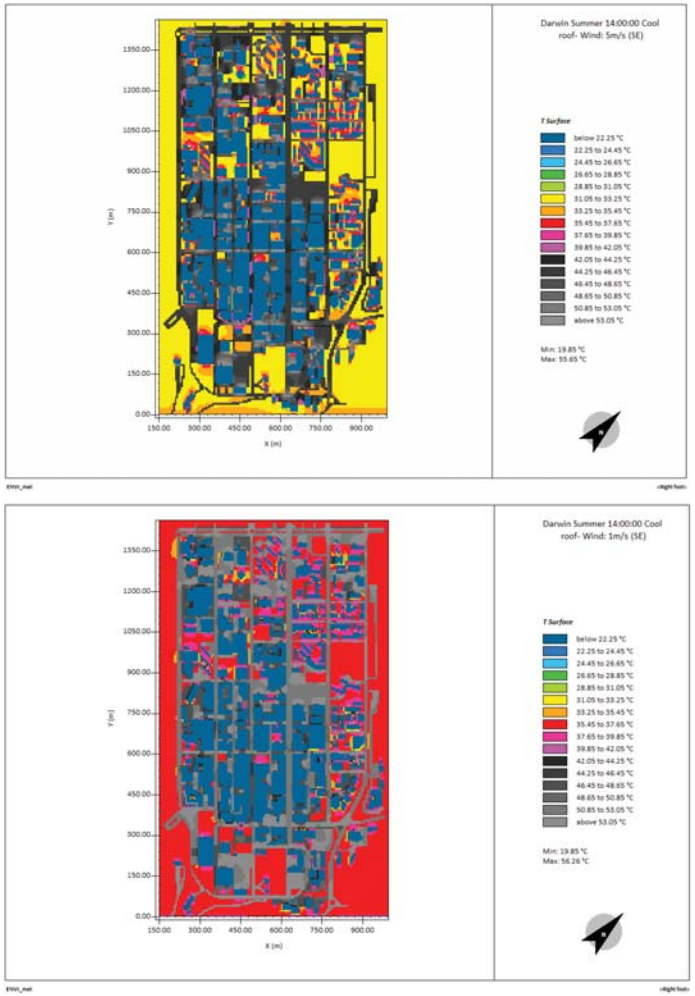


Figure 6. Cool roof: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario is given in Figures 5 and 6.

The maximum surface temperatures are 55.43°C and 55.65°C with the wind speed of 5m/s from North west and South west, respectively. These temperatures at the surface level are just slightly lower than those observed in the reference model for both wind direction at the speed of 5m/s. When wind speed is taken as 1m/s, the surface temperature seems very similar to the reference scenario.

Wind speed (m/s)

NW winds

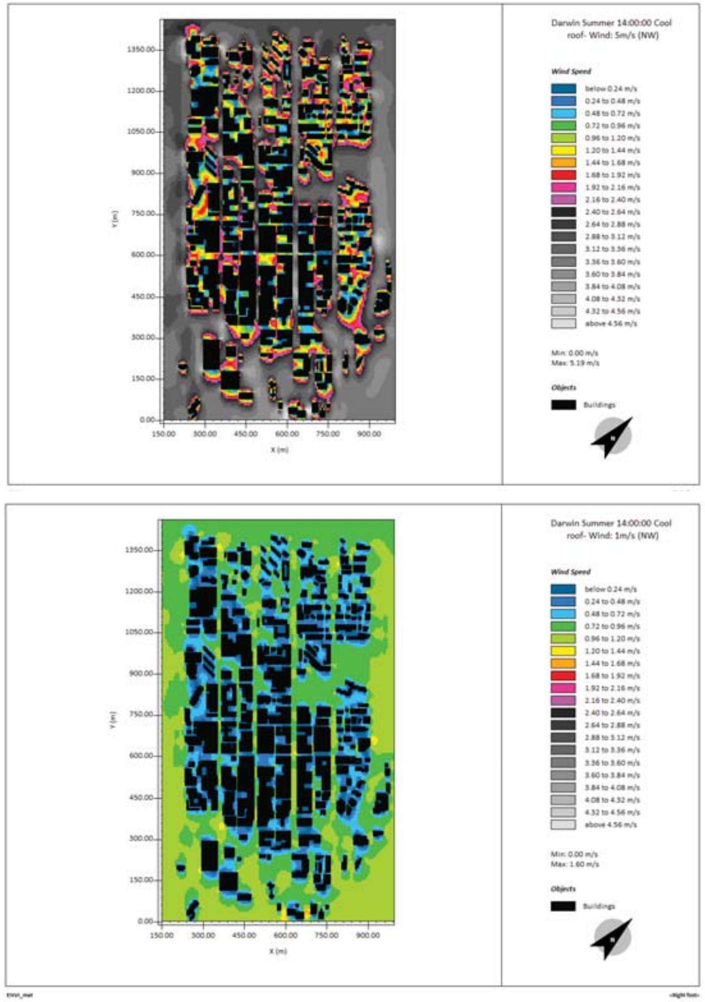


Figure 7. Cool roof: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

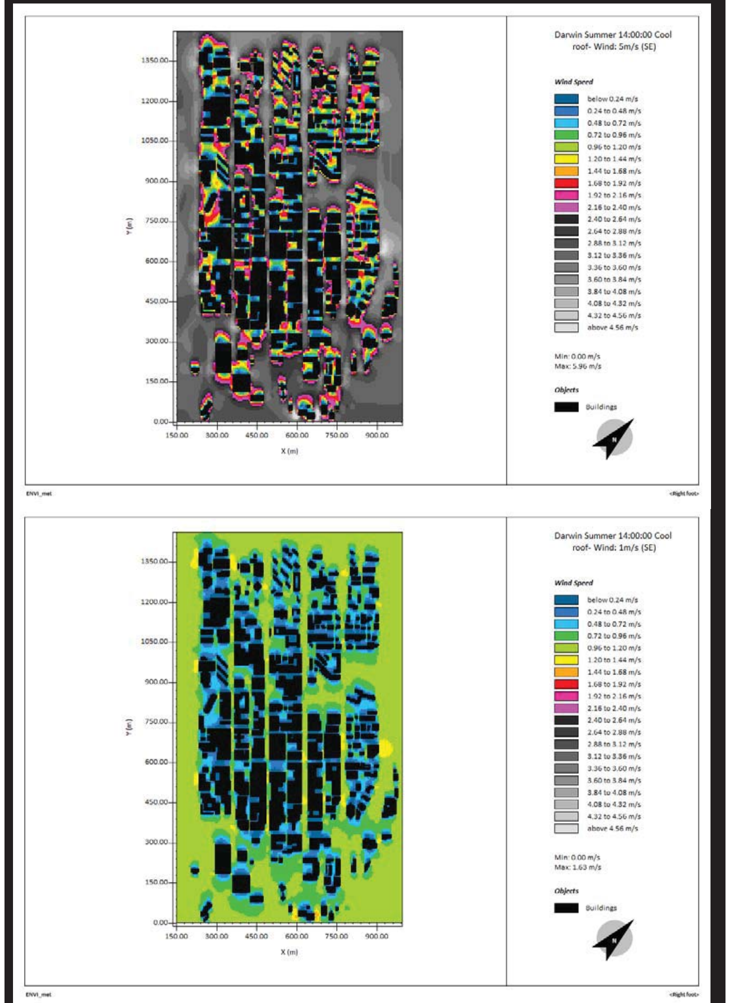


Figure 8. Cool roof: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution the study area when cool roof is used. The wind speed distribution is almost same as that obtained from the simulation of the reference scenario. It has been shown that the wind speed in open spaces and major car parks of the CBD is mostly above 2.40 m/s and 0.72 m/s in the simulations with 5m/s and 1m/s winds, respectively.

Cost

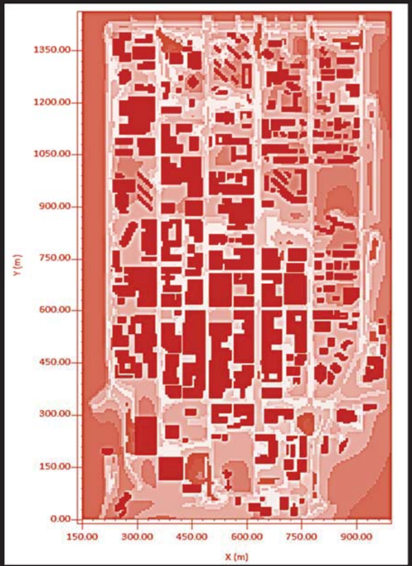
Table 3 shows the estimated cost for this scenario.

Table 3. Cost of the cool roof scenario

	Area (m2)	Cost per m² (AUS$)	Total Cost
Total building roof/floor area (m²)	314272	15	4714080
Total			4714080

Concluding remarks

The use of cool roof is investigated in Darwin CBD. It has been shown that the local maximum temperature drop achieved in this scenario is about 0.70 (K) for the wind speed of 5 m/s. The local maximum temperature decrease with the wind speed of 1m/s is slightly lower than that with the wind speed of 5m/s. The results show that the local ambient temperature decrease of 0.49 (K) and 0.59 (K) may be achieved when wind speed is taken as 1m/s and for the North westerly and South easterly directions, respectively.



Heat Mitigation Program

Darwin, NT

MITIGATION SCENARIO 2:

Use of Cool Pavements

UNSW

Project leader:

M. Santamouris

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Research team: Shamila Haddad, Giulia Ulpiani, Riccardo Paolini, Afroditi Synnefa, Francesco Fiorito, Samira Garshasbi

Decreasing the surface temperature of pavements may contribute highly to improve the thermal conditions in cities suffering from high urban temperatures. This can be achieved by replacement of conventional paving surfaces with new ones presenting much lower surface temperatures during the warm period, reconstruction, preservation and rehabilitation of the existing pavements to improve their thermal performance and shading of the paved surfaces to decrease absorption of solar radiation. Advanced materials and surfaces, known as cool pavements, have been developed and are available for use in urban environments. Cool pavements are mainly based on the use of surfaces presenting a high albedo to solar radiation combined to a high thermal emissivity (reflective pavements).

The present mitigation scenario investigates the climatic impact of cool pavements when implemented in the city of Darwin. As pavements are defined the areas of the parking lots, the streets, the pedestrian walks and all other horizontal surfaces on the ground surface. The performance of the proposed mitigation strategy is evaluated through detailed simulation techniques. The results are compared against the corresponding results obtained for the reference case, and then the potential distribution of the temperature decrease is calculated

Ambient temperature (◦C)

NW winds

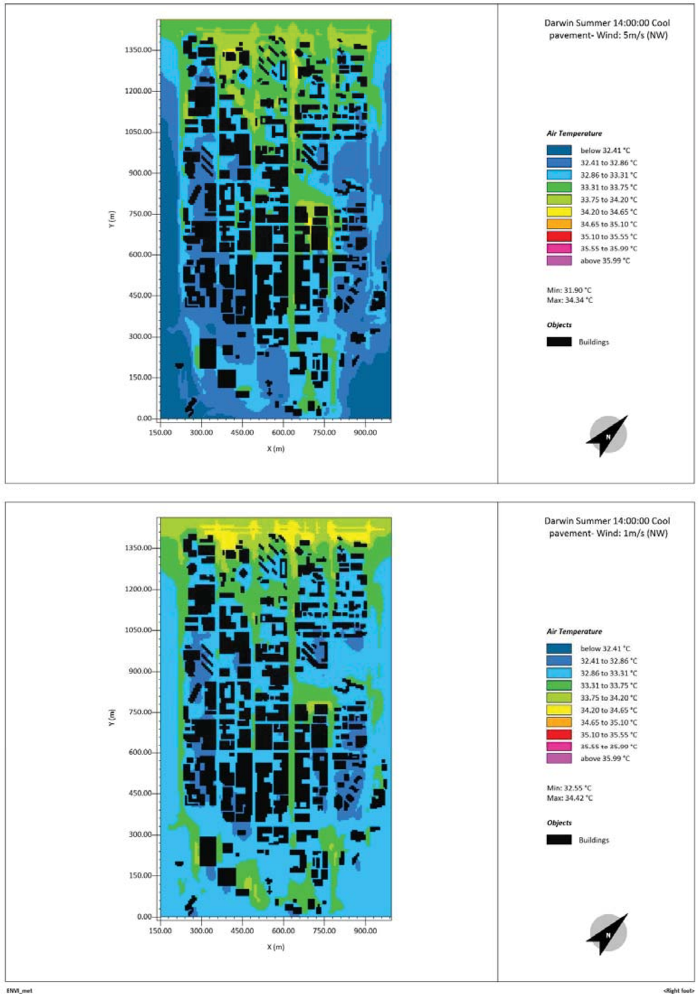


Figure 1. Cool pavement: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

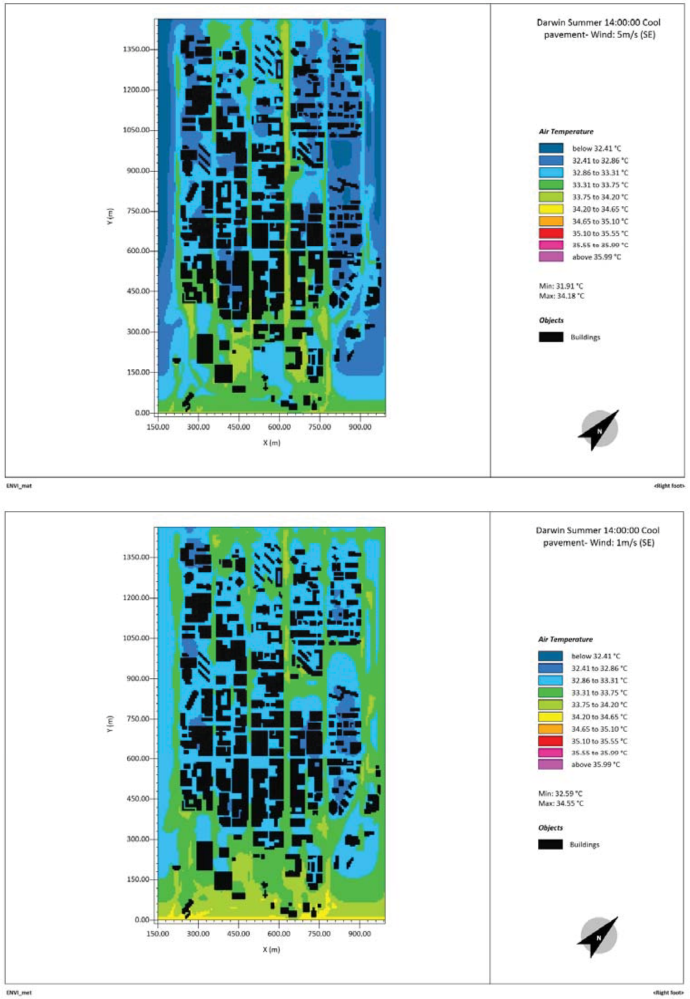


Figure 2. Cool pavement: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The average albedo of all horizontal surfaces in the city, including car parks, streets and pedestrian walks, is taken equal to 0.5.

Figure 1 and 2 shows the simulated distribution of the ambient temperature when cool pavements are used in the study area. The ambient temperature at 14:00:00 ranges between about 31.90°C to 34.55°C at the street level of the open spaces. The maximum ambient temperature in the study area, after use of cool pavements, is decreased to 34.34°C and 34.18°C for wind speed of 5m/s, which is about 2°C lower than that observed in the reference model. It should be noted that the maximum ambient temperature in the reference model was 36.44°C and 36.00°C for North westerly and South easterly winds at the speed of 5m/s, respectively. It clearly shows the significant effect of cool material used for the pavements. When wind speed is taken as 1m/s, the ambient temperature varies from about 32.55°C to 34.55°C.

Tables 1 and 2 summaries the minimum and maximum temperatures, reduction of the maximum and minimum temperatures, and the local maximum temperature drop achieved in this scenario. Reduction of the maximum and minimum temperature is given based on the difference with the reference scenario.

Air temperature difference (K)

NW winds

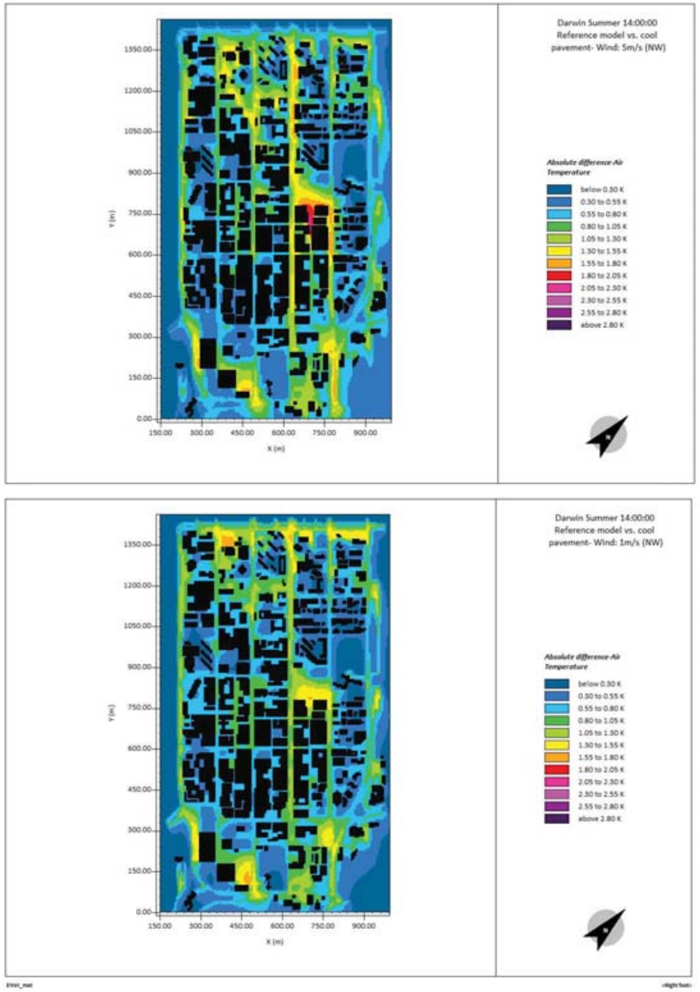


Figure 3. Cool pavement: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

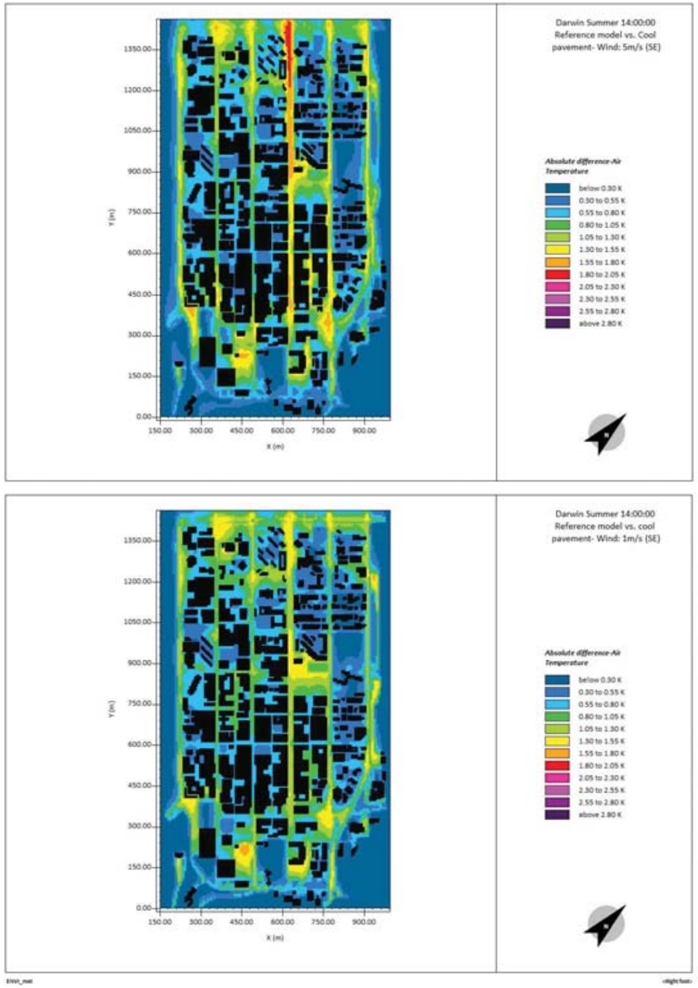


Figure 4. Cool pavement: Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares the scenario of cool pavement (albedo of 0.5) with the base case model. The temperature reduction distribution is given in Figures 3-4.

The results indicate that by implementing cool pavement with the albedo of 0.5, the local maximum temperature reduction is 2.16(K) and 1.99 (K) for the wind speed of 5m/s and directions of North westerly and South easterly winds, respectively. The local maximum temperature reduction when wind speed is 1m/s is 1.71 (K) and 1.64 (K) for North westerly and South easterly winds, respectively.

Table 1. Statistical summery of the mitigation results – North westerly 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	-	-	-	-	-	-
Cool pavements	34.34	34.42	31.9	32.55	2.10	1.66	0.06	0.29	2.16	1.71

Note: ': Maximum temperature decrease achieved based on the scenarios compared to the reference model

Table 2. Statistical summery of the mitigation results – South easterly 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	-	-	-	-	-	-
Cool pavements	34.18	34.55	31.91	32.59	1.82	1.17	0.13	0.38	1.99	1.64

Note: ': Maximum temperature decrease achieved based on the scenarios compared to the reference model

Surface temperature (°C)

NW winds

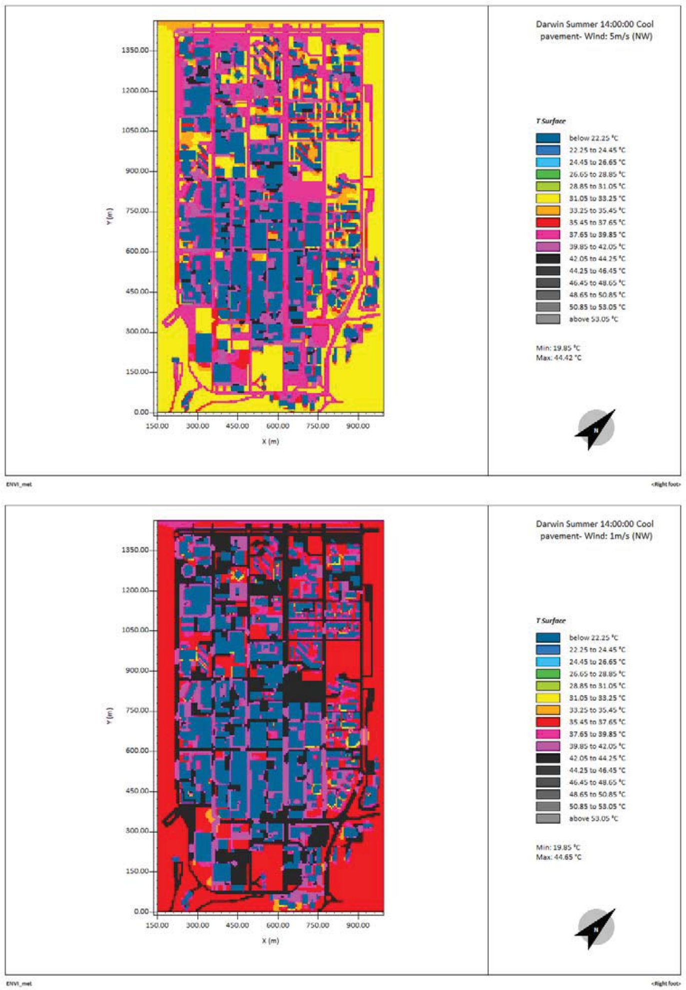


Figure 5. Cool pavement: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

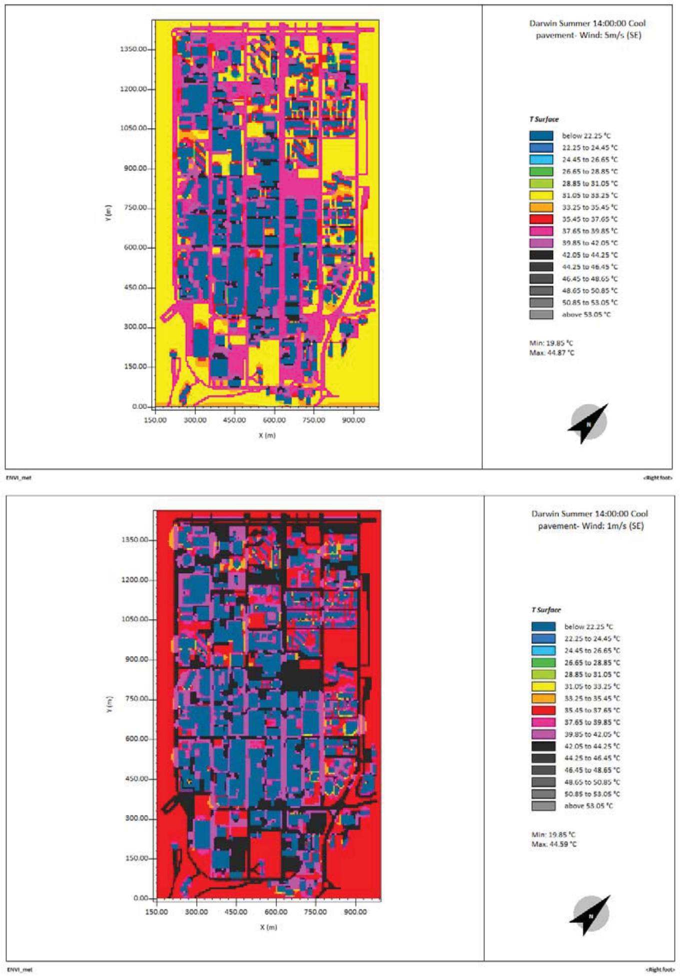


Figure 6. Cool pavement: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario is given in Figures 5 and 6. The results of surface temperature distribution are provided for two wind speeds of 5m/s and 1m/s and two wind directions from North west and South east.

The maximum surface temperature reaches to 44.87°C when cool pavement is used in the simulation. This is 10.95°C lower than that obtained in the simulation of the reference model when the air speed is 5m/s and wind direction is from South east.

The maximum surface temperature in the reference model for the North-westerly winds, varied between 55.60°C to 56.51°C (5m/s and1m/s, reactively). By using cool pavement with the albedo of 0.5, the maximum surface temperature in the same condition is reduced to 44.42°C to 44.65°C.

Wind speed (m/s)

NW winds

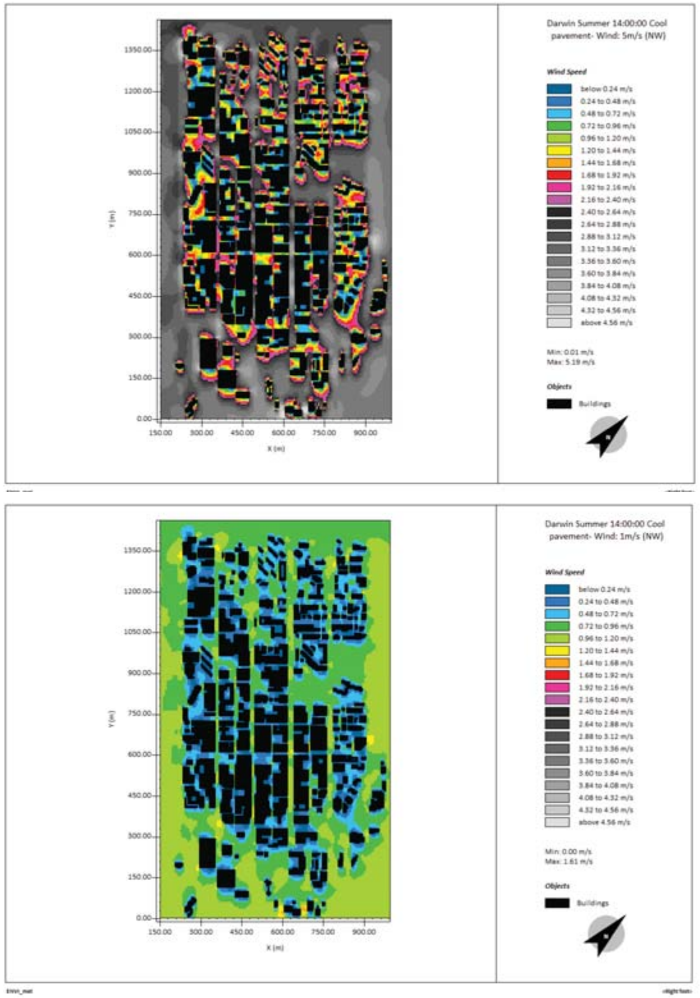


Figure 7. Cool pavement: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

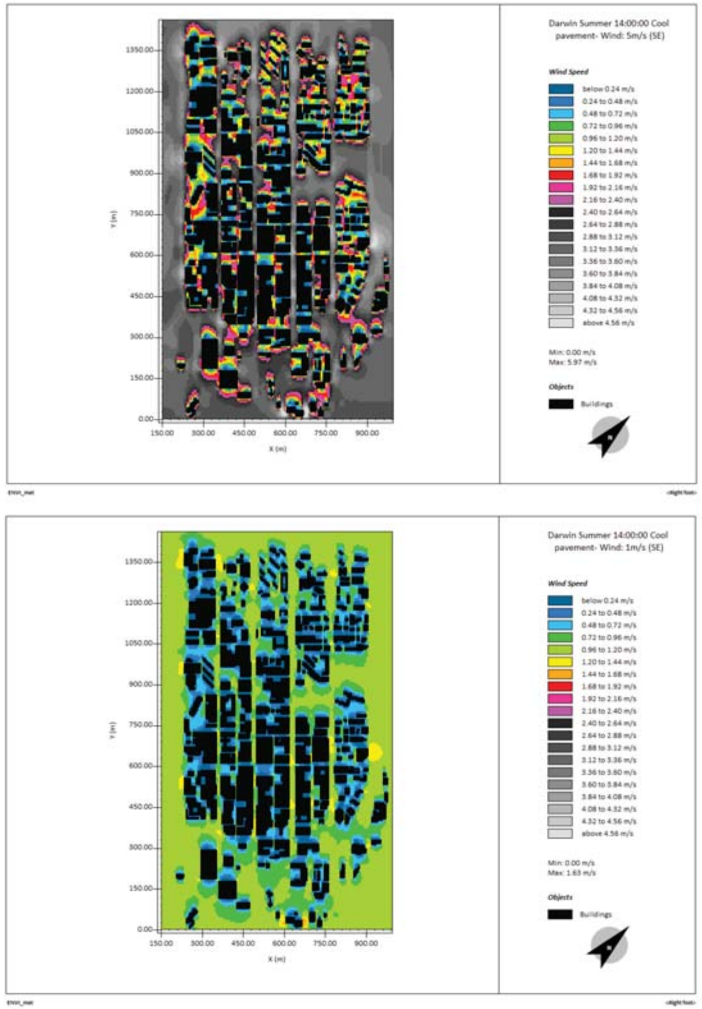


Figure 8. Cool pavement: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution when cool pavement is used in the study area. The simulation was performed for two wind speeds of 5m/s and 1m/s and two wind directions from North west and South east as shown in Figures 7 and 8. The wind speed distribution is almost same as that obtained from the simulation of the reference model.

Cost

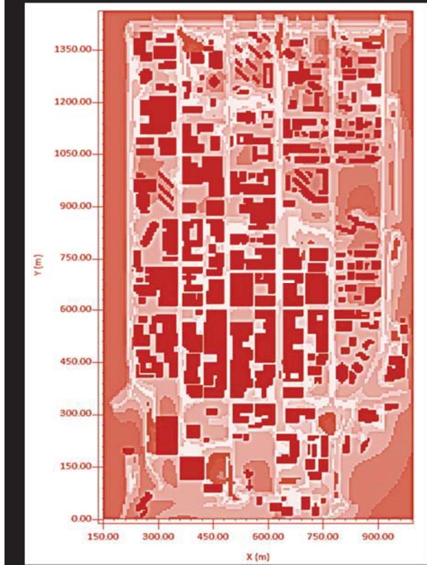
Table 3 shows the estimated cost for this scenario.

Table 3. Cost of the cool pavement

	Area (m2)	Cost per m2	Total Cost (AUS$)
Total Car park area in asphalt (m^2)	117684	30	3530520
Total area of pavements streets and other horizontal surfaces, (m^2)	652244	30	19567320
Total			23097840

Concluding remarks

This scenario investigates the climatic impact of cool pavements when implemented in the city of Darwin. The results of simulation show that the use cool pavements in the streets, pavements and parking lots is an effective strategy to improve the microclimate of urban areas. The local maximum temperature drop achieved in this scenario is 2.16 (K) and 1.99 (K) for the North westerly and South easterly winds at the speed of 5 m/s. The local maximum temperature decrease of about 1.71 (K) and 1.64 (K) may be achieved for the wind speed of 1m/s from North west and South east, respectively.



Heat Mitigation Program

Darwin, NT

MITIGATION STRATEGY 3: Increase of the reflectivity of the city. Global Albedo = 0.4 Simulated Mitigation Potential

UNSW

Project leader:
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Research team: Shamila Haddad, Giulia Ulpiani, Riccardo Paolini, Afroditi Synnefa, Francesco Fiorito, Samira Garshasbi

INTRODUCTION

It is well known and documented that large-scale change of albedo has a serious impact on the local peak ambient temperature. Increase of the albedo in a city can be achieved using materials of high diffuse solar reflectivity and high emissivity value, (Cool materials). The specific materials should be applied mainly in roofs, pavements and all other horizontal surfaces in the city. Cool materials can be pavement tiles, paints, membranes, etc. Usually present a light color, but darker colored materials can be used, provided that they present a high reflectivity in the infrared spectrum. The possible increase of the albedo of the vertical surfaces has to be moderate to avoid problems of glare and contrast. The present mitigation scenario investigates the climatic potential of global reflective technologies. The main assumption of the scenario is that the average albedo of the city increases from 0,2 to 0,4. This is a reasonable assumption that can be easily met through the replacement of the external materials used in the roofs of the buildings, the pavements and the other horizontal urban surfaces, (parking lots, etc). The climatic potential of this scenario is evaluated using advanced simulation techniques. The results are compared against the corresponding outcomes of the reference scenario and the special mitigation potential is calculated. In the chapters below all results and conclusions are presented.

Ambient temperature (◦C)

NW winds

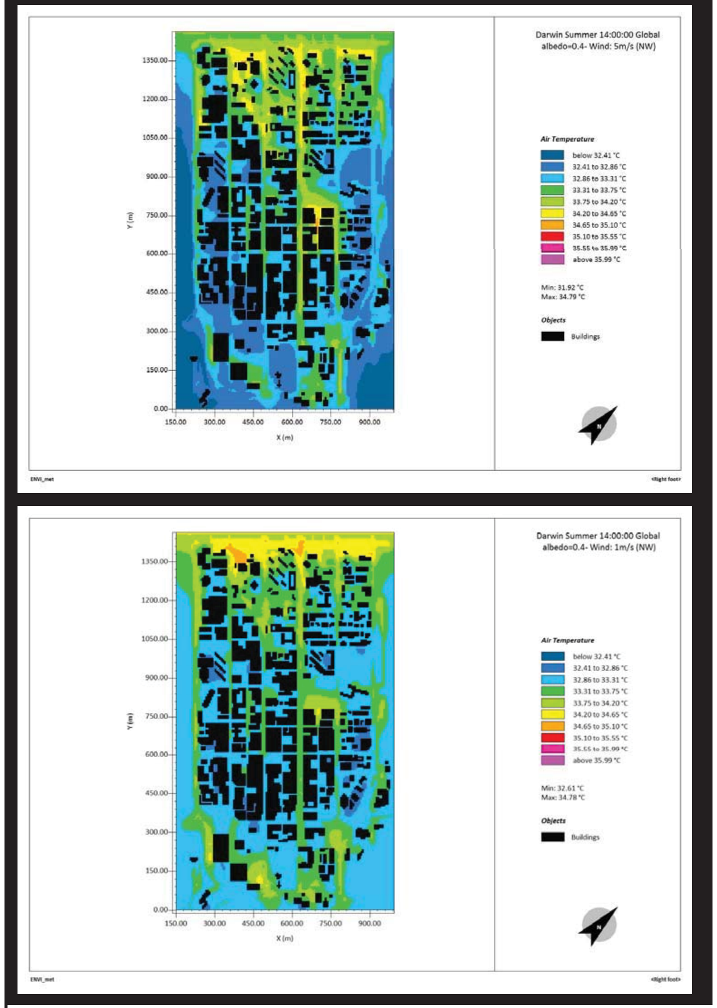

Figure 1. Global albedo 0.4: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

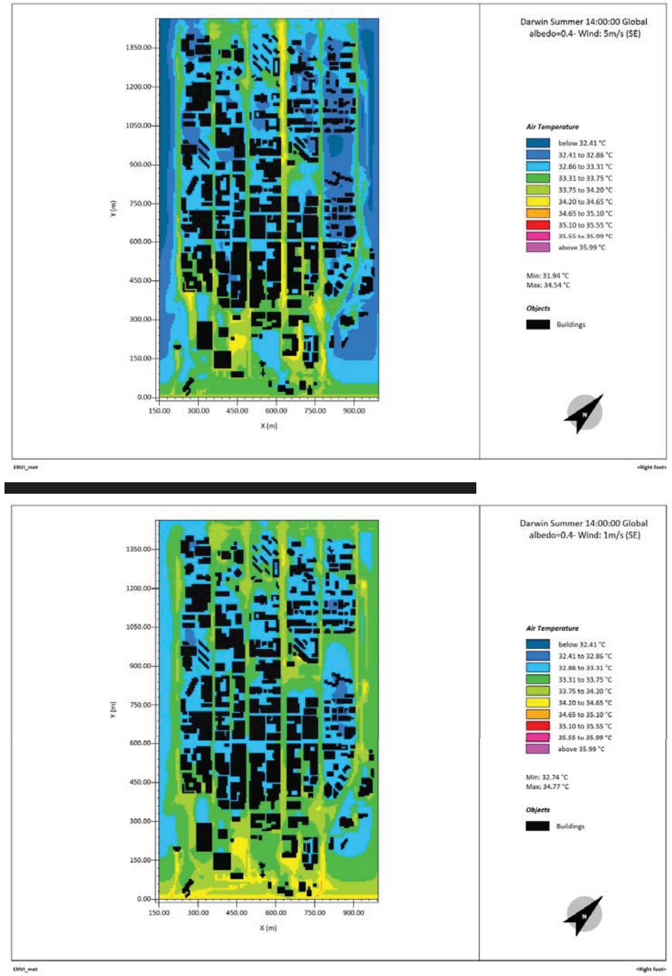

Figure 2. Global albedo 0.4: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

To simulate the present scenario, the same inputs as in the reference model was used. The database is adjusted to have the global albedo of 0.4 in the urban environment. Therefore, radiative properties of building walls and roofs, concrete pavements and asphalts was taken as 0.4 in this scenario.

The simulated distribution of the ambient temperature in this scenario is given in Figures 1 and 2 for the wind speeds of 5m/s and 1m/s and North westerly and South easterly winds. Thermal maps of the analyzed area are shown, considering the warmest moment of the day (at 14:00:00). The ambient temperature at the street level of the open spaces (2 m above the ground) ranges between 31.9°C to 34.8°C. The calculated results indicate that an increase of the global albedo to 0.4, may decrease the maximum ambient temperature by 1.6 K compared to the base case model.

The minimum temperature when wind speed is 5m/s is about 0.8°C lower that that when wind speed is 1 m/s which highlights the effects of convection in the study are. Tables 1 and 2 summaries the minimum and maximum temperatures and the local maximum temperature drop achieved in this scenario. Reduction of the maximum and minimum temperature is given based on the difference with the reference scenario.

Air temperature difference (K)

NW winds

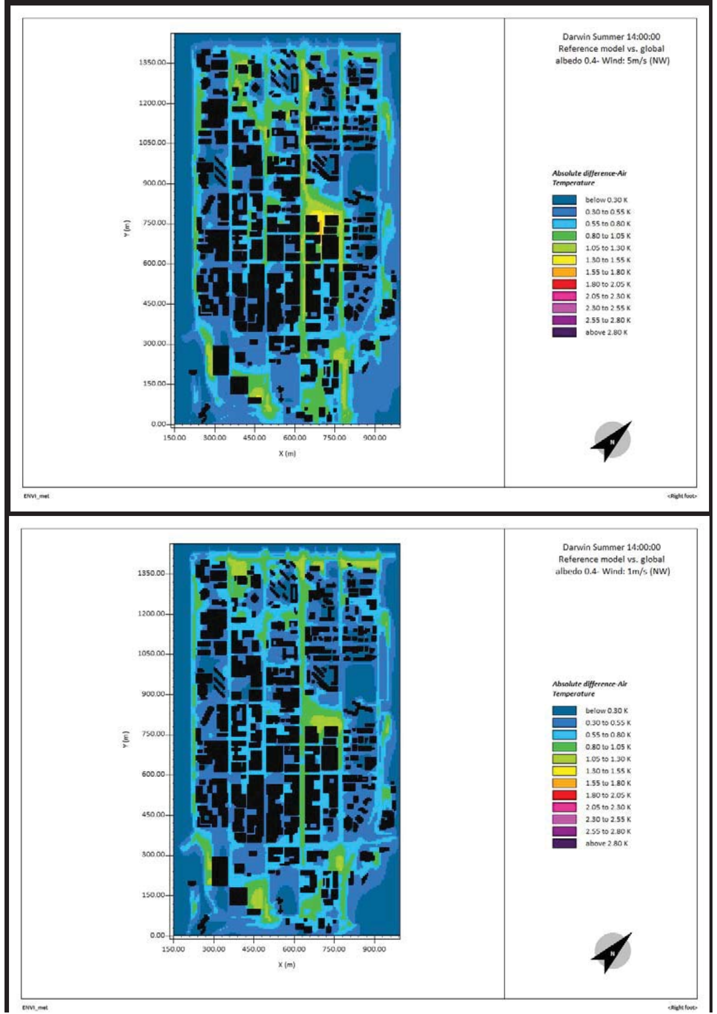

Figure 3. Global albedo 0.4: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

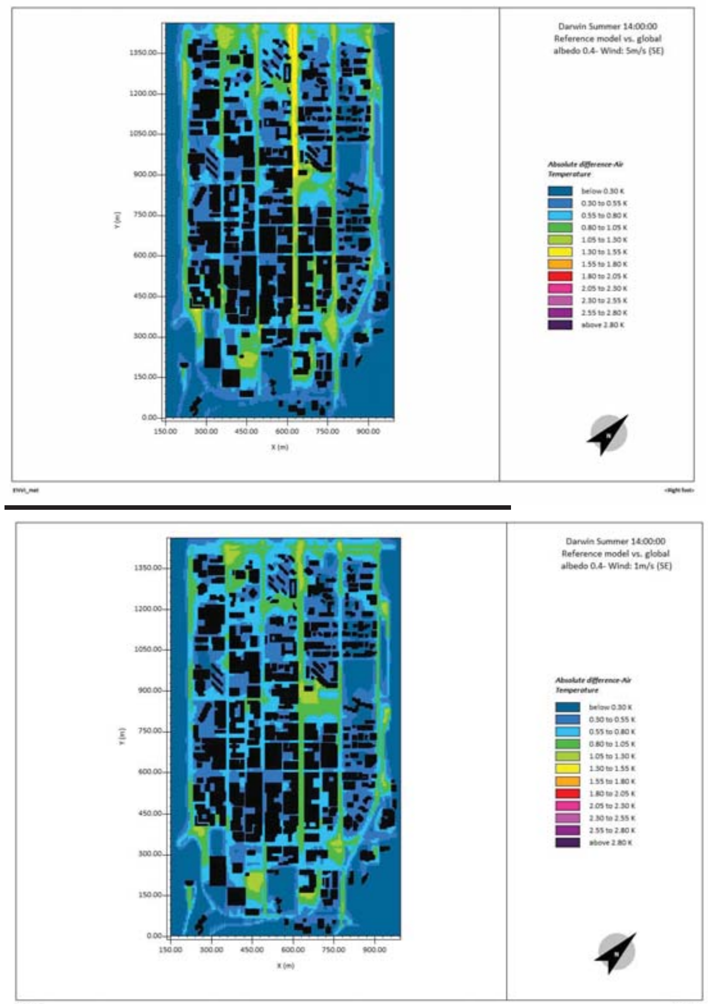

Figure 4. Global albedo 0.4: Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares the present scenario (global albedo of 0.4) with the base case model. The temperature reduction distribution that corresponds to a global albedo of the area equal to 0.4 is given in Figures 3-4 for the wind speeds of 5m/s and 1m/s and North westerly and South easterly winds.

The results indicate that by increasing the global albedo to 0.4, the local maximum temperature reduction is 1.67(K) and 1.57 (K) for the wind speed of 5m/s and directions of North westerly and South easterly winds, respectively.

The local maximum temperature reduction when wind speed is 1m/s is about 1.30 (K) for both wind directions.

Table 1. Statistical summery of the mitigation results – North westerly 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

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Table 2. Statistical summery of the mitigation results – South easterly 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

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Surface temperature (°C)

NW winds

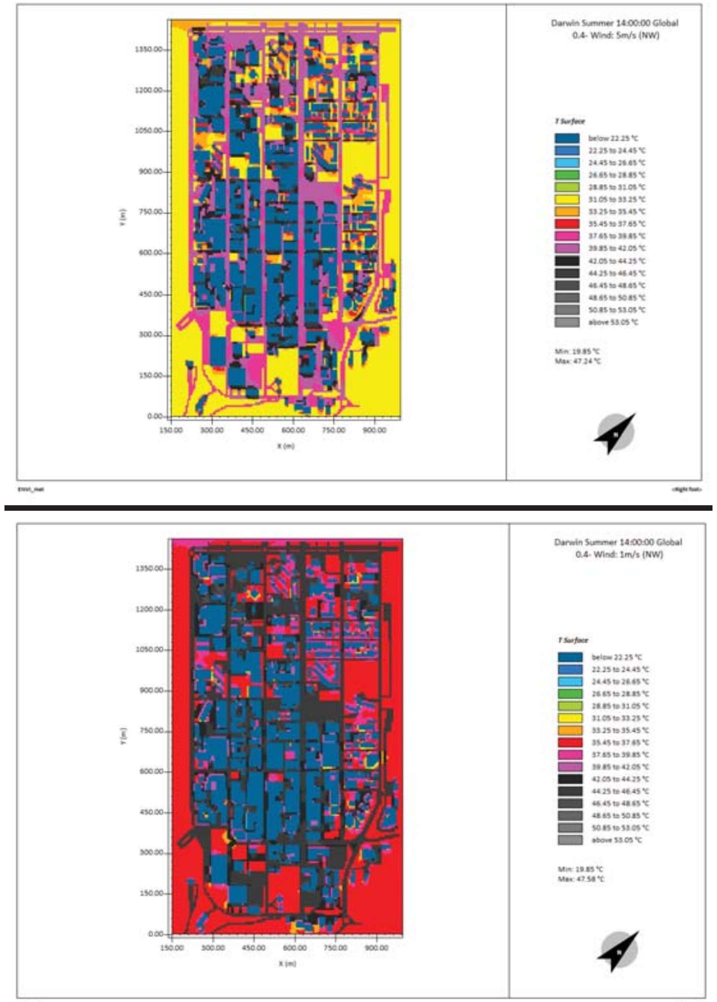

Figure 5. Global albedo 0.4: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

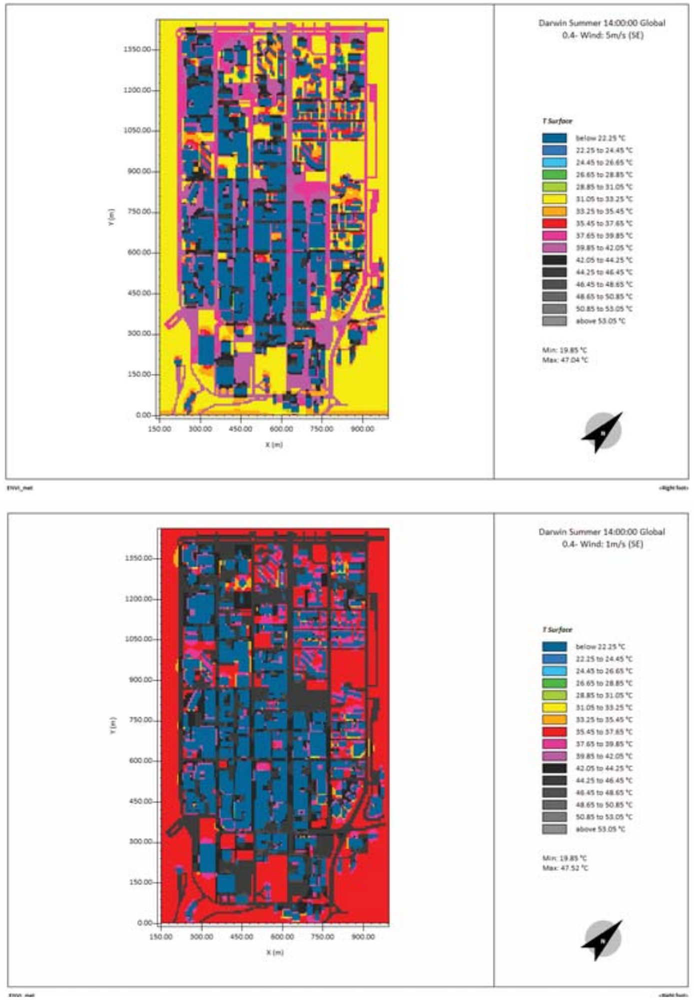

Figure 6. Global albedo 0.4: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario (global albedo=0.4) is shown in Figures 5 and 6. The results of surface temperature distribution are provided for two wind speeds of 5m/s and 1m/s and two wind directions from North west and South east.

Similar to the results of the reference model, the main streets and car parks show the highest surface temperature compared to the other surfaces. However, it is shown that the surface temperature, when global albedo is 0.4, reaches to 47.58°C which is about 8.9°C lower than that obtained in the simulation of the reference model (when the air speed is 1m/s and wind direction is from North west).

The surface temperature ranges from 19.85°C to 47.24°C when North westerly wind with the speed of 5m/s was considered. The maximum surface temperature is slightly lower for the South easterly wind (5m/s); i.e. 47.04°C. When wind speed of 1m/s was taken into account, the maximum surface temperature is about 47.50°C for North westerly and south easterly winds.

Wind speed (m/s)

NW winds

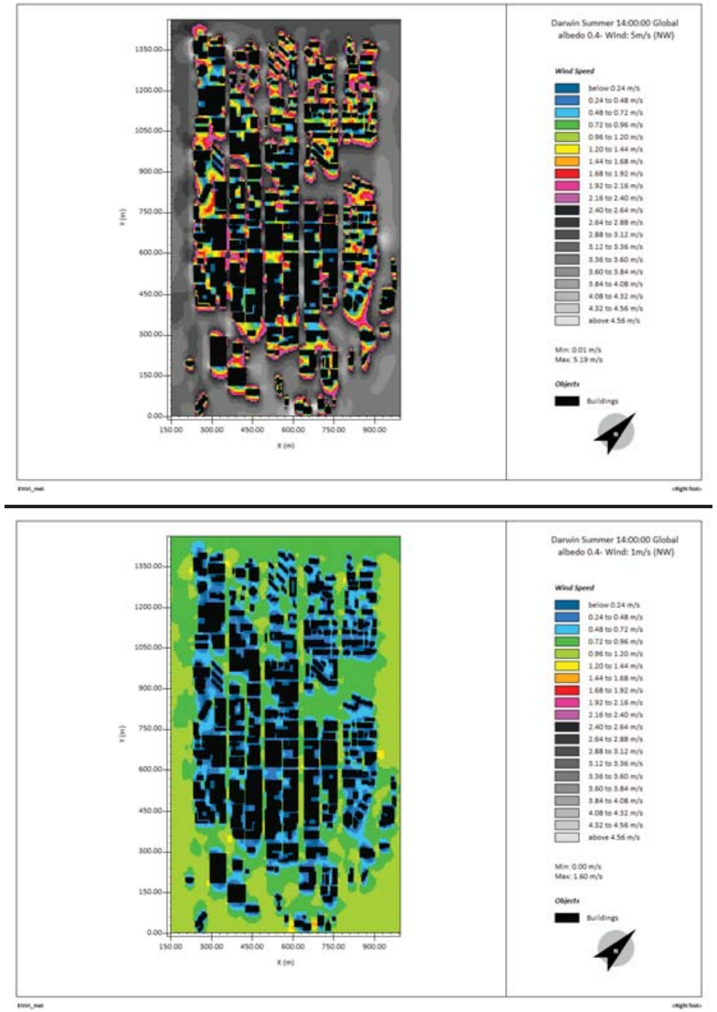

Figure 7. Global albedo 0.4: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

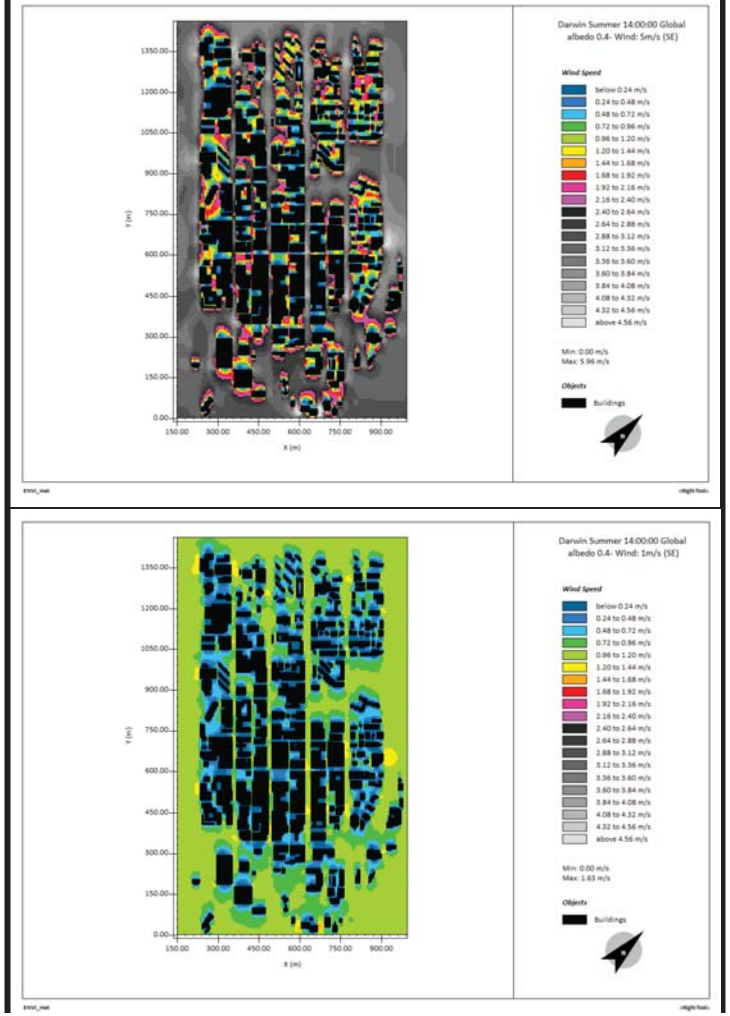

Figure 8. Global albedo 0.4: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution in the present scenario (global albedo=0.4). Simulation results show that highest wind speed is observed for South easterly winds. Since the model configuration was kept unchanged, the wind speed distribution is similar to the reference model.

Cost

Table 3 shows the estimated cost for this scenario.

Table 3. Cost of the Increase of the reflectivity of the city.
Global Albedo = 0.4

	Area (m2)	Cost per m2	Total Cost (AUS$)
Total building roof/floor area (m^2)	314272	15	4714080
Total Car park area in asphalt (m^2)	117684	30	3530520
Total area of pavements and streets(m^2)	652244	30	19567320
Total			27811920

Concluding remarks

This scenario investigates the climatic impact of the cool material when implemented in building walls and roofs, pavements and surfaces. The results of simulation show that the use of cool materials (global albedo of 0.4) improves the microclimate of urban areas. The local maximum temperature drop achieved in this scenario is 1.67 (K) and 1.57 (K) for the North westerly and South easterly winds at the speed of 5 m/s. The local maximum temperature decrease of about 1.30 (K) and 1.25 (K) may be achieved for the wind speed of 1m/s from North west and South east, respectively.

Heat Mitigation Program
Darwin, NT

MITIGATION STRATEGY 4: Increase of the reflectivity of the city. Global Albedo = 0.6 Simulated Mitigation Potential

UNSW

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Research team: Shamila Haddad, Giulia Ulpiani, Riccardo Paolini, Afroditi Synnefa, Francesco Fiorito, Samira Garshasbi

UNSW SYDNEY

INTRODUCTION

It is well known and documented that large-scale change of albedo has a serious impact on the local peak ambient temperature. Increase of the albedo in a city can be achieved using materials of high diffuse solar reflectivity and high emissivity value, (Cool materials). The specific materials should be applied mainly in roofs, pavements and all other horizontal surfaces in the city. Cool materials can be pavement tiles, paints, membranes, etc. Usually present a light color, but darker colored materials can be used, provided that they present a high reflectivity in the infrared spectrum. The possible increase of the albedo of the vertical surfaces has to be moderate to avoid problems of glare and contrast. The present mitigation scenario investigates the climatic potential of global reflective technologies. The main assumption of the scenario is that the average albedo of the city increases from 0,2 to 0,6. This is a reasonable assumption that can be easily met through the replacement of the external materials used in the roofs of the buildings, the pavements and the other horizontal urban surfaces, (parking lots, etc). The climatic potential of this scenario is evaluated using advanced simulation techniques. The results are compared against the corresponding outcomes of the reference scenario and the special mitigation potential is calculated. In the chapters below all results and conclusions are presented.

Ambient temperature (◦C)

NW winds

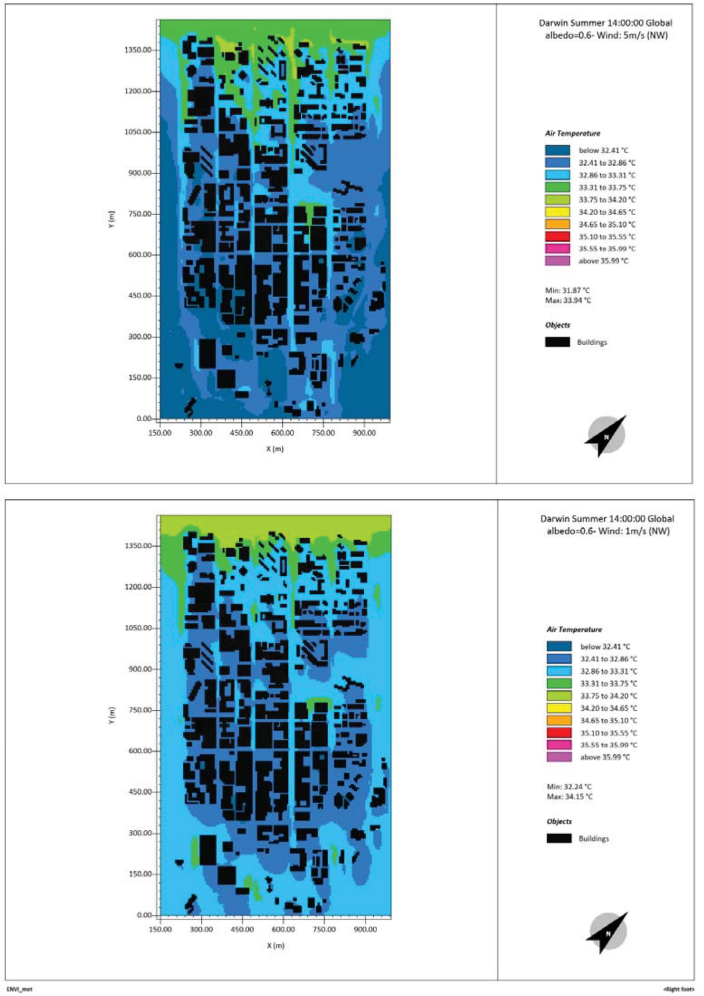

Figure 1. Global albedo 0.6: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

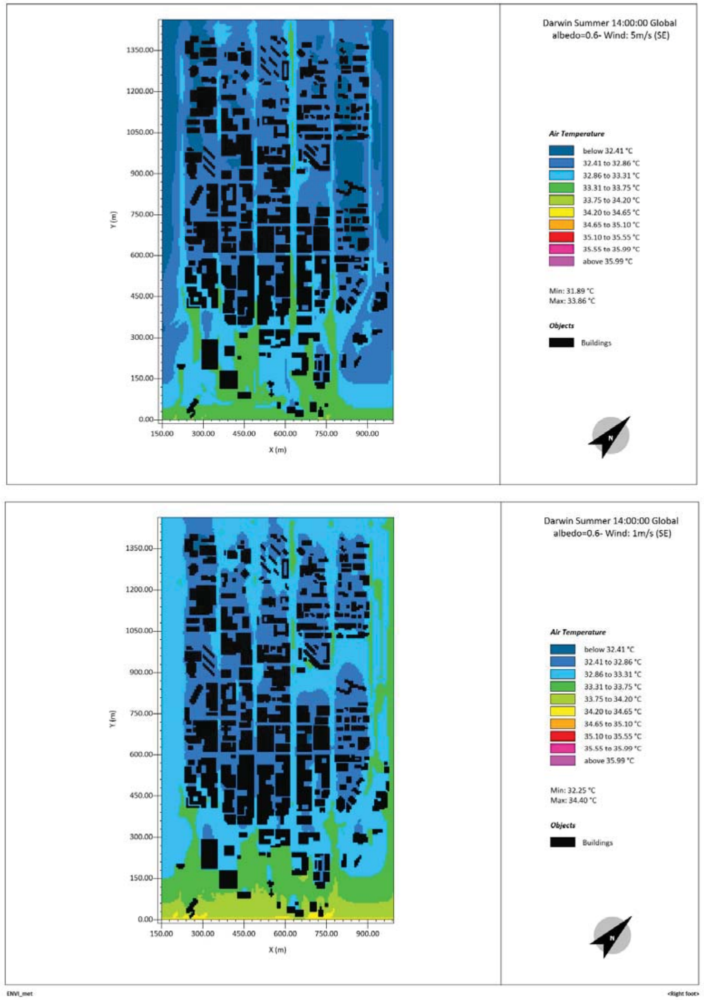

Figure 2. Global albedo 0.6: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

In this scenario, the model was simulated for the global albedo of 0.6. The radiative properties of all building walls and roofs, concrete pavements and asphalts was taken as 0.6 in this scenario.

Figure 1 and 2 shows the simulated distribution of the ambient temperature when global albedo is taken as 0.6. Thermal maps of the analyzed area are shown, considering the warmest moment of the day (at 14:00:00). The ambient temperature at the street level of the open spaces ranges between about 31.90°C to 34.40°C considering all investigated wind directions and wind speeds. The maximum temperature is decreased to 33.94°C and 33.86°C when wind speed is 5m/s, which is about 2.1°C to 2.5°C lower than that observed in the reference model. As shown in the maps, most urban spaces in the CBD fall below 32.41°C.

Tables 1 and 2 summaries the minimum and maximum temperatures, reduction of the maximum and minimum temperature, and the local maximum temperature drop achieved in this scenario. Reduction of the maximum and minimum temperature is given based on the difference with the reference scenario.

Air temperature difference (K)

NW winds

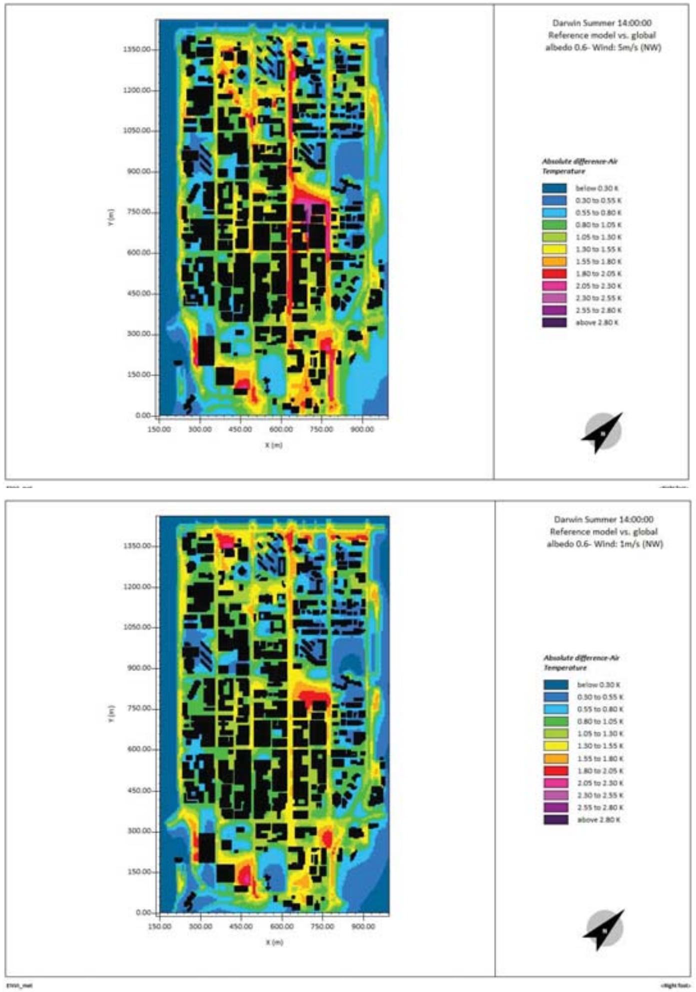

Figure 3. Global albedo 0.6: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

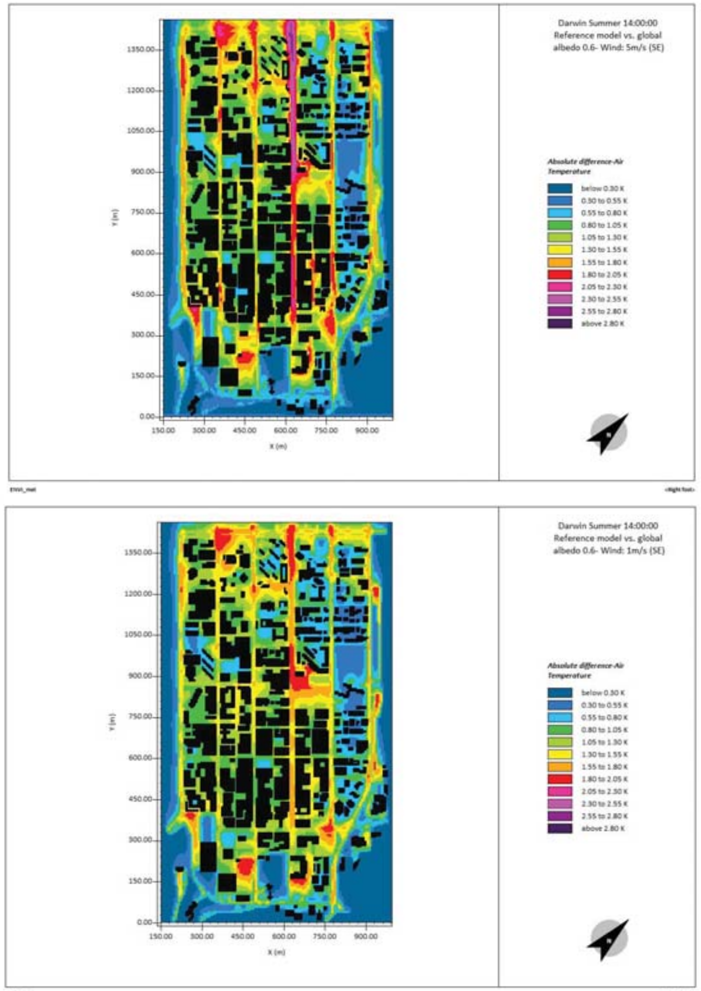

Figure 4. Global albedo 0.6: Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares this scenario (global albedo of 0.6) with the reference model. The temperature reduction distribution that corresponds to a global albedo of the area equal to 0.6 is given in Figures 3-4.

The results indicate that by increasing the global albedo to 0.6, the local maximum temperature reduction is 2.79 (K) and 2.63 (K) for the wind speed of 5m/s and directions of North westerly and South easterly winds, respectively. The local maximum air temperature reduction when wind speed is 1m/s is about 2.10 (K) for both wind directions. The results show that increase of global albedo to 0.6, may decrease the local ambient temperature by about 1(K) more than that when global albedo was taken as 0.4.

Table 1. Statistical summery of the mitigation results – North westerly 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	33.94	34.15	31.87	32.24	2.50	1.93	0.09	0.60	2.79	2.14

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Table 2. Statistical summery of the mitigation results – South easterly 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=0.6	33.86	34.4	31.89	32.25	2.14	1.32	0.15	0.72	2.63	2.06

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Surface temperature (°C)

NW winds

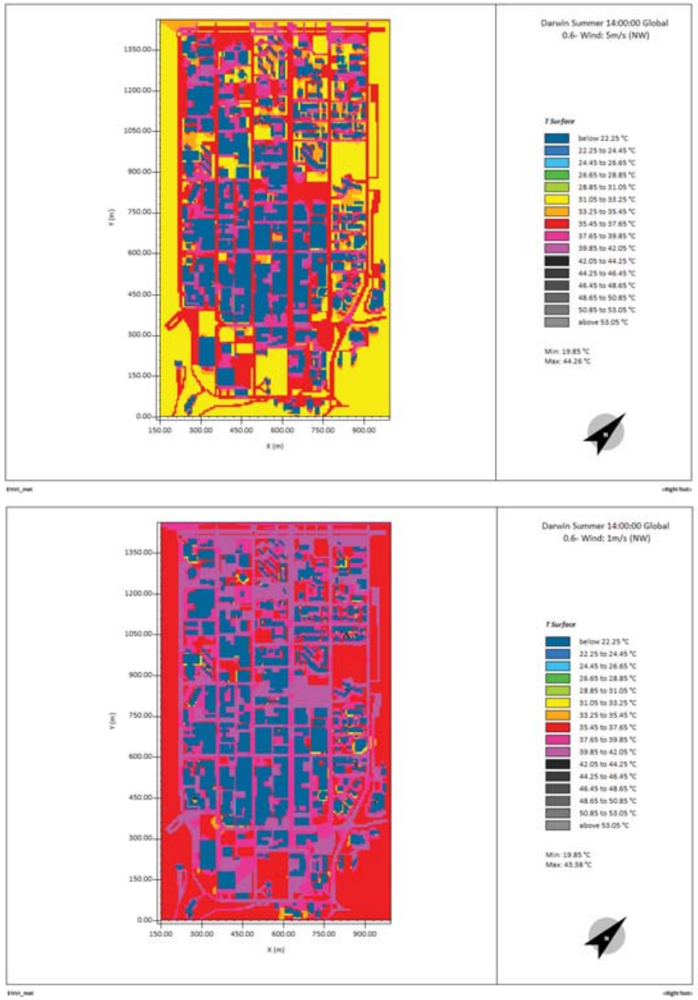

Figure 5. Global albedo 0.6: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

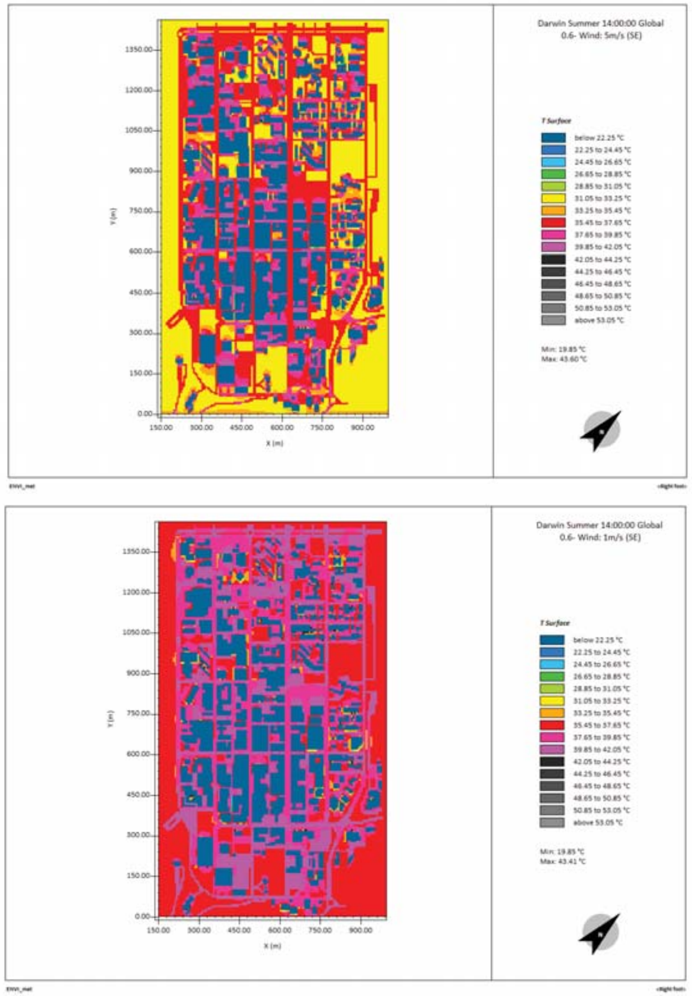

Figure 6. Global albedo 0.6: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario (global albedo =0.6) is given in Figures 5 and 6 for wind speeds of 5m/s and 1m/s and for two wind directions from North west and South east.

The main asphalt streets and car parks have highest surface temperature compared to the other surfaces. When global albedo is taken as 0.6, the maximum surface temperature reaches to 44.3°C which is 12.21°C lower than that obtained in the simulation of the reference model (i.e. when the air speed is 5m/s and wind direction is from North west). The surface temperature ranges from 19.85°C to 44.26°C for North westerly wind with the speed of 5m/s was considered. The maximum surface temperature is slightly lower for the South easterly wind (5m/s); i.e. 43.60°C. When wind speed of 1m/s was considered, the maximum surface temperature is about 43.40°C for North westerly and south easterly winds.

Wind speed (m/s)

NW winds

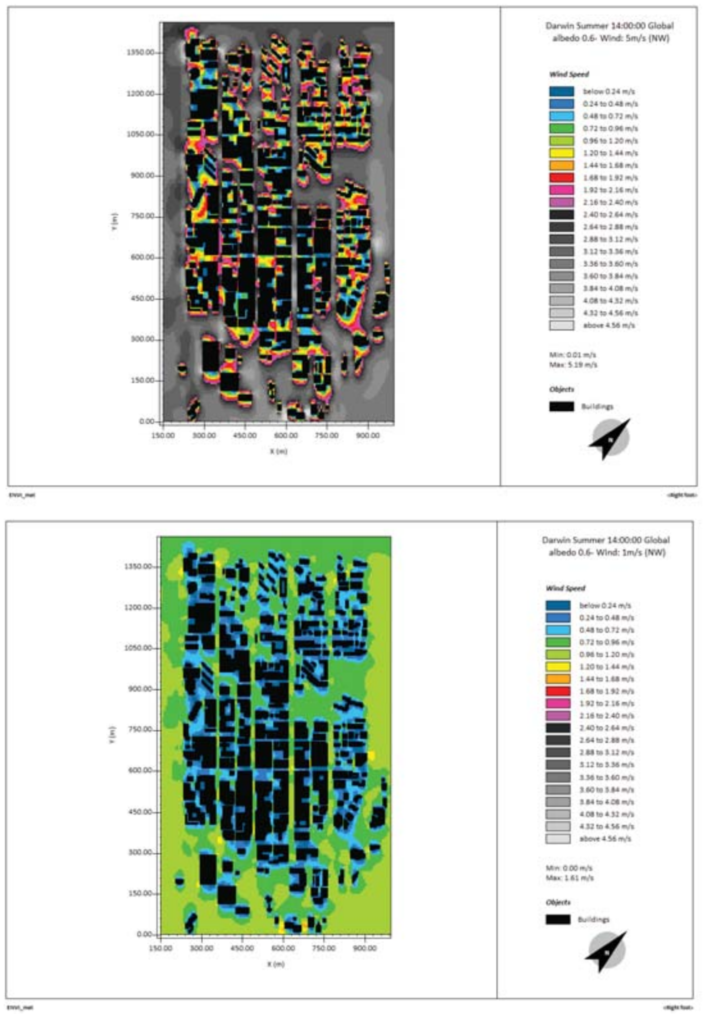

Figure 7. Global albedo 0.6: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

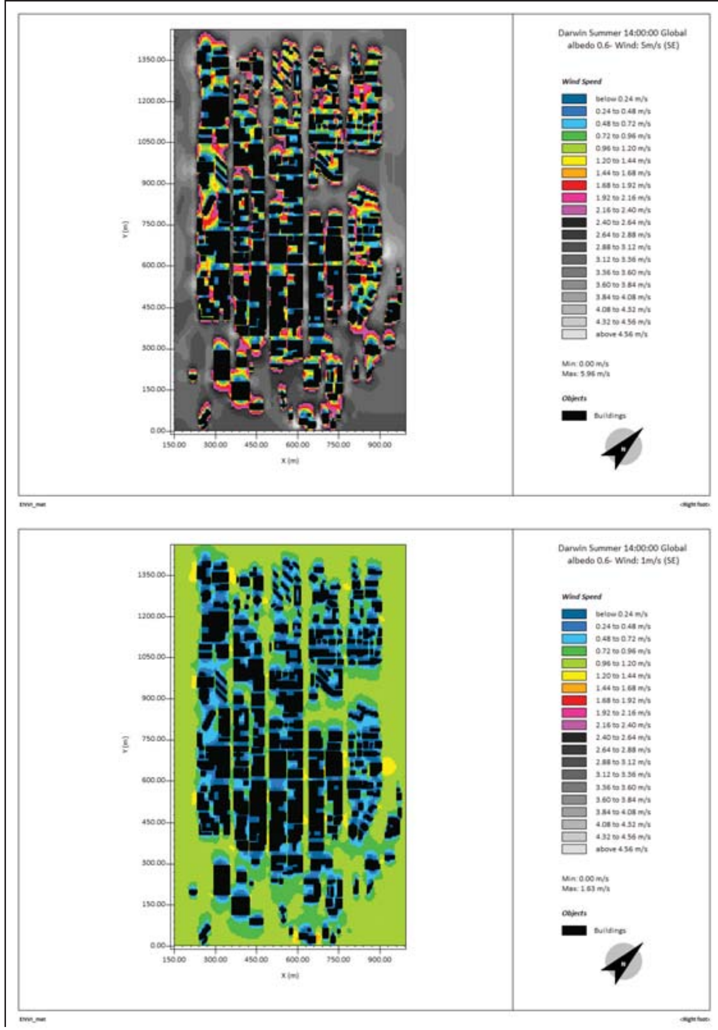

Figure 8. Global albedo 0.6: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution in this scenario (global albedo=0.6) for North westerly and South easterly winds and speeds of 5m/s and 1m/s. It has been shown that the wind speed distribution is the same as that obtain from the simulation of the reference model.

Cost

Table 3 shows the estimated cost for this scenario.

Table 3. Cost of the Increase of the reflectivity of the city.
Global Albedo = 0.6

	Area (m^2)	Cost per m^2	Total Cost (AUS$)
Total building roof/floor area (m^2)	314272	15	4714080
Total Car park area in asphalt (m^2)	117684	30	3530520
Total area of pavements and streets(m^2)	652244	30	19567320
Total			27811920

Concluding remarks

This scenario investigates the climatic impact of material when implemented in building walls and roofs, pavements and surfaces. The results of simulation show that the use of cool materials (global albedo of 0.6) improves the microclimate of urban areas. The local maximum temperature drop achieved in this scenario is 2.79 (K) and 2.63 (K) for the North westerly and South easterly winds at the speed of 5 m/s. The local maximum temperature decrease of about 2.14 (K) and 2.06 (K) may be achieved for the wind speed of 1m/s from North west and South east, respectively.

Heat Mitigation Program

Darwin, NT

MITIGATION SCENARIO 5: Green Roofs

UNSW

Project leader:
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Research team: Shamila Haddad, Giulia Ulpiani, Riccardo Paolini, Afroditi Synnefa, Francesco Fiorito, Samira Garshasbi

Green roofs are defined as the roof systems partially or fully covered by plants and a growing medium. They are distinguished in extensive type green roofs which are light systems covered by low height vegetation and intensive type where shrubs and small trees may be supported.

Green roofs provide solar and heat protection to the buildings while contributing mainly through latent heat processes to mitigate the excess urban heat. Vegetative roofs lower the surface temperature of the roofs and decrease the release of sensible heat to the atmosphere. In parallel, apart from the energy conservation and the urban heat island mitigation, they present a variety of advantages, like noise reduction, better air quality, storm water management.

The performance of green roofs is determined by climatic parameters like solar radiation, ambient humidity and temperature, wind speed and precipitation, optical parameters like the absorptivity of the plants, thermal parameters like the U value of the thermal capacitance of the roof, hydrological parameters like the frequency of watering and plants parameters like the Leaf Area Index, LAI, that is the amount of leaf material and is defined as the total one-sided area of photosynthetic tissue per unit ground surface area. Previous research has shown that LAI is the main parameter defining the evaporation losses from green roofs.

Ambient temperature (◦C)

NW winds

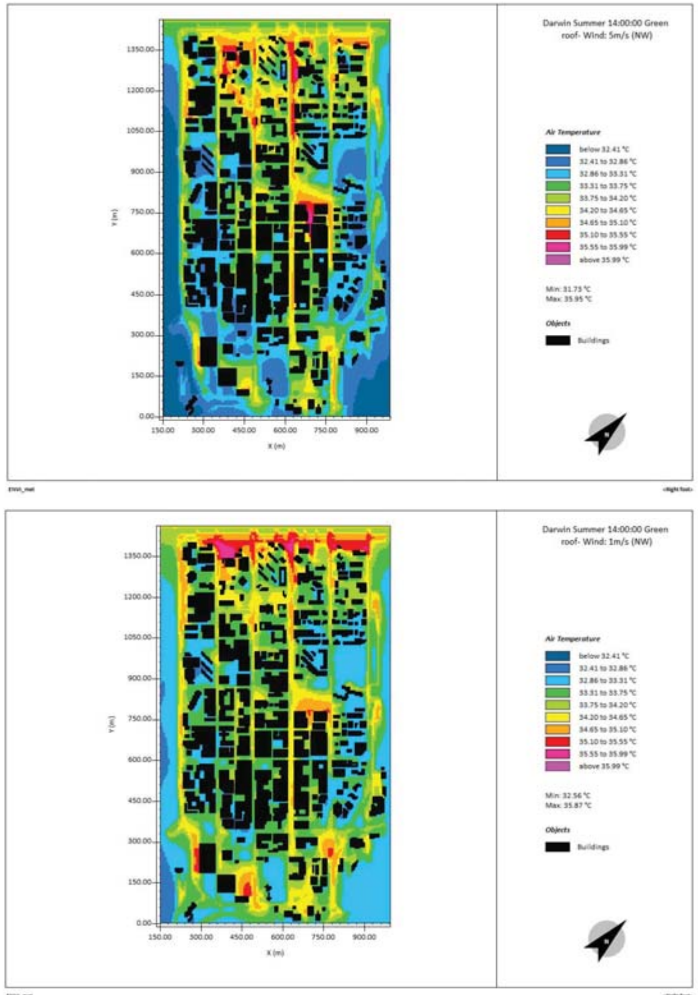


Figure 1. Green roof: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

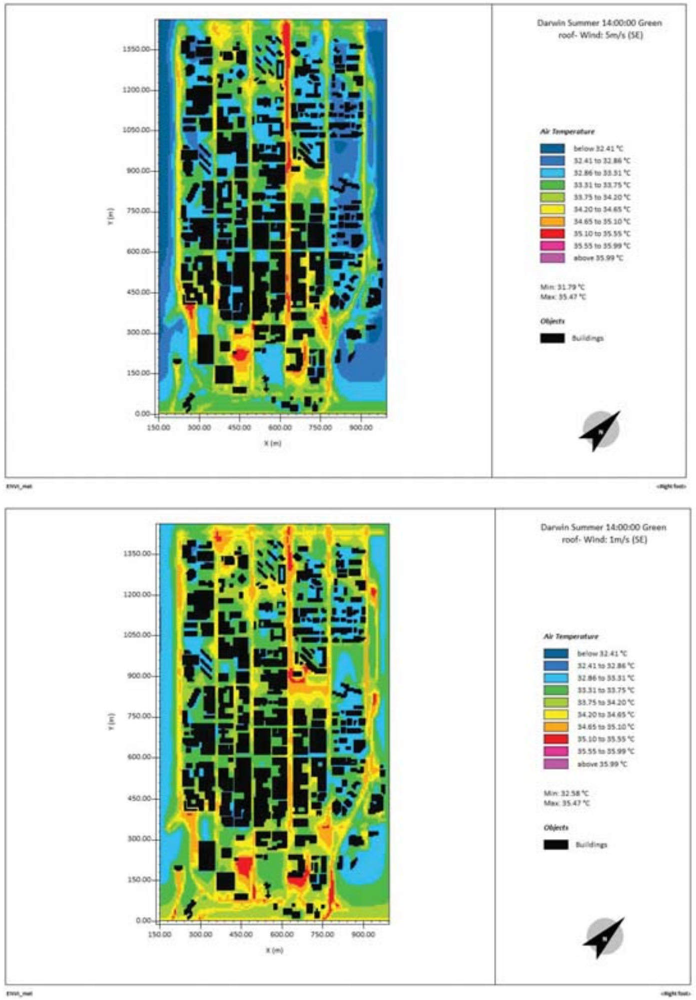


Figure 2. Green roof: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The use of green roofs installed in the buildings of the CBD area in Darwin was simulated in this scenario. Grass with leaf area density (LAD)=0.3 and albedo=0.2 is used on top of all buildings in this investigation. In the grass setting, plant height is taken as 0.20 m. The total roof area used in the model is equal to 314272 m^2.

Figure 1 and 2 show the simulated distribution of the ambient temperature when green roofs are used in the study area. The ambient temperature at 14:00:00 ranges between about 31.73°C to 35.95°C at the street level of the open spaces (1.46 m).

Tables 1 and 2 summaries the minimum and maximum temperatures, reduction of the maximum and minimum temperatures, and the local maximum temperature drop achieved in this scenario.

Table 1. Statistical summery of the mitigation results – North westerly 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	-	-	-	-	-	-
Green roof	35.95	35.87	31.73	32.56	0.49	0.21	0.23	0.28	1.63	1.30

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference scenario

Table 2. Statistical summery of the mitigation results – South easterly 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	-	-	-	-	-	-
Green roof	35.47	35.47	31.79	32.58	0.53	0.25	0.25	0.39	1.99	1.64

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference scenario

Air temperature difference (K)

NW winds

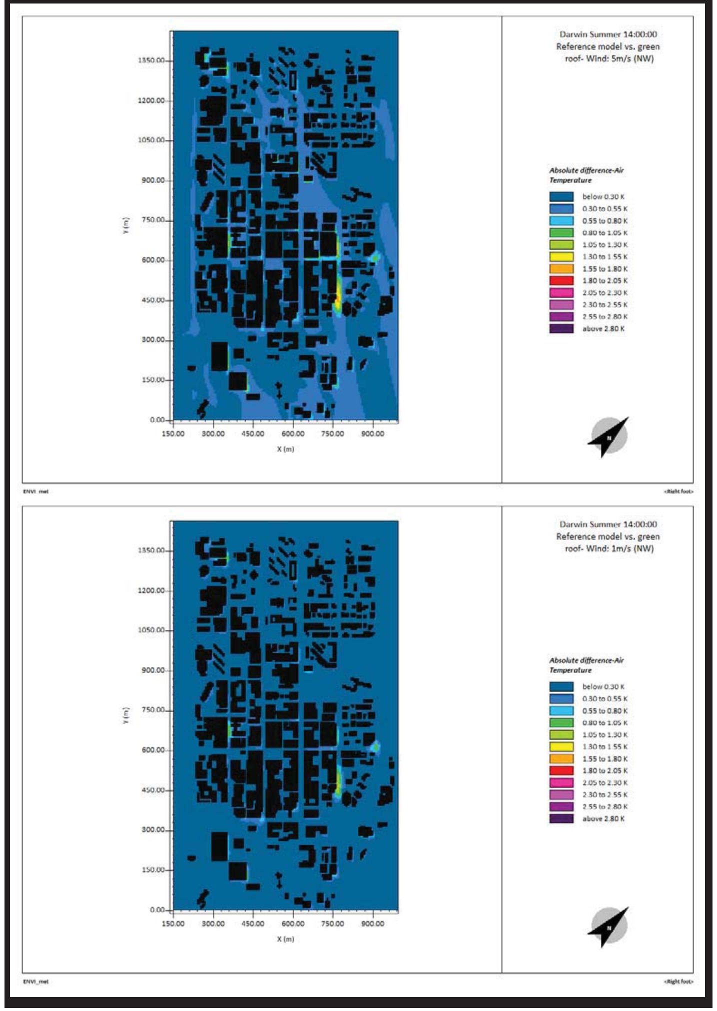


Figure 3. Green roof: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

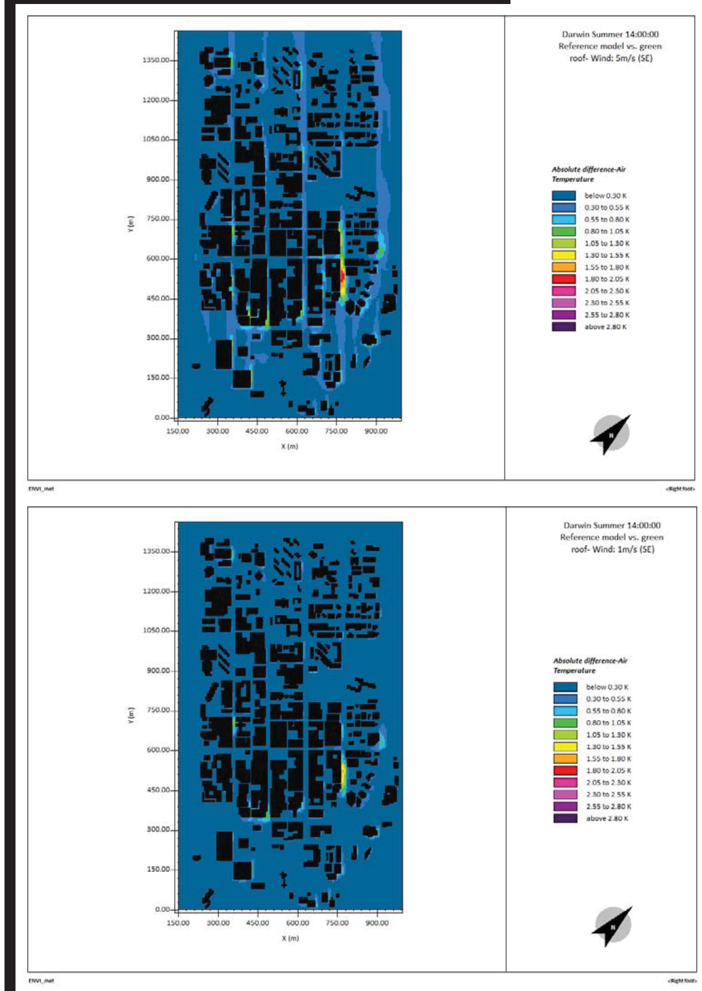


Figure 4. Green roof: Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares the scenario of green roof with the base case scenario. The temperature reduction distribution is given in Figures 3-4.

The results indicate that by implementing green roof, the local maximum temperature reduction is 1.63 (K) and 1.99 (K) for the wind speed of 5m/s and directions of North westerly and South easterly winds, respectively. The local maximum temperature reduction, when wind speed is 1m/s, is 1.30 (K) and 1.64 (K) for North westerly and South easterly winds, respectively.

"Compared to the mitigation potential of urban trees, green roofs seem to present a much lower mitigation performance. Although the air temperature above the roof level may be considerably reduced because of the latent heat used by the green roof, cooler air may not reach the street level as a result of the non favourable air flow conditions above buildings" (Santamouris et al., 2016).

Surface temperature (°C)

NW winds

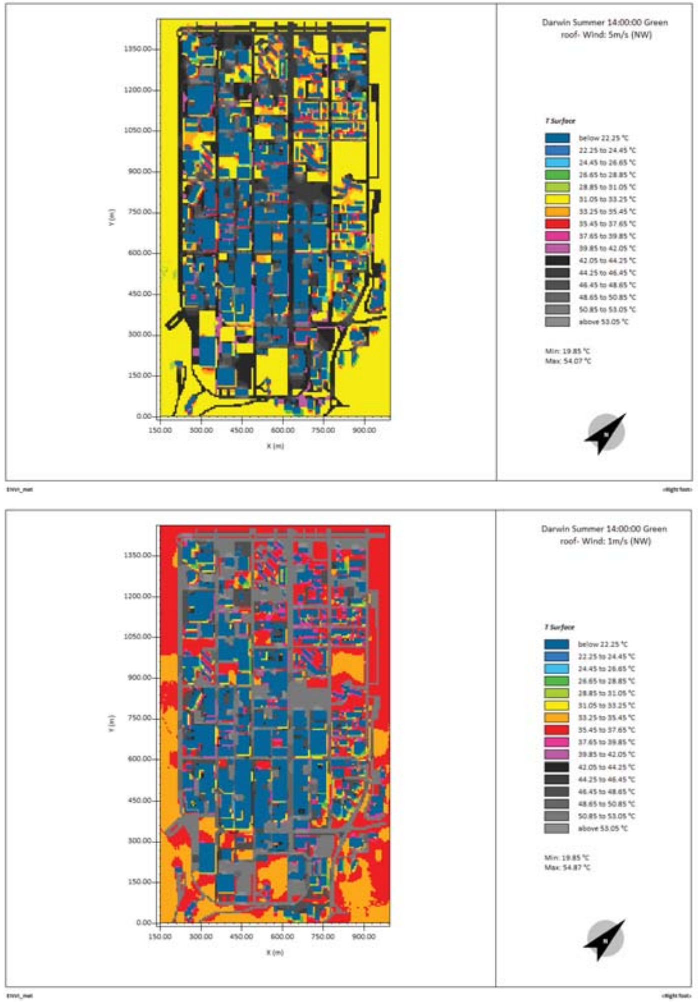


Figure 5. Green roof: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

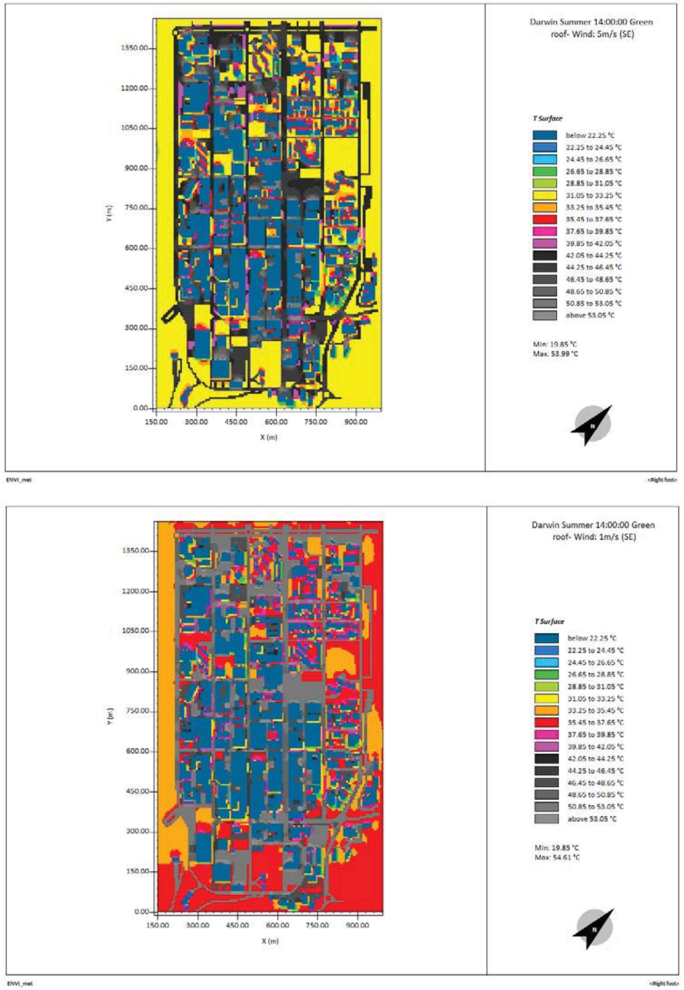


Figure 6. Green roof: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario is given in Figures 5 and 6.

The maximum surface temperature reaches to about 54.00°C in asphalt pavements when wind speed is 5 m/s. This is about 1.50°C lower than that in the reference model. The most predominant surface temperature reduction achieved for asphalt pavements and streets varies between 1-2°C when wind speed is taken as 5m/s for both North westerly and South easterly winds. However, the maximum reduction of the surface temperature is about 21-22°C in some locations. The surface temperature in most asphalt streets and parking lots varies between 50.85°C and 53.05°C for the wind speed of 1m/s. The highest surface temperature in the model, when wind speed is 1m/s, is 54.87°C and 54.61°C, for North westerly and South easterly winds, respectively. This is about 1.65°C lower than that in the base case model.

Wind speed (m/s)

NW winds

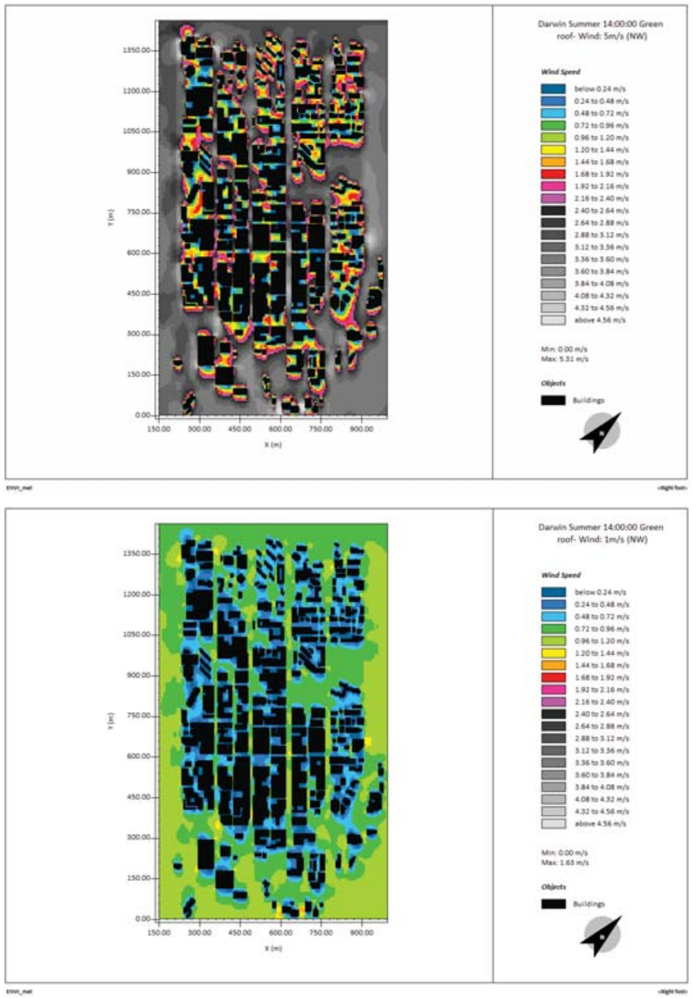


Figure 7. Green roof: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

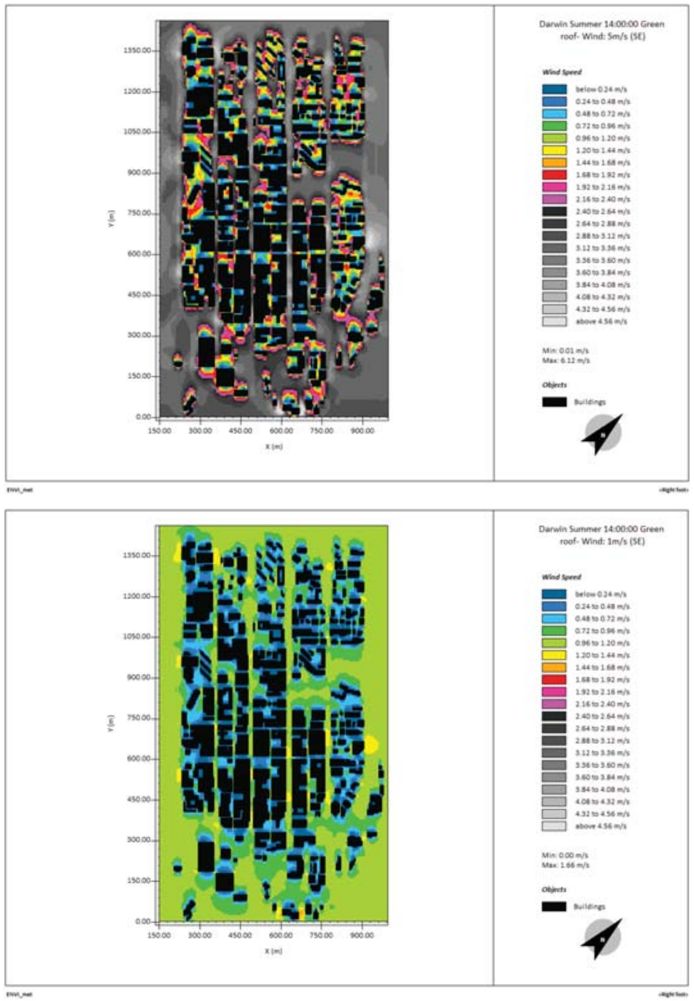


Figure 8. Green roof: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution in the study area when green roof is used. The wind speed distribution in open spaces is slightly affected by the grass size on roof tops compared to the wind speed distribution in the reference model. The wind speed distribution in the State square car park mostly ranges between about 0.24 m/s to 4.56 m/s, and falls within a range of lower than 0.24 to 1.2 m/s in the simulations with 5m/s and 1m/s winds, respectively. There are a few parts of the area with highest wind speed which is consistent between all investigated wind conditions.

Cost

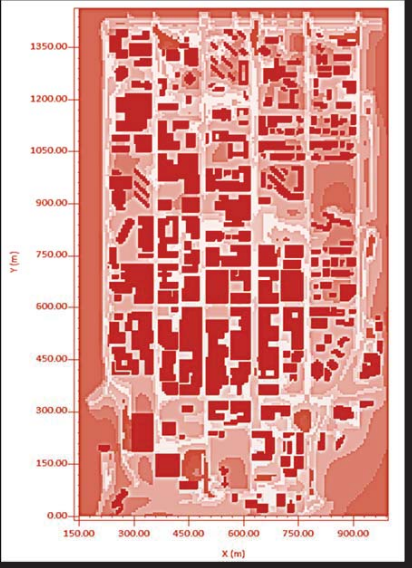
Table 3 shows the estimated cost for this scenario.

Table 3. Cost of the green roof scenario

	Area (m2)	Cost per m^2 (AUS$)	Total Cost
Total building roof/floor area (m^2)	314272	150	47140800
Total			47140800

Concluding remarks

The use of green roof is investigated in this simulation. It has been illustrated that the local maximum temperature reduction achieved in this scenario is slightly higher at higher wind speeds. The local maximum temperature drop is about 1.63 (K) and 1.99 (K) for the wind speed of 5 m/s and North westerly and South easterly directions, respectively. The local maximum temperature drop is 1.30 (K) and 1.64 (K) for North westerly and South easterly winds at the speed of 1m/s.



Heat Mitigation Program

Darwin, NT

MITIGATION SCENARIO 6: Solar Control of the Main Streets in Darwin

UNSW

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Research team: Shamila Haddad, Giulia Ulpiani, Riccardo Paolini, Afroditi Synnefa, Francesco Fiorito, Samira Garshasbi

Use of solar control devices on the top of the main streets in Darwin, decreases the absorbed solar radiation by the asphalt and the pavements and contributes towards lower surface temperatures, less sensible heat and better comfort conditions. The present mitigation scenario considers the application of shading devices on the top of the main streets of Darwin. The average shading coefficient for all streets was taken equal to 30 %. This means that in average the solar radiation that reaches the surface of the streets and parking lots is reduced by 30 %. The specific mitigation scenario is evaluated using advanced simulation techniques. The outcomes of the simulation are compared against the corresponding results of the reference scenario and the expected distribution of the ambient and surface temperature are calculated.

Ambient temperature (◦C)

NW winds

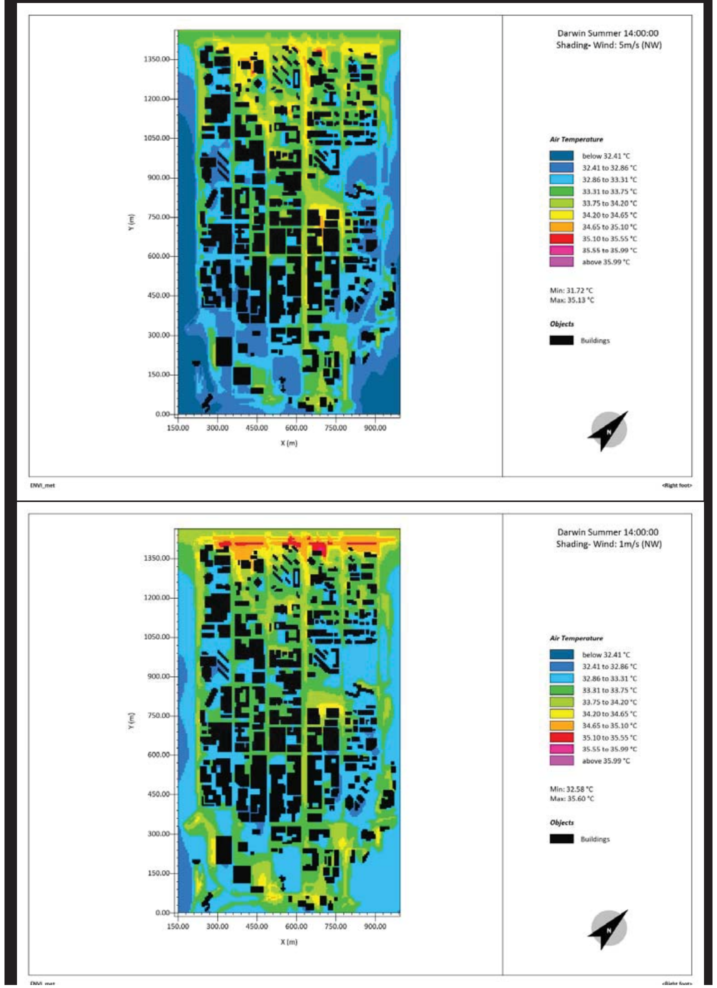


Figure 1. Shading: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

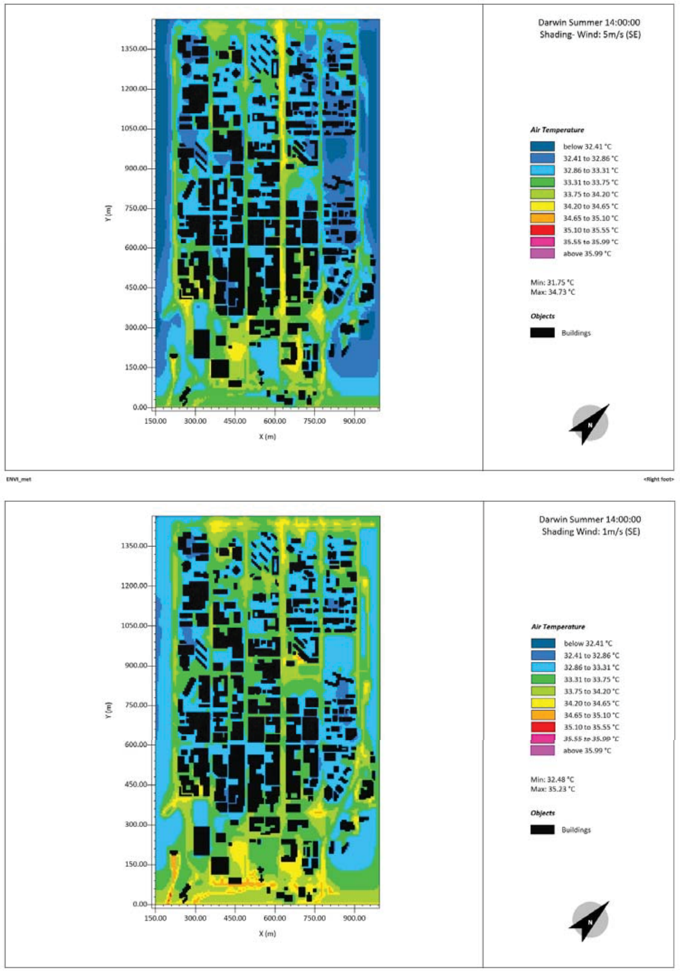


Figure 2. Shading: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

In this scenario, the effect of shading of the main streets of Darwin is investigated, it was observed that the main CBD streets show higher ambient and surface temperatures. Therefore, in this scenario shading has been applied mainly on the following streets: Wood St, Cavenagh St, Smith St, Mitchel St, Esplanade St, and McMinn St. The nearby car parks also considered in this scenario.

Simulation results

The average solar radiation incident on the above streets and car parks s reduced by 30 %.

Figure 1 and 2 shows the simulated distribution of the ambient temperature when shading devices are used in the study area. The ambient temperature at 14:00:00 ranges between about 31.72°C to 35.60°C at the street level of the open spaces. The maximum ambient temperature in the study area is decreased to 35.13°C when wind speed is 5m/s from North west, which is 1.31°C lower than that observed in the reference model; i.e. 36.44°C. Tables 1 and 2 summaries the minimum and maximum temperatures, reduction of the maximum and minimum temperatures, and the local maximum temperature drop achieved in this scenario. Reduction of the maximum and minimum temperature is given based on the difference with the reference scenario.

Air temperature difference (K)

NW winds

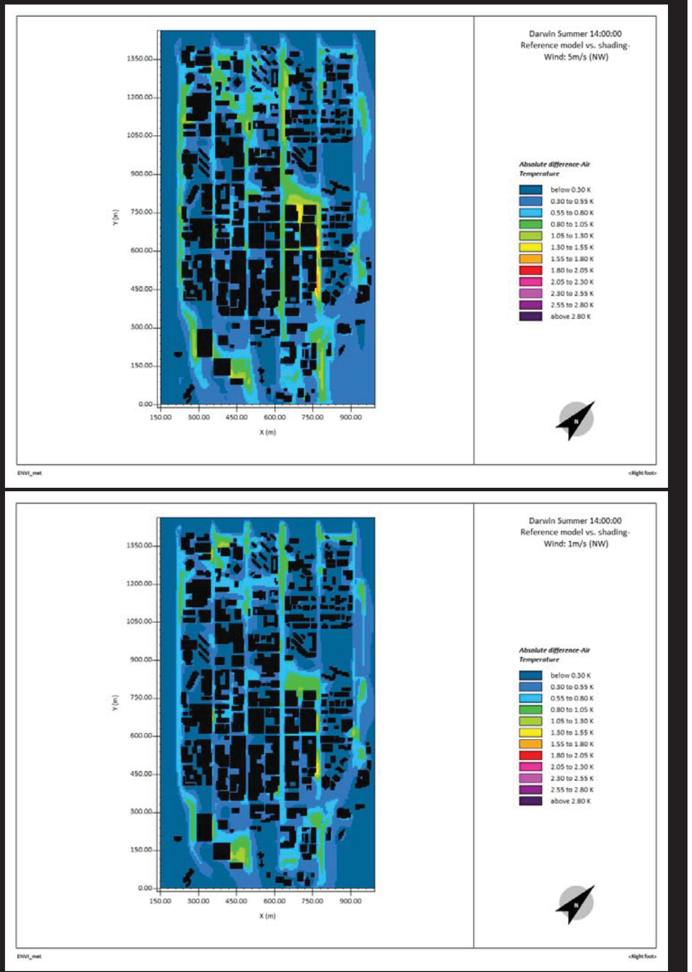


Figure 3. Shading: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

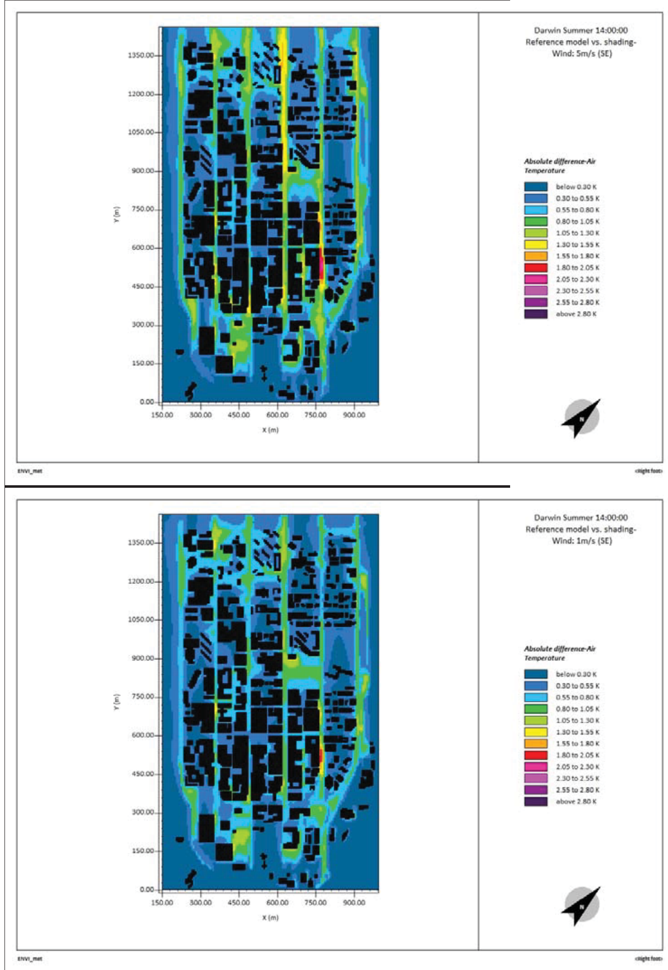


Figure 4. Shading: Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares the scenario of shading (decrease of the incident solar radiation on the streets, pavements and parking lots by 30%) with the base case model. The temperature reduction distribution is given in Figures 3-4. The results show that by providing shading, the local maximum temperature reduction is 2.30 (K) and 1.93 (K) for the wind speed of 5m/s and directions of North westerly and South easterly winds, respectively. The local maximum temperature reduction when wind speed is 1m/s is 1.95 (K) and 1.46 (K) for North westerly and South easterly winds, respectively. The local maximum temperature drop is higher for the wind speed of 5m/s than for the wind speed of 1m/s. The maximum impact can bee seen in the northern part of Cavenagh street and central part of Woods street (South easterly winds at the speed of 5m/s), and central part of Cavenagh and Woods street (North westerly winds at the speed of 5m/s).

Table 1. Statistical summery of the mitigation results – North westerly 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	-	-	-	-	-	-
Shading	35.13	35.60	31.72	32.58	1.31	0.48	0.24	0.26	1.93	1.46

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Table 2. Statistical summery of the mitigation results – South easterly 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	-	-	-	-	-	-
Shading	34.73	35.23	31.75	32.48	1.27	0.49	0.29	0.49	2.30	1.95

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Surface temperature (°C)

NW winds

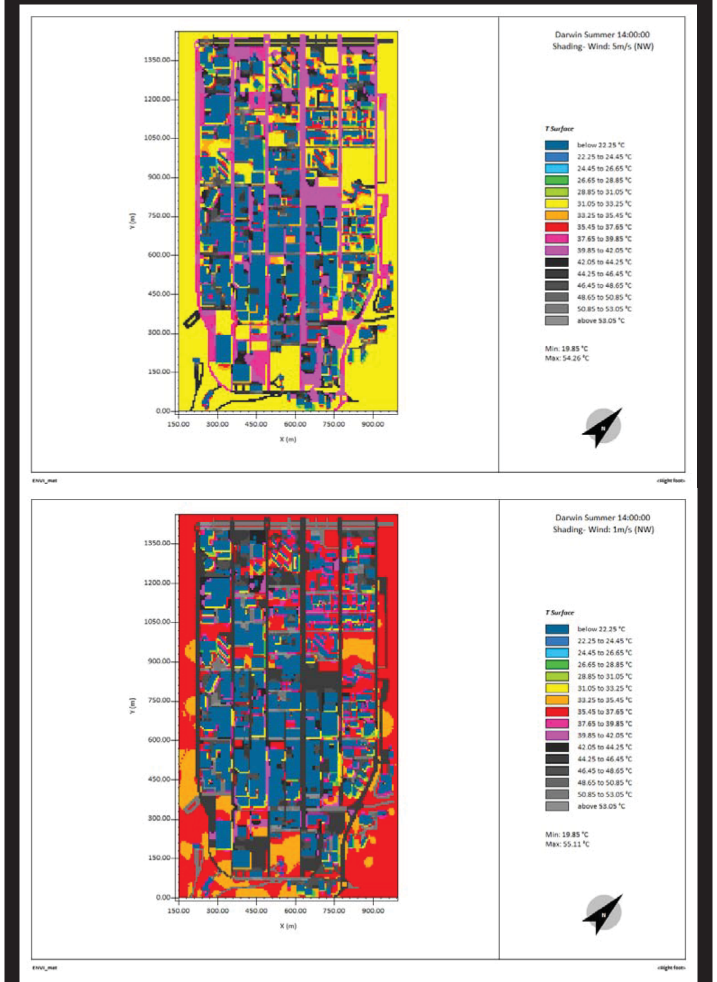


Figure 5. Shading: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

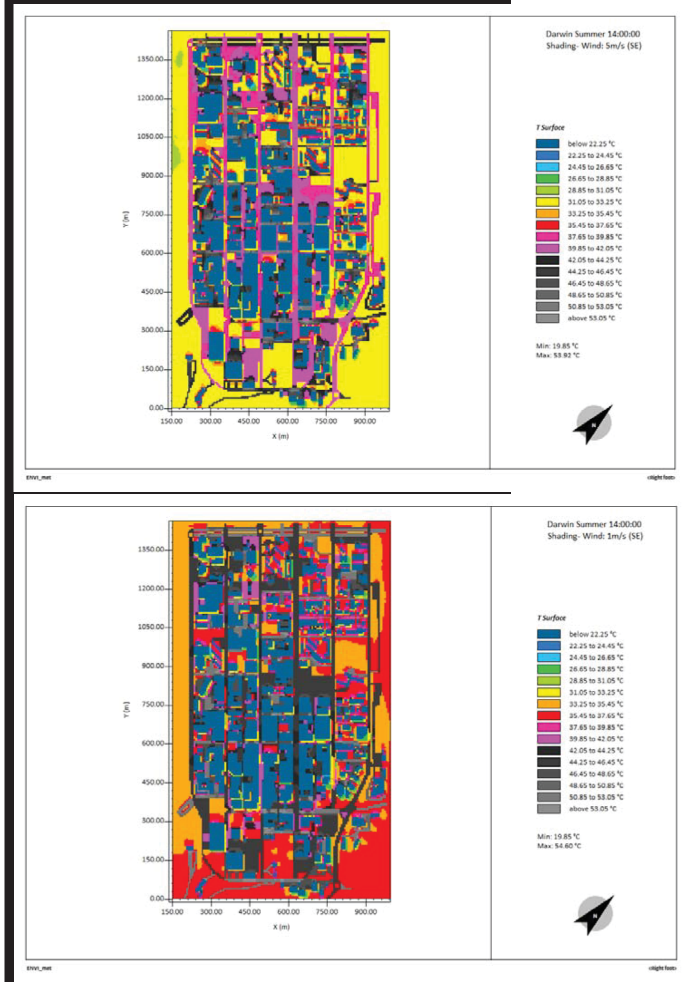


Figure 6. Shading: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario is illustrated in Figures 5 and 6. The results of surface temperature distribution are provided for two wind speeds of 5m/s and 1m/s and two wind directions from North west and South east.

The surface temperature in the main streets and parking lots, after providing shading, mainly varies between 39.85°C and 42.05°C (when the air speed is 5m/s). The surface temperature of streets and car parks may be reduced to the range of 37.65°C-39.85°C when shading devices are used. This is about 10°C to 12°C reduction in the surface temperatures compared to the same location in the reference model. Similarly, the surface temperature of asphalt car parks and street pavements is reduced when wind speed is taken as 1m/s; it mostly falls within a range of 42.05°C to 46.45°C.

Wind speed (m/s)

NW winds

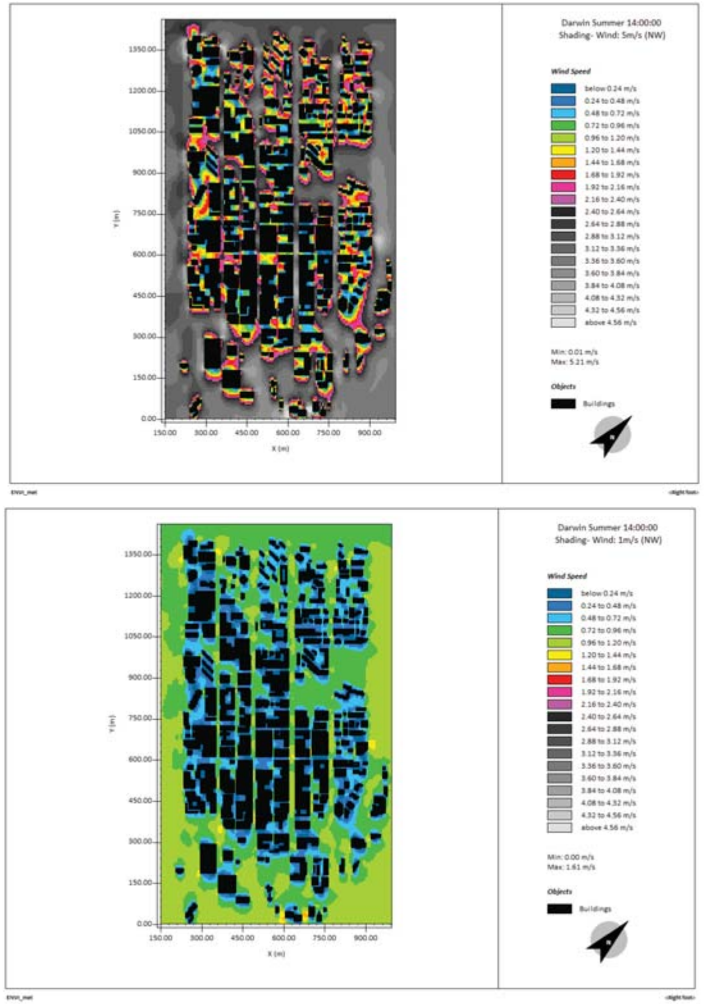


Figure 7. Shading: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

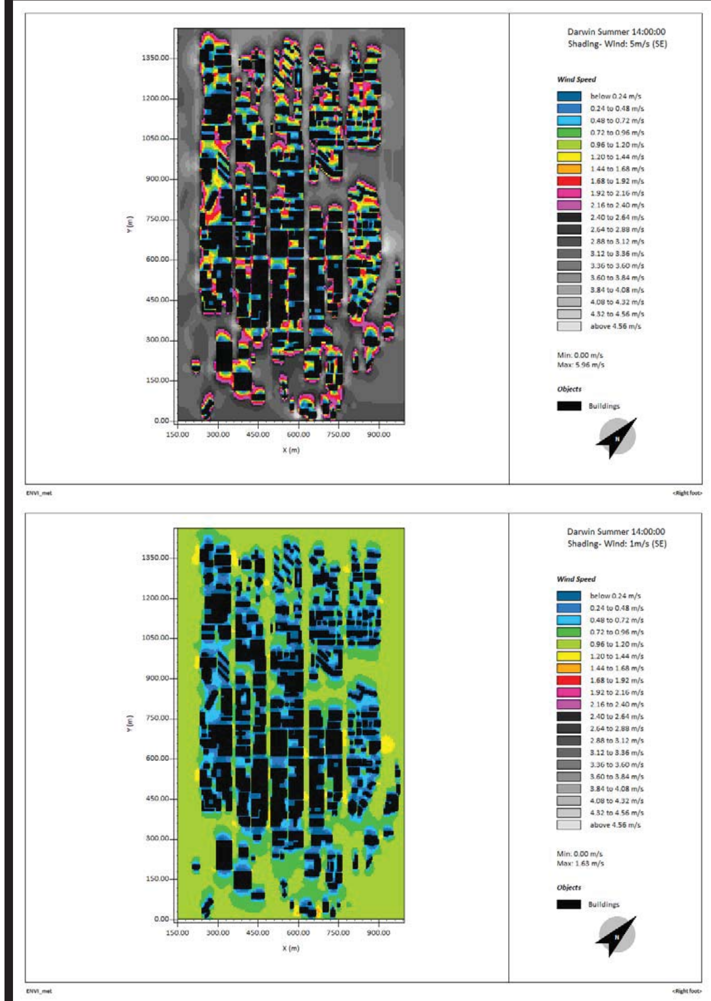


Figure 8. Shading: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution in the study area when the incident solar radiation on the streets, pavements and parking lots is decrease by 30%. The wind speed distribution is almost same as that obtained from the simulation of the reference model.

Cost

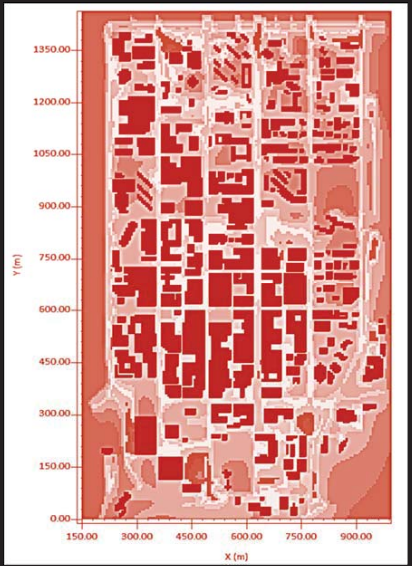
Table 3 shows the estimated cost for this scenario.

Table 3. Cost of the shading scenario

	total surface m²	cost per m², AU$	total cost AU$
Shading the Main Streets and Car Parks	275436	70	19280520

Concluding remarks

This scenario investigates the effects of shading devices on the main streets and pavements. It has been shown that the decrease of the incident solar radiation on the streets, pavements and parking lots by 30% is an effective strategy to improve the microclimate of urban areas. The local maximum temperature drop achieved in this scenario is 1.93 (K) and 2.30 (K) for the North westerly and South easterly winds at the speed of 5 m/s. The local maximum temperature decrease of about 1.46 (K) and 1.95 (K) may be achieved when wind speed is taken as 1m/s for the North westerly and South easterly winds, respectively.



Heat Mitigation Program

Darwin, NT

MITIGATION SCENARIO 7: Use of Water- Evaporative Cooling

UNSW

Project leader:

M. Santamouris

Faculty of Built Environment, UNSW, Sydney, Australia

Research team: Shamila Haddad, Giulia Ulpiani, Riccardo Paolini, Afroditi Synnefa, Francesco Fiorito, Samira Garshasbi

UNSW SYDNEY

The use of water in reducing ambient temperature has been known for many centuries. The latent heat used to evaporate water in the atmosphere decreases the ambient temperature and may improve the thermal comfort conditions, both indoors and outdoors. It is characteristic that the evaporation of 1 kg of water may decrease the temperature of 2000 cubic meters of water by 1 K In parallel, the surface temperature of the water may be several degrees lower that of the surrounding built environment and contribute to cool the ambient air through convective processes. The mitigating potential of water-based techniques has been thoroughly investigated by studies analyzing the temperature patterns in cities surrounded by lakes, rivers and other water reservoirs   It is a common conclusion that urban wetlands contribute to create 'Urban Cooling Islands' resulting in a significant decrease of the urban temperature.

The mitigating potential of wetlands is a function of many parameters and mainly of the wetland proximity to the city, its shape and the landscape characteristics around the water body. Analysis of existing experimental data has shown that urban wetlands may decrease the city's ambient temperature by 1–2 K. Apart from the natural water bodies in the cities, various technologies or techniques based on the evaporation of water, are used to design and integrate urban evaporative cooling systems able to decrease the ambient temperature. A variety of passive systems like pools, ponds and fountains are widely used in public spaces for decorative and climatic reasons while active or hybrid water components like evaporative wind towers, sprinklers and water courtains have been developed, installed and tested in urban public spaces around the world.

The present mitigation scenario investigates the climatic potential of evaporative techniques when applied in the Mall area in Darwin. Advanced simulation techniques are used to calculate the distribution of the main parameters in the area, while the final results are compared against the corresponding outcomes of the reference scenario to estimate the potential temperature decrease.

Ambient temperature (◦C)

NW winds

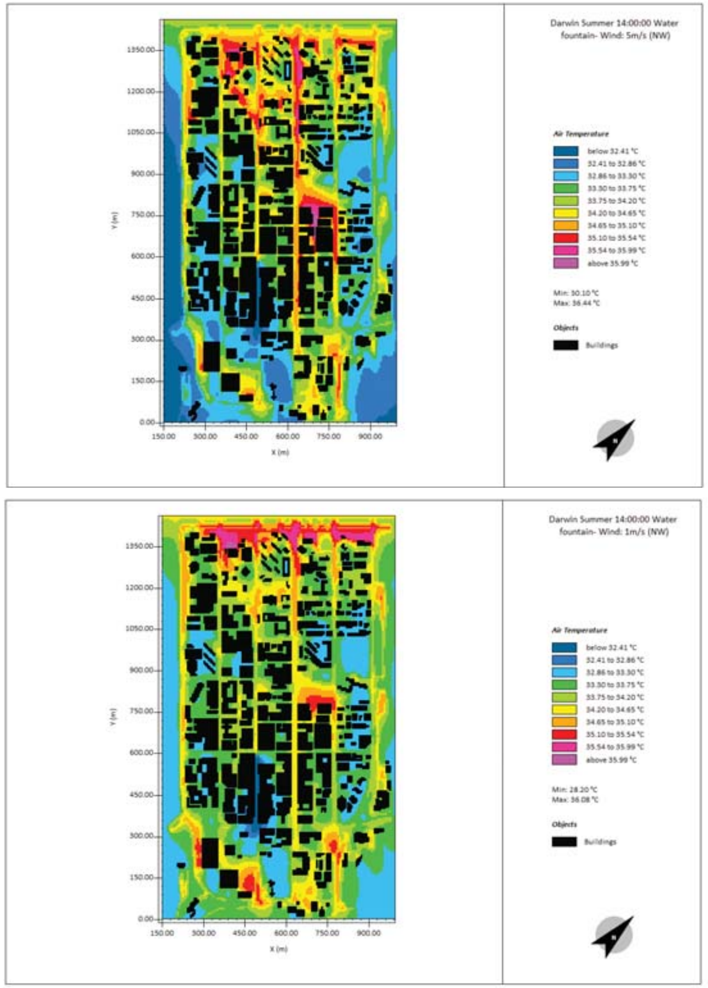


Figure 1. Water fountain: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

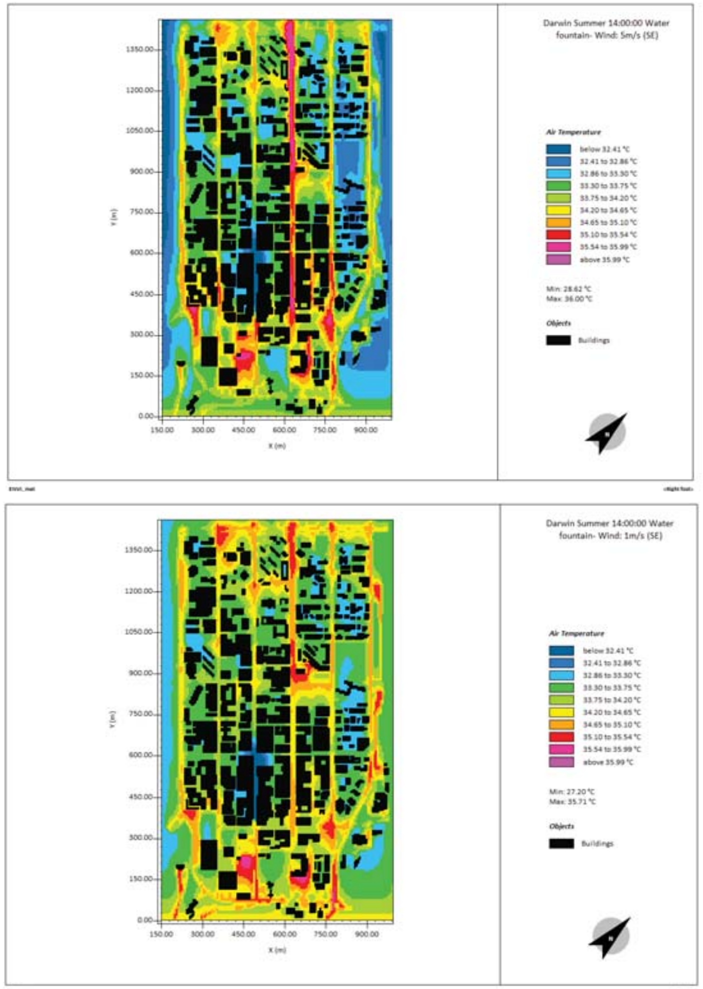


Figure 2. Water fountain: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The present scenario considers the application of water fountains placed in The Mall and investigates the cooling effect of water spray in local scale. 10 water fountains (dx=dy=6m, dz=4m) are used in this investigation. All water fountains are located at the vicinity of 18m from each other. Figure 1 and 2 shows the simulated distribution of the ambient temperature when water fountains are used in the Mall. The ambient temperature at 14:00:00 ranges between about 27.20°C to 36.44°C at the street level of the open spaces (the whole CBD area). However, the ambient temperature of The Mall is bellow 32.41°C in all conditions investigated here. Figures 1 and 2 provides the maximum and minimum of ambient temperature for the whole area. Tables 1 and 2 summaries the **local** *minimum and maximum temperatures where mitigation strategy was used, reduction of the local maximum and minimum temperatures, and the local maximum temperature drop achieved in this scenario.*

Location of the water fountains in the Mall, Darwin

Air temperature difference (K)

NW winds

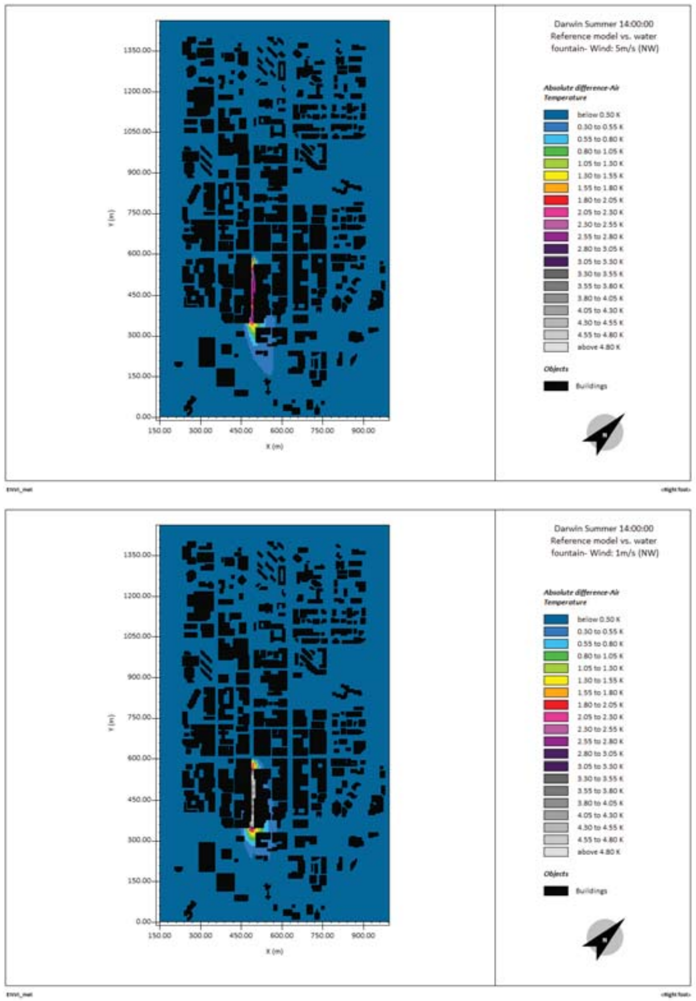


Figure 3. Water fountain: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

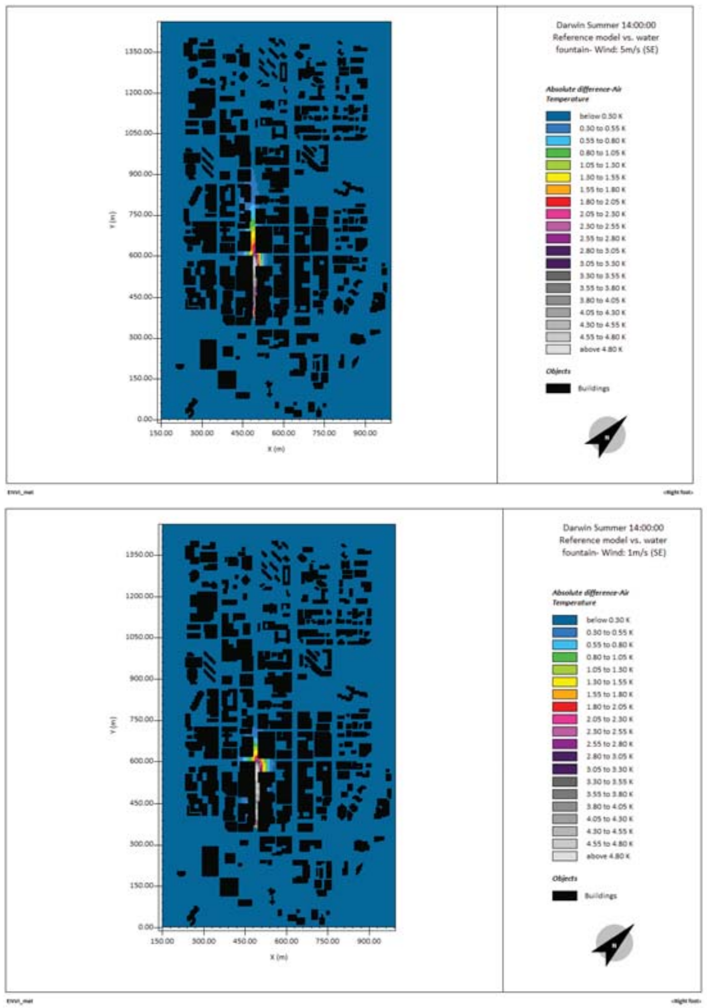


Figure 4. Water fountain Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares the scenario of water fountain (with water spray cooling effect) with the base case model. The temperature reduction distribution is given in Figures 3-4.

The results indicate that by implementing water fountain, the maximum temperature reduction at local scale is 3.92 (K) and 5.83 (K) for the wind speed of 5m/s and directions of North westerly and South easterly winds, respectively. The local maximum temperature reduction achieved, when wind speed is 1m/s, is 5.46 (K) and 6.67 (K) for North westerly and South easterly winds, respectively. Figure 3 and 4 show that the maximum temperature reduction achieved is observed along the Mall (Smith street) for the wind speed of 1m/s. When wind speed is taken as 5m/s the temperature reduction effects is slightly extended to Southern and Northern part of the Mall for North westerly and South easterly winds, respectively.

Table 1. Statistical summery of the mitigation results – North westerly 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	-	-	-	-	-	-
Water fountain**	34.48	33.52	30.10	28.20	1.96	2.56	1.86	4.64	3.92	5.46

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model
**: Maximum temperature and reduction of the maximum ambient temperature (K) is given for the local scale where mitigation strategy was employed

Table 2. Statistical summery of the mitigation results – South easterly 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	-	-	-	-	-	-
Water fountain**	35.13	34.49	28.62	27.20	0.87	1.23	3.42	5.77	5.83	6.67

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model
**: Maximum temperature and reduction of the maximum ambient temperature (K) is given for the local scale where mitigation strategy was employed

Surface temperature (°C)

NW winds

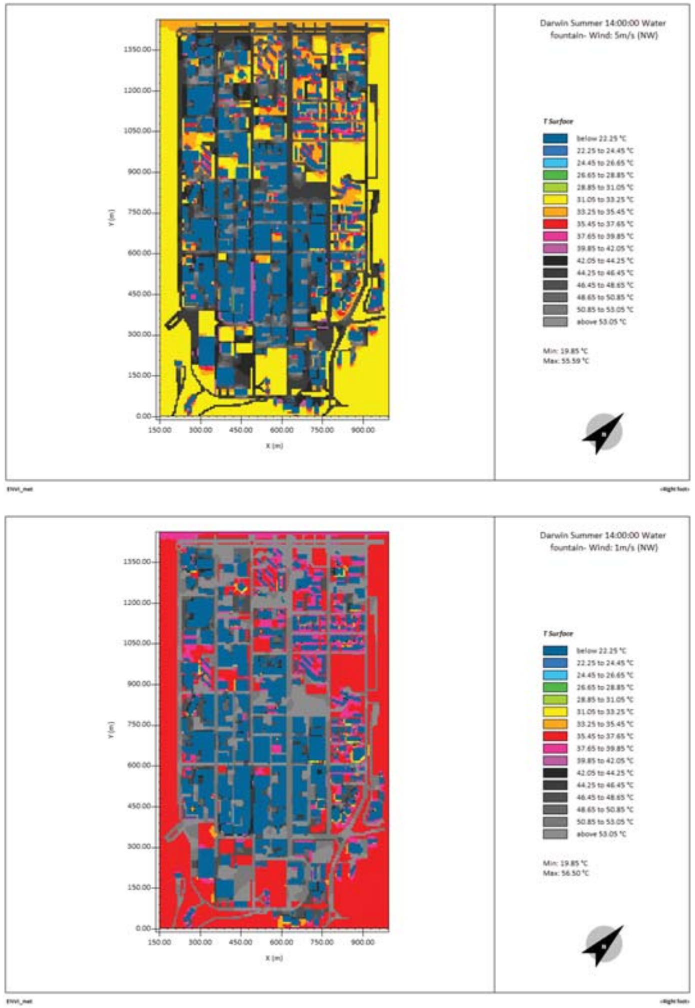


Figure 5. Water fountain: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

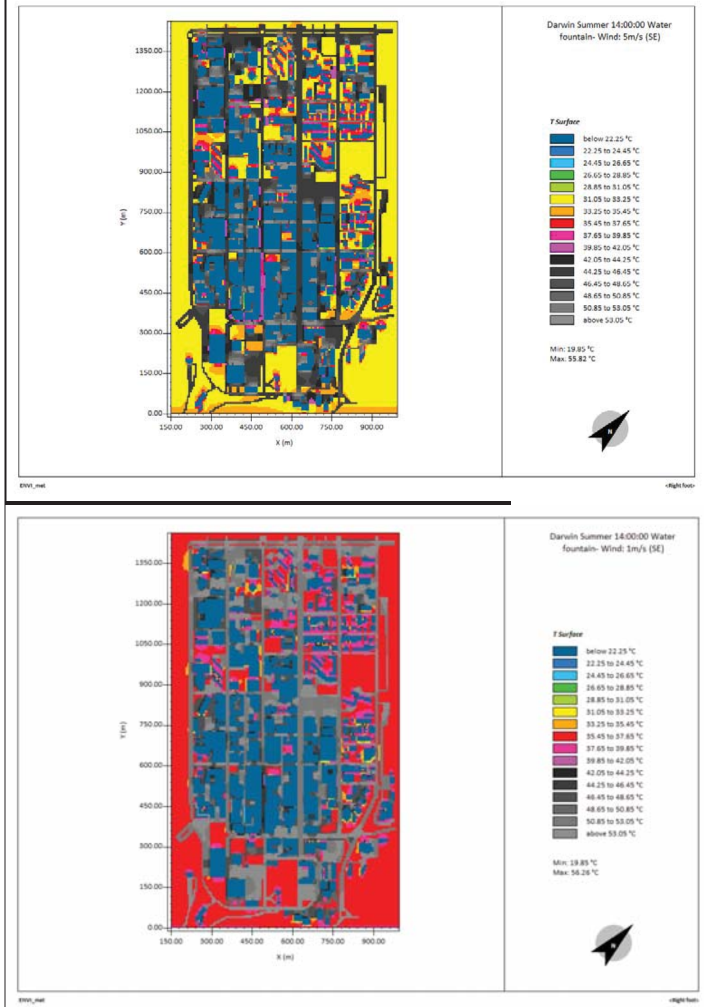


Figure 6. Water fountain: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario is given in Figures 5 and 6.

The surface temperature in the Mall mostly varies between 39.85°C and 42.05°C when water fountain is used in the simulations (when wind speed is 5m/s). This is about 2.2°C lower than that obtained in the simulation of the reference model when the air speed is 5m/s. The maximum and minimum surface temperatures in the Mall for the North westerly at the speed of 5m/s are 33.94°C and 46.39°C, respectively. The maximum and minimum surface temperatures for the same wind speed is 36.78°C and 47.54°C when wind direction is from South west.

The surface temperature of the Mall, when wind speed is 1m/s, mostly ranges between 44.25°C and 46.45°C which is up to 3°C lower than that in the reference model. However, this difference reaches to about 5°C where water fountains were employed. The maximum surface temperature reaches to about 48°C in the northern part of the Mall, when wind speed is 1m/s.

Wind speed (m/s)

NW winds

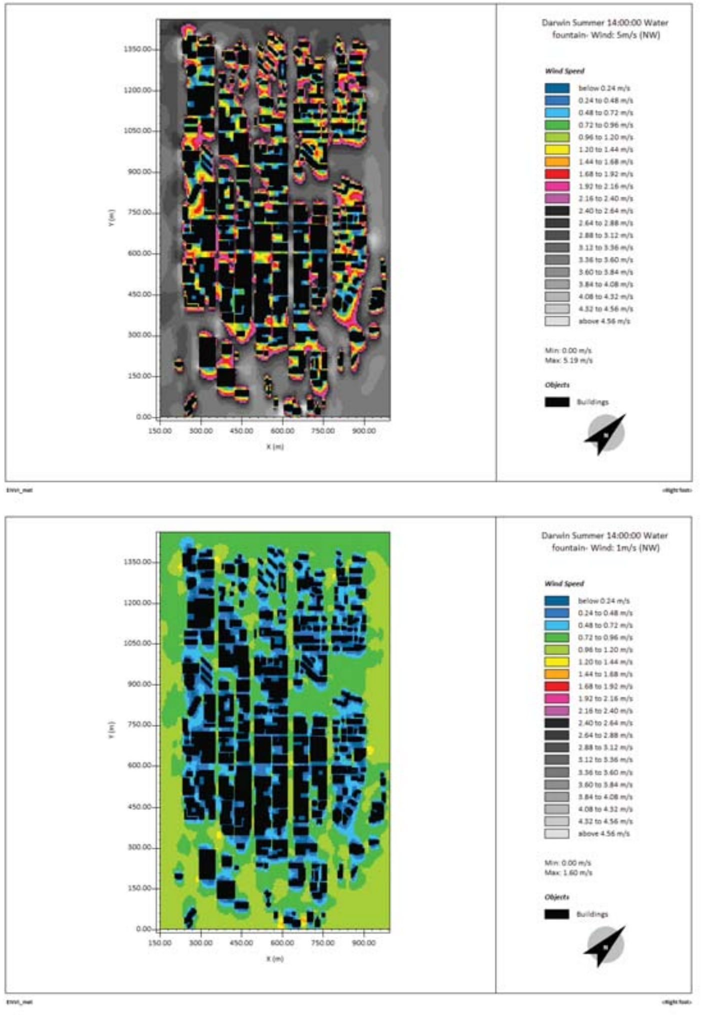


Figure 7. Water fountain: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

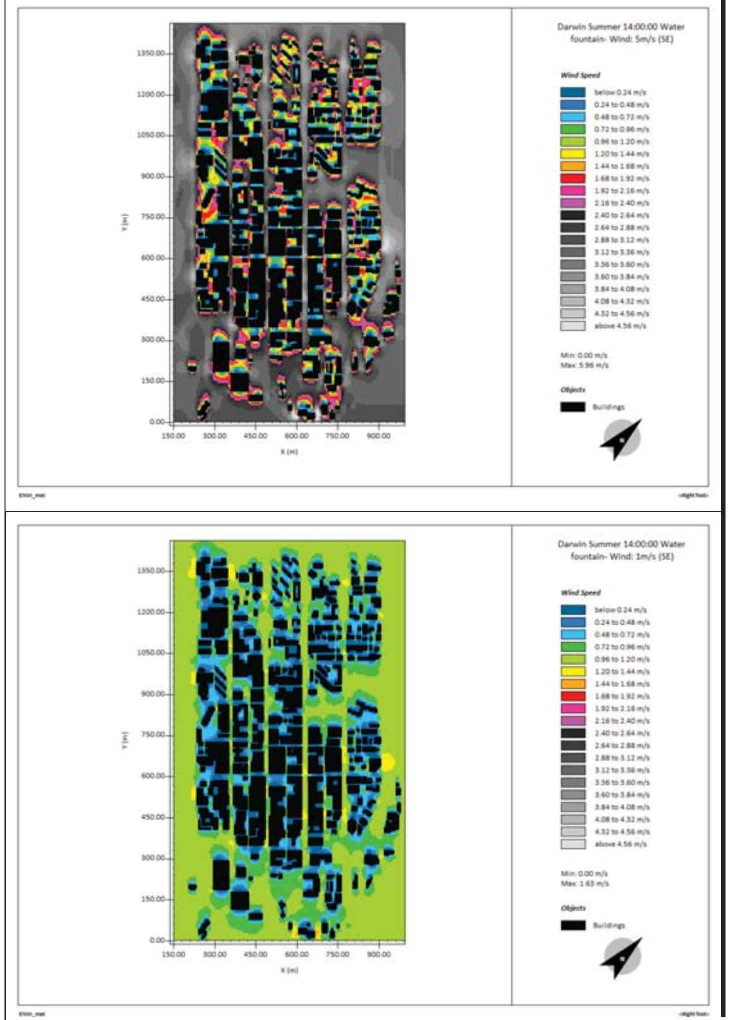


Figure 8. Water fountain: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution in the study area when water fountain is used. The wind speed distribution is almost same as that obtained from the simulation of the reference model.

Cost

The average cost for each fountain is estimated close to 15000 Dollars and the total cost close to 150000 dollars.

Concluding remark

The results of simulation show that the use of 10 water fountains in the Mall, which spray water from 4 m above the ground, is a very effective mitigation strategy at a local scale. It has been illustrated that the local maximum temperature reduction achieved in the Mall, Darwin CBD, with application of the water fountain is about 3.92 (K) and 5.83 (K) for the wind speed of 5 m/s and North westerly and South easterly directions, respectively. The local maximum temperature drop is 5.46 (K) and 6.67(K) for North westerly and South easterly winds at the speed of 1m/s.

Heat Mitigation Program

Darwin, NT

MITIGATION SCENARIO 8: increase the Greenery to cover 20 % of the CBD Area

UNSW

Project leader:
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Research team: Shamila Haddad, Giulia Ulpiani, Riccardo Paolini, Afroditi Synnefa, Francesco Fiorito, Samira Garshasbi

Urban greenery can bring about benefits to the microclimate through processes of shading, evapotranspiration, regulation of the air movement and heat exchange urban greenery contribute highly to decrease ambient temperatures in the adjacent urban zones while help to mask urban noise, filter urban pollutants, prevent erosion and stabilize the soil and also provide relaxation to the visitors. Urban greenery offer an important mitigation potential in cities. The exact contribution on the climate quality of a city depends on complex regional and local factors like the size and structure of the greenery, the local weather conditions, the type of plants used, the watering frequency, the thermal balance around the planted zone, and the thermal characteristics of the whole city. Most of the existing studies aiming to identify the proper size of urban greenery concluded that the larger the green area the higher its mitigation potential is. The present mitigation scenario, investigates the climatic impact of additional greenery in the city. Trees have been added in the Cavenagh road and the surrounding car parks. In total, it is supposed that 260 mature trees are planted. The specific mitigation scenario has been evaluated using advanced simulation techniques. The outcomes of the simulation have been compared against the corresponding results of the reference scenario and the expected temperature reduction has been calculated.

Ambient temperature (◦C)

NW winds

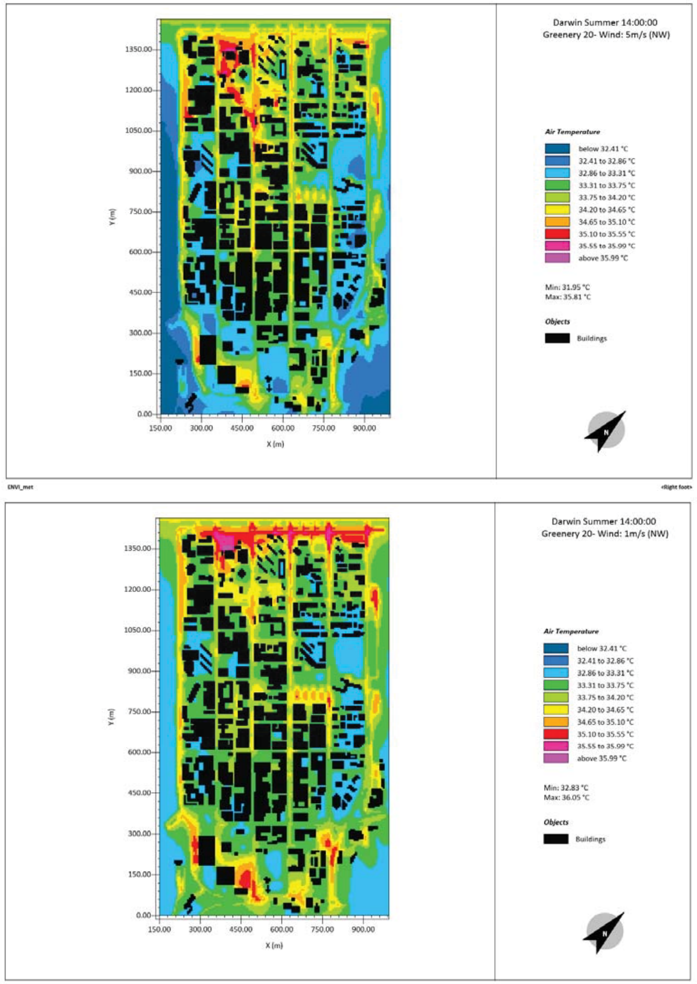


Figure 1. Greenery 20%: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

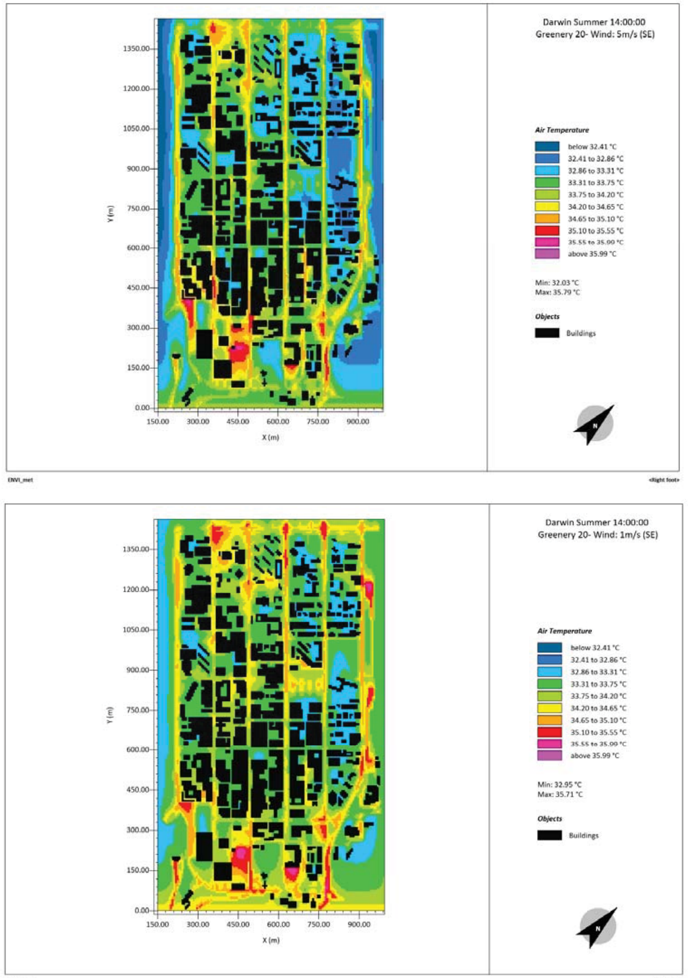
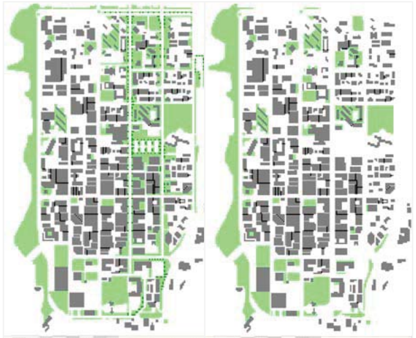


Figure 2. Greenery 20%: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The model was simulated for the increase of the urban greenery to occupy about 18-20% of the open spaces. For the modelling of the vegetation, two different plant types have been employed: tree 15 m tall, very dense foliage, distinct crown layer, and grass with average density, 20 cm tall. In this scenario, the interventions were mainly made in the Cavenagh street and surrounding asphalt parking lots located in this area. Figure 1 and 2 illustrates the simulated distribution of the ambient temperature when urban greenery is increased by about 20% in the study area. The scenario was assessed with two wind speeds of 5m/s and 1m/s and two wind directions from North west and South east. The ambient temperature at 14:00:00 in Cavenagh street and Daly street and surrounding car parks has been reduced by increase of greenery. The maximum and minimum ambient temperatures are provided in each map for the whole CBD area. However, the ambient temperature mostly varies between 32.86°C and 34.20°C, where mitigation strategy with additional trees was employed.

Greenery app. 20 % (left), reference model (right)



Air temperature difference (K)

NW winds

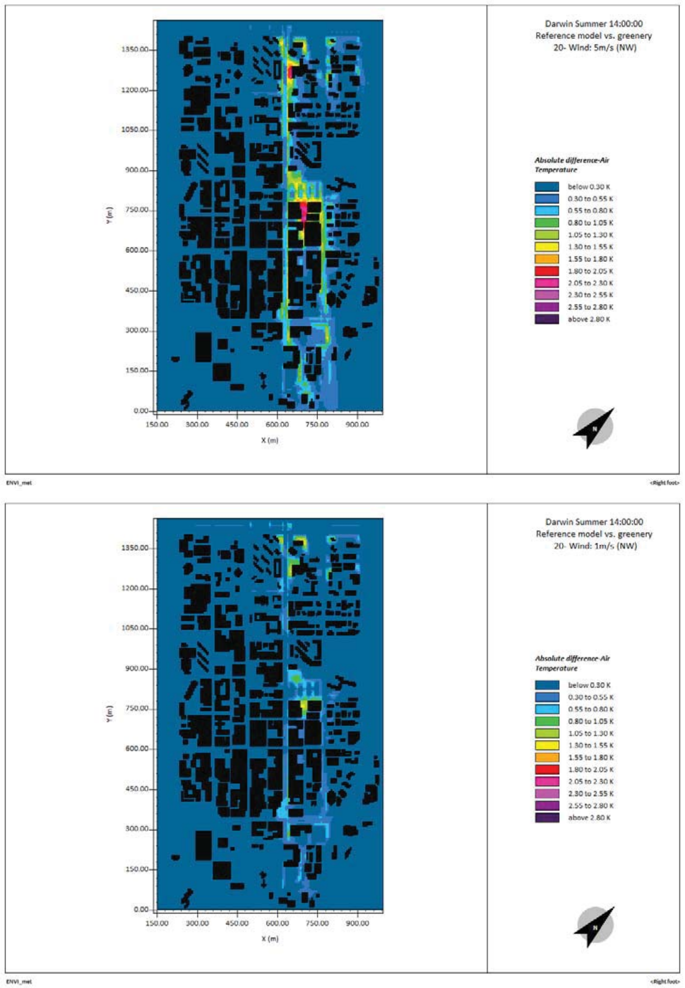


Figure 3. Greenery 20%: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

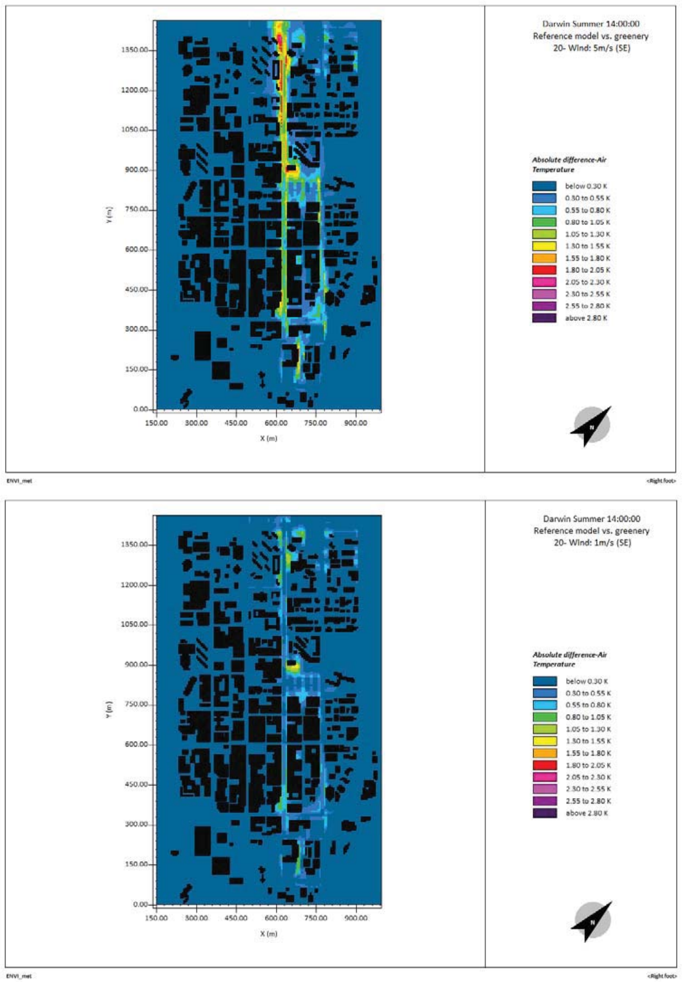


Figure 4. Greenery 20%: Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares the scenario of increasing vegetation to occupy about 20% of the open spaces with the base case model. The temperature difference distribution map is given in Figures 3-4. The results of simulation reveal that by providing additional vegetation, grass and trees, mainly in Cavenagh and Woods street, the local maximum temperature reduction is 2.57 (K) and 2.35 (K) for the wind speed of 5m/s and directions of North westerly and South easterly winds, respectively. The local maximum temperature reduction when wind speed is 1m/s is about 1.41 (K) for North westerly and South easterly winds. Tables 1 and 2 summaries the minimum and maximum temperatures, reduction of the maximum and minimum temperatures, and the local maximum temperature drop achieved in this scenario. Reduction of the maximum and minimum temperature is given based on the difference with the reference scenario.

Table 1. Statistical summery of the mitigation results – North westerly 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	-	-	-	-	-	-
Greenery 20 %	35.81	36.05	31.95	32.83	0.63	0.03	0.01	0.01	2.57	1.41

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Table 2. Statistical summery of the mitigation results – South easterly 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	-	-	-	-	-	-
Greenery 20 %	35.79	35.71	32.03	32.95	0.21	0.01	0.01	0.02	2.35	1.42

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Surface temperature (°C)

NW winds

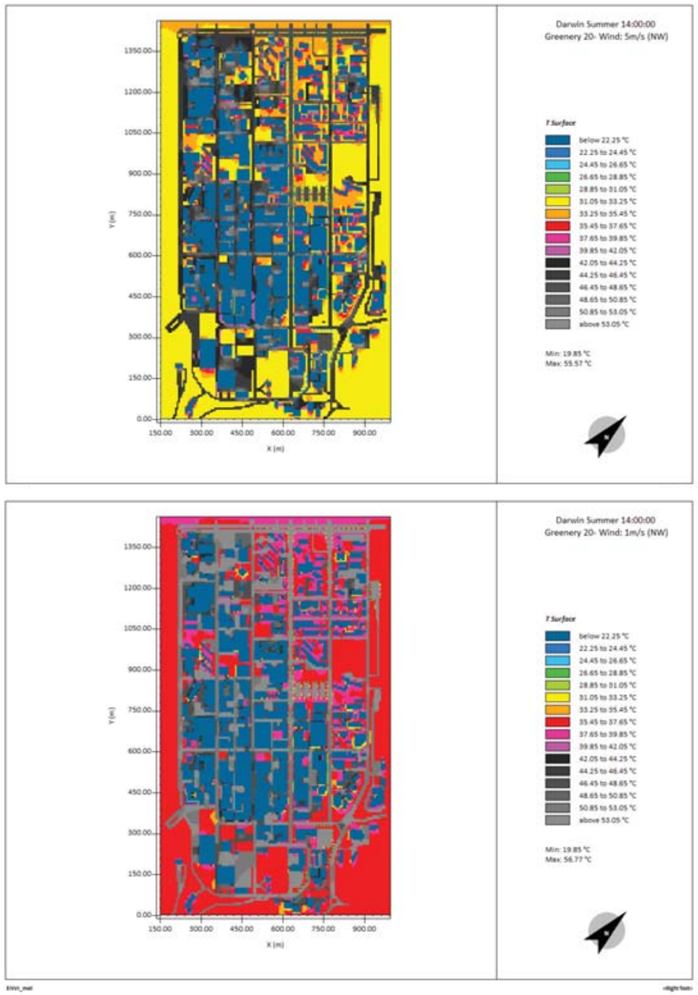


Figure 5. Greenery 20%: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

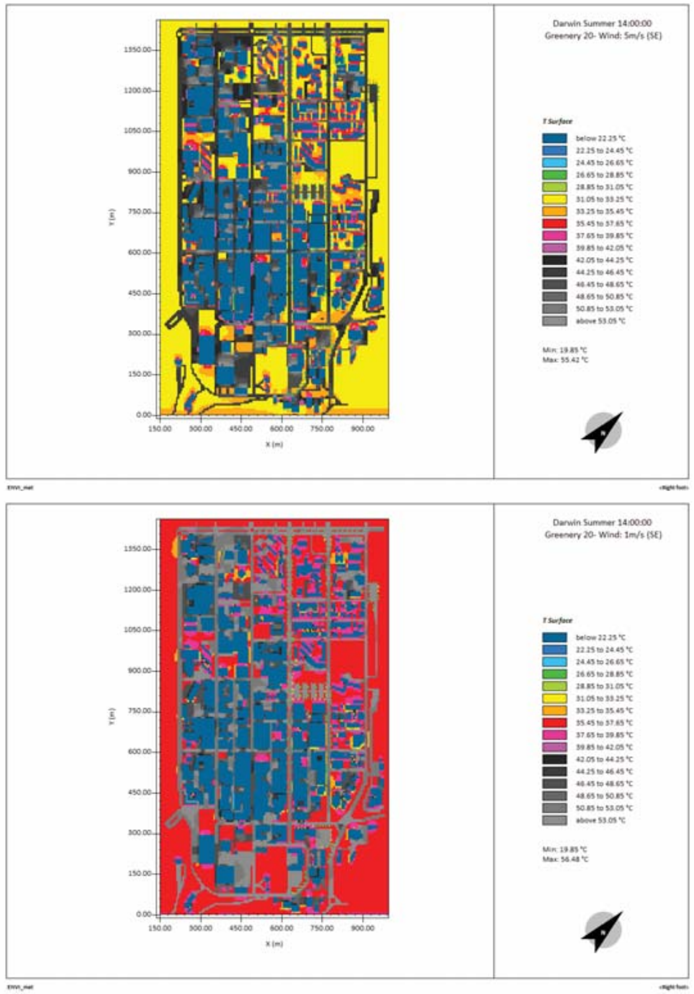


Figure 6. Greenery 20%: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario is given in Figures 5 and 6. The results of surface temperature distribution are provided for two wind speeds of 5m/s and 1m/s and two wind directions from North west and South east.

By applying urban greenery on both side of Cavenagh St, and redesigning the major car parks along this street, the surface temperature is mostly reduced to the range of 31.05°C -33.25°C (wind speed=5m/s) where asphalt car parks is replaced by vegetation (grass). This is about 11°C lower than that obtained in the simulation of the reference model. However, where trees were also added, this effect is up to 23.25°C and 26.18°C reduction in the surface temperature for North westerly and South easterly winds, respectively. For the wind speed of 1m/s, the effect of surface temperature reduction is up to about 15°C and 25°C where additional grass and trees were employed, respectively.

Wind speed (m/s)

NW winds

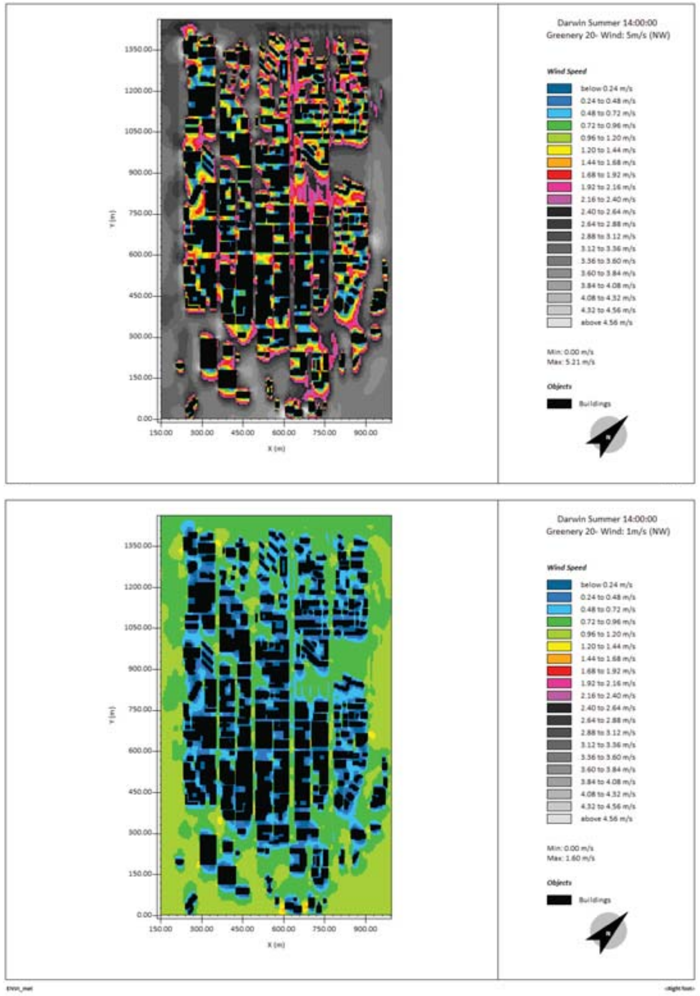


Figure 7. Greenery 20%: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

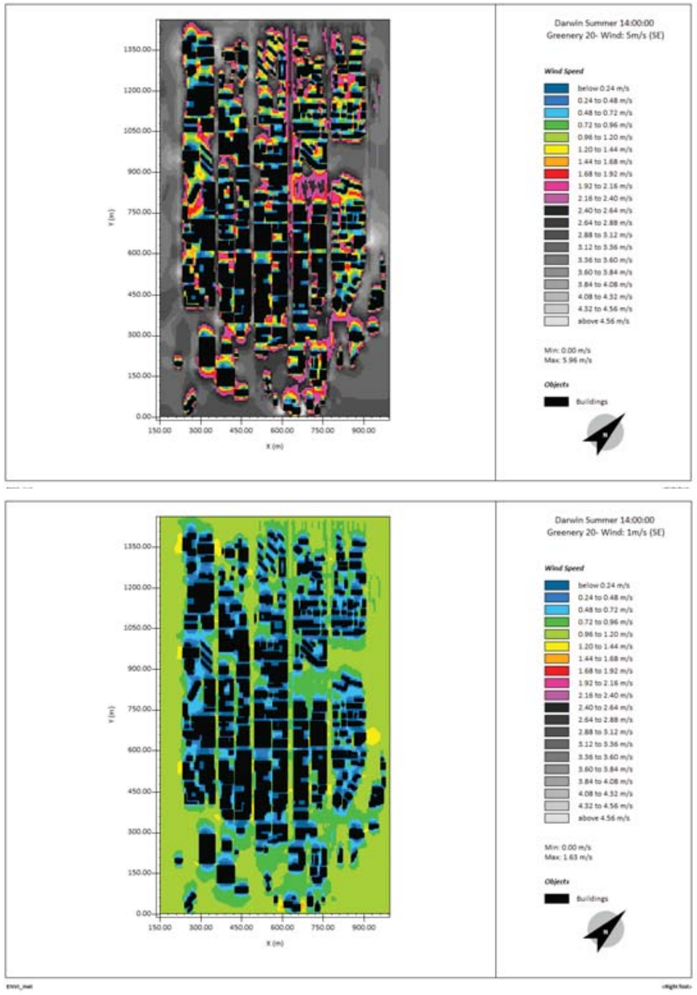


Figure 8. Greenery 20%: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution in the study area when additional vegetation (grass and tree) is used. Comparison of the wind speed distribution maps with those of the reference model illustrates the effects of additional trees on the distribution of the wind speeds in urban open spaces. Wind speed mostly appears to be within a range of 1.68 to 2.40 m/s for the simulations with wind speed of 5 m/s, and 0.48 to 0.96 m/s with wind speed of 1m/s in the urban areas where additional trees were employed (car parks or streets open spaces).

Cost

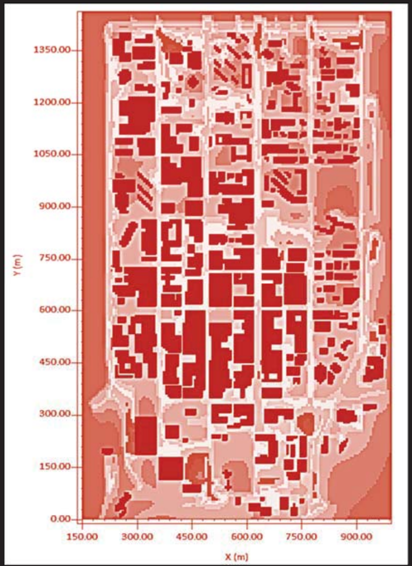
Table 3 shows the estimated cost for this scenario.

Table 3. Cost of the greenery 20% mitigation scenario

Scenario	Number of Trees	Cost Per tree (planted)	Total Cost
1. Mature Trees - 10 m height	260	25000	6500000
2. Average size Tree - 4 m height	260	14000	3640000

Concluding remarks

The increase of greenery to occupy 20% of CBD open spaces is investigated in this mitigation scenario. It has been shown that increase of greenery is an effective strategy to improve the microclimate of urban areas. The local maximum temperature drop achieved in this scenario is 2.57 (K) and 2.35 (K) for the North westerly and South easterly winds at the speed of 5 m/s. The local maximum temperature decrease of about 1.40 (K) may be achieved when wind speed is taken as 1m/s.



Heat Mitigation Program

Darwin, NT

MITIGATION SCENARIO 9: Increase the Greenery to cover 30 % of the CBD Area

UNSW

Project leader:
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Research team: Shamila Haddad, Giulia Ulpiani, Riccardo Paolini, Afroditi Synnefa, Francesco Fiorito, Samira Garshasbi

UNSW SYDNEY

MANU ET MENTE

SCIENTIA

[redacted]

Urban greenery can bring about benefits to the microclimate through processes of shading, evapotranspiration, regulation of the air movement and heat exchange urban greenery contribute highly to decrease ambient temperatures in the adjacent urban zones while help to mask urban noise, filter urban pollutants, prevent erosion and stabilize the soil and also provide relaxation to the visitors. Urban greenery offer an important mitigation potential in cities. The exact contribution on the climate quality of a city depends on complex regional and local factors like the size and structure of the greenery, the local weather conditions, the type of plants used, the watering frequency, the thermal balance around the planted zone, and the thermal characteristics of the whole city. Most of the existing studies aiming to identify the proper size of urban greenery concluded that the larger the green area the higher its mitigation potential is.

The present mitigation scenario, investigates the climatic impact of additional greenery in the city. Trees have been added in the Esplanade, Mitchel, Smith, Cavenagh and Woods streets, and the surrounding car parks. In total, it is supposed that 477 mature trees are planted. The specific mitigation scenario has been evaluated using advanced simulation techniques. The outcomes of the simulation have been compared against the corresponding results of the reference scenario and the expected temperature reduction has been calculated.

Ambient temperature (◦C)-NW winds

NW winds

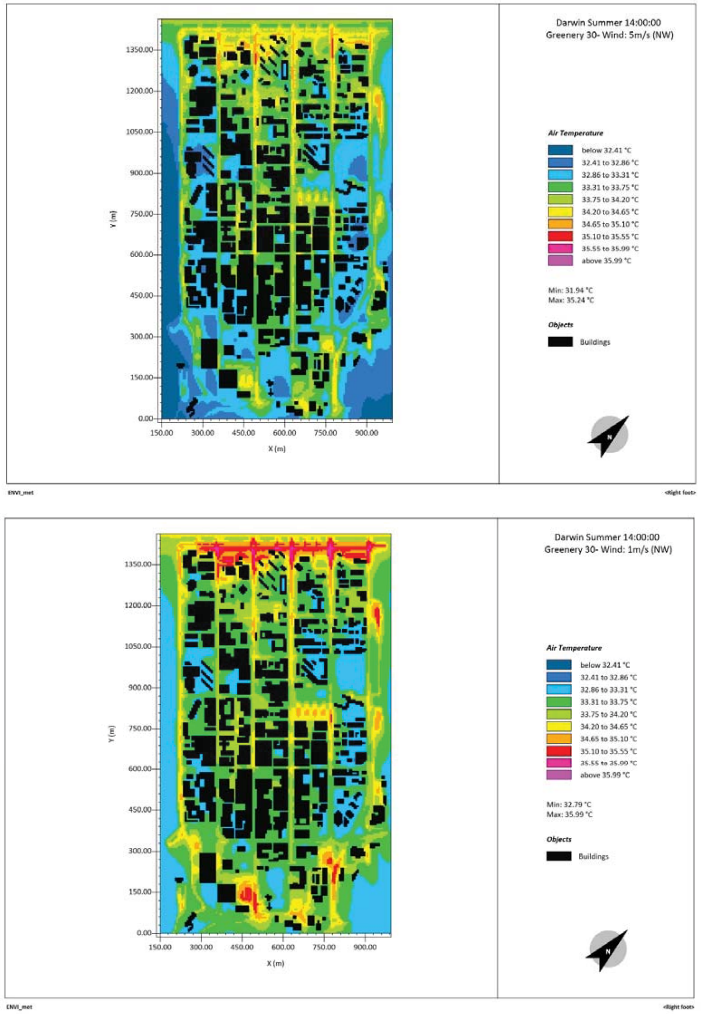

Figure 1. Greenery 30%: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

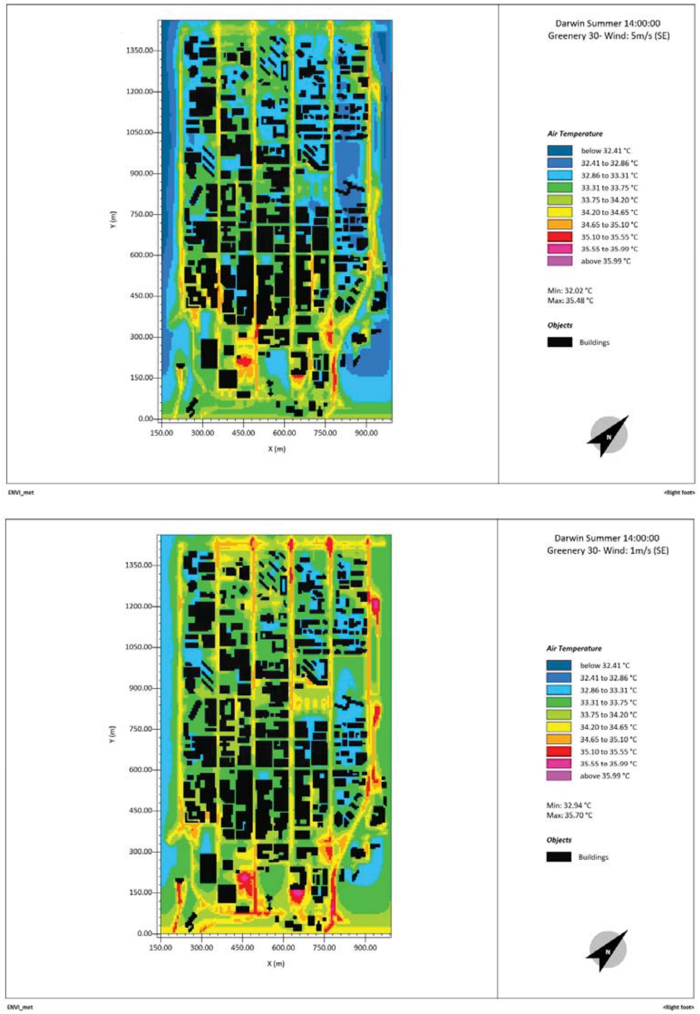

Figure 2. Greenery 30%: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The model was simulated for the increase of the urban greenery to occupy 30% of the open spaces. For the modelling of the vegetation, two different plant types have been employed: tree 15 m tall, very dense foliage, distinct crown layer, and grass with average density, 20 cm tall. The total number of trees used in this investigation is 477. In this scenario, the interventions were mainly made in the northern part of the study area and major car parks located in the CBD.

Figure 1 and 2 show the simulated distribution of the ambient temperature when urban greenery is increased by 30% in the study area for two wind speeds of 5m/s and 1m/s from North West and South east. The ambient temperature at 14:00:00 has been reduced by increase of greenery in the study area. It has been shown that air temperature in the major car parks located. The ambient temperature at 14:00:00 ranges between about 31.85°C to 34.36°C at the height of 1.46m. However, as shown in the maps, majority of the CBD urban area fall bellow 32.86°C considering all investigated wind speed and directions.

Greenery 30 % (left), reference model (right)

Air temperature difference (K)

NW winds

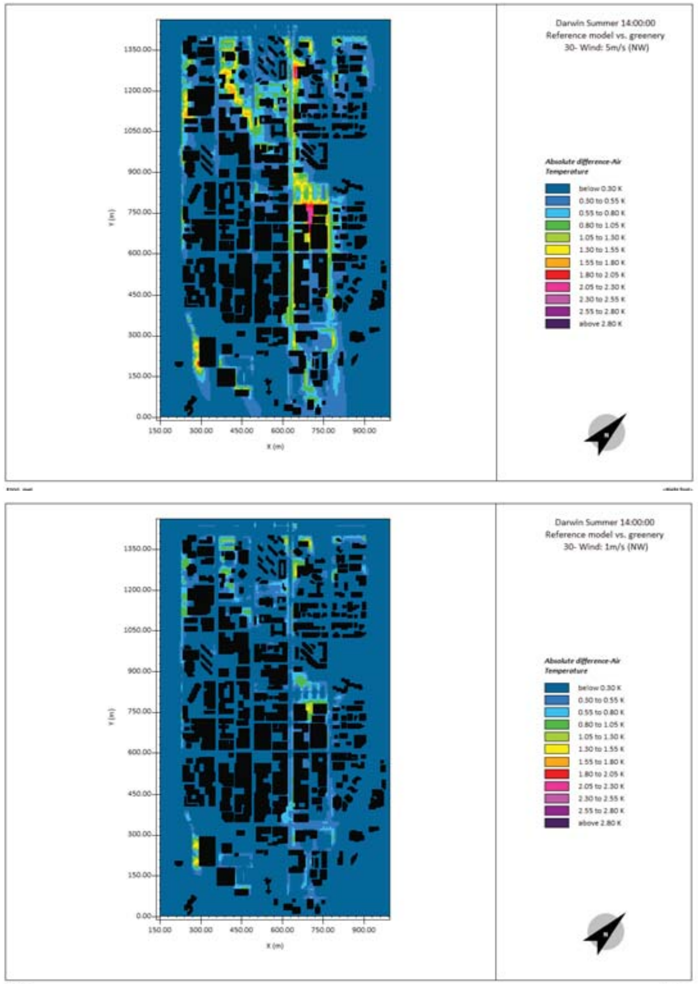

Figure 3. Greenery 30%: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

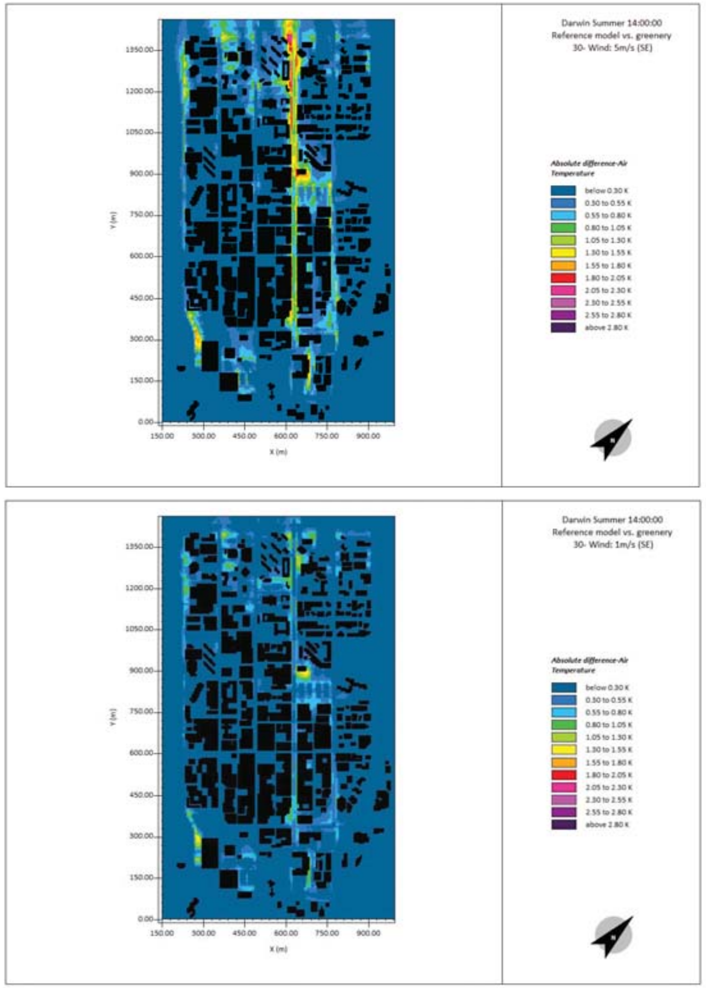

Figure 4. Greenery 30%: Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares the scenario of increasing vegetation to occupy 30% of the open spaces with the base case model. The temperature difference distribution map is given in Figures 3-4.

The results of simulation reveal that by providing additional vegetation, grass and trees (mainly in northern parts of the Esplanade, Mitchel, Smith, Cavenagh and Woods streets, and major parking lots of the CBD), the local maximum temperature reduction achieved is 2.66 (K) and 2.41 (K) for the wind speed of 5m/s and directions of North westerly and South easterly winds, respectively. The local maximum temperature reduction when wind speed is 1m/s is about 1.60 (K) and 1.41 (K) for North westerly and South easterly winds, respectively. Tables 1 and 2 summaries the minimum and maximum temperatures, reduction of the maximum and minimum temperatures, and the local maximum temperature drop achieved in this scenario. Reduction of the maximum and minimum temperature is given based on the difference with the reference scenario.

Table 1. Statistical summery of the mitigation results – North westerly 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	-	-	-	-	-	-
Greenery 30 %	35.24	35.99	31.94	32.79	1.20	0.09	0.02	0.05	2.66	1.60

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Table 2. Statistical summery of the mitigation results – South easterly 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	-	-	-	-	-	-
Greenery 30 %	35.48	35.7	32.02	32.94	0.52	0.02	0.02	0.03	2.41	1.45

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Surface temperature (°C)

NW winds

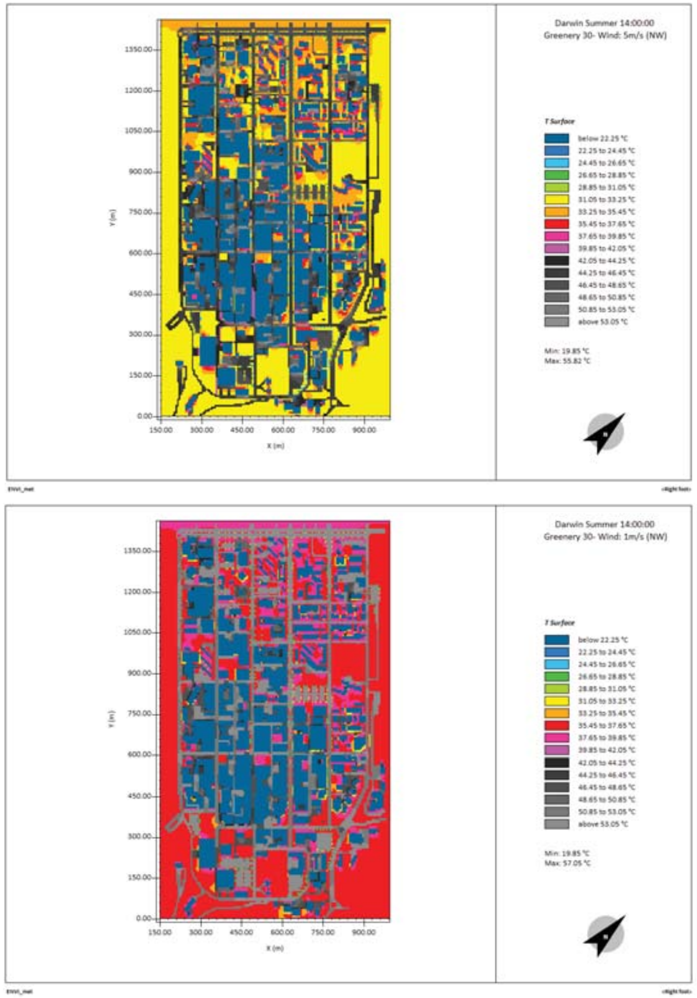

Figure 5. Greenery 30%: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

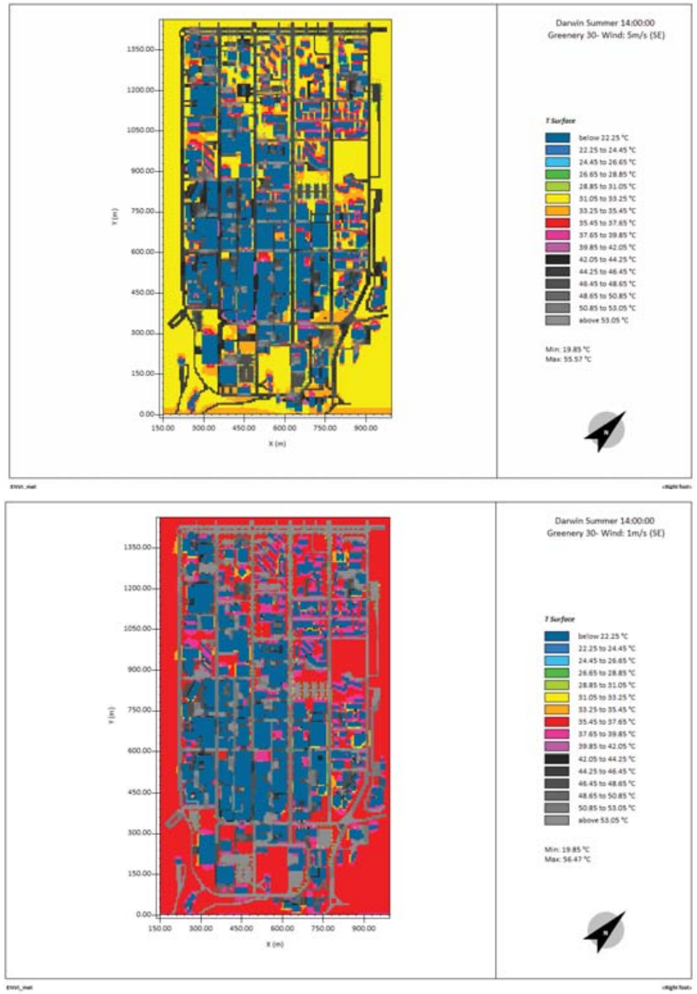

Figure 6. Greenery 30%: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario is given in Figures 5 and 6. The results of surface temperature distribution are provided for two wind speeds of 5m/s and 1m/s and two wind directions from North west and South east.

By applying urban greenery to occupy 30% of open spaces, and redesigning the major car parks with additional tress, the surface temperature is significantly reduced. The maximum surface temperature is reduction achieved is about 27.32°C and 26.58°C when wind speed is taken as 5m/s for North westerly and South easterly winds, respectively. The surface temperature may be decreased by 26.60°C and 26.33°C for North westerly and South easterly winds at the speed of 1m/s, respectively. Figures 5 and 6 show that the surface temperature of the parking lots, which is replaced by vegetation (grass), varies mostly within a range of 31.05°C to 35.45°C when wind speed is 5m/s. The surface temperature fall within a range of 24.45°C to 28.85°C where trees were employed. The surface temperature of car parks ranges from 35.45°C to 37.67°C for the wind speed of 1m/s; however, it mostly varies within 26.65°C to 28.85°C under the trees.

Wind speed (m/s)

NW winds

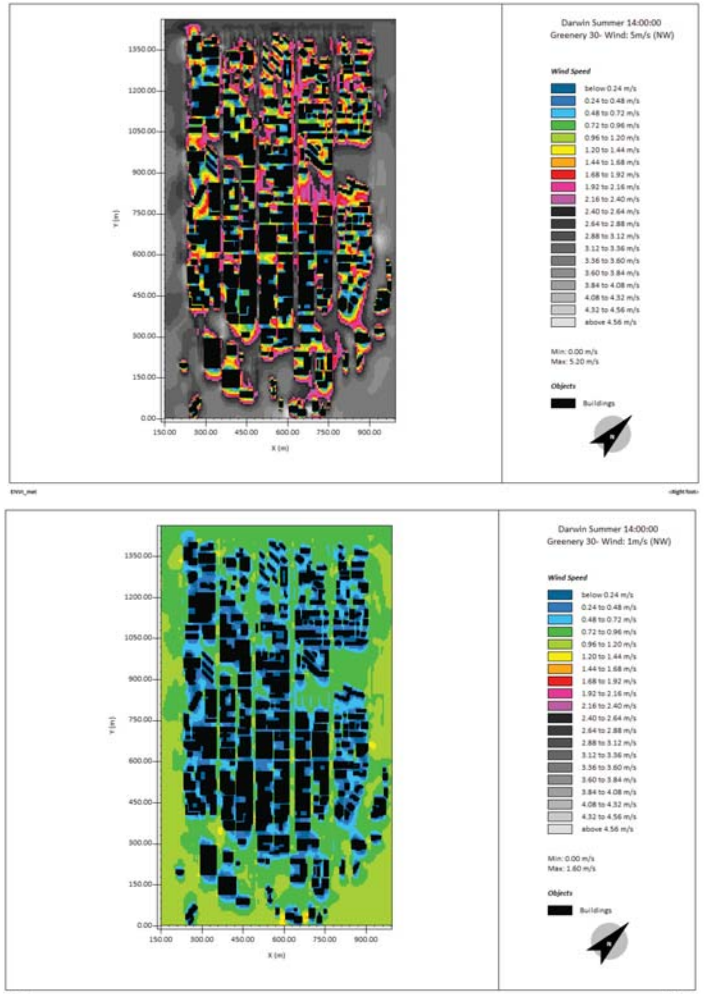

Figure 7. Greenery 30%: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

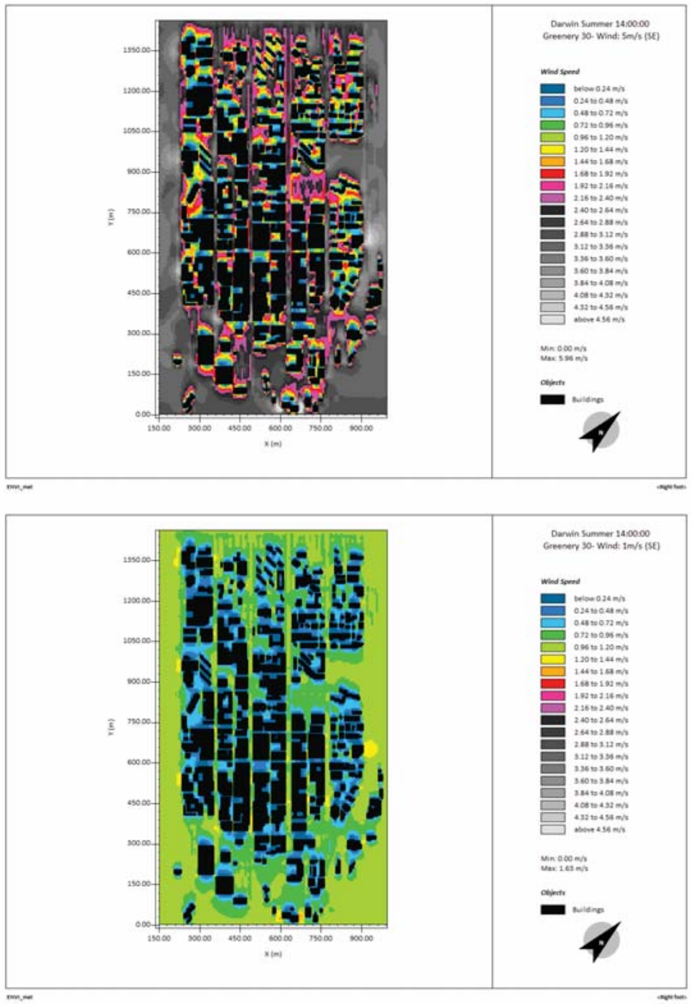

Figure 8. Greenery 30%: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution in the study area when additional vegetation (grass and tree) is used. Comparison of the wind speed distribution maps with those of the reference model illustrates the effects of additional trees on the distribution of the wind speeds in the streets and urban open spaces located in northern parts of the Esplanade, Mitchel, Smith, Cavenagh and Woods streets, and major parking lots of the CBD. However, the maximum and minimum wind speed in the whole map is very similar to the reference model.

Cost

Table 3 shows the estimated cost for this scenario.

Table 3. Cost of the greenery 30% mitigation scenario

Scenario	Number of Trees	Cost Per tree (planted)	Total Cost
1. Mature Trees - 10 m height	477	25000	11925000
2. Average size Tree - 4 m height	477	14000	6678000

Concluding remarks

The increase of greenery is investigated in this mitigation scenario. It has been shown that increase of greenery is an effective strategy. The local maximum temperature drop achieved in this scenario is 2.66 (K) and 2.41 (K) for the North westerly and South easterly winds at the speed of 5 m/s. The local maximum temperature decrease of 1.60 (K) and 1.45 (K) may be achieved when wind speed is taken as 1m/s for the North westerly and South easterly, respectively.

Heat Mitigation Program

Darwin, NT

MITIGATION SCENARIO 10: Combined scenario: global increase of albedo to 0.6, application of shading, and 30% greenery in open spaces

UNSW

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Several technologies and systems may be combined to mitigate the urban heat island. It is of great interest to explain how mitigation technologies of different natures and characteristics may work together and to assess their combined climatic performance.

It is important to point out that the final mitigation potential of any combination of mitigation technologies should be quite lower than the sum of the contributions of each individual technology involved. Most of the considered mitigation technologies perform under the same outdoor temperature levels and their thermal interaction reduces the utilisability function of each one individually.

The present mitigation scenario considers the use of reflective materials for roofs and pavements, application of shading in specific zones of the city. And increase of the urban greenery. The combined scenario is simulated using advanced methods and the obtained results are compared against the corresponding outcomes of the reference scenario to estimate the potential temperature decrease.

Ambient temperature (◦C)

NW winds

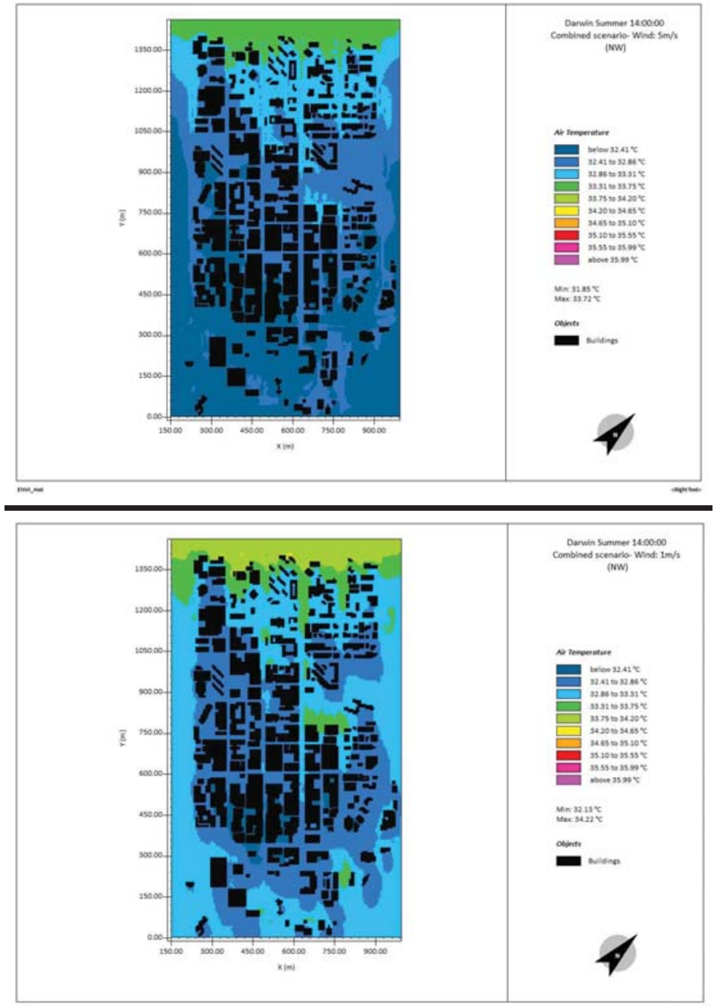


Figure 1. Combined scenario: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

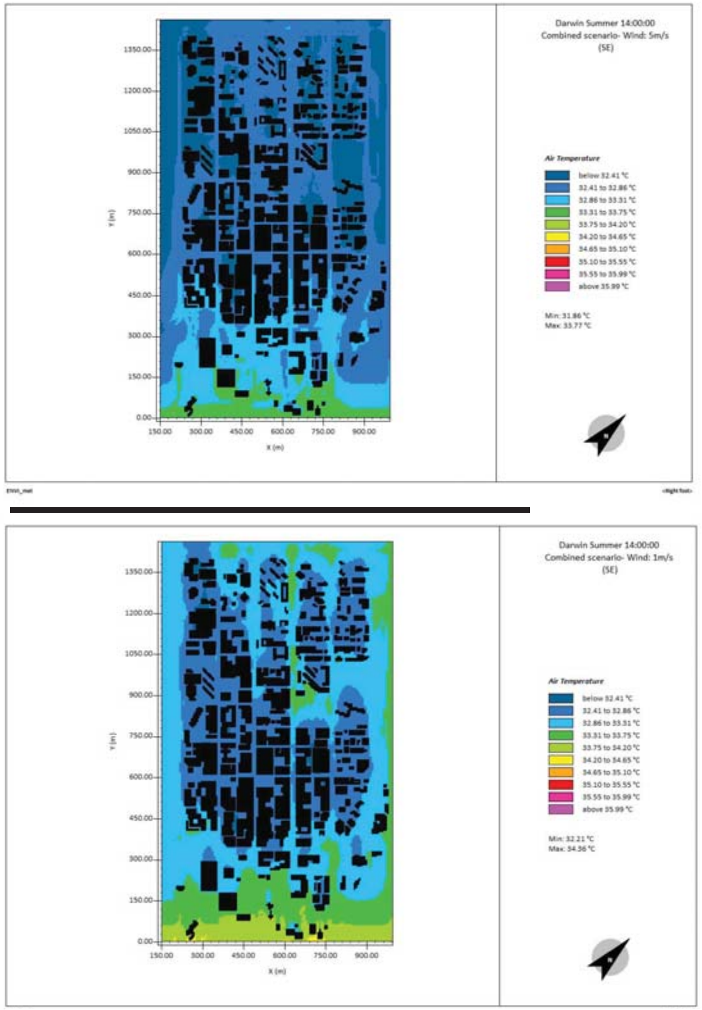


Figure 2. Combined scenario: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The combined scenario investigated here refers to combination of increase of global albedo to 0.6, application of shading (mainly on Wood St, Cavenagh St, Smith St, Mitchel St, Esplanade St, and McMinn St and the nearby car parks), and 30% greenery in open spaces.

In this scenario, therefore, albedo of walls and roofs=0.6, albedo of streets and pavements=0.72. For additional greenery to occupy 30% open spaces, Daly street and major car parks in the CBD including state square parking area are also considered in addition to above-mentioned streets where shading is provided. For the modelling of the vegetation, two different plant types have been employed: tree 15 m tall, very dense foliage, distinct crown layer, and grass with average density, 20 cm tall. The total number of trees used in this investigation is 477. Figure 1 and 2 shows the simulated distribution of the ambient temperature for the combined scenario. The ambient temperature at 14:00:00 ranges between about 31.85°C to 34.36°C at the height of 1.46m. However, as shown in the maps, majority of the CBD urban area fall bellow 32.86°C considering all investigated wind speed and directions.

Tables 1 and 2 summaries the minimum and maximum temperatures, reduction of the maximum and minimum temperatures, and the local maximum temperature drop achieved in this scenario.

Air temperature difference (K)

NW winds

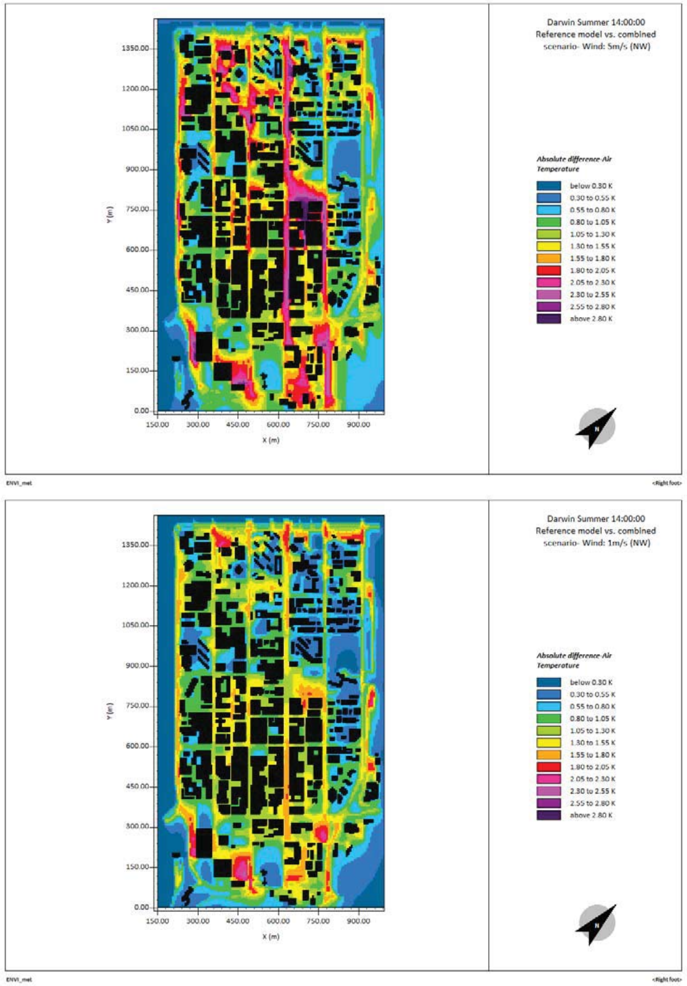


Figure 3. Combined scenario: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

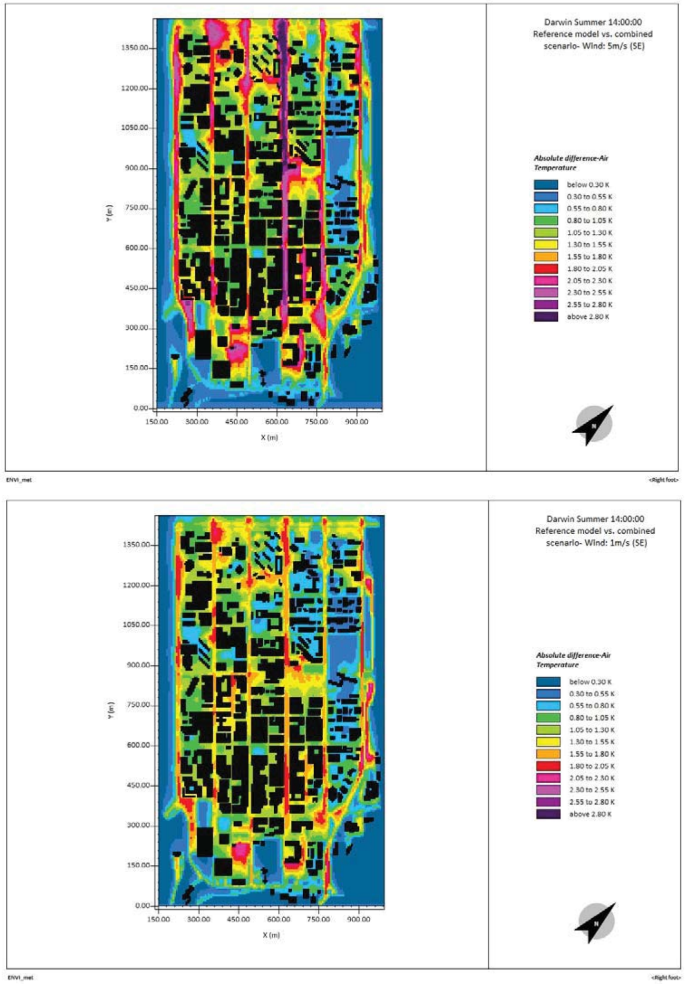


Figure 4. Combined scenario: Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares the combined scenario of global increase of albedo to 0.6, application of shading, and 30% greenery in open spaces with the base case model. The temperature reduction distribution is given in Figures 3-4. The results indicate that by combining three effective scenarios (global albedo of 0.6, application of shading, and 30% greenery), the local maximum temperature reduction achieved is 3.52 (K) and 3.44 (K) for the wind speed of 5m/s and directions of North westerly and South easterly winds, respectively. The local maximum temperature reduction achieved, when wind speed is 1m/s, is 2.43 (K) and 2.35 (K) for North westerly and South easterly winds, respectively. Figure 3 and 4 (wind speed of 5m/s) show that the local maximum temperature reduction (above 2.80 (K) is mostly observed in Cavenagh street and in major asphalt car parks in CBD (Cavenagh street, State square, Mitchell street, McMinn street). The maximum temperature reduction achieved in the combined scenario occurs in the CBD major car parks, followed by asphalt pavements when wind speed is taken as 1m/s.

Table 1. Statistical summery of the mitigation results – North westerly 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	-	-	-	-	-	-
Combined scenario	33.72	34.22	31.85	32.13	2.72	1.86	0.11	0.71	3.52	2.43

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Table 2. Statistical summery of the mitigation results – South easterly 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	-	-	-	-	-	-
Combined scenario	33.77	34.36	31.86	32.21	2.23	1.36	0.18	0.76	3.44	2.35

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Surface temperature (°C)

NW winds

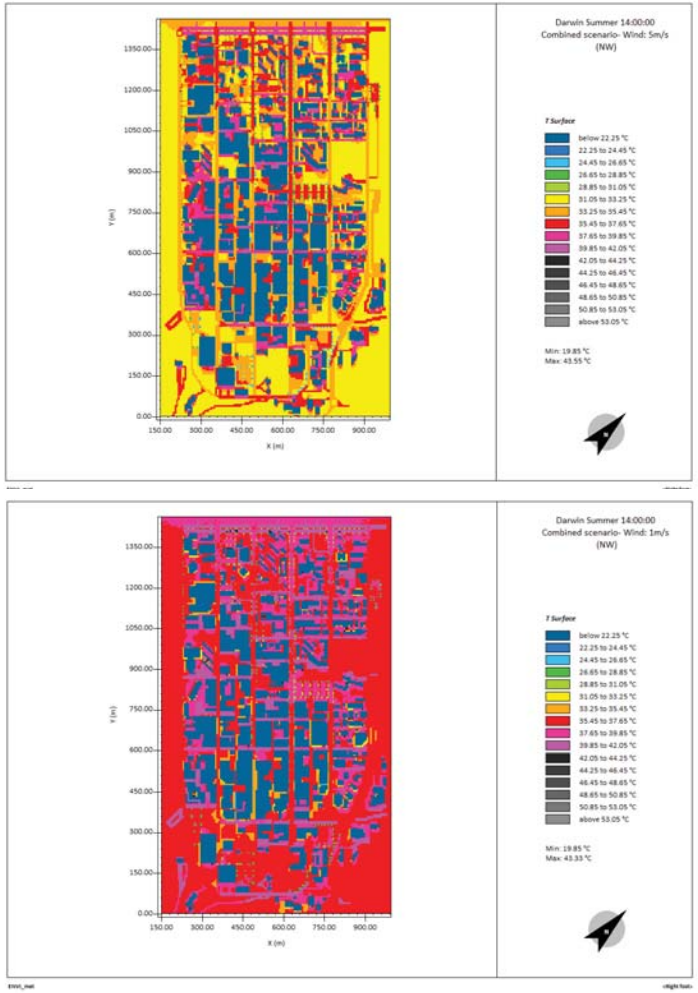


Figure 5. Combined scenario: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

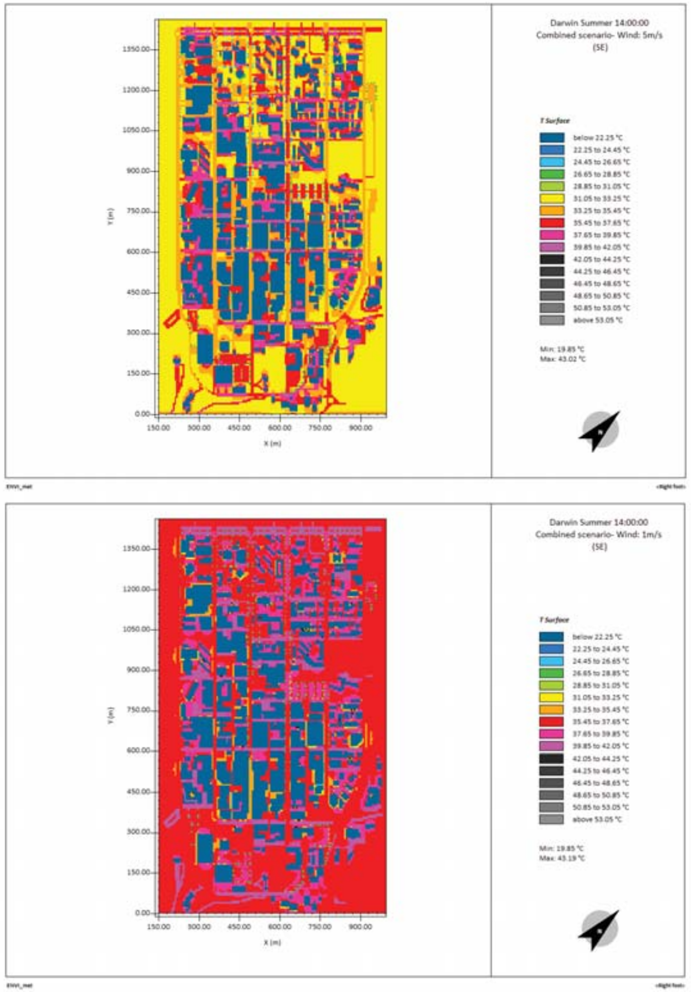


Figure 6. Combined scenario: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario is given in Figures 5 and 6.

The surface temperature varies between 19.85°C and 43.55°C when combined scenario is used in the simulations. Figures 5 and 6 show that the surface temperature of the streets and pavements are reduced significantly compared to the reference scenario. In the combined scenario, wind speed of 5 m/s, the surface temperature of the major asphalt parking area ranges from 33.25°C to a maximum of 37.65°C. It should be noted that the surface temperature of the same areas in the reference model varies from 44.25°C to above 53.05°C. The surface temperature is mainly reduced to the range of 24.45°C to 28.85°C when trees were used in the green area (wind speed=5m/s). This clearly shows the effects of the combined scenario on the surface temperature reduction. Similar to the results of the combined scenario with wind speed of 5 m/s, the surface temperature of asphalt car parks varies from 35.45°C to 39.85°C when wind speed is 1 m/s. The surface temperature is mostly reduced to a range of 26.65°C to 31.05°C when trees were used in the green area (wind speed =1m/s).

Wind speed (m/s)

NW winds

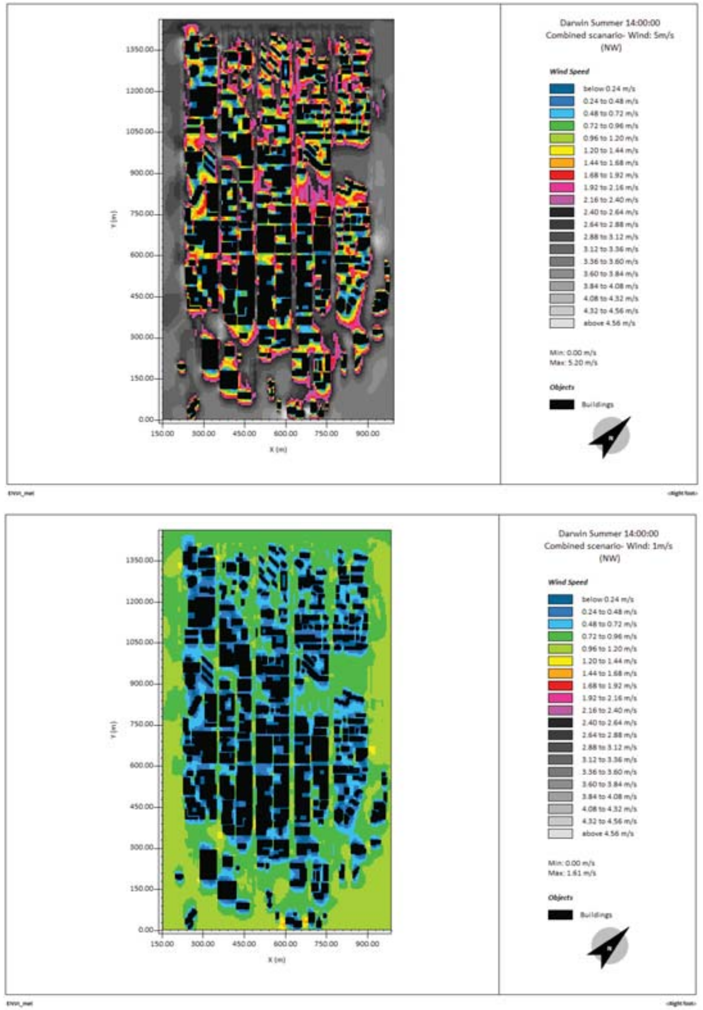


Figure 7. Combined scenario: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

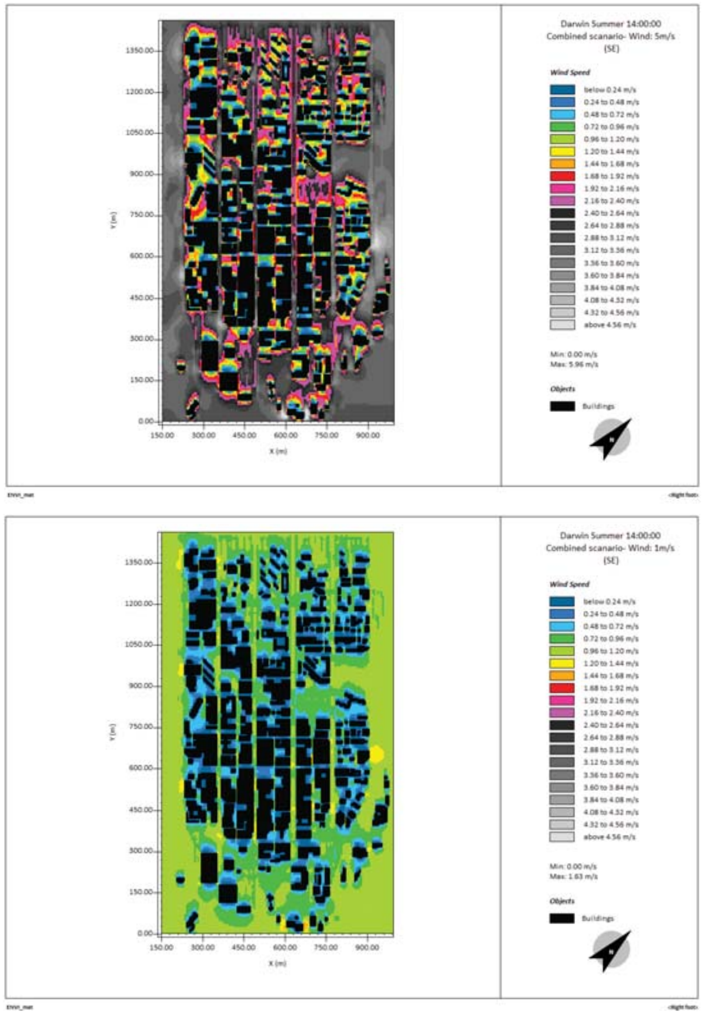


Figure 8. Combined scenario: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution in the study area when the combined scenario (global increase of albedo to 0.6, application of shading, and 30% greenery in open spaces) is used.

The wind speed distribution in the major car park in Cavenagh street shows a lower range of wind speeds compared to the same area in the reference model for both investigated wind directions at the speed of 5m/s. This effect is caused by the additional trees used in the combined scenario. Compared to the base case wind speed distribution, wind speed mostly appears to be lower (within a range of 1.68 to 2.40 m/s for the simulations with wind speed of 5 m/s and 0.48 to 0.96 m/s for the simulations with wind speed of 1m/s) where additional urban trees were employed in the combined scenario; Dally street, northern parts of Cavenagh Esplanade, Mitchel, Smith, and Woods streets, and major parking lots of the CBD.

Cost

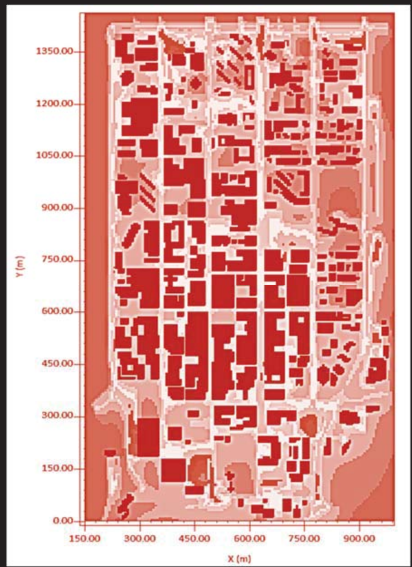
Table 3 shows the cost of the combined mitigation scenario.

Table 3. Cost of combined mitigation scenario

Mitigation Strategy	Total Area	Number of Trees	Cost per Unit, AUS$	Cost of Mitigation Strategy	Total Cost
Increase the albedo to 0.6					
Total building roof/floor area (m^2)	314272		15	4714080	4714080
Total Car park area in asphalt (m^2)	117684		30	3530520	8244600
Total area of pavements and streets(m^2)	652244		30	19567320	27811920
Shading the Main Streets and Car Parks	275436		70	19280520	47092440
Greenery 30 % 1. Mature Trees - 10 m height		477	25000	11925000	59017440
2. Average size Tree - 4 m height		477	14000	6678000	53770440

Concluding remark

The combined use of greenery, reflective materials, and shading to improve the microclimate of urban areas is a very popular and effective mitigation strategy. It has been shown that the local maximum temperature reduction achieved in Darwin with combined scenario is approximately 3.50 (K) and 2.40 (K) for the wind speed of 5m/s and 1 m/s, respectively.



Heat Mitigation Program

Darwin, NT

MITIGATION SCENARIO 11: Combined scenario: global increase of albedo to 0.6, application of shading, 30% greenery in open spaces, and water fountain

UNSW

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Research team: Shamila Haddad, Giulia Ulpiani, Riccardo Paolini, Afroditi Synnefa, Francesco Fiorito, Samira Garshasbi

Several technologies and systems may be combined to mitigate the urban heat island. It is of great interest to explain how mitigation technologies of different natures and characteristics may work together and to assess their combined climatic performance.

It is important to point out that the final mitigation potential of any combination of mitigation technologies should be quite lower than the sum of the contributions of each individual technology involved. Most of the considered mitigation technologies perform under the same outdoor temperature levels and their thermal interaction reduces the utilisability function of each one individually.

The present mitigation scenario considers the use of reflective materials for roofs and pavements, application of shading in specific zones of the city, increase of the urban greenery, and use of evaporative systems in the area of the Mall. This combined scenario is simulated using advanced methods and the obtained results are compared against the corresponding outcomes of the reference scenario to estimate the potential temperature decrease.

Ambient temperature (◦C)

NW Winds

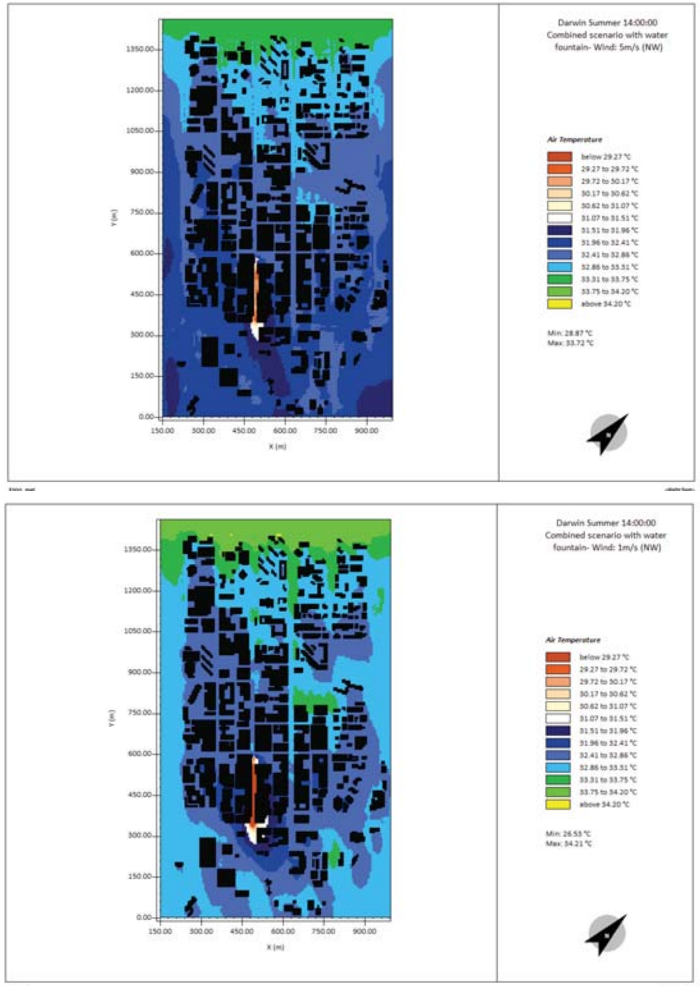


Figure 1. Combined scenario with water fountain: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

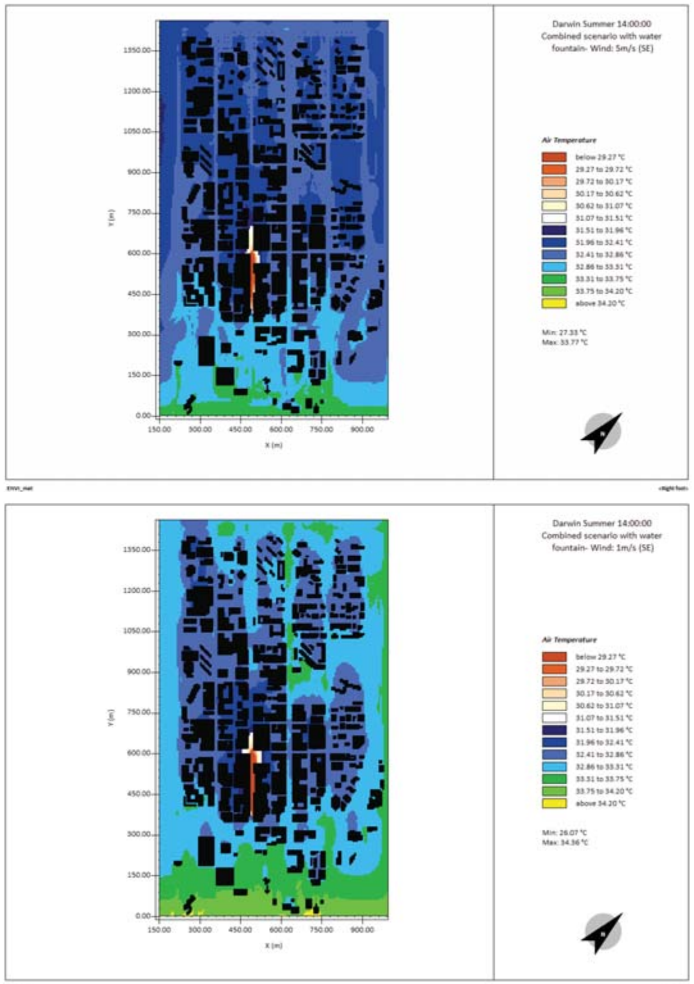


Figure 2. Combined scenario with water fountain: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Reflective materials, shading, and greenery may combine with water based mitigation techniques to further decrease the peak ambient temperature. Therefore, the model was simulated for the combined scenario and water spray system in the Mall. In this scenario, global albedo is taken as 0.6, solar control mitigation techniques are used, greenery is increased to occupy 30% of open spaces, and water fountain with spray cooling effect was employed every 18m in the Mall. In this scenario, therefore, albedo of walls and roofs=0.6, albedo of streets and pavements=0.72. Two different plant types have been employed: tree 15 m tall, very dense foliage, distinct crown layer, and grass with average density, 20 cm tall. The total number of trees used in this investigation is 477. Figure 1 and 2 shows the simulated distribution of the ambient temperature for the combined scenario. The ambient temperature at 14:00:00 ranges between about 26.07°C to 34.36°C at the height of 1.46m. However, as shown in the maps, majority of the CBD central urban area fall bellow 32.86°C considering all investigated wind speeds and directions. The ambient temperature observed in the Mall mostly falls bellow 30.17°C where water based systems were used. The ambient temperature in this area of Darwin CBD is mostly reduced by about/over 4.80°C. Tables 1 and 2 summaries the minimum and maximum temperatures, reduction of the maximum and minimum temperatures, and the local maximum temperature drop achieved in this scenario.

Air temperature difference (K)

NW winds

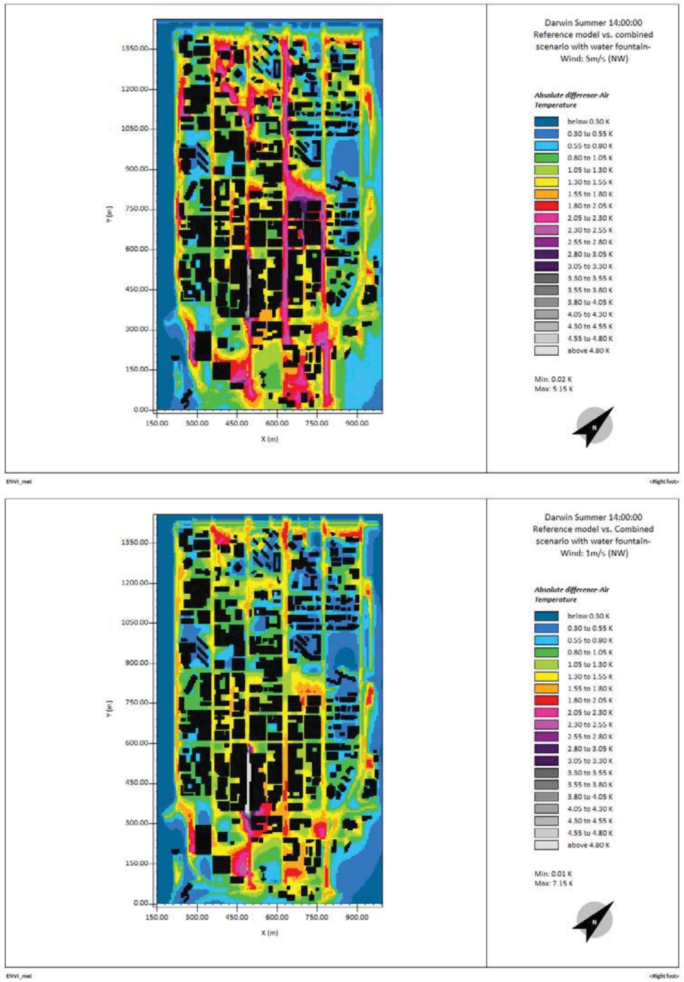


Figure 3. Combined scenario with water fountain: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

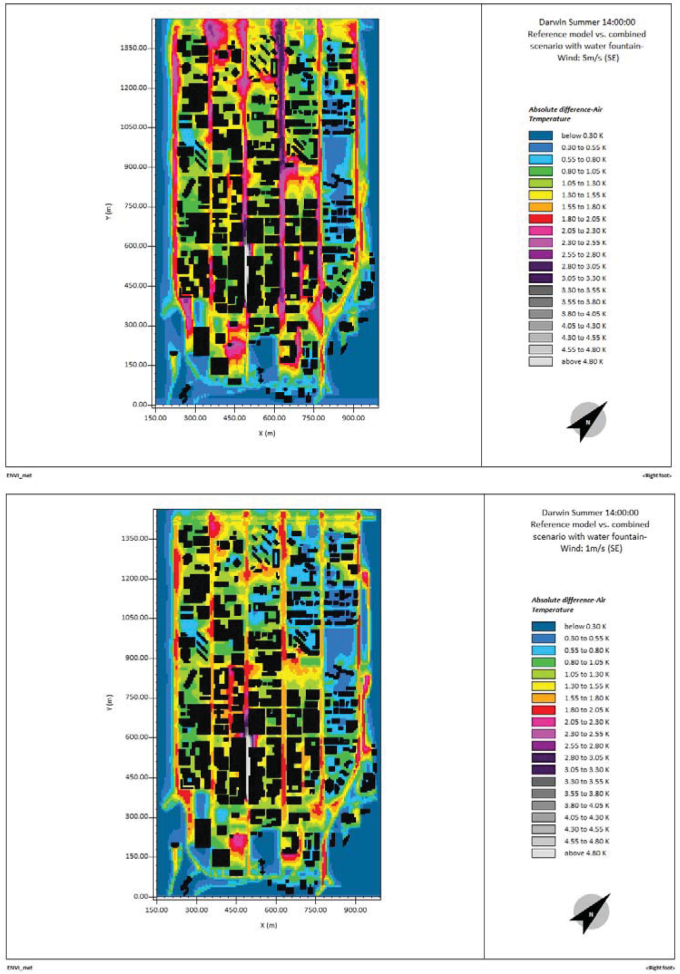


Figure 4. Combined scenario with water fountain: Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares the combined scenario of reflective materials, shading device, greenery, and water fountain, with the base case model. The temperature reduction distribution is given in Figures 3-4. The results indicate that by combining four effective scenarios, the local maximum temperature reduction achieved is 5.15 (K) and 7.05 (K) for the wind speed of 5m/s and directions of North westerly and South easterly winds, respectively. The local maximum temperature reduction achieved, when wind speed is 1m/s, is 7.15 (K) and 7.80 (K) for North westerly and South easterly winds, respectively. Figure 3 and 4 show that the local maximum temperature reduction, mostly above 4.80 (K), is observed in the Mall where water based system with spray cooling effect was used. This is followed by Cavenagh street and major asphalt car parks in CBD (Cavenagh street, State square, Mitchell street, McMinn street) where maximum temperature reduction achieved is above 2.80 (K). The magnitude of the temperature reduction achieved in the combined scenario is higher when wind speed is 5m/s compared to simulations when wind speed is taken as 1m/s.

Table 1. Statistical summery of the mitigation results – North westerly 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	-	-	-	-	-	-
Combined scenario with water fountain	33.72	34.21	28.87	26.53	2.72	1.87	3.09	6.31	5.15	7.15

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Table 2. Statistical summery of the mitigation results – South easterly 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	-	-	-	-	-	-
Combined scenario with water fountain	33.77	34.36	27.33	26.07	2.23	1.36	4.71	6.9	7.05	7.80

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model

Surface temperature (°C)

NW winds

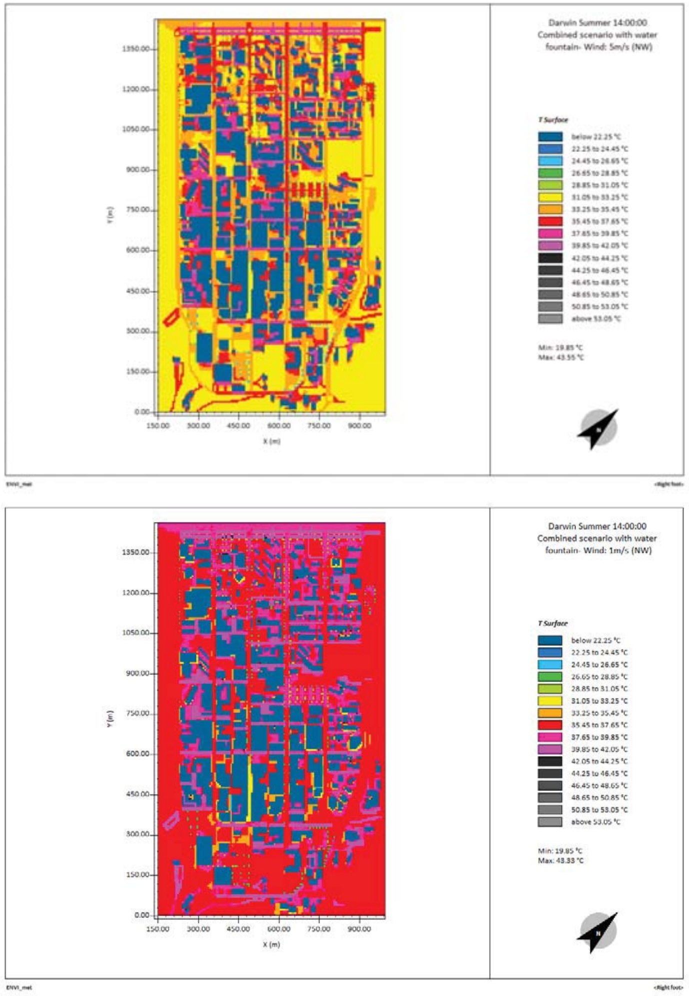


Figure 5. Combined scenario with water fountain: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

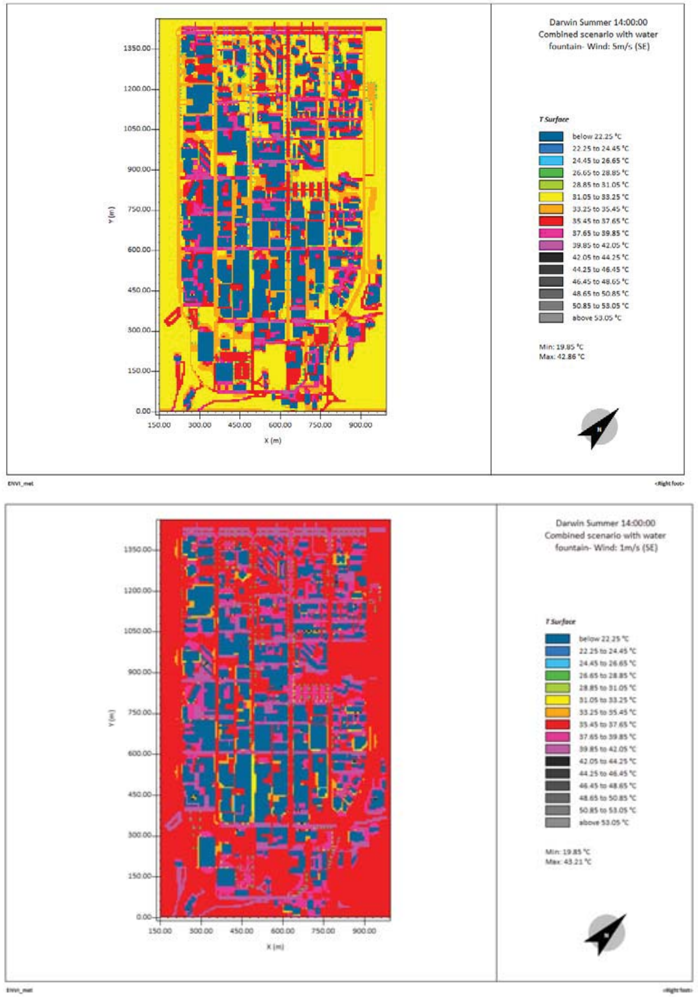


Figure 6. Combined scenario with water fountain: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario is given in Figures 5 and 6.

The maximum surface temperature varies between 19.85°C and 43.55°C when combined scenario is used in the simulations. Figures 5 and 6 show that the surface temperature of the streets and pavements are reduced significantly compared to the reference scenario. The results of the combined scenario illustrate that the surface temperature of the major asphalt car parks mainly varies between 33.25°C and 37.65°C, and from 35.45°C to 39.85°C in the simulations with the wind speed of 5 m/s and 1m/s, respectively. Compared to the surface temperature of the same areas in the reference model, (44.25°C to above 53.05°C), the combined scenario significantly reduces the surface temperature of the urban areas. The surface temperature is mainly reduced to the range of 24.45°C to 28.85°C (wind speed=5 m/s) and to a range of 26.65°C to 31.05°C (wind speed =1 m/s) where trees were used in the green area. By application of the water based system, the surface temperature of pavements in the Mall is within a range of 31.05°C to 33.25°C, whereas the surface temperature of the Mall in the reference model falls within a range of 39.85 to 48.65°C.

Wind speed (m/s)

NW winds

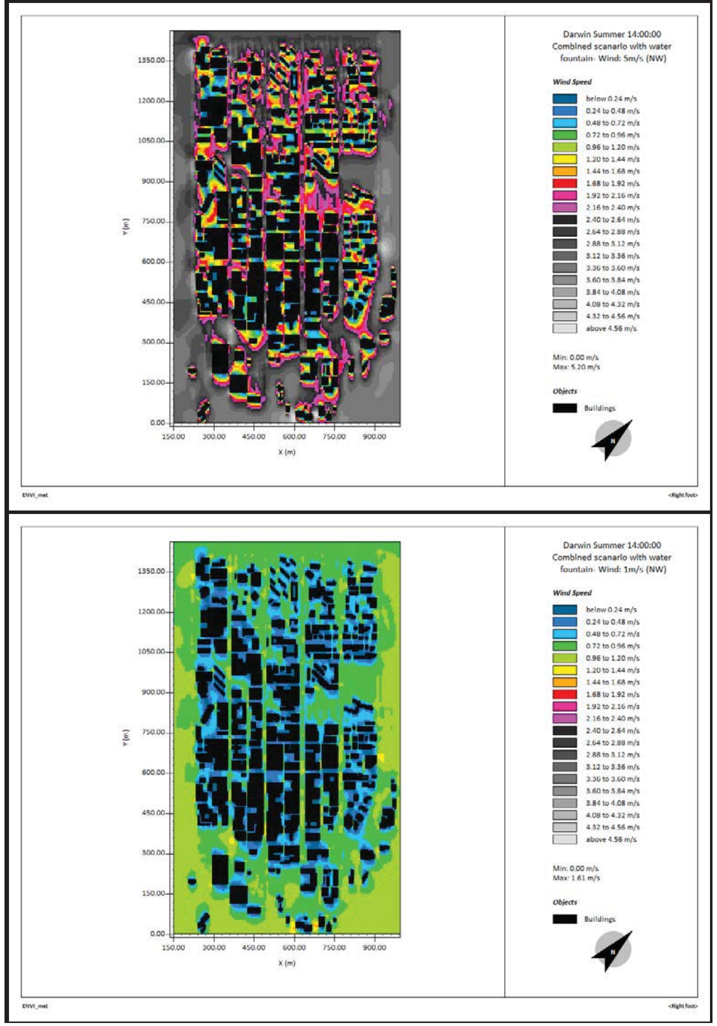


Figure 7. Combined scenario with water fountain: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

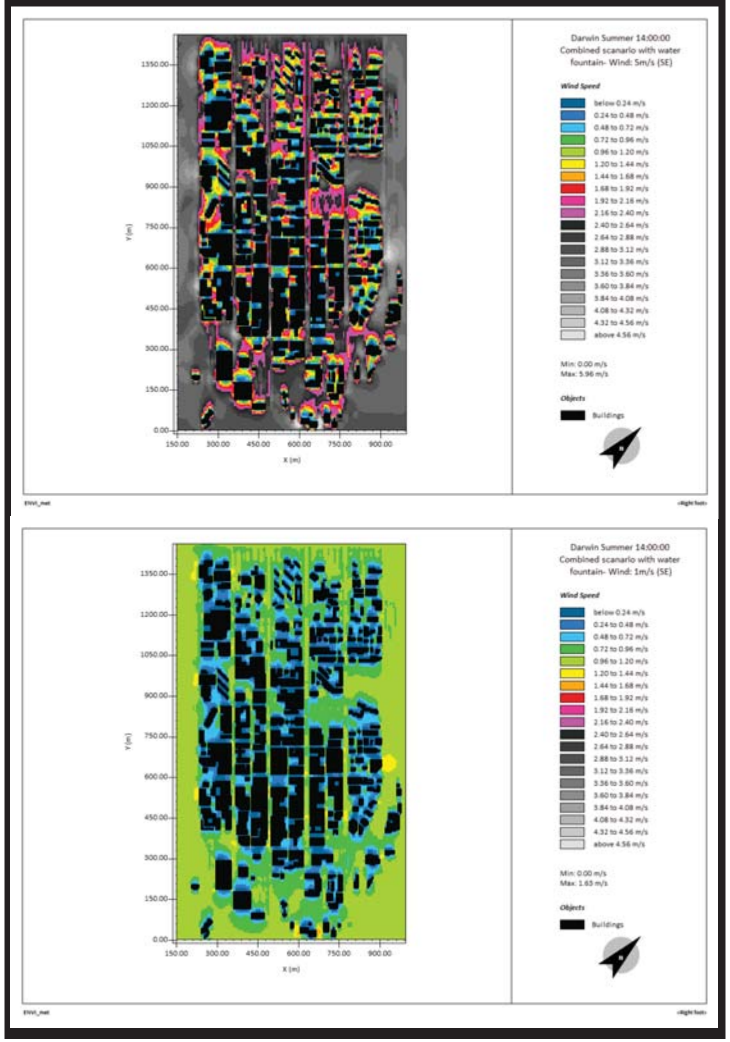


Figure 8. Combined scenario with water fountain: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution in the study area when the combined scenario (global increase of albedo to 0.6, solar control mitigation techniques, 30% greenery, and water fountain) is used. The wind speed distribution in the major car parks shows a lower range of wind speeds compared to the same area in the reference model for all wind directions at the speed of 5m/s. This effect is likely caused by the urban trees used in the combined scenario. Compared to the base case, wind speed mostly appears to be lower (within a range of 1.68 to 2.40 m/s for the simulations with wind speed of 5m/s and 0.48 to 0.96 m/s for the simulations with wind speed of 1m/s) where additional urban trees were employed; Dally street, northern parts of Cavenagh Esplanade, Mitchel, Smith, and Woods streets, and major parking lots of the CBD.

Cost

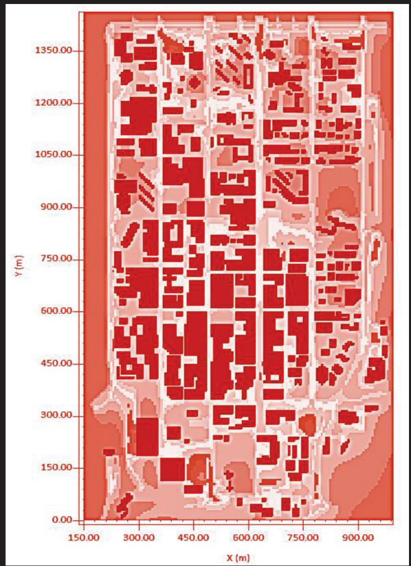
Table 3 shows the cost of the combined mitigation scenario with water fountain.

Table 3. Cost of the combined mitigation strategy with the use of water fountain

Mitigation Strategy	Total Area	Number of Trees	Number of Fountains	Cost per Unit, AUS$	Cost of Mitigation Strategy	Total Cost
Increase the albedo to 0.6						
Total building roof/floor area (m^2)	314272			15	4714080	4714080
Total Car park area in asphalt (m^2)	117684			30	3530520	8244600
Total area of pavements and streets(m^2)	652244			30	19567320	27811920
Shading the Main Streets and Car Parks	275436			70	19280520	47092440
Water Scenario			10	15000	150000	47242440
Greenery 30 %						
1. Mature Trees - 10 m height		477		25000	11925000	59167440
2. Average size Tree - 4 m height		477		14000	6678000	53920440

Concluding remark

The combined use of greenery, reflective materials, shading, and water based system is shown to be the most effective mitigation strategy in this investigation. The local maximum temperature reduction achieved in Darwin using the combined scenario with water fountain is above 7 (K) for all wind speeds and directions except for the simulation with North westerly wind at the speed of 5m/s which is over 5 (K).



Heat Mitigation Program

Darwin, NT

MITIGATION SCENARIO 12: Combined scenario cold/dry season: global increase of albedo to 0.6, application of shading, and 30% greenery in open spaces

UNSW

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UNSW SYDNEY

Ambient temperature (◦C)

NW Wind

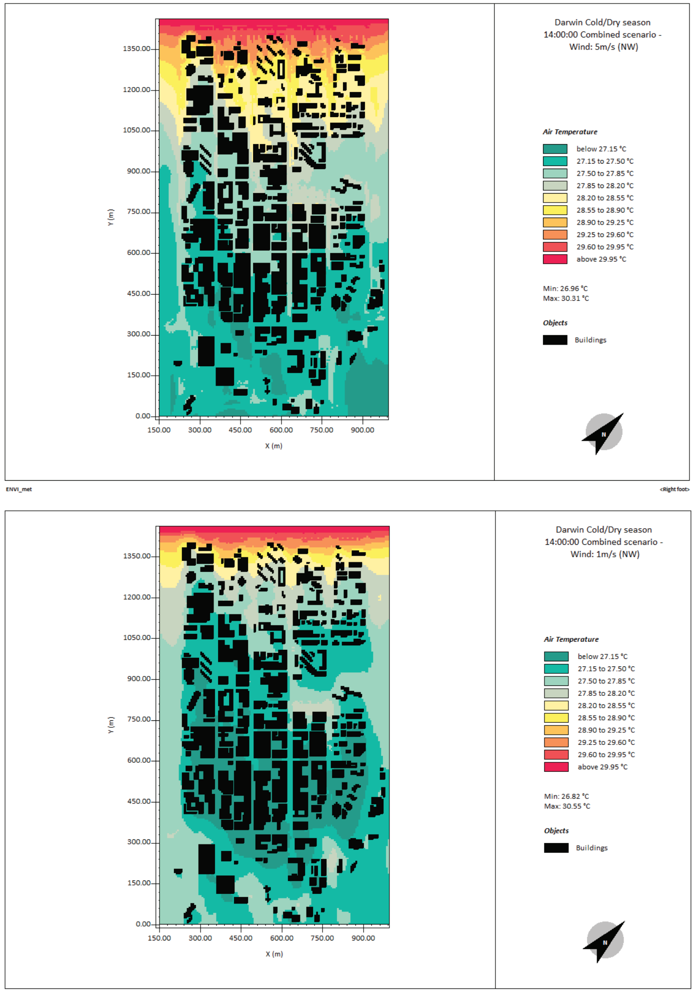


Figure 1. Combined scenario (cold/dry): Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

E winds

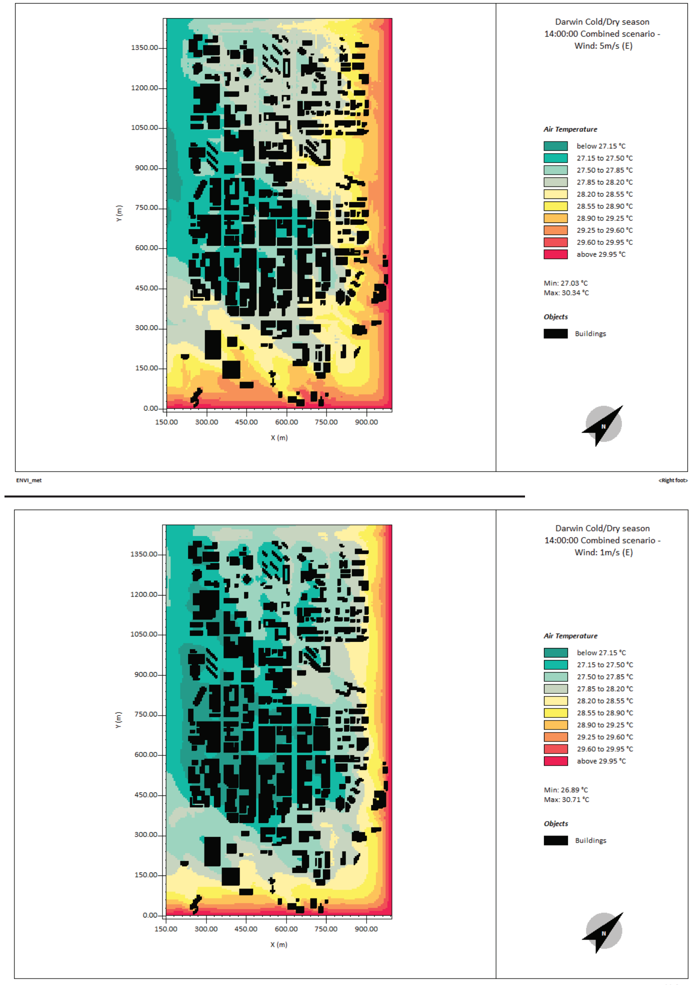


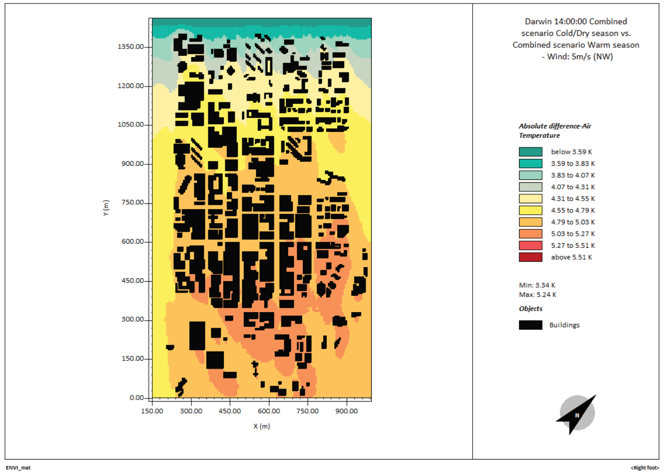
Figure 2. Combined scenario (cold/dry): Temperature distribution of the ambient temperature in the selected area: 5m/s-E (top), 1m/s-E (bottom).

Simulation results

This scenario investigates the mitigation technologies during cold and dry season in Darwin. The combined scenario investigated here refers to combination of increase of global albedo to 0.6, application of shading (mainly on Wood St, Cavenagh St, Smith St, Mitchel St, Esplanade St, and McMinn St and the nearby car parks), and 30% greenery in open spaces. In this scenario, albedo of walls and roofs=0.6, albedo of streets and pavements=0.72. For additional greenery to occupy 30% open spaces, Daly street and major car parks in the CBD including state square parking area are also considered in addition to above-mentioned streets where shading is provided.

The model setting implemented in this scenario is the same as combined scenario during warm season; however, climatic parameters were adjusted based on the prevailing conditions in Darwin during cold/dry season at the warmest time of the day 14:00:00. Two prevailing afternoon wind directions investigated are from North west and East. Figure 1 and 2 shows the simulated distribution of the ambient temperature for the combined scenario. The ambient temperature at 14:00:00 ranges between about 26.82°C to 30.71°C at the height of 1.46m. However, as shown in the maps, majority of the CBD urban area fall bellow 28.75°C considering all investigated wind speed and directions.

NW winds



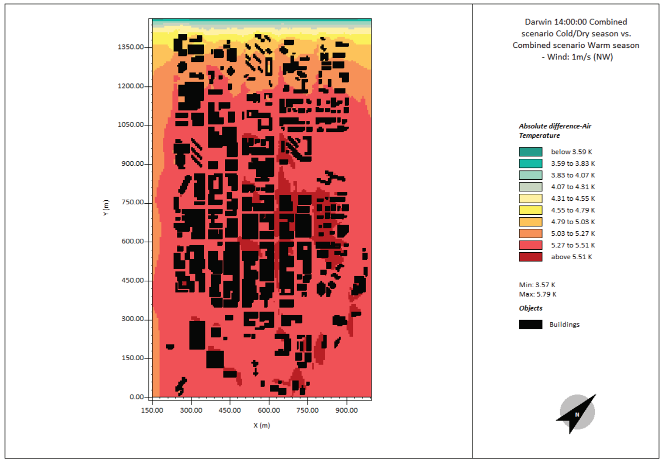


Figure 3. Combined scenario (cold/dry): Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

Tables 1 and 2 summaries the minimum and maximum ambient temperatures, reduction of the maximum and minimum temperatures, and the local maximum temperature drop achieved in this scenario. These tables also compare the results with the results of the other mitigation strategies.

Table 1. Statistical summery of the mitigation results – North westerly 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 2. Statistical summery of the mitigation results – South easterly 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

The air temperature difference maps investigate the combined scenario of global increase of albedo to 0.6, application of shading, and 30% greenery in open spaces during cold/dry season. The ambient temperature in the combined scenario during cold/dry season is compared with that of combined scenario during the warm season for North westerly winds at the speed of 1m/s and 5m/s. It should be noted that the prevailing wind from North west is taken as it is similar between the two conditions investigated. The temperature reduction distribution is given in Figures 3.

The results indicate that by combining three effective scenarios (global albedo of 0.6, application of shading, and 30% greenery) the local maximum temperature reduction during cold/dry season compared to the combined scenario during the warm season is 5.24 (K) and 5.79 (K) for the wind direction of North westerly, and speed of 5m/s and 1m/s, respectively. Figure 3 (wind speed of 5m/s) shows that the local temperature reduction falls within a range of 4.55 to 5.27 (K) in central and southern part of CBD. It can be seen that the local temperature reduction achieved in the combined scenario occurs in the CBD varies from 5.27 K to 5.79 K when wind speed is 1m/s.

Surface temperature (°C)

NW winds

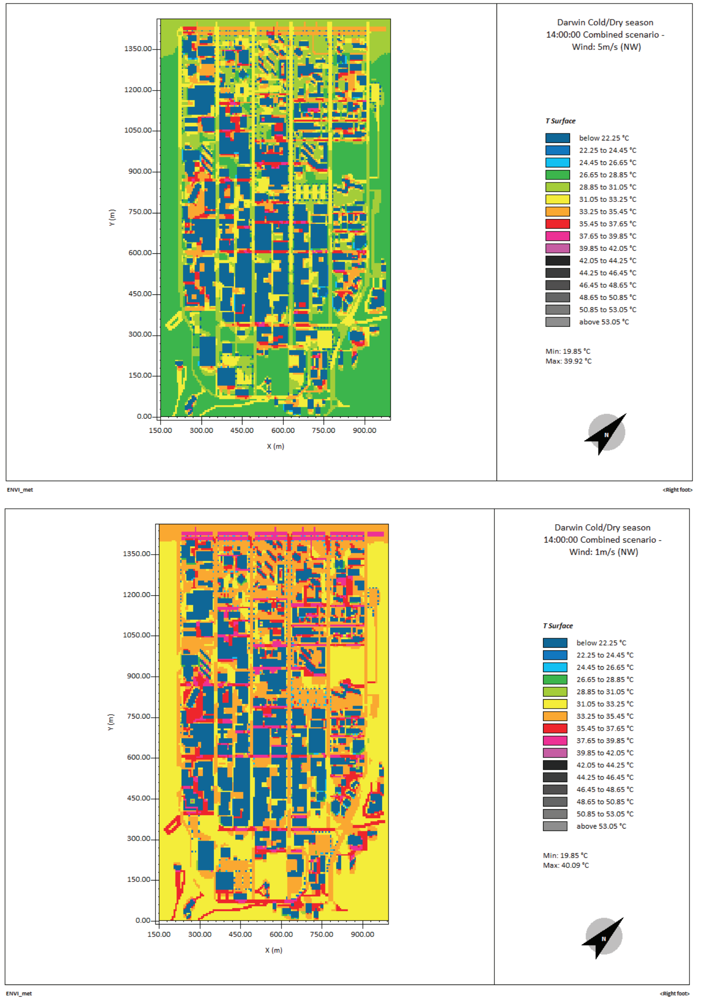


Figure 4. Combined scenario (cold/dry): Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

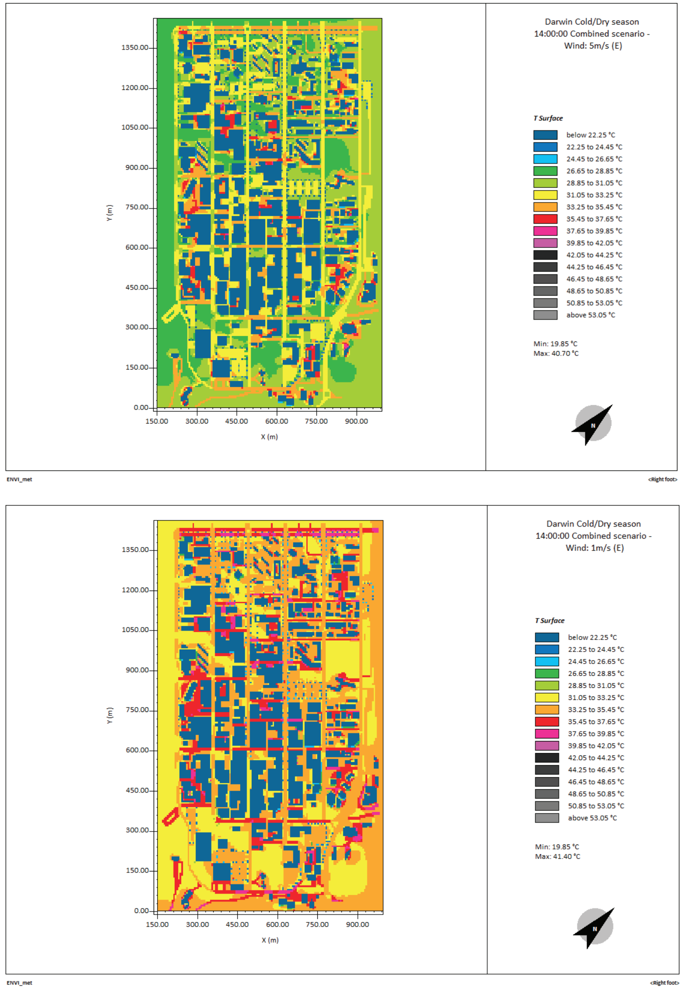


Figure 5. Combined scenario (cold/dry): Surface temperature in the selected area:5m/s-E (top), 1m/s-E (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario is given in Figures 4 and 5.

The maximum surface temperature varies between 39.92°C and 41.40°C when combined scenario during cold/dry season is used in the simulations. Figures 5 and 6 show that the surface temperature of the streets and pavements are significantly lower than that in the combined scenario during warm season. In the combined scenario (cold/dry season), when the wind speed is 5 m/s, the surface temperature of the major asphalt parking area ranges from 31.05°C to a maximum of 33.25°C. It should be noted that the surface temperature of the same areas in the combined scenario of warm season varies from 33.25°C to a maximum of 37.65°C. The surface temperature is mainly reduced to the range of temperatures below 22.25°C when trees were used in the green area with the wind speed of 5m/s. Similar to the results of the combined scenario with wind speed of 5 m/s, the surface temperature of asphalt car parks varies from 33.25°C to 35.45°C when wind speed is 1 m/s. The surface temperature is mostly reduced to a range of below 26.65°C when trees were used in the green area (wind speed =1m/s).

Wind speed (m/s)

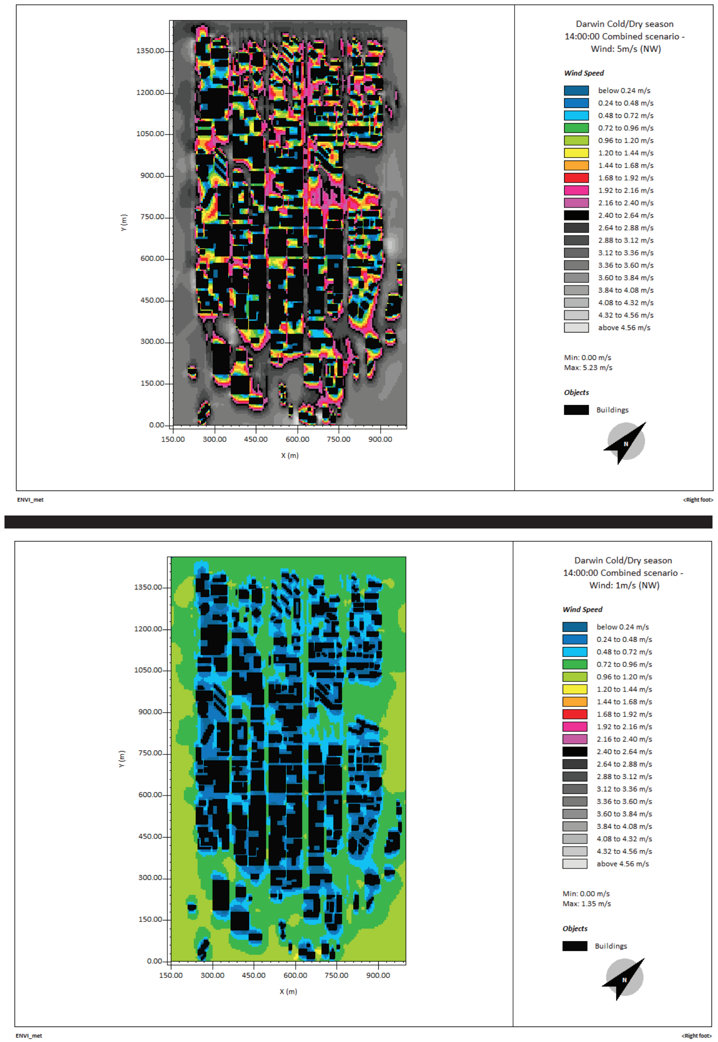


Figure 6. Combined scenario (cold/dry): Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

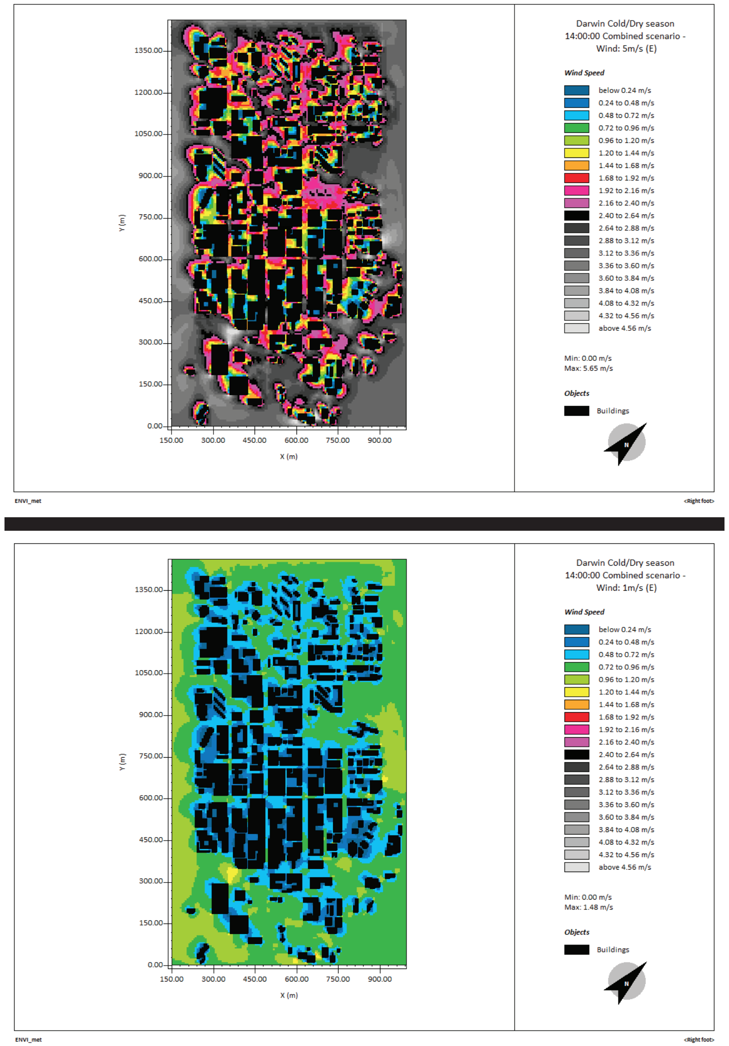


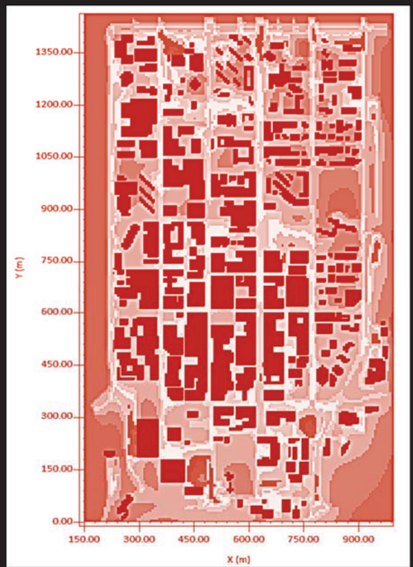
Figure 7. Combined scenario (cold/dry): Wind speed in the selected area:5m/s-E (top), 1m/s-E (bottom).

Simulation results

Figures 6 and 7 show the wind speed distribution in the study area when the combined scenario (global increase of albedo to 0.6, application of shading, and 30% greenery in open spaces) is used for the cold/dry season. The wind speed distribution in the major car park in Cavenagh street shows a lower range of wind speeds compared to the same area in the reference model for North westerly wind directions at the speed of 5m/s. This is very similar to the wind speed distribution in the combined scenario during warm season. This effect is caused by the additional trees used in the combined scenario. Compared to the base case wind speed distribution, wind speed mostly appears to be lower (within a range of 1.68 to 2.40 m/s for the simulations with wind speed of 5 m/s and 0.48 to 0.96 m/s for the simulations with wind speed of 1m/s) where additional urban trees were employed in the combined scenario.

Concluding remark

The local maximum temperature difference achieved in Darwin between the combined scenarios during the cold/ dry season and the warm season is 5.24 (K) and 5.79 (K) for the North westerly winds at the speed of 5m/s and 1 m/s, respectively. The local minimum ambient temperature difference between the combined scenarios during the cold/ dry and the warm seasons are 3.34(K) and 3.49(K) for the wind speed of 5m/s and 1 m/s, respectively.



Heat Mitigation Program
Darwin, NT

MITIGATION SCENARIO 13: State square changes (increase of greenery, application of water fountain, use of reflective material in the pavements of Smith street)

UNSW

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UNSW SYDNEY

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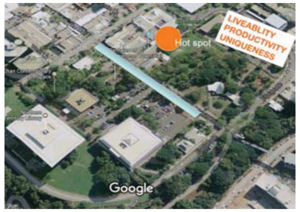

State square: under-grounding all on-grade car parking and replacing with trees and greenery (1), removing Chan building (2), adding a new pool with fountains and mist in what was Smith St (3), replacing asphalt and concrete pavements with cool materials (4).

Ambient temperature (◦C)

NW winds

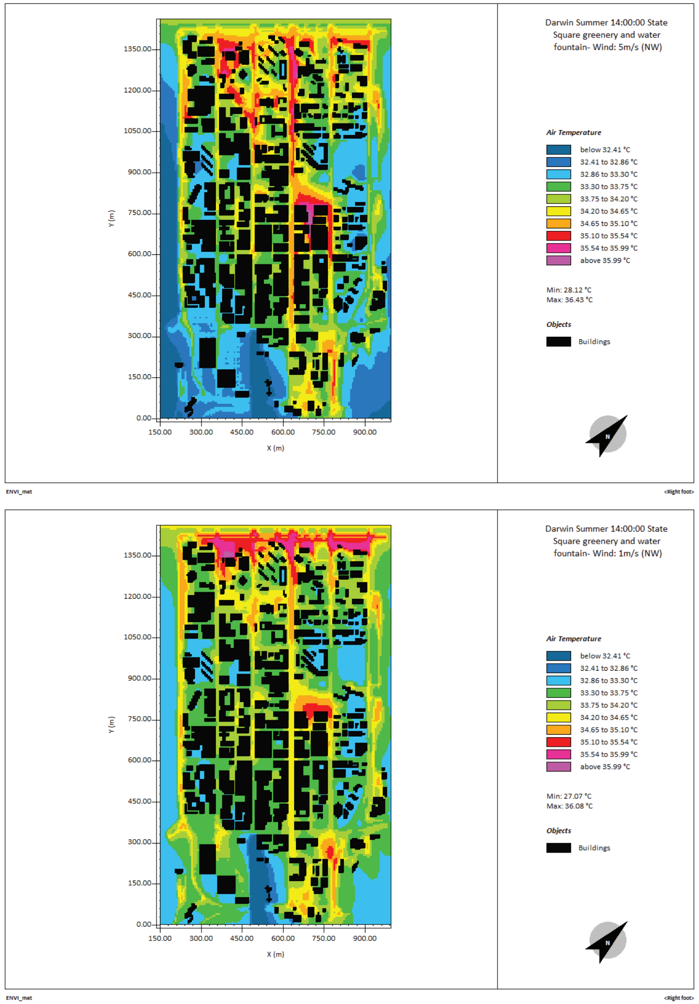

Figure 1. State square: Temperature distribution of the ambient temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

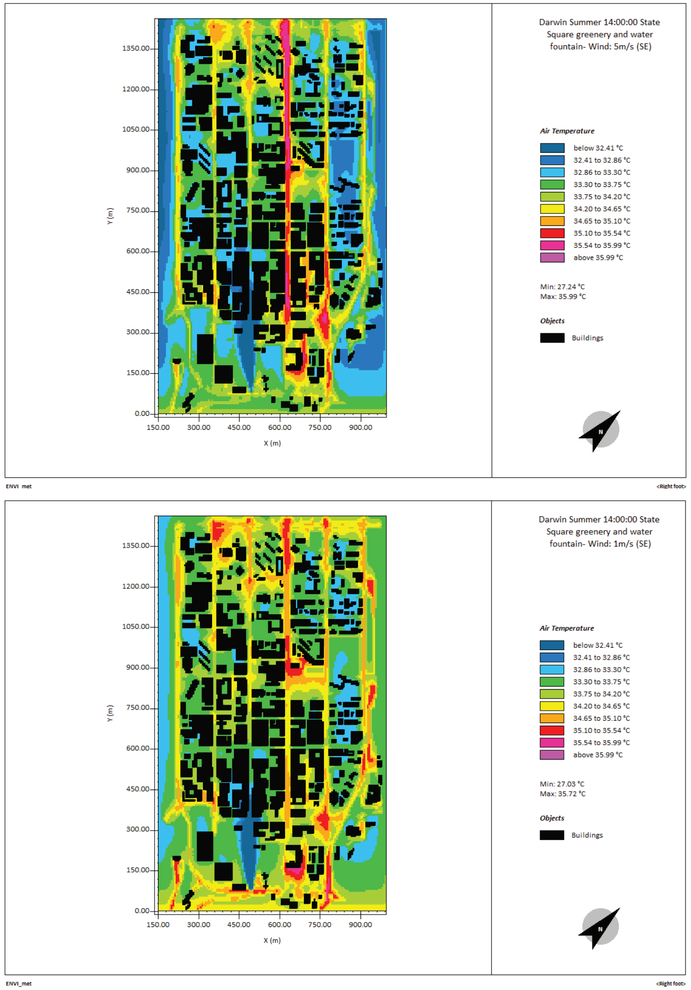

Figure 2. State square: Temperature distribution of the ambient temperature in the selected area: 5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The present scenario considers three mitigation strategies in the State square, Darwin. In this scenario, Chan building is removed, all car parks located in the Sate square were replaced by the urban greenery, water fountains with spray cooling effect were applied in Smith street, and existing asphalt and concrete pavements in Smith street and State square green area were replaced by cool pavement with the albedo of 0.5. For the modelling of the vegetation, two different plant types have been employed: tree 15 m tall, very dense foliage, distinct crown layer, and grass with average density, 20 cm tall. The total number of trees used in this investigation is 168. Eleven water fountains (dx=dy=6m, dz=6m) are used in this investigation every 18 m. Figure 1 and 2 shows the simulated distribution of the ambient temperature for the whole CBD area when urban greenery is increased by 30%. The ambient temperature at 14:00:00 has been reduced by increase of greenery in the study area. Results of analysis show that the ambient temperature in the State square is significantly reduced by mitigation strategies employed. The local ambient temperature in the State square mostly varies between 28.12°C to 33.30°C, and 27.24°C to 33.75°C when wind speed is 5m/s for North westerly and South easterly winds, respectively. It ranges between about 27.00°C and 33.75°C when wind speed is 1m/s. Tables 1 and 2 summaries the ***local*** *minimum and maximum temperatures (where mitigation strategy was used), reduction of the local maximum and minimum temperatures, and the local maximum temperature drop achieved in this scenario.*

Air temperature difference (K)

NW winds

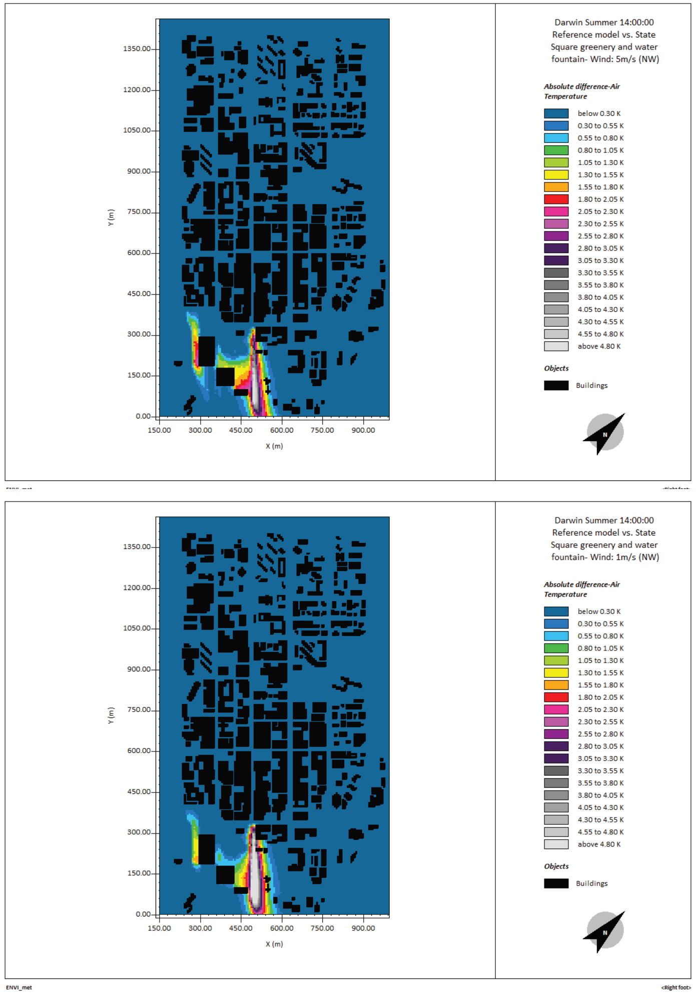

Figure 3. State square: Air temperature difference in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

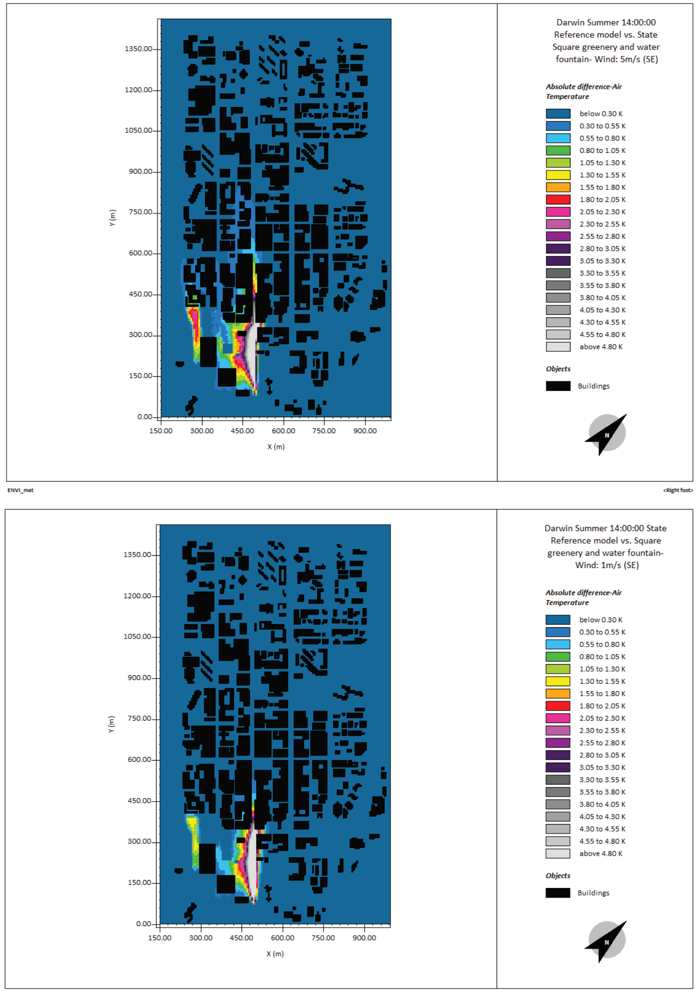

Figure 4. State square: Air temperature difference in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The air temperature difference map compares the scenario of increasing vegetation in the State square, application of water fountain and cool pavement in nearby Smith street, with the base case model. The temperature difference distribution map is given in Figures 3-4. The results of simulation clearly reveal that by providing additional vegetation (grass and trees) in the Sate square car parks and in the existing place of Chan building, application of the water fountain with spray cooling effect, and cool materials in Smith streets and State square pavements, the local maximum temperature reduction achieved is 6.52 (K) and 8.02 (K) for the wind speed of 5 m/s and directions of North westerly and South easterly winds, respectively. The local maximum temperature reduction when wind speed is 1m/s is about 8.18 (K) and 8.13 (K) for North westerly and South easterly winds, respectively. The local maximum temperature reduction is shown where water fountains and cool pavements were used in the Smith street.

Table 1. Statistical summery of the mitigation results – North westerly 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	-	-	-	-	-	-
State square***	34.02	34.76	28.12	27.07	2.42	1.32	3.84	5.77	6.52	8.18

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model
**: Maximum temperature and reduction of the maximum ambient temperature (K) is given for the local scale where mitigation strategy was employed

Table 2. Statistical summery of the mitigation results – South easterly 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	-	-	-	-	-	-
State square**	34.44	35.10	27.24	27.03	1.56	0.62	4.80	5.94	8.02	8.13

Note: *: Maximum temperature decrease achieved based on the scenarios compared to the reference model
**: Maximum temperature and reduction of the maximum ambient temperature (K) is given for the local scale where mitigation strategy was employed

Surface temperature (°C)

NW winds

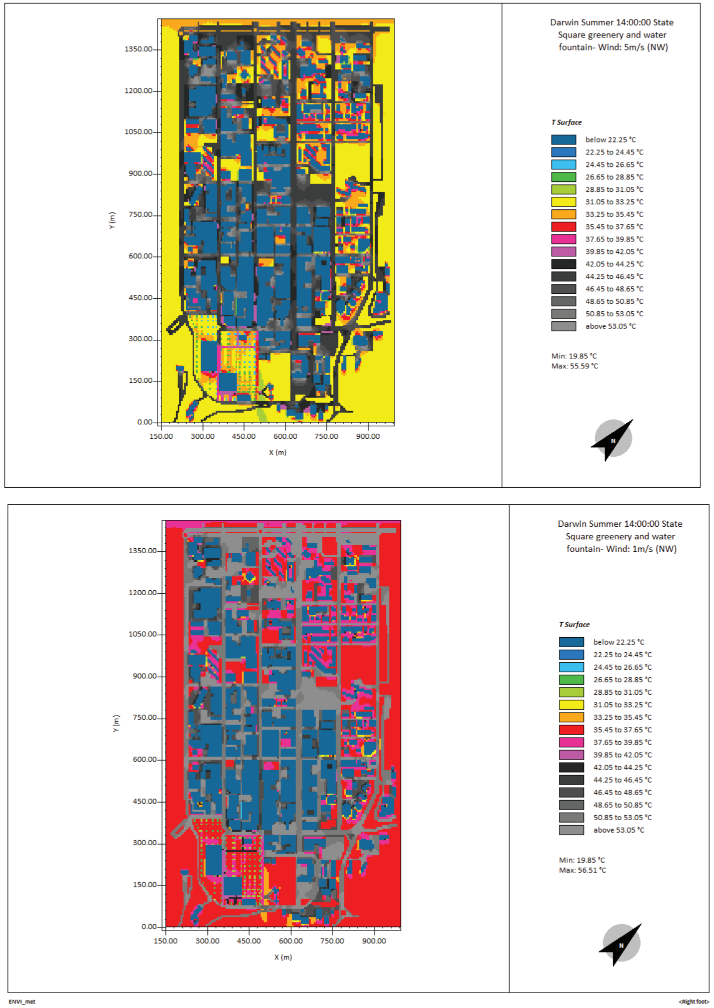

Figure 5. State square: Surface temperature in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

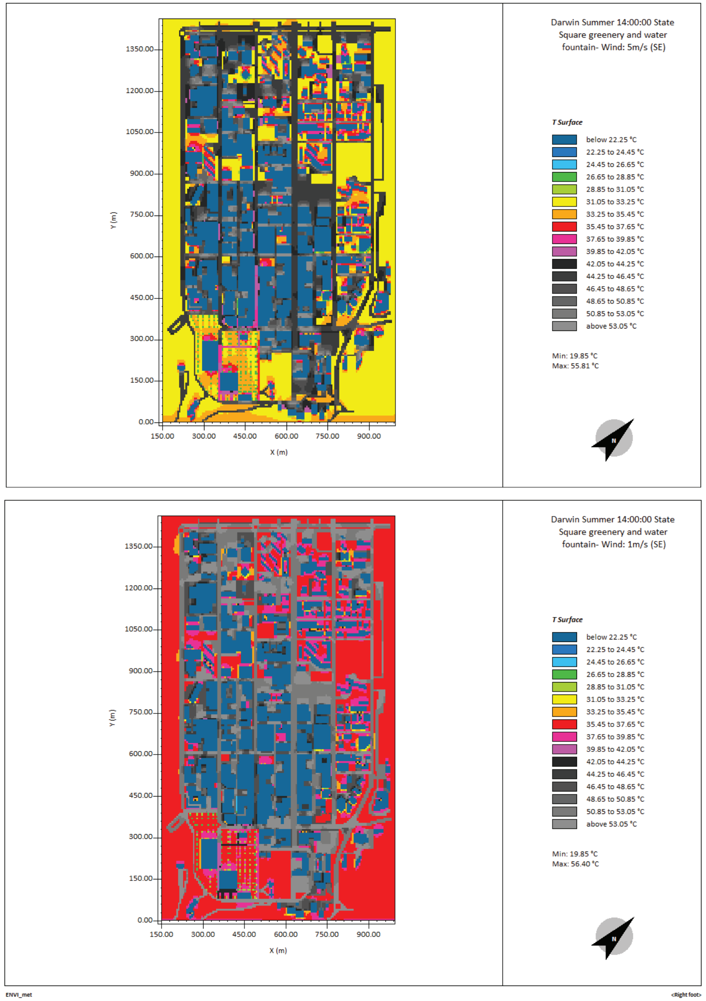

Figure 6. State square: Surface temperature in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

The simulated distribution of the surface temperature in this scenario is given in Figures 5 and 6. By applying urban greenery to, and redesigning the major asphalt car parks in the Sate square with additional grass and trees, the surface temperature is significantly reduced. Application of the water fountain, which sprays water from the height of 6m above the ground, and replacing asphalt carparks and pavements in Smith street with cool material, were also very effective to reduce the surface temperature. The maximum surface temperature reduction achieved is 25.33°C and 25.35°C when wind speed is taken as 5m/s for North westerly and South easterly winds, respectively. The surface temperature may be decreased by about 26.00°C and 26.73°C for North westerly and South easterly winds at the speed of 1m/s, respectively. The surface temperature in Smith street is within a range of 35.45°C to 37.65°C when the wind speed is 5m/s, which is mostly about 11-13°C lower in the reference model. Where water fountain is located, this is reduced by about 20°C. In the state square, where car parks are replaced by greenery, the surface temperature varies from 31.05 to 35.45°C and 35.45 to 37.65°C for 5m/s and 1m/s wind speeds, respectively. However, where trees were added the mitigation effect is more significant; the surface temperature mostly falls within a range of 24.45 to 28.85°C.

Wind speed (m/s)

NW winds

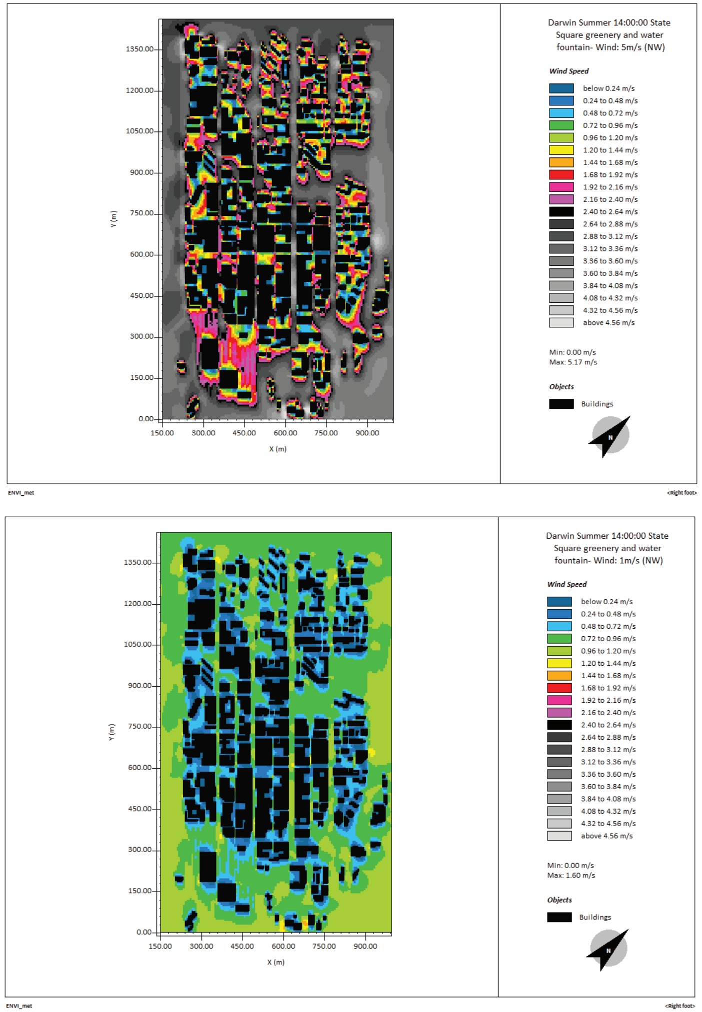

Figure 7. State square: Wind speed in the selected area:5m/s-NW (top), 1m/s-NW (bottom).

SE winds

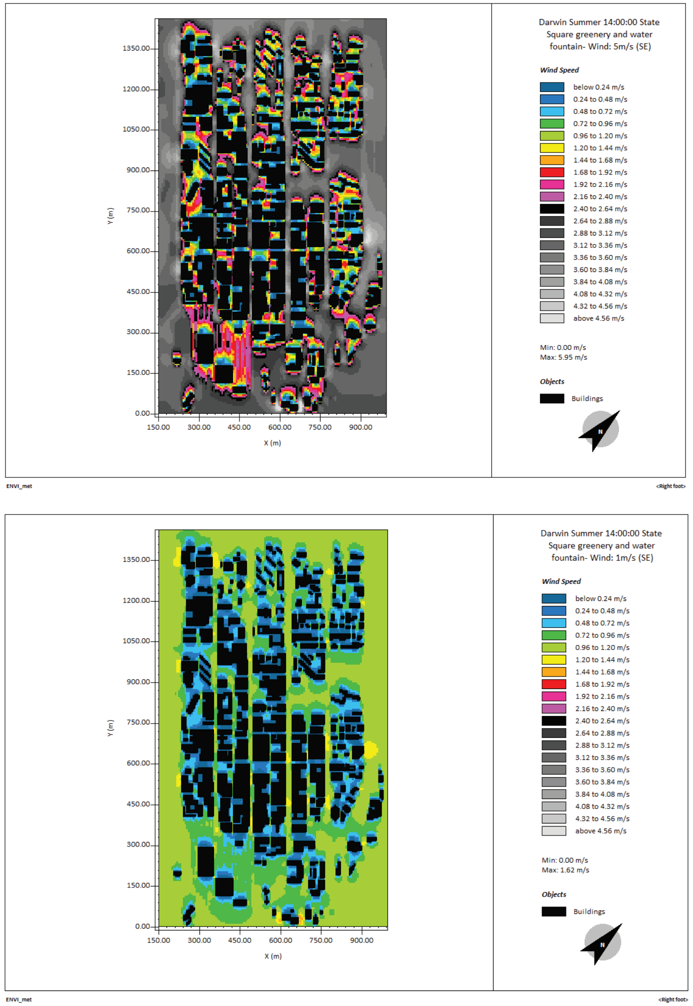

Figure 8. State square: Wind speed in the selected area:5m/s-SE (top), 1m/s-SE (bottom).

Simulation results

Figures 7 and 8 show the wind speed distribution in the study area when additional vegetation (grass and tree) is used in the State square and water fountain and cool materials were employed in Smith street. Comparison of the wind speed distribution maps with those of the reference model illustrates the effects of additional trees on the distribution of the wind speeds in southern part of Smith and Esplanade streets, car parks and open spaces near Chan building and Northern Territory library in the State square, Darwin. The distribution of wind speeds show that wind speeds are reduced in both simulation condition (5m/s and 1m/s wind speeds) where additional trees were employed in the State square. The wind speed in the State square mostly varies within a rage of 1.92 m/s to 2.40 m/s and 0.72 m/s to 0.92 m/s in the simulated condition for the wind speeds of 5m/s and 1m/s, respectively. However, the maximum and minimum wind speed for each map is very similar to the reference model.

Concluding remarks

The combined use of greenery, reflective materials, and water fountain improve the microclimate of the State square. It has been shown that the local maximum temperature reduction achieved in the southern part of Darwin with the proposed mitigation strategies is up to 8.00 (K) and 8.10 (K) for the wind speed of 5m/s and 1 m/s, respectively.

SPECIFICATIONS

Heat Mitigation Program Darwin, Northern Territory

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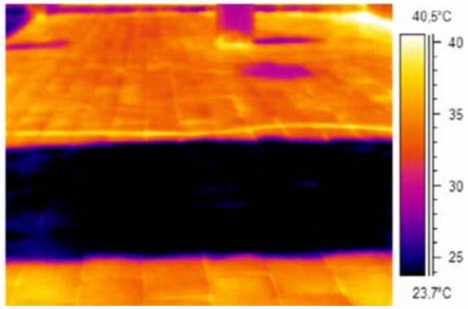
SPECIFICATIONS

Flat or low sloped roofs (1)

Situation		Options	Key parameters and ranges	Design and maintenance recommendations
Non-ballasted exposed waterproofing membrane	Single-ply membrane (mechanically anchored or adhered) or factory applied coatings on single-ply membranes	Synthetic membranes: in PVC; flexible or thermoplastic polyolefins (FPO/TPO); EPDM	Unaged solar reflectance up to 0.90 Thermal emittance = 0.80-0.90 After two-four years of ageing, the solar reflectance can drop at 0.50 even for material initially very reflective. There are materials that can minimize the solar reflectance loss due ageing. White and cool coloured options are available. The highest values in solar reflectance can only be achieved with white cool roofs. Slope > 2% (as built, upon loading)	 A minimum slope is not required only to prevent leaking, but also to reduce the impact of soiling and thus biological growth, which greatly affect the solar reflectance and the service life of roofing. For the same reason, the drainage system shall be designed to avoid ponding. The minimum slope shall be granted as-built (not just in design condition), to prevent that upon loading the slope is insufficient. Normal maintenance for roofing, inspecting the drains. In tropical locations, using materials that resist to biological growth (algae or mould) is recommended. This can be achieved with anti-algae or self-cleaning treatments (e.g., photocatalytic, silicone-based or with fluoropolymers), or a very smooth surface. The self-cleaning or anti-algae treatment itself is subject to ageing and its efficiency can decrease within a few years. A manufacturer shall provide evidence of the suitability of their product for the application in tropical climates (e.g., via natural ageing programme or previous applications on buildings in similar climates)
	Built-up	Field applied coating or sprayed foams (usually protected with a coating) on modified bitumen (one coat or primer-coating systems)		 Same as for single-ply membranes. In addition, cleaning and re-coating approximately every four years is usually recommended. It can be applied on existing as well as on new built-up roofing. The application, usually, can be done with a roll or spray (depending on the product). Prior to the application, cleaning and preparation of the substrate is necessary. A new cool field applied coating cannot be applied onto a damaged membrane or built-up bitumen roof.

Flat or low sloped roofs (2)

Situation		Options	Key parameters and ranges	Design and maintenance recommendations
Non-ballasted exposed waterproofing membrane	Built-up	Field applied coating on granulated modified bitumen	Unaged solar reflectance up to 0.75 (white as well as cool coloured) Thermal emittance = 0.80-0.90 Same as above with regard to aged performance.	Same as for field applied coating on modified bitumen. Since the surface of granulated modified bitumen is rough, the paint consumption is higher and is difficult to achieve a smooth surface. This prevents to reach extremely high values in solar reflectance.
Inverted roof (built up)	Tiles and slates	Clay, concrete, ceramic, field applied coating on existing ceramic or concrete tiles	Unaged solar reflectance up to 0.90 Thermal emittance = 0.80-0.90 Usually, glossy ceramic tiles are less susceptible to ageing	For new constructions or reroofing, highly reflective ceramic tiles may provide high resistance to ageing, provided that sufficient slope and drainage is designed and granted, requiring no specific maintenance afterwards. The solar reflectance of existing flat roofs with tiles or slates can be easily increased with field applied coatings.



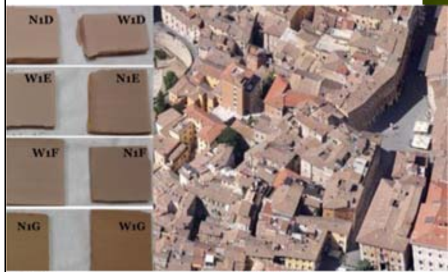
Flat or low sloped roofs (3)

Situation		Options	Key parameters and ranges	Design and maintenance recommendations
Non-ballasted discontinuous roofing	Metal roofing	Corrugated metal roofing, sandwich panels. Can be factory or field applied coating on metal (white or cool coloured) or sprayed foam applied onto the metal roofing (normally protected by a coating)	Unaged solar reflectance up to 0.90 Thermal emittance = 0.80-0.90	 Minimum slope as recommended by the manufacturer. The surface shall be prepared with a primer. The coating (being factory or field applied) needs to be thick enough so as grant high thermal emittance. Polished bare metals have low thermal emittance, usually lower than 0.20. Even when soiled, their thermal emittance is still low (soiling may increase the thermal emittance of uncoated metals from 0.20 to 0.40). The same metal roof assembly, highly insulated, with solar reflectance equal to 0.60, would have an exterior surface temperature equal to 54 °C with thermal emittance of 0.90 or equal to 64 °C if its thermal emittance is of 0.20. Therefore, the thermal emittance measurements for metal roofing are very important (while the thermal emittance of roofing membranes or concrete pavers, for instance, is normally in the 0.80-0.95 range).
Ballasted	Inert ballast	Cool Gravel	SR up to 0.80 TE = 0.80-0.90	The highest solar reflectance is achieved with fine grains, which is not always a viable  option, since it has to be evaluated considering the maximum wind speed reached in the context of application. Gravel is not immune to soiling and the growth of infestans plants, that may grow in airborne soil. The accumulation of airborne soil can be prevented with suited slope underneath the gravel layer and with proper design and regular maintenance of the drainage system. Therefore, a minimum level of maintenance with if anti-infestans treatment (usually once per year) is commonly a good practice to prevent the growth of plants whose roots may damage the roofing membrane underneath the gravel.
		Cool ballast pavers	SR up to 0.80 TE = 0.80-0.90	Can be concrete or stone slates. Also in this case, the solar reflectance of existing assemblies can be upgraded with field applied coatings.

Flat or low sloped roofs (4)

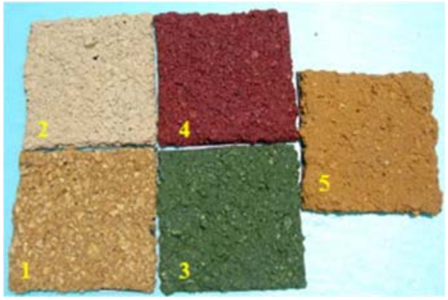
Situation		Options	Key parameters and ranges	Design and maintenance recommendations
Ballasted	Green roof	Extensive Light intensive Intensive	Vegetation coverage and leaf area index Drought resistance of the vegetation (typically granted for succulent plants such as sedum) Runoff coefficient (typically, of approximately 0.3 for soils 15-25 cm thick) Resistance of the waterproofing layer to roots penetration Capacity of the storage layer	 The most important feature of a green roof system is its suitability to the context of application. As they are vegetative layers, green roof systems can perform well in some climate context and may not survive in others. This might seem trivial, but several failures are documented for green roof systems developed in one context and applied in other conditions. Evidence of the suitability of a green roof system for a context of application shall be provided prior to proceeding with large scale applications. Another key aspect to be assessed is the resistance to infestans species. Green roofs require careful selection of the green roof system, design of the specific installation project and suited maintenance, including irrigation and mowing/pruning. The recommendations on green roofs herein outlined are only introductory. Specific design and maintenance guidelines are provided by the German standard DIN 18035 and Italian standard UNI 11235 (unfortunately not available in English).

Steep sloped roofs

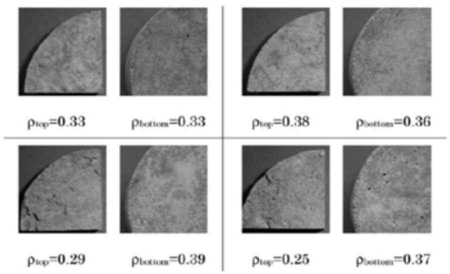
Situation		Options	Key parameters and ranges	Design and maintenance recommendations
Continuous roofing non-ballasted	Roofing membranes (uncoated or with field or factory applied coating)	Same as for flat roofs	Same as for flat roofs	Same as for flat and low sloped roof
Discontinuous roof (the watertightness is granted by the slope)	Metal roofing	Factory or field applied coating on corrugated metal	Unaged solar reflectance up to 0.90 Thermal emittance = 0.80-0.90	Same as for low sloped roofing. The coating shall be thick enough to grant high thermal emittance 
	Tiled roofs	Terracotta clay tiles	Unaged solar reflectance up to 0.65 Thermal emittance = 0.80-0.90	
		Terracotta clay tiles with factory applied coating/paint Glazed ceramic or concrete roof tiles	Unaged solar reflectance up to 0.80-0.90 Thermal emittance = 0.80-0.90	 
	Shingles	Asphalt Singles		It is difficult to achieve very high solar reflectance without white applied coating on top, since the rough surface of  a asphalt shingles (or roofing felts) and the solar absorptive background of the modified bitumen underneath the granules, which is partially exposed.

Street pavements

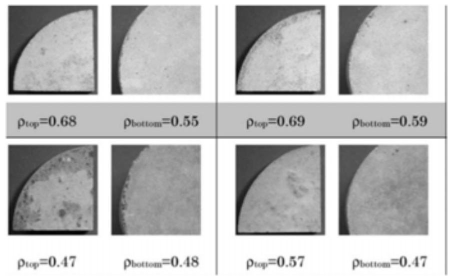
Situation		Options	Key parameters and ranges	Design and maintenance recommendations
Existing pavements: pedestrian, cycling, and low to high traffic load	Asphalt concrete or cement concrete	Field applied coatings on pavements Polymer bound field applied wearing coarse Renewal of the wearing coarse	Aged solar reflectance up to 0.30 -0.40 (depending on wearing and traffic load)	Normal street paving specifications and maintenance. Field applied coatings often display low wearing resistance and are therefore most suited for pedestrian areas (unless evidence is provided).
New pavements: pedestrian, cycling, and low to high traffic load	Asphalt concrete or cement concrete	Cool coloured asphalt concrete or white cement concrete	Aged solar reflectance up to 0.50 (depending on wearing and traffic load)	Normal street paving specifications and maintenance.



Examples of cool asphalts



Examples of grey cement concrete

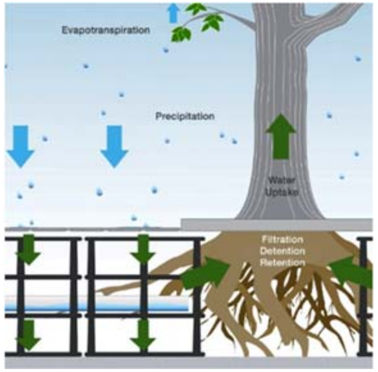


Examples of white cement concrete

Greenery and tree planting

<table>
<tr><th colspan="2">Situation</th><th>Options</th><th>Key parameters and ranges</th><th>Design and maintenance recommendations</th></tr>
<tr><td>Small areas</td><td>Greenery and green spots</td><td>Generic green spots
Engineered green spots to maximize water capacity and runoff reduction</td><td>Evapotranspiration efficiency of the plants, drought resistance of the plants, coverage, and water retention capability by the soil (depending on soil type and compaction)</td><td>Normal vegetated spots are already effective. However, in areas where storm-water management is particularly needed, an effective engineered solution is represented by rain (or infiltration) gardens. The pavement close to the rain is sloped, converging towards the rain garden that collects rainwater from a larger area than its footprint. A rain garden has sufficient soil depth to soak stormwater running of from impervious surfaces nearby. Then, the absorbed water slowly evaporates from the soil and gets used by the plants for transpiration and their other biological processes. Evaporation and transpiration slowly cool the air around the rain garden, at street level, after the stormwater event is over.

</td></tr>
<tr><td>Avenues and parking lots with sufficient space for tree planting</td><td>Tree planting</td><td>Generic green spots
Engineered green spots to maximize water capacity and runoff reduction</td><td>Evapotranspiration efficiency of the trees, size of their crown (ability to offer shade), ozone generation, and water retention capability by the soil (depending on soil type and compaction)</td><td>Normal tree planting can effectively provide shading, without excessively limit the air circulation at street level (as an artificial closed shading would do). In addition to normal tree planting, the use of suspended pavements helps to grant the best growth of the roots of urban trees (unrestricted by the nearby asphalt). This limits the damages by the roots to the street pavements and, especially, supports the growth of the trees, maximizing the evapotranspiration efficiency.



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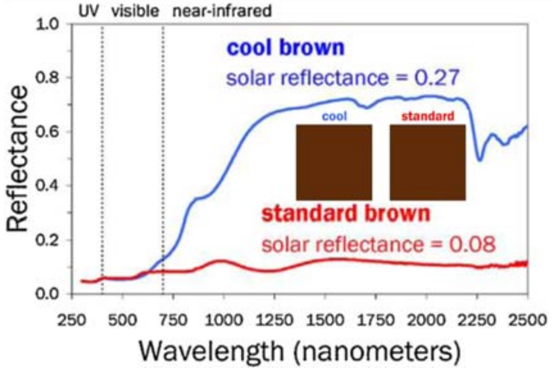
Street shading (artificial)

Situation		Options	Key parameters and ranges	Design and maintenance recommendations
Streets with high solar access or parking lots	Fixed shading	Tensile structures (fabrics and polymers), metallic, wooden, solar control glazing (all also with the possibility of integrating photovoltaic modules)	Solar reflectance Solar transmittance Infrared transmittance Air permeability (of the whole shading system)	It's important to avoid preventing air circulation. Thus, the shading system should be made of several elements/modules or present openings. Several design alternatives are possible. For all, their aerodynamics shall be assessed, including resistance to wind load.
	Removable shading	Tensile structures (from light to intermediate)		

Examples of cool coloured coatings and achievable levels of solar reflectance with different colours

Color	Solar reflectance (%)		% Increase $SR_{(cool-stand)}$
	Cool	Standard	
Orange	63	53	19
Light blue	42	40	5
Blue	33	18	83
Green	27	20	35
Black (1)	12	6	100
Anthracite	26	7	271
Brown	34	23	48
Chocolate brown	27	9	200
Light brown	36	22	64
Black (2)	27	5	440



CONCLUSIONS

Heat Mitigation Program
Darwin, Northern Territory

UNSW SYDNEY

Built Environment

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Conclusions

1) Darwin suffers from high ambient temperatures and poor outdoor thermal comfort conditions.

Ambient temperatures may exceed 37 mperatures and poor outdoor thermal comfort conditions. n, because of the positive thermal balance, the CBD area presents about 2 fort conditions. perature than the airport area (Figure 1).

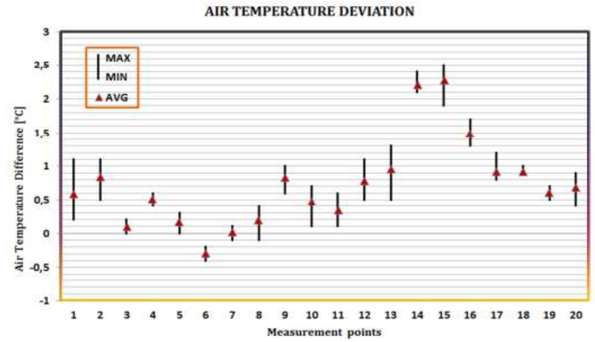

Figure 1. Magnitude of the Urban Heat Island in Darwin, as measured in March 2017.

2) Important temperature differences are observed between the various zones of the CBD area.

This is caused by the significant variability of the thermal conditions and the high magnitude of the locally released anthropogenic heat, in the city. These temperature differences within the CBD area may exceed 1 °C (Figure 2).

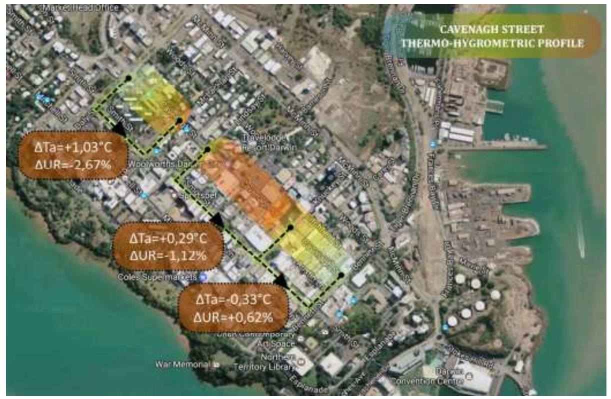

Figure 2. Distribution of the ambient temperature and relative humidity along the Cavenagh Street.

3) Several reasons behind the temperature differences:
- urban materials
- wind speed reduction
- lack of sea breeze
- anthropogenic heat.

The significant amplitude of the urban heat island in the city is due to several reasons:

a. The materials used in the urban fabric (i.e., asphalt of street pavements and parking lots and dark built-up or metal roofs and vehicles) have high solar absorbance and this results in high urban surface temperatures. Built surfaces at higher temperature than the ambient air release heat to the urban atmosphere, by means of advection and thermal radiation (Figure 3). Monitoring shows that the surface temperatures in the city easily exceed 60 °C;

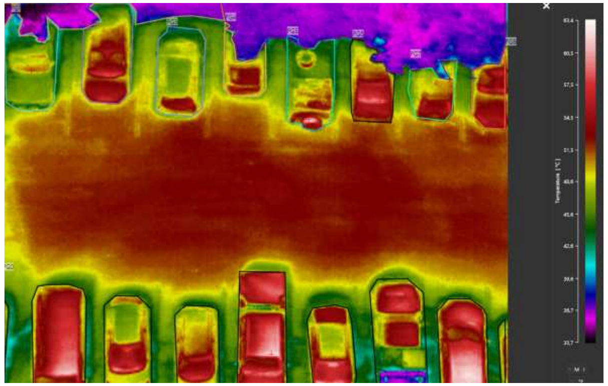

Figure 3. Surface temperature in the central CBD area of Darwin exceeds 60 °C.

b. The wind speed in the urban area is seriously reduced compared to the suburban areas. While in the airport area the mean wind speed exceeds 5 m/s, the average speed in the CBD area is close to 0.5 m/s (Figure 4);

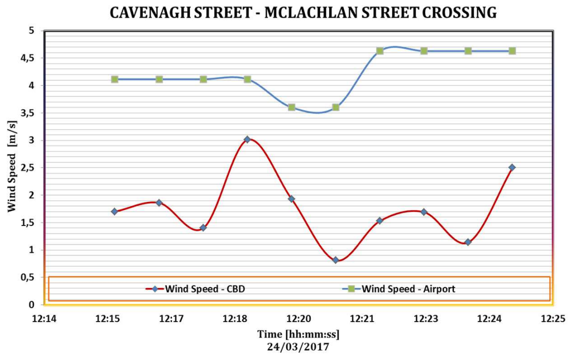

Figure 4. Wind speed as measured at the airport of Darwin.

c. The sea breeze in the city is negligible mainly because of the significantly high temperature of the sea water; and

d. The anthropogenic heat released in the city by the traffic and the air conditioning is quite high and contributes highly to increase the ambient temperature.

4) Very efficient mitigation technologies are currently available.

During the recent years, mitigation technologies to counteract the local overheating have been developed, proved effective and reliable, and applied in hundreds of real scale projects around the world. Mitigation technologies aim to decrease the energy gains and increase the thermal losses in the city. Among the most successful technologies are:

a. Reflective technologies, aiming to increase the global albedo of the city through the use of cool roofs, cool pavements and total increase of the solar reflectance of the opaque elements

b. Additional greenery in the urban environment like trees, grass etc, or green roofs;

c. Evaporative cooling systems like pools, fountains, sprinklers, etc.

d. Urban shading devices and solar protections (e.g., technical tents) providing shade and reducing the solar access especially to pedestrian pathways and parking lots, but allowing air circulation;

e. Heat dissipation techniques like ground to air heat exchangers, etc. The existing knowledge acquired through the monitored applications shows that it is possible to decrease the peak temperature of the cities by up to 2.5 °C (Figure 5).

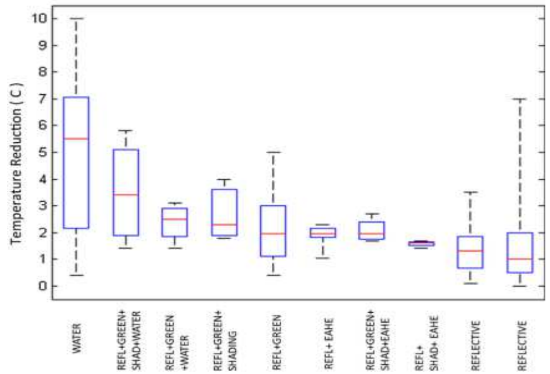

Figure 5. Range of the peak ambient temperature reduction for all the considered mitigation systems and technologies.

5) Fourteen mitigation scenarios have been designed

Fourteen mitigation scenarios have been designed aiming to decrease the ambient temperature in the Darwin area (Table 1). All scenarios are simulated using detailed and advanced simulation tools. The 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 are calculated in detail. Simulations have been performed for two synoptic conditions, NW and SE wind direction, and for low and high wind speeds (i.e., 1 and 5 m/s). Also, the final combined scenario has been simulated under the climatic conditions of the cold period. In total, 54 scenarios have been simulated.
A representative sample of the obtained temperature distribution is given in Figure 6.

No	Description of scenarios	
1	Reference Model	Albedo of walls and roofs=0.2, Asphalts Albedo=0.05, Concrete pavements Albedo=0.2, Loamy soil Albedo=0.15, 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 open space
3	Global albedo 0.6	Global Albedo=0.6, Greenery < 10 % of the total pavements and open space
4	Cool pavement	Albedo of streets and pavements=0.5, Greenery < 10 % of the total pavements and open space
5	Shading	Albedo of streets (Asphalt)=0.34, Albedo of concrete pavement=0.44, Greenery < 10 % of the total pavements and open 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 open space
9	Green roof	Green roof in all buildings
10	Water fountain	Application of water fountain on The Mall
11	State square	Replacing car parks with greenery, removing Chan building, application of water fountain in Smith street
11	Combined scenario	Global albedo=0.6, Greenery 30%, and Shading
12	Combined scenario with water fountain	Global albedo=0.6, Greenery 30%, Shading, and water fountain across the mall
14	Combined scenario-Cold and dry season	Global albedo=0.6, Greenery 30%, and Shading

Table 1. Description of the considered mitigation scenarios

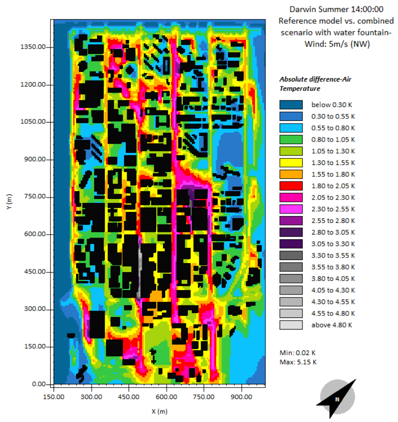

Figure 6. Simulated ambient temperature distribution for the combined scenario in Darwin

6) The proposed mitigation technologies can decrease the maximum ambient temperature from 36.5°C to 33.7°C

The results of the simulation shown that the proposed mitigation technologies can decrease the maximum ambient temperature from 36.5°C down to 33.7°C. In parallel, the minimum ambient temperature in the area can decrease from 31.2°C to 28.9°C. The maximum and minimum ambient temperatures in the whole area, as calculated for each mitigation scenario are given in Figure 7.

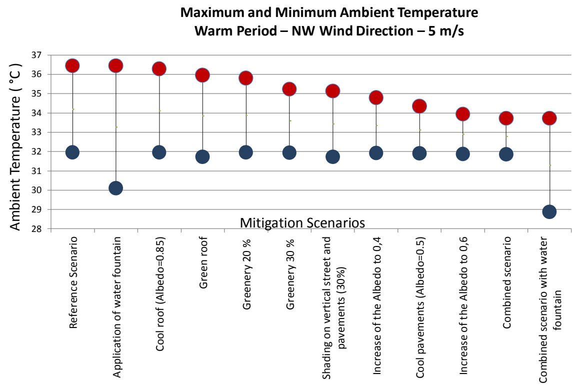

Figure 7. Maximum and minimum temperature in the CBD area calculated for each mitigation scenario.

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. The above figures present to the difference of the maximum or minimum ambient temperature as calculated in the reference scenario against the corresponding maximum or minimum temperature calculated for each of the scenarios. The maximum or the minimum temperature at the reference and in each scenario may not correspond to the same place in the CBD area. When the temperature difference is calculated for exactly the same place, the difference is mentioned as maximum or minimum local ambient temperature. The distribution of the ambient temperature drop in the whole CBD area for all the scenarios is given in Figures 8-10.

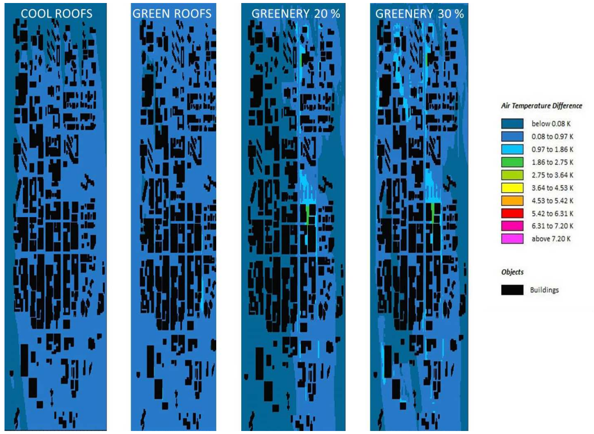

Figure 8. The distribution of the ambient temperature drop in the CBD area of Darwin when cool roofs, green roofs, and increase of the urban greenery by 20 % and 30 % are implemented.

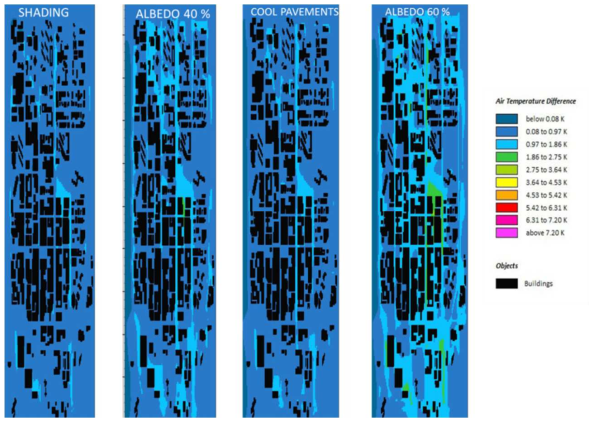

Figure 9. The distribution of the ambient temperature drop in the CBD area of Darwin with shading systems, cool pavements and an increase of the albedo to 40 % and 60 %.

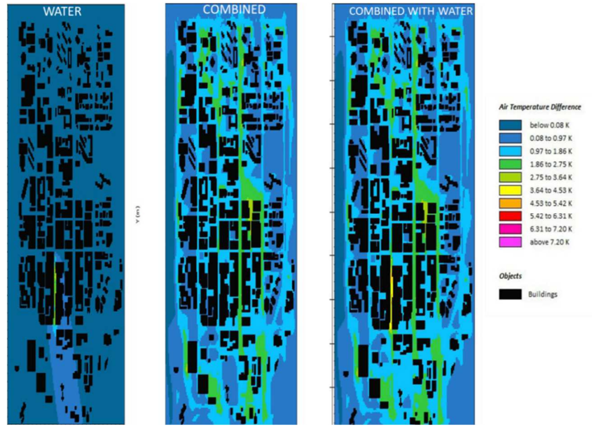

Figure 10. The distribution of the ambient temperature drop in the CBD area of Darwin when water systems combined solutions are implemented.

The maximum temperature drop (maximum in the reference scenario minus the maximum in the specific scenario) is achieved through the combination of the various mitigation technologies. The minimum performance corresponds to the use of cool roofs (without additional technologies). It is important to mention that the evaporative technologies are applied just in specific streets of the CBD and their impact is very local. The achieved decrease of the maximum temperature in the implementation zone exceeds 6 °C, but the global decrease of the maximum temperature in the whole CBD area is close to zero. The achieved drop of the maximum and minimum ambient temperature in the area of CBD is given in Figures 11 and 12, respectively.

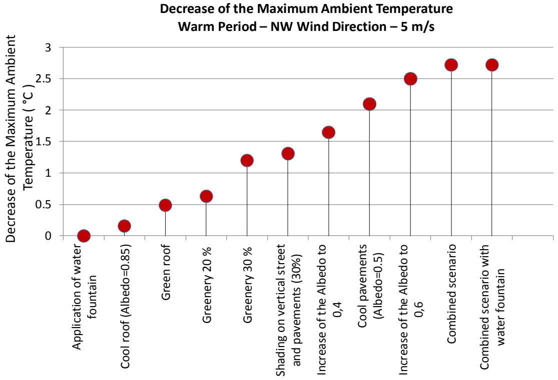

Figure 11. Decrease of the maximum ambient temperature achieved by the various considered mitigation scenarios.

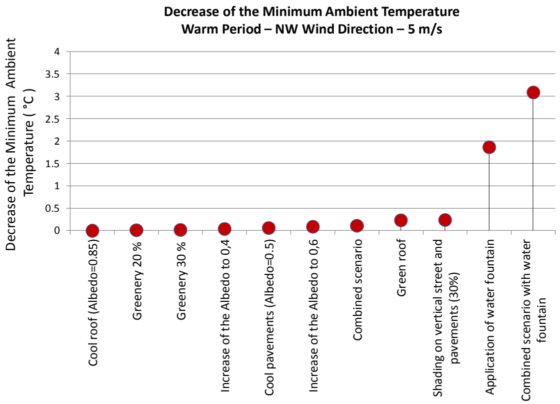

Figure 12. Decrease of the minimum ambient temperature achieved in the CBD area by the various considered mitigation scenarios.

7) Specific mitigation scenario for State Square inbdicates a very high potential

A detailed mitigation scenario has been developed concerning the zone around the State Square. The scenario considered that the Chan building is removed, all car parks located in the State square are replaced by the urban greenery, water fountains with spray cooling effect applied in Smith street, and existing asphalt and concrete pavements in Smith Street and State Square green area are replaced by cool pavements with an albedo equal to 0.5. The mitigation scenario has been evaluated and compared against the reference case. The maximum computed ambient temperature drop for the whole area is 2.2 °C, while the drop of the minimum temperature is of 3.8 °C, for NW winds and 5 m/s wind speed. The maximum local temperature drop is much higher, close to 6.5 °C (Figure 13). Such a high temperature drop is due to the use of the evaporation systems and has an exclusively local impact.

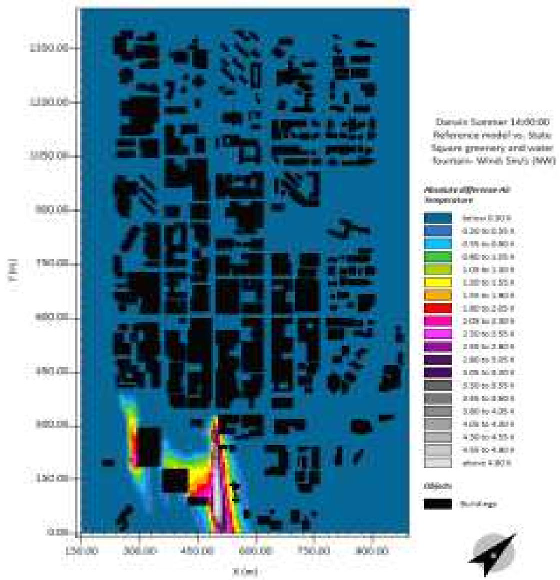

Figure 13. Distribution of the ambient temperature drop in the State Square zone of Darwin, NW wind direction, 5 m/s.

8) Important variability as a function of the synoptic weather conditions

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. As already mentioned, the mitigation potential of the considered technologies is evaluated for two synoptic conditions: NW and SE winds and for low and high wind speeds, namely 1 and 5 m/s. The maximum ambient temperature drop, for all the mitigation scenarios and for all the considered synoptic conditions, is given in Figure 14.

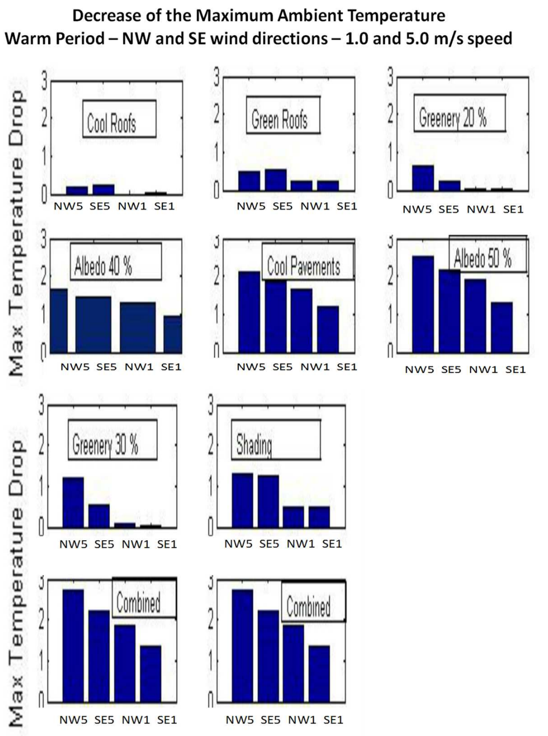

Figure 14. Decrease of the Maximum ambient temperature as calculated under the considered synoptic weather conditions: NW=North Western, SE=South Eastern, NW5 = North Western Winds of 1 m/s speed.

An increase of the wind speed has a positive impact on the mitigation potential of all scenarios related to reflective scenarios (increase of the albedo, cool roofs and cool pavements). Higher wind speeds increase the heat transfer between the ambient air and the roofs or the pavements and contribute to an increased convective cooling of the built surfaces. Under NW synoptic conditions, the mitigation potential of the reflective technologies increases up to 0.5 °C, compared to the potential when the wind speed is equal to 1 m/s. Similar results are obtained for the shading and greenery mitigation scenarios. Shaded surfaces present a low surface temperature and high wind speeds increase the convective transfer to the low temperature pavements, streets and car parks. In parallel, higher wind speeds enhance the evapotranspiration potential of the urban greenery and contribute to lower the ambient temperatures.

On the contrary, higher wind speeds decrease the mitigation potential of the evaporative water based systems. High wind speeds remove faster the water droplets from the considered urban zone and decrease their evaporation potential. For all reasons described previously, the mitigation potential of all the combined scenarios is seriously deceased under lower wind speeds.

The mitigation potential of the considered technologies evaluated under SE winds, may differ substantially than when NW winds are blowing in the area. In particular, the maximum temperature drop of the greenery scenarios is reduced to about 40-50 % under SE wind compared to NW synoptic conditions. Because of the layout of buildings and urban structures, under SE synoptic conditions, the wind speed is seriously reduced in the urban areas where the additional greenery is placed and the whole CBD area. Low wind speeds reduce the evapotranspiration potential of the trees and reduce the potential temperature drop in the area. Especially, in the northern part of the planted zone, the mitigation impact of greenery is seriously reduced because of the lower wind speeds. For similar reasons, the global mitigation potential of the evaporative technologies is considerably reduced under SE synoptic conditions, although the local temperature drop in the urban zone where the water systems are installed is quite high. The mitigation potential of the reflective technologies is not seriously affected by the change of the synoptic conditions. Because of the lower wind speeds in the CBD area under SE winds, the convective transfer between the cool surfaces and the ambient air is slightly decreased. Finally, the mitigation potential of the shading systems is not seriously affected.

9) Significant local temperature reduction.

Some of the considered mitigation scenarios are implemented in specific zones and not in the whole CBD area. As a result, their mitigation impact is local and it does not affect the temperature in the rest of the city. As a matter of fact, the previously reported maximum temperature drop for the whole CBD area is very low or even zero (evaporative scenarios). However, the local maximum temperature reduction is usually significant. In Figure 15, the evaporative scenarios based on the use of water sprinklers, present a local maximum temperature drop close to 2 °C, while the mitigation scenario designed for the State Square succeeds to decrease the local maximum temperature by up to 3.2 °C, despite its impact in the whole CBD area is negligible. Likewise, while the maximum temperature drop in the whole CBD area caused by the combined mitigation scenario including the use of evaporative technologies is close to 2.7 °C, the local maximum temperature reduction in the area where the sprinklers are placed is close to 4 °C.

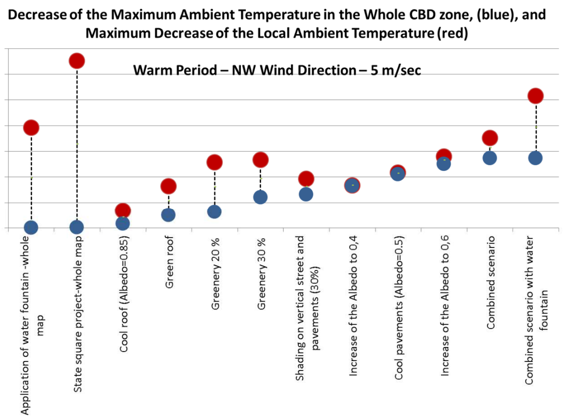

Figure 15. Decreased of the maximum temperature in the whole CBD area, (blue), and the corresponding maximum decrease of the local temperatures.

10) Specific analysis for the warm period.

While the whole mitigation study has been carried out for the warm and humid period of the year, the impact of the considered technologies, during the less warm and dry period of the year, is evaluated in detail. Simulations are performed for the combined scenario, considering that the global albedo will increase to 0.6, shading will be applied mainly on Wood St, Cavenagh St, Smith St, Mitchel St, Esplanade St, and McMinn St and the nearby car parks, and greenery will cover 30 % of the open spaces. It is found that although the undisturbed temperature in the city is of 31.2 °C, the temperature in the CBD area may vary between 26.8 °C to 30.7 °C (Figure 16). The majority of the CBD urban area falls below 28.8 °C.

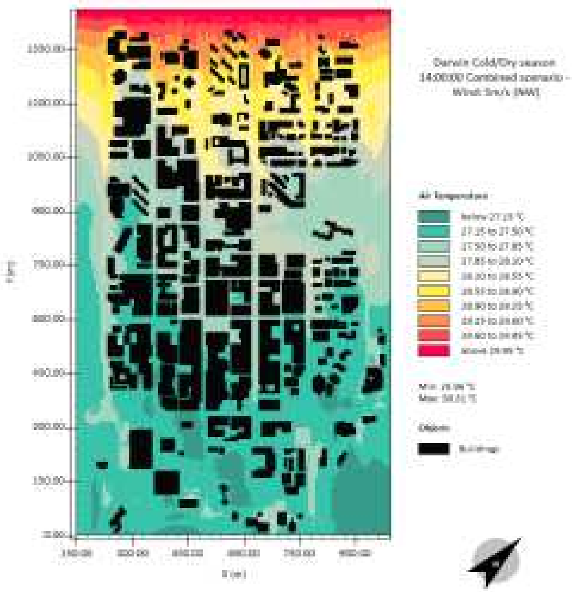

Figure 16. Temperature distribution in the CBD area during the dry period. The graph refers to NW wind directions and 5 m/s wind speed.

The results validate the assumption that the proposed mitigation techniques will enhance thermal comfort conditions during the dry period and will improve the local climatic conditions.

11) High reductions of the surface temperature of materials.

Besides the important reduction of the ambient temperature, the considered mitigation technologies contribute to decrease considerably the surface temperature in the CBD area. Lower surface temperatures correspond to improved thermal comfort levels as the emitted infrared radiation and the convected heat from the opaque surfaces is seriously reduced. The maximum surface temperature reduction found to vary between 1 to 15 °C (Figure 17). 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.

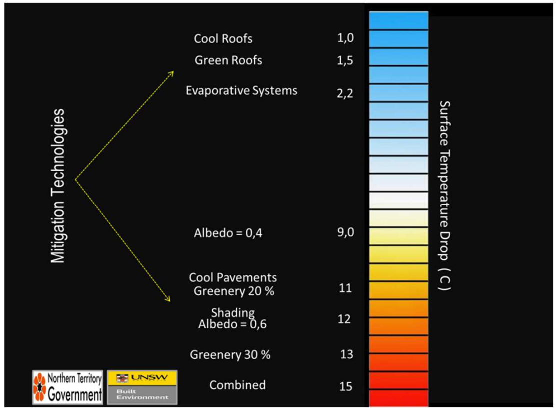

Figure 17. Reduction of the Maximum Surface Temperature as caused by each mitigation scenario, in the whole CBD area of Darwin.

12) Cost assessment of the proposed mitigation scenarios

The cost of the proposed mitigation scenarios has been evaluated using data received from various credible market sources. We trust that 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 18.

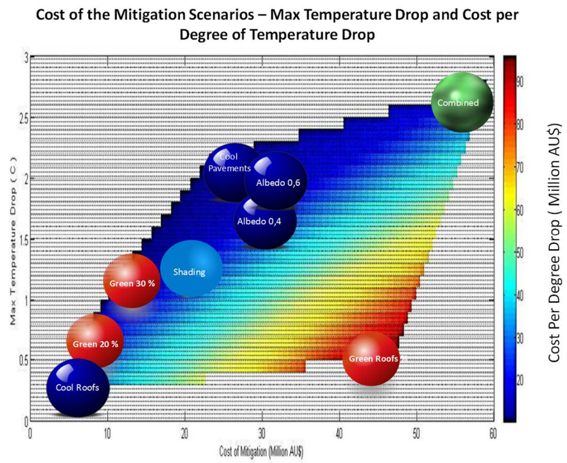

Figure 18. Classification of the cost per degree of temperature drop for each of the considered mitigation technology.

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.

APPENDIX CLIMATIC DATA

Heat Mitigation Program
Darwin, Northern Territory

Built Environment

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APPENDIX- Climatic Data

A PRELIMINARY ANALYSIS OF THE CLIMATIC DATA OF DARWIN AIRPORT METEOROLOGICAL STATION

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Methodology

Hourly data of the ambient temperature, relative humidity, wind speed and wind direction, collected at the Darwin airport between 2006-2016, are analysed. Clustering techniques have been used to extract the main scientific conclusions. In particular, twelve different clusters of climatic data, have been created and analysed. Four clusters have been generated for each of the three main climatic parameters: the ambient temperature, ambient humidity and wind direction. The analysis, permit to extract some preliminary conclusions about the main climatic characteristics of the city. To better understand the specificities of the local climate and extract unbiased conclusions, further analysis involving the use of more climate stations is necessary,
The specific results for each of the twelve clusters are given in the Appendix. The main findings of this preliminary analysis are presented in the following.

Main Findings

- The highest levels of the average ambient temperature in the city, are observed when the air flows from North Western Directions. These synoptic conditions correspond to a time period equal to the 24 % of the whole year. The average ambient temperature is close to 29,4 C and the maximum one is 37 C. The average relative humidity is close to 67 % and the maximum is almost 100 %. The potential for evaporative cooling is not negligible. The average wind speed, during this period, is close to 4,7 m/sec and the maximum speed exceed 15 m/sec. The potential of convective cooling is very limited because of the high temperature of the incoming air. Systems of wind protection and modulation in the NW parts of buildings and open spaces may be useful, (high level trees). Multi story buildings should be placed in this part of the city to block the flow of the warm air into the main urban zones. The development of a cool sink, (urban park of extended green spaces), in the western and northwestern parts of the city may be examined to dissipate the excess heat of the incoming air. Natural ventilation through openings located in Western and Northwestern facades may be avoided.

- For almost 22 % of the time the air flows from southern and southwestern directions. These synoptic conditions correspond to high ambient temperature and humidity levels. The average ambient temperature is 27,7 C while the average relative humidity is 77 %. The average wind speed is 4,1 m/sec. The potential for convective and evaporative cooling is very low if not negligible. Urban planning should attempt to block the flow of the southwestern wind into the city. Multistory buildings should be placed in this part of the city. Urban

corridors of this direction should be avoided. The development of a major cool sink in the southwest part of the city has to be examined. The southwester parts of buildings and open spaces should be protected and the overall design should block the air flow.

- Average ambient temperatures correspond to winds flowing from Northern and North Eastern directions. Very probably, this is the period where the sea breeze is developed and consist the dominant cooling mechanism in the city. The specific synoptic conditions correspond to the 24 % of the whole year. The average ambient temperature is close to 27 C and the average relative humidity is 71 %. The maximum temperature is 36 and the maximum humidity is close to 100 %. The average wind speed is reduced compared to the previous synoptic conditions, and is close to 3,4 m/sec. The developed sea breeze is quite weak because of the high surface temperature of the water. During this period, the potential for convective cooling is increased while the potential for evaporative cooling, is quite limited but not negligible. Future urban design, should enhance and facilitate the penetration of the Northen and Northwestern winds into the city. High story buildings and other obstructions should not to be placed in the Northern and Northwestern parts of the city to allow the penetration of the sea breeze in the main urban area. Zones of low pressure close to the north and western fronts of the city, have to be developed to promote and enhance the air flow into the urban zone. Open spaces have to be relatively open and unobstructed in their North and West sides. Evaporative cooling may be avoided close to the Northern and Western fronts of the city, but may be used at a certain distance from the coast.

- The lowest average ambient temperatures in the city, are observed when the air flows from South East and South directions. These are the prevailing synoptic conditions in the city. For almost 30 % of the time, the air flows from South Eastern directions. 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 4,1 m/sec. The climatic system of the southwestern winds seems to be the main cooling mechanism of the city. The advected air is highly influenced, cooled, by the national parks located in the southeastern parts of the city. The potential for convective cooling is very high while the corresponding potential for evaporative cooling is important. The overall planning and urban design should promote the flow of southeastern winds in the city. Multi storey buildings and other important obstructions should be avoided in the South Eastern parts of the city. Urban corridors to enhance and facilitate the air flow from South Eastern directions have to be designed. Building openings for natural ventilation should be oriented, if possible, in South Eastern directions. Open spaces should be open and non obstructed in their South East sides.

THERMAL VIDEOS

Heat Mitigation Program
Darwin, Northern Territory

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Thermal Videos

Methodology

As an integral part of the aerial survey, thermal videos were recorded over almost all the same areas mapped through thermal shots in order to provide a powerful and immediate means of summarizing information.

The raw videos returned by the Zenmuse XT camera have been post-processed and detailed as follows:

- each videos has been cut into 100 frames and reassembled in both thermo-chromatic scale and radiometric greyscale in order to manipulate the time intervals between the shots and make it easier to locate and analyse each point of interest;
- specific temperature indications have been added in synch with the videos in order to flash out reference values of the surface temperature of the city landscape components playing a major role in the UHI phenomenon. The values are obtained by comparing the videos with the correspondent emissivity-adjusted thermal shots;
- Darwin terrain maps have been additionally provided alongside the video and supplemented by a moving viewer pane to retrace the drone's path and to ease the association between the series of time-lapse images and the target objects.

By overlapping all these pieces of information it is possible to get the feeling of the overall situation at a glance. Therefore such re-shaped thermal videos are effective tools for kickstarting the mitigation strategy design process.