CONCLUSIONS

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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).

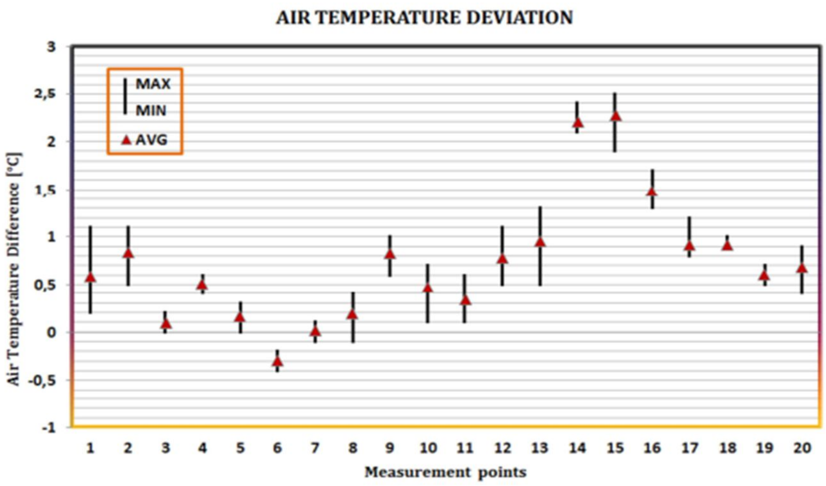

Figure 1. Magnitude of the Urban Heat Island in Darwin, as measured in March 2017.

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;

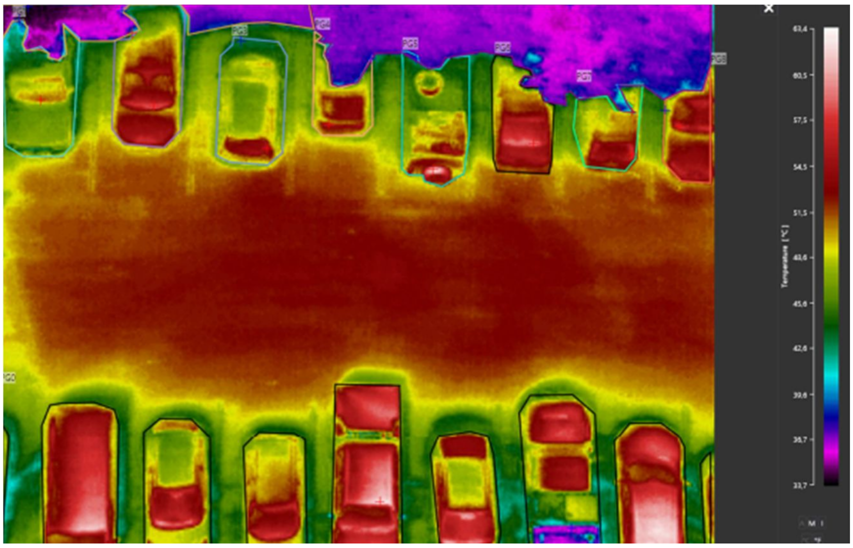

Figure 3. Surface temperature in the central CBD area of Darwin exceeds 60 °C.

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 exceed 5 m/s, the average speed in the CBD area is close to 0.5 m/s (Figure 4);

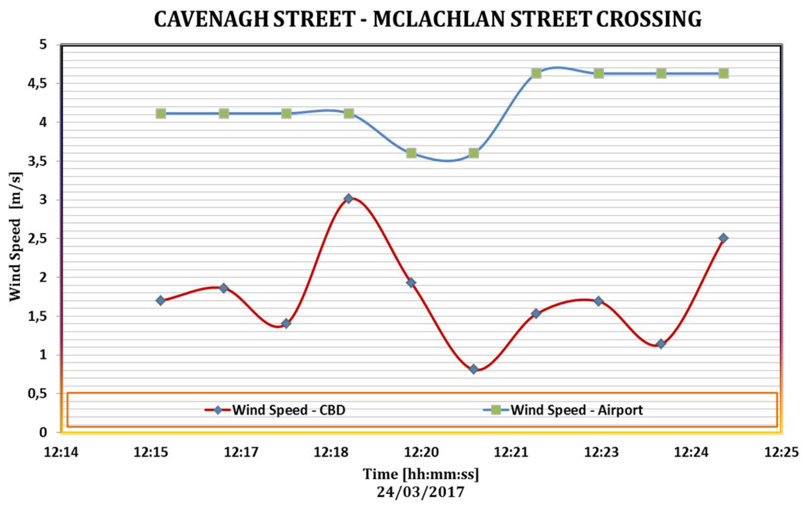

Figure 4. Wind speed as measured at the airport of Darwin.

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).

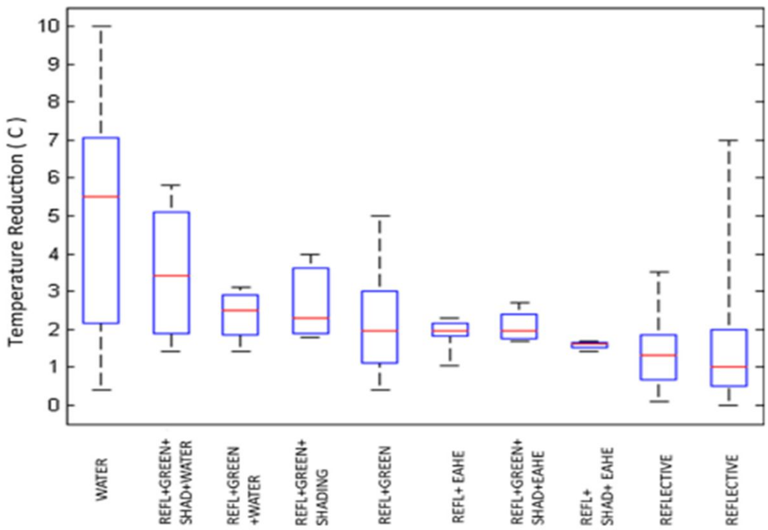

Figure 5. Range of the peak ambient temperature reduction for all the considered mitigation systems and technologies.

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 details. 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

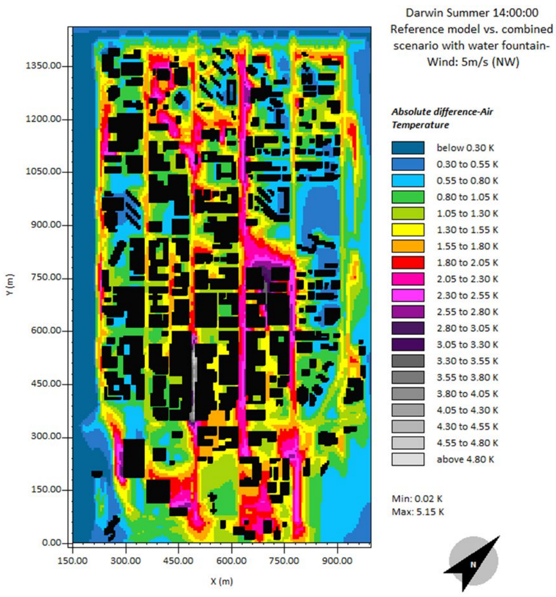

Figure 6. Simulated ambient temperature distribution for the combined scenario in Darwin

6) The proposed mitigation technologies can decrease the maximum ambient temperature from 36.5 n the Darwin ar

The results of the simulation show that the proposed mitigation technologies can decrease the maximum ambient temperature from 36.5 os are simulat In parallel, the minimum ambient temperature in the area can decrease from 31.2 temperature in the maximum and minimum ambient temperatures in the whole area, as calculated for each mitigation scenario, are given in Figure 7.

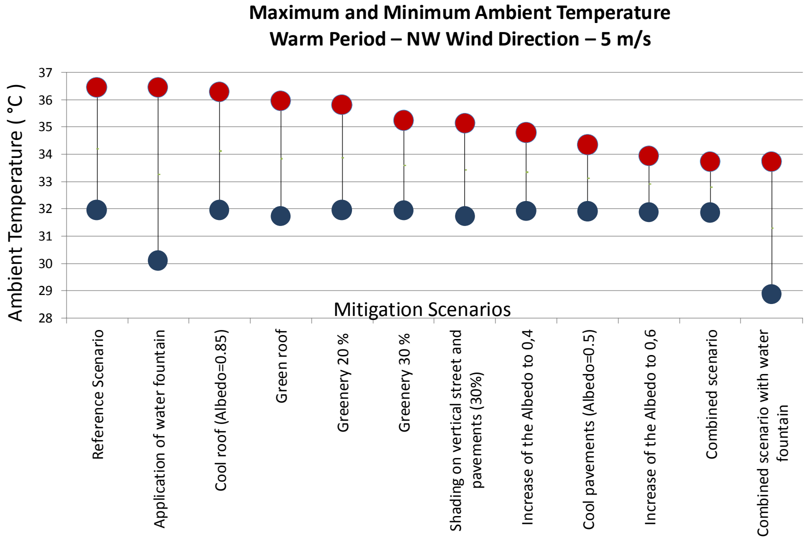

Figure 7. Maximum and minimum temperature in the CBD area calculated for each mitigation scenario.

The achieved decrease of the maximum ambient temperature is close to 2.8 each mitigation scenario.imum ambient temperature from 36.5 os are simulat In parallel, the minimum ambiesent the difference of the maximum or minimum ambient temperature as calculated in the reference scenario against the corresponding maximum or minimum temperature, respectively, calculated for each scenario. The maximum or the minimum temperature in the reference and in each scenario may not correspond to the same place in the CBD area (as different mitigation options may mitigate more a specific hot spot than another one). 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.

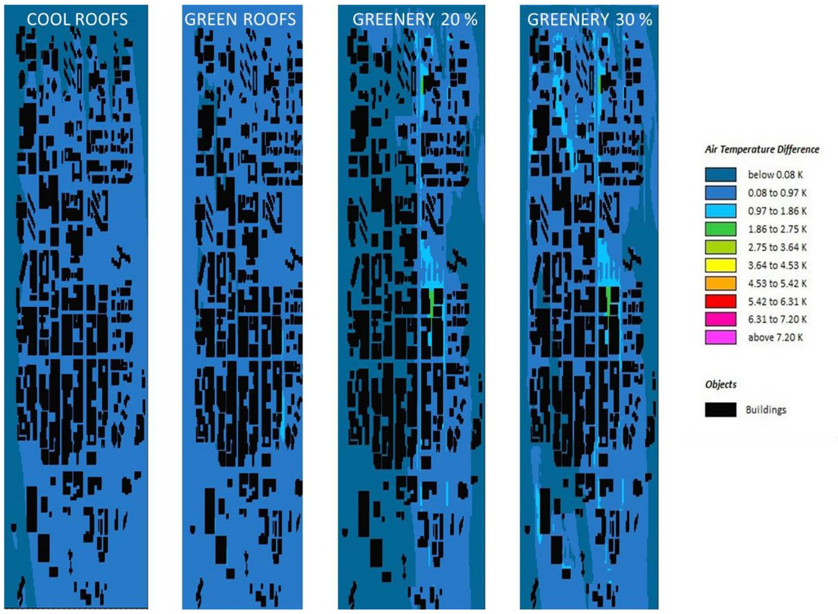

Figure 8. The distribution of the ambient temperature drop in the CBD area of Darwin when cool roofs, green roofs, and increase of the urban greenery by 20 % and 30 % are implemented.

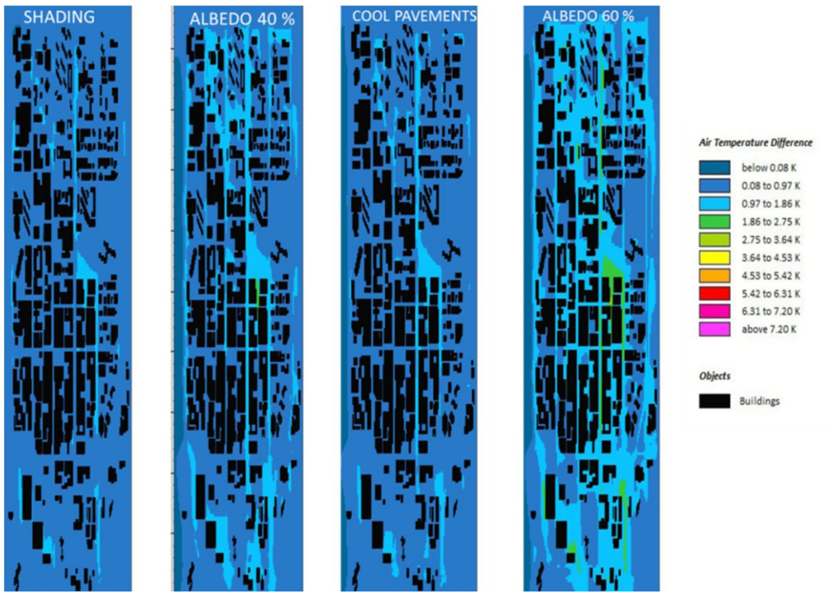

Figure 9. The distribution of the ambient temperature drop in the CBD area of Darwin with shading systems, cool pavements and an increase of the albedo to 40 % and 60 %.

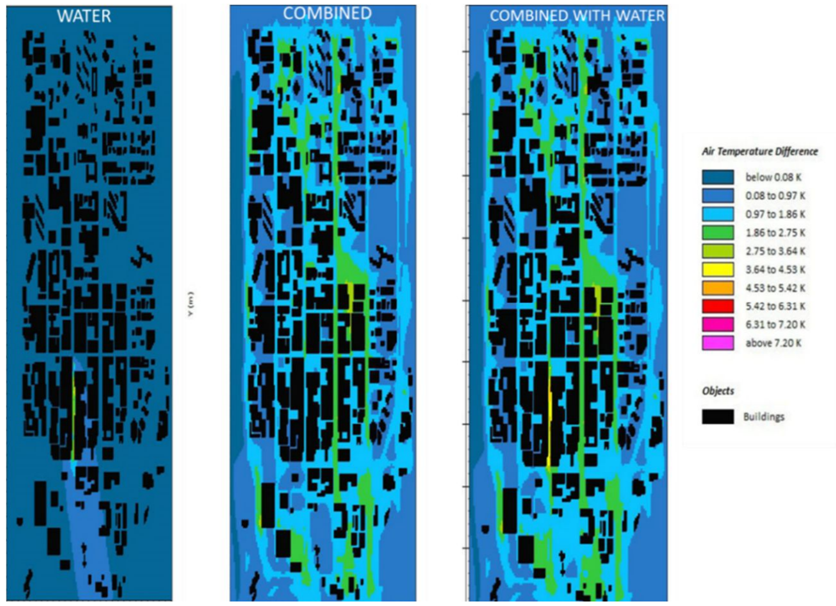

Figure 10. The distribution of the ambient temperature drop in the CBD area of Darwin when water systems combined solutions are implemented.

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.

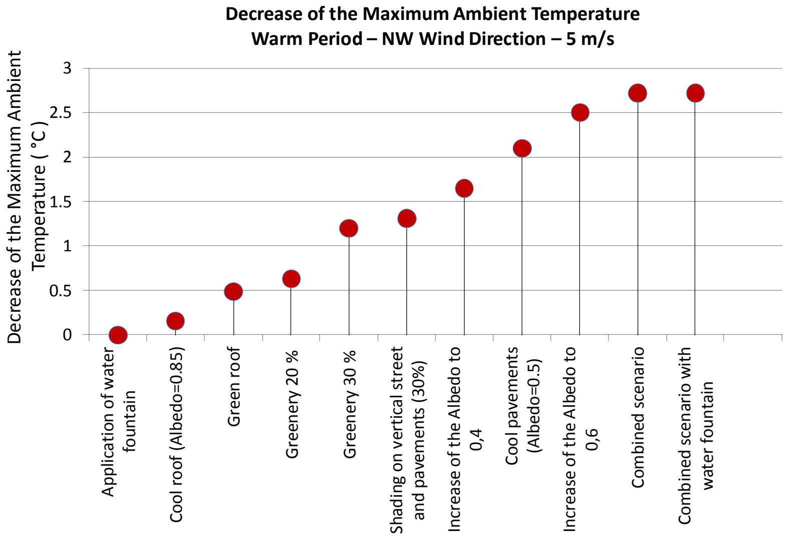

Figure 11. Decrease of the maximum ambient temperature achieved by the various considered mitigation scenarios.

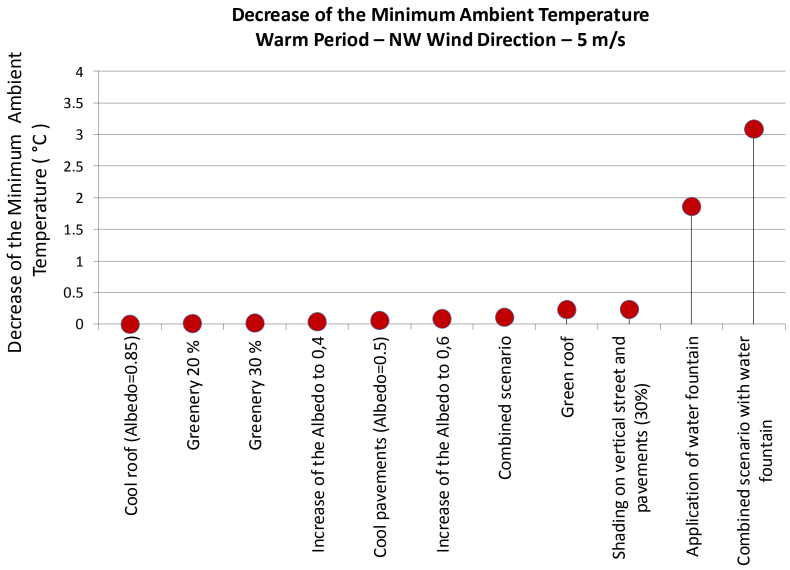

Figure 12. Decrease of the minimum ambient temperature achieved in the CBD area by the various considered mitigation scenarios.

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.

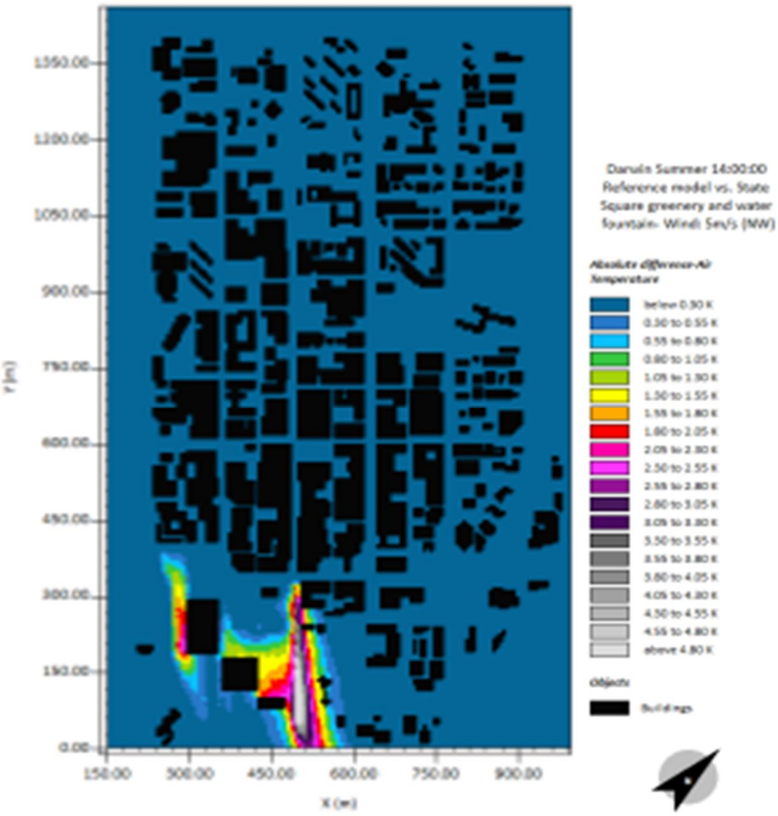

Figure 13. Distribution of the ambient temperature drop in the State Square zone of Darwin, NW wind direction, 5 m/s.

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.

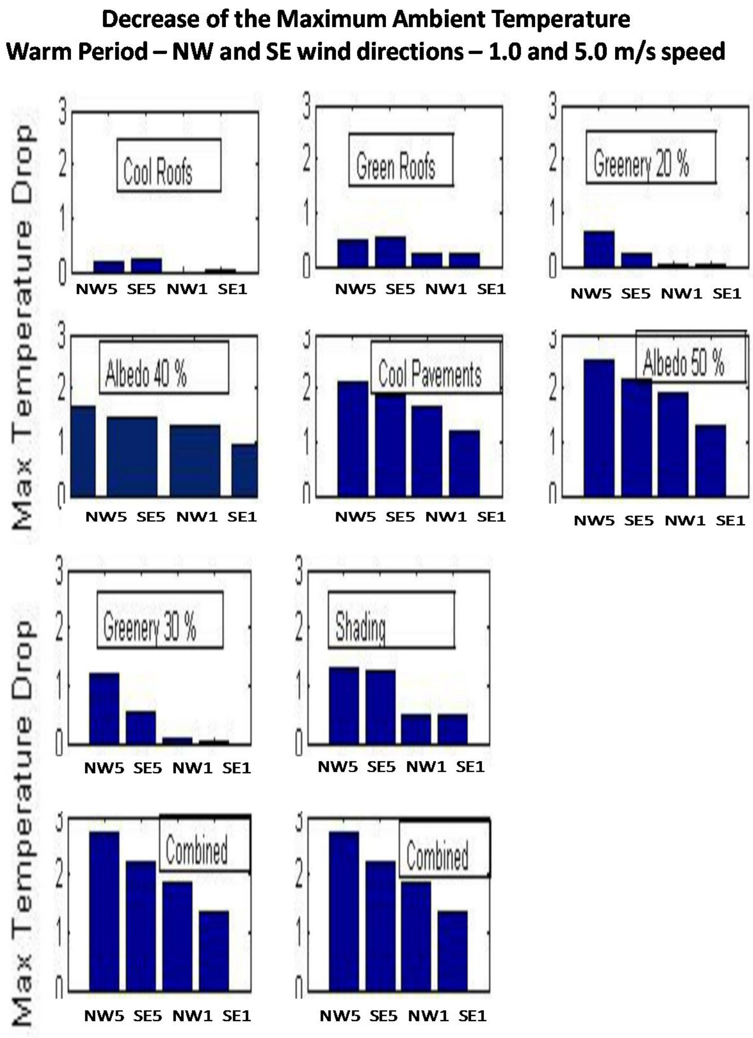

Figure 14. Decrease of the Maximum ambient temperature as calculated under the considered synoptic weather conditions: NW=North Western, SE=South Eastern, NW5 = Nort Western Winds of 1 m/s speed.

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.

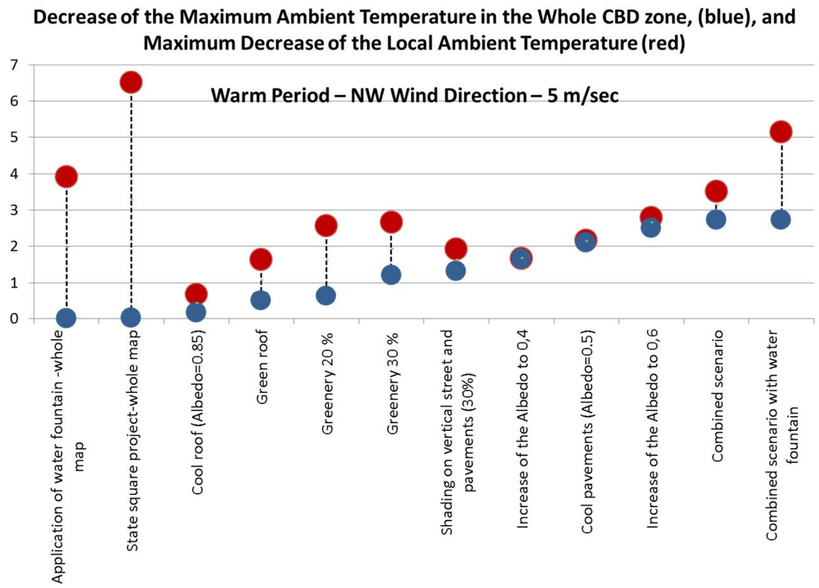

Figure 15. Decreased of the maximum temperature in the whole CBD area, (blue), and the corresponding maximum decrease of the local temperatures.

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 details. 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.

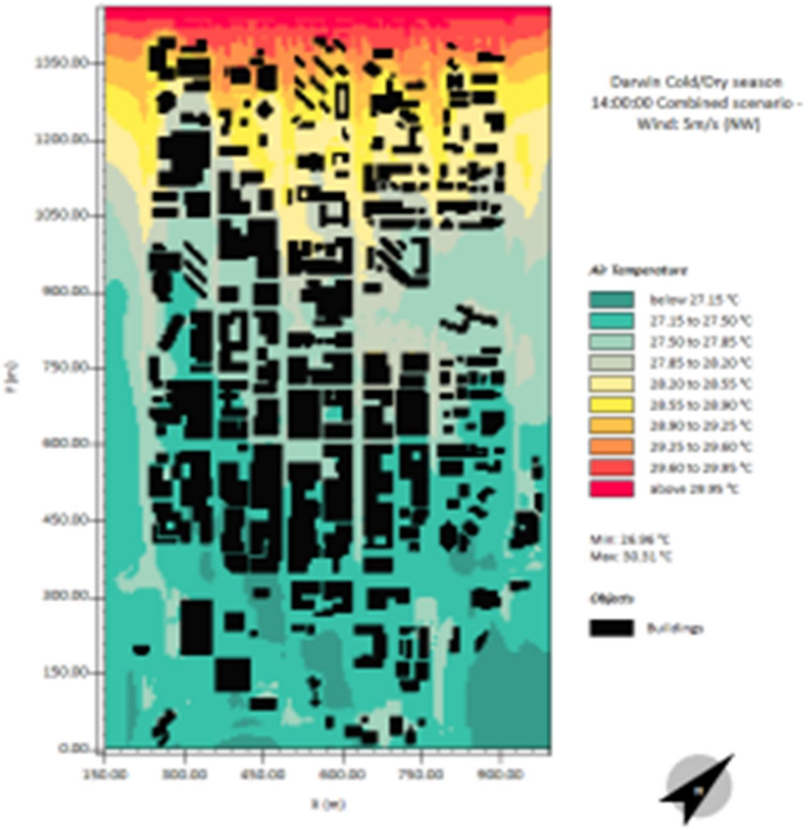

Figure 16. Temperature distribution in the CBD area during the dry period. The graph refers to NW wind directions and 5 m/s wind speed.

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 tehnologies may exceed 20-25 °C.

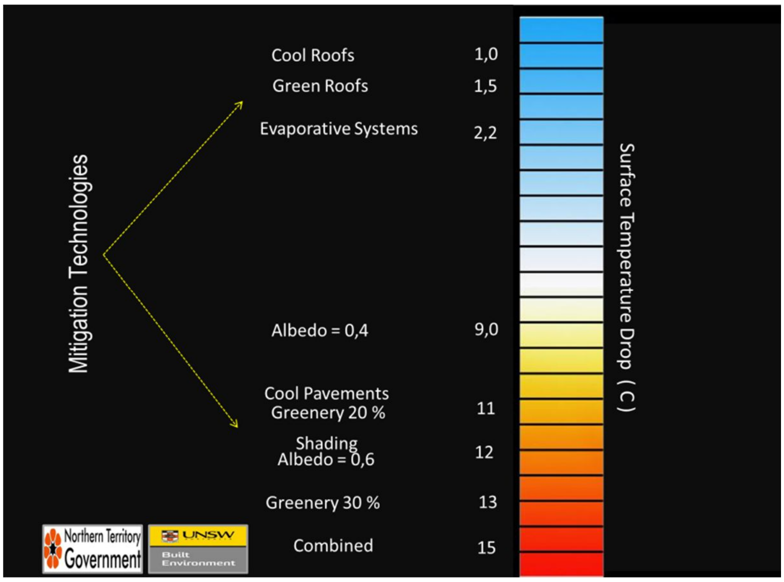

Figure 17. Reduction of the Maximum Surface Temperature as caused by each mitigation scenario, in the whole CBD area of Darwin.

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.

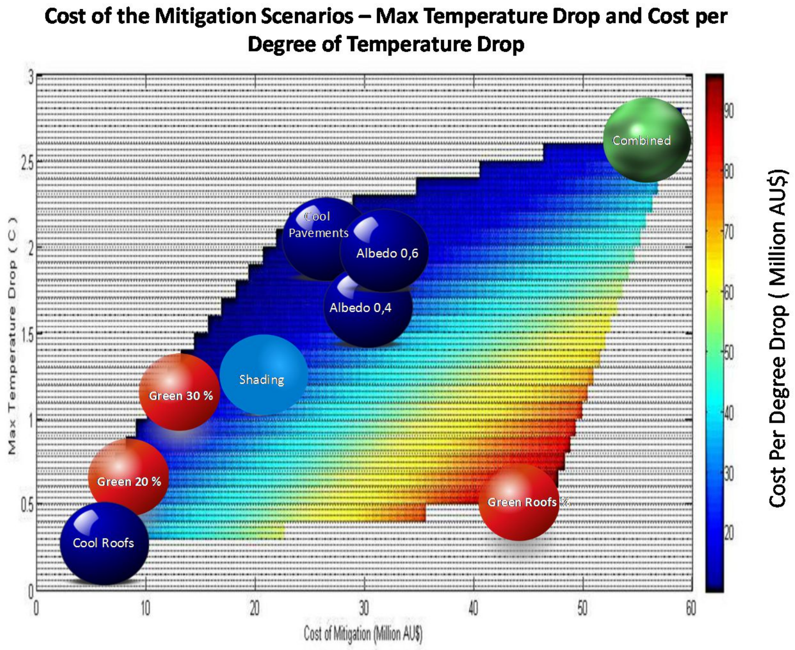

Figure 18. Classification of the cost per degree of temperature drop for each of the considered mitigation technology.

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.