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Research plan & progress report

COOL ROOFS
COST BENEFIT ANALYSIS

Volume 7 - Climatic and Energy Performance of Cool Roofs in Adelaide

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Contents

Executive summary

This study is performed to assess the energy and environmental benefits as well as the cost-benefit of reflecting or cool roofs in the city of Adelaide, Australia. Specifically, the purposes of this report are:

1) To evaluate the existing reference climatic conditions in the city of Adelaide, understand the characteristics of the urban overheating, and develop detailed climatic data through advanced mesoscale climatic modelling.
2) To evaluate the magnitude and spatial variation of the mitigation /cooling potential generated by the cool roofs when implemented at the city scale, as well as how its application affects the urban ambient temperature and the other main climatic parameters.
3) To investigate the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Adelaide.
4) To understand the way of how specific building characteristics affect the performance of cool roofs and the advantages of applying cool roofs in various stations.

The whole study involved the following Phases:

Phase 1: Mesoscale simulation of the current climatic conditions. In the first phase, a full mesoscale climatic model for the entire city of Adelaide using a weather research forecasting model is created to simulate the distribution of the main climatic parameters in the city. Simulations are performed for two representative summer months

Phase 2: Mesoscale simulation of the climatic conditions when cool roofs are implemented at the city scale. During the second phase, mesoscale climatic simulations are performed considering that cool roofs are implemented at the city scale. The modified climatic parameters are also calculated as in the first phase; the results of the first and second phases are compared to assess the climatic benefits arising from the use of cool roofs at the city. Specifically, the ambient temperatures, surface temperatures, sensible heat flux, latent heat flux, wind, PBL dynamics, and the regional impact on sea breeze circulations in the two scenarios have been compared.

Phase 3: Cooling degree hours calculation. In this phase, cooling degree hours (CDH) base 26 °C, which measures how much, and for how long, ambient air temperature is higher than 26 °C, has been calculated for 19 weather stations in Adelaide for the entire simulation period, serving as a rough indication of the regional climatic severity. CDH for reference cases, cool roof applied cases, their differences, as well as the percentage of CDH reduction due to the implementation of the cool roof in the 19 weather stations, has been calculated. The frequency and spatial distribution of the calculated CDH are analyzed as well.

Phase 4: Assessment of the energy Cooling/heating load under various boundary conditions during the summer period. Simulations were performed for seventeen types of buildings and nineteenth weather stations across Adelaide. The cooling load simulations were performed for two summer months of January and February using weather data simulated by WRF as in phases 1 and 2. Three scenarios are simulated a) Using the reference climatic data assuming conventional roofs, b) Using the reference climatic data but considering roofs are reflecting, and c) Using the modified climatic data calculated in Phase 2 considering that the roofs are reflecting.

Phase 5 Assessment of the energy Cooling/heating load under various boundary conditions during the whole year. The annual cooling and heating load estimations were also performed to assess the annual cooling load savings of cool roofs against their corresponding annual heating penalty. The annual cooling and heating load simulations were performed using the weather data obtained from the Bureau of Meteorology (BoM).

Phase 6: Assessment of the Indoor Air Temperature under free-floating conditions under three climatic conditions. Additionally, the impact of cool roofs on indoor air temperature was assessed under free-floating conditions in weather stations, presenting the lowest and highest ambient temperatures in Adelaide during a typical summer and winter period.

Phase 7: Analysis of the Impact of Building Characteristics on the Performance of Cool Roofs. Finally, the energy characteristics and mainly the magnitude of thermal losses through the building envelopes and its impact on the performance of cool roofs are assessed in various stations in Adelaide and the results have been compared. Specifically, for the seventeen building types, the linear regression has been generated between CDH and the total cooling load in a building with a conventional roof, the cooling load reduction when applying a cool roof, and the cooling load reduction for the same building with a cool roof using the climatic data simulated by WRF considering the impact of a cool roof. Focus is put on the slope of the regression line, which indicates the heat loss coefficient of the overall envelope or the effectiveness of a cool roof under different climatic conditions. The heat loss coefficient of buildings with or without insulation, built in older years or recently, and with different heights has been compared, as well as the energy-saving advantage of the cool roof under various climatic conditions.

To summarise, it is expected that this study can present a comprehensive overview of the existing climatic conditions, and the overall climatic effect, as well as the modification in building energy and thermal balance after applying the cool roof in the entire city of Adelaide.

Collectively, the following conclusions have been drawn:

1) An increase of albedo fraction in Adelaide city can decrease the peak ambient temperature up to 1.9°C and surface temperature up to 6.6°C.
2) The maximum decrease of sensible heat and latent heat flux were 179.5 Wm-2 and 15.8 Wm-2, respectively.
3) The highest decrease of wind speeds up to 2.3ms-1. Cool roofs increase the pressure over core urban at local-scale and decrease the wind advection from the adjacent bare surface of desert fetch.
4) Cooling degree hours indicating the climatic severity during the summer period, range from 185.8 to 1328.5, under the existing conditions, increasing from the southeast of the city to the northwest.
5) When cool roofs are used in the city, CDH ranges from 261.5 to 3551.5. The percentage of CDH reduction due to the implementation of the cool roof ranges from 16.2% to 44.3%.
6) In existing low-rise buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in individual buildings (scenario 1) is significant. For instance, application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 6.3-10 kWh/m2.
7) In existing low-rise buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in both individual buildings and at the whole urban area (scenario 2) is significant. For instance, the application of cool roofs in both individual buildings and at the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 12.5-13.9 kWh/m2.
8) In new low-rise buildings with high insulation level, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) has a noticeable impact on cooling load reduction. For instance, cooling loads savings by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 3.6-4.3 kWh/m2 in a typical new low-rise office building.
9) In high-rise buildings, application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.2 kWh/m2 for a new high-rise office building with insulation.
10) In high-rise buildings, the cooling load reduction through application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.5-0.6 kWh/m2 in an

existing high-rise shopping mall centre, which is expected to increase to 6.0-9.2 kWh/m2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).

11) The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in majority of building types. For instance, the annual cooling load saving in a low-rise office building without insulation is 11.0-19.2 kWh/m2, while the corresponding heating penalty is just 1.4-3.6 kWh/m2.
12) The annual heating penalty of cool roofs may exceed the cooling benefits in residential buildings in Adelaide. For instance, the heating penalty can be up to 6.9-11.4 kWh/m2 compared to the equivalent 5.1-8.7 KWh/m2 in an existing stand-alone house.
13) In existing low-rise buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in individual buildings (scenario 1) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 7.6-8.4 ^{o}C.
14) In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in both individual building and at the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and at the whole urban area (scenario 2) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 8.4-10.0 ^{o}C.
15) In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual building and at the whole urban area (scenario 2) can significantly decrease the number of hours with an indoor air temperature above 26 ^{o}C. For instance, the number of hours with an indoor air temperature above 26 ^{o}C in a typical low-rise office building without insulation is predicted to reduce from 436-457 hours to 326-367 hours and 251-333 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
16) In new low-rise buildings with high insulation level and under free-floating condition in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the maximum indoor air temperature during a typical summer period. For instance, the maximum indoor air temperature reduction by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 2.1-3.0 ^{o}C in a typical new low-rise office building.

17) In new low-rise buildings with high insulation level and under free-floating condition in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the number of hours with an indoor air temperature above 26 ^{o}C during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 ^{o}C in new low-rise office building with insulation is predicted to reduce from 494-510 hours to 388-456 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
18) The maximum indoor air temperature reduction by cool roofs in a typical winter period is significantly lower than the maximum indoor air temperature reduction during a typical summer period. For instance, the maximum indoor air temperature reduction by application cool roofs in individual buildings in low-rise office building without roof insulation is predicted to be 7.6-8.4 ^{o}C in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 0.4-1.8 ^{o}C during a typical winter month.
19) The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 ^{o}C and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.3 ^{o}C occurs when the indoor air temperature is 24.0 ^{o}C.
20) The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 ^{o}C especially during the operational hours of the buildings in a typical winter period. For instance, it is predicted that the application of cool roofs in individual buildings (scenario 1) can increase the total number of operational hours with ambient temperature below 19 ^{o}C from 176-239 hours to 210-274 hours in a typical existing low-rise office building with roof insulation.

Objectives

This study is performed to assess the energy and environmental benefits as well as the cost-benefit of reflecting or cool roofs in the city of Adelaide, Australia. Specifically, the purposes of this report are:

1) To evaluate the existing reference climatic conditions in the city of Adelaide, understand the characteristics of the urban overheating, and develop detailed climatic data through advanced mesoscale climatic modelling.
2) To evaluate the magnitude and spatial variation of the mitigation /cooling potential generated by the cool roofs when implemented at the city scale, as well as how its application affects the urban ambient temperature and the other main climatic parameters.
3) To investigates the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Adelaide.
4) To understand the way of how specific building characteristics affect the performance of cool roofs and the advantages of applying cool roofs in various stations.

Methodology

The whole study involved the following phases:

Phase 1: Mesoscale simulation of the Current climatic conditions. In the first phase, a full mesoscale climatic model for the entire city of Adelaide using weather research forecasting model is created to simulate the distribution of the main climatic parameters in the city. Simulations are performed for two representative summer months.

Phase 2: Mesoscale simulation of the climatic conditions when cool roofs are implemented at the city scale. During the second phase, mesoscale climatic simulations are performed considering that cool roofs are implemented at the city scale. The modified climatic parameters are also calculated as in the first phase. The results of the first and second phases are compared to assess the climatic benefits arising from the use of cool roofs at the city. Specifically, the ambient temperatures, surface temperatures, sensible heat flux, latent heat flux, wind, PBL dynamics, and the regional impact on sea breeze circulations in the two scenarios have been compared.

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Specifically, two scenarios, one as the reference case (Solar reflectance_ roof, streets, and walls=0.15; thermal emissivity _ roof, streets, and walls =0.85), the other applied with the cool roof (Solar reflectance _ roof = 0.80; Solar reflectance _ walls and streets=0.15; thermal emissivity _ roof, streets, and walls =0.85) are simulated and analysed in this study. Collectively, it is expected that this study can present a comprehensive overview of the existing climatic conditions, and the overall climatic effect, as well as the modification in building energy and thermal balance after applying the cool roof in the entire city of Adelaide.

1. Report of mesoscale simulations _ Simulation of the base case and cool roof scenarios

1.1 Introduction

The mounting urban heats, driven primarily by the burning of fossil fuels, exacerbated extreme events were reported around the globe and in Australia in 2017 (Bureau of Meteorology, Australia, 2017a, b). Human-induced regional climate change is heating up the urban areas and urbanization augments the risks associated with extreme events. Climate change magnifying extreme events, cities aren't adapting as quickly enough. Urbanization suppresses evaporative cooling process from urban surface and amplifies heatwave intensity with a strong influence on minimum near surface temperatures. Frequent heat waves are recognized as a abstemious threat for human health worldwide; with urban areas being more exposed due to the urban warming effect. Extreme urban heat along with regional climate change can affect the health and wellbeing of human, the environmental quality, and the socio-economic performance of cities. Higher magnitude of urban temperatures (and for longer periods) is considerably affecting citizen's quality of life and outdoor activities of the citizens. Extreme urban heat is being augmented by local and regional climate change which leads to an increase in the magnitude, intensity, frequency, and duration of extreme temperature, prolonged thermal distress and heat stress, and increased heat-related mortality and morbidity (Santamouris et al., 2017). To undertake the extreme urban heat and perk up the quality and comfort levels of outdoor and indoor environments, it is imperative to investigate and evaluate the feat of cool roof strategies at city-scale during an extreme heat condition.

1.2 Objectives of the study

This study is performed to assess urban heat and mitigation potential of cool materials in the city of Adelaide, Australia. The magnitude and the characteristics of the extreme urban heat have been assessed in the city of Adelaide through mesoscale simulations. The purpose of this report is:

- To evaluate the existing climatic conditions (base case) in the city of Adelaide.
- To evaluate the cooling potential of cool roof technology when they are implemented in the city of Adelaide.
- To compare the impacts of cool roof strategies at diurnal and monthly scale over urban domain

1.3 Domain and method of simulation

We use a full mesoscale climatic model for the entire city of Adelaide using weather research forecasting model (WRF v4.3) which is an advanced commonly used numerical climate model. The model is created to simulate the distribution of the main climatic conditions in the city under all climatic, synoptic, and land use conditions. The resolution of the grid in the simulation is 500 x 500 meters (**Table 1 and Figure 1**). The developed mesoscale model is used to calculate the hourly distribution of the main climatic parameters in Adelaide under the existing heat wave conditions and one mitigation scenarios. The albedo or emissivity as a single fraction was applied uniformly to all urban grid cells. The cool materials were examined by test case of 100% cool surfaces (on the roof only) with changing albedo and emissivity fractions for roofs at the urban scale (**Table 2**). We performed extensive analysis to analyze the performance of cool roof scenario and its cooling potential. One mitigation scenario is evaluated in this report. The mitigation strategy is examined in this study at city-scale.

Table 1 WRF/SLUCM Model configuration

Configuration	Domain 01 (d1)	Domain 02 (d2)	Domain 03 (d3)
Version	ARW-WRF v4.3		
Initial and boundary conditions	ERA-Interim reanalysis		
Run time	31 December 00:00h, 2016 to 1 March 00:00h, 2017 IST		
Time period for analysis	1 January 12:00h, 2017 to 28 February 00:00h, 2017 IST		
Grid distance (m)	4500	1500	500
Grid number	200x200	202x202	202x202
Number of vertical layers	40 layers		
Microphysics	WRF Single-Moment 6-class scheme		
Surface layer model	Noah-LSM+Single layer UCM (Chen &Dudhia, 2001; Kusaka et al., 2001)		
Turbulence	Mellor and Yamada’s (1974) TKE scheme		
Short-wave radiation	Dudhia scheme (Dudhia, 1989)		
Long-wave radiation	RRTM scheme (Mlawer et al., 1997)		
Planetary boundary layer	Asymmetrical Convective Model version 2 (ACM2) (Pleim, 2007)		
Cumulus parameterization	Kain-Fritsch (KF) scheme (Kain, 2004)		

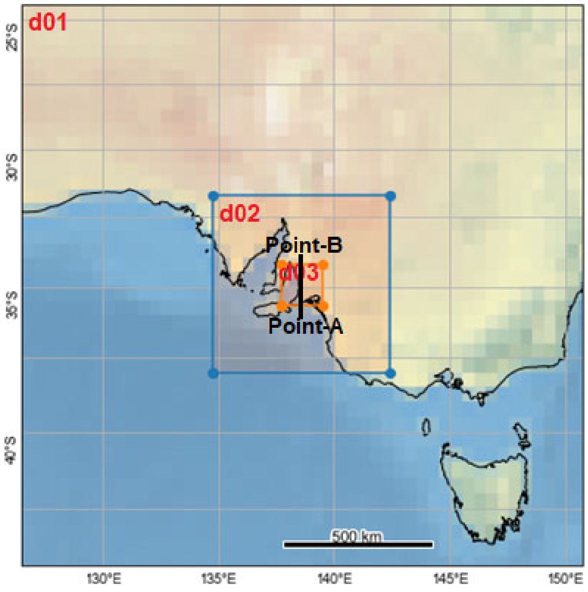

Figure 1 WRF domain shows (a) dynamical downscaling with domain 1 (d01) as outermost parent domain with 4500m grid spacing, domain 2 (d02) with 1500m grid spacing and, an innermost domain 3 (d03) with 500m grid spacing; (b) innermost d03 with 500m grid spacing which encompasses the Greater Adelaide. The Point-A (left) and Point-B (right) are the points used for drawing horizontal-vertical cross-sections to analyze meteorological conditions for **Figure 9**.

Table 2 Numerical design for cool roof for Adelaide.

Scenarios	**Albedo**			**Emissivity**		
	Roof	Wall	Ground	Roof	Wall	Ground
Control	0.15	0.15	0.15	0.85	0.85	0.85
Scenario	0.80	0.15	0.15	0.85	0.85	0.85

1.4 Model evaluation

To evaluate the performance of the WRF-SLUCM system, we compared hourly simulated 2-m ambient air temperature against local measurements for the control case simulation over urban grid cells in the innermost domain. A statistical comparison of the mean bias error (MBE), mean absolute error (MAE), root mean square error

(RMSE), correlation coefficient (r), and the index of agreement (IOA) for hourly 2m air temperature for the 24-hour duration are listed in **Table 3 and Figure 2**. The model evaluation is based on correlation between the WRF model and observations for 2m-temperature across the diurnal cycle. The coupled WRF-SLUCM model accurately captures the temperature observed at different stations (mean R=0.964; mean bias=-1.77) for(a) Adelaide Airport, (b) Parafields Airport, (c) Nourlunga, and (d) Roswarthy. The base case simulation produced urban meteorological conditions well and statistically, agreed with local observation ($p<0.05$). The simulated average UHI intensity varied from 2.3°C to5.5°C in the high-density urban residential areas relative to rural (i.e., surrounding) landscapes, as a function of the prevailing local weather conditions. The range of MBE and RMSE of air temperature was -1.33°C to -2.28°C and 1.47°C to 2.53°C, respectively. The range of IOA was 0.86 to 0.92 with average values of 0.91 when considering all observation stations. The model slightly overestimated the daily average 2m ambient air temperature, potentially resulting from an overestimate of anthropogenic heating over the urban domain. We also assess impacts on local meteorological stations as it is these stations that are most influenced by utility of the UCM scheme. The well-simulated daytime warming is balanced by equally well-simulated nighttime cooling, resulting in a diurnal range that is of similar magnitude to observations. The comfort level of different dew points is >21°C for the stations represents the uncomfortable situation in urban environment. The difference is identical when quantifying impacts on local meteorological stations. Although WRF does not display considerable warm (comfort) bias over urban locales, the representation of the 24-h averaged diurnal range of dew point temperature is well captured. In addition, model biases are most likely caused by: (a) lack of proper urban morphological representation, and (b) uncertainties in model physical schemes, input data used, and locally meaningful urban biophysical parameters. Nevertheless, our initial evaluation highlights that the model can replicate the urban environment realistically, including a well-simulated evolution of the diurnal cycle of both near-surface temperature and dew-point, and the model framework can be used to predict the regional meteorology and investigate the regional influence of cool roof strategies.

Table 3 Comparison of the simulation results with observation data at an average 24-h scale for 59 days.

Parameters	**Local weather stations**			
	Adelaide Airport	Parafields Airport	Nourlunga	Roswarthy
Correlation coefficient	0.96	0.97	0.95	0.97
Mean bias error	-2.28	-1.7	-1.78	-1.33
Mean absolute error	-2.277	-1.703	-1.776	-1.327

Root mean square error	2.53	1.92	1.95	1.47
Index of agreement	0.86	0.92	0.87	0.92
Parameters	0.96	0.97	0.95	0.97

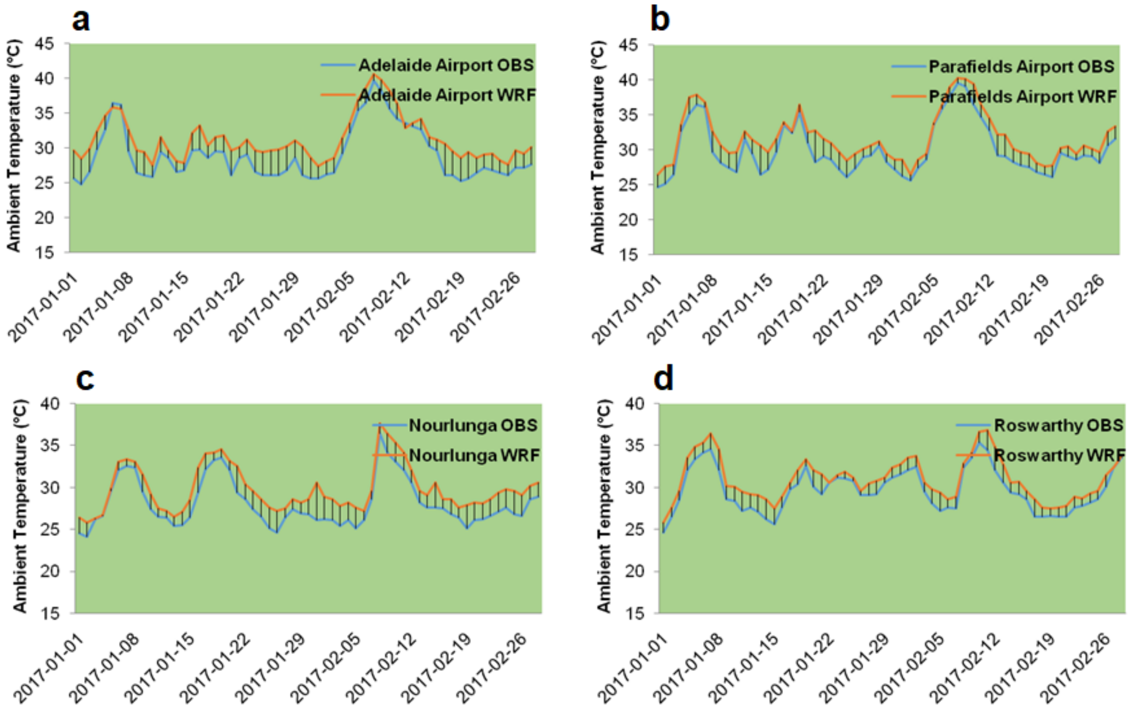

Figure 2 Validation of the WRF Model and the corresponding observed air temperature for the 24-hour average duration for four local meteorological stations: (a) Adelaide Airport, (b) Parafields Airport, (c) Nourlunga, and (d) Roswarthy.

1.5 Results of the mesoscale simulations

The results of the control scenario (existing condition) are used as a reference to compare with the cool roof scenario. The predictions of the mesoscale model have been compared against the collected data from the main ground climatic stations in Adelaide to ensure the robustness and accuracy of the model. The results of base case are presented for two months of summer. The simulated summer period is from January 1st, 2017 to March, 2017. The mitigation scenario presented here has been analyzed during summer period for 59 days of two months (January and February). These two months was warmer than average during 2017 for both daytime and overnight temperatures in the Greater Adelaide. In 2017, Adelaide experienced its hottest Christmas Day since 1941. Temperatures in Greater Adelaide were very warm overall in 2017, with Adelaide's mean temperature the warmest on record. The mean maximum temperature equaled the record set in 2016 (Bureau of Meteorology, Australia, 2017a, b).

1.5.1 Ambient temperatures

Ambient temperatures can be calculated from the surface energy balance flux partitions in the WRF-SLUCM urban modeling system. Under the cool roof materials scenario, the ambient temperature at 14:00 ranges between 23.8 °C and 39.2 °C. At 06:00 LT, it varies between 18.9°C and 31.1°C .The results show that the use of cool roof materials maximum reduces the peak ambient temperature (Tambient) by 1.9ºC over high density residential areas and 1.6°C for whole urban average compared to control case. The average ambient temperature reduction at 14:00 over the whole summer is 1.1°C near the Port Adelaide Enfields, Charies and The West Torrens area of the city.. The maximum decrease of the ambient temperature during 18:00 LT is 1.3°C near coastal fringe (some parts of Port Adelaide and the Charies Sturt area)and average decrease of summer months is 0.8°C **(Figure 3)**.

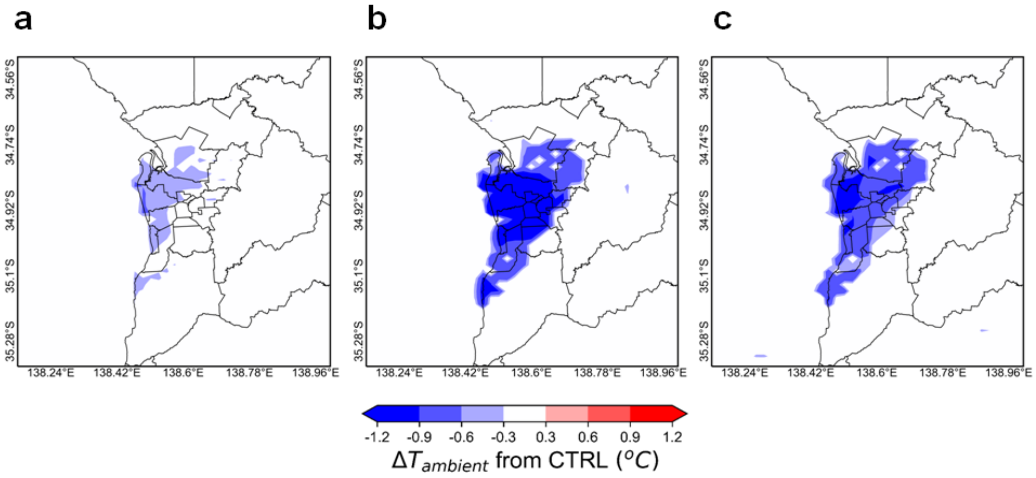

Figure 3 Reduction of ambient temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT

1.5.2 Surface temperatures

Under the cool roof scenario, the surface temperature (Tsurface) ranges between 25.3°C to 40.8°C at 14:00, 21.4°C to 36.8°C at 18:00 LT and 21.3°C to 34.8°C at 6:00 LT over city. The maximum decrease of surface temperature during 14:00 LT is 6.1°C over urban surface with average reduction of whole summer is about 5.5over urban domain.

But, in the high-density residential urban area, the maximum decrease of surface temperature is about 6.6°C during 14:00 LT of summer months along the coastal region (Port Adelaide Enfield, Charies, West Torrens and the Holdfast Bay) of the city. The maximum surface temperature reduction at 18:00 LT is about 4.9°C over the Charies Sturt area of the city. The average decrease of urban surface temperature is 4.3°C at 18:00 LT and 1.5°C at 06:00 LT compared to control case for the whole summer month in city **(Figure 4)**.

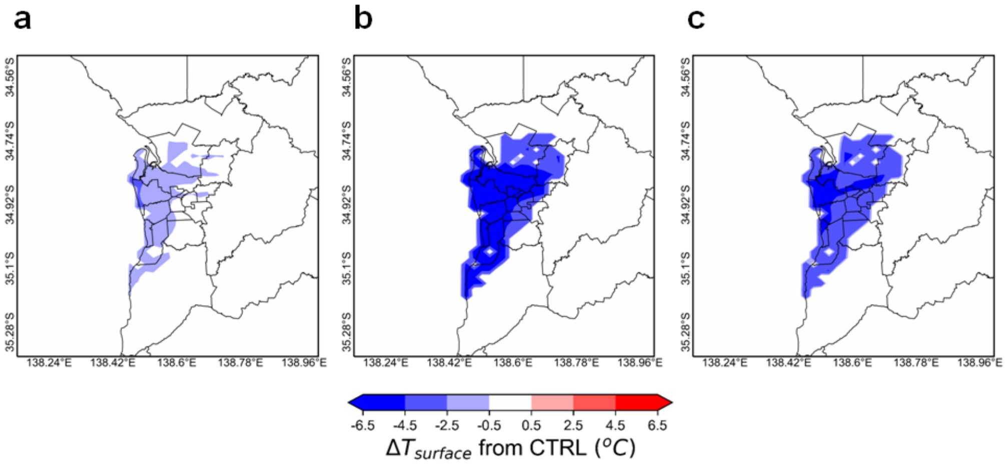

Figure 4 Reduction of surface temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT

1.5.3 Sensible heat flux

The WRF-SLUCM reasonable computed the sensible heat flux from the urban surface. Under the cool roof scenario, the maximum and average sensible heat flux (Qsensible) over city during 14:00 LT is 472.3Wm-2 and 336.1Wm-2,. At 18:00LT, the average sensible heat flux is 99.8Wm-2. The maximum decrease the sensible heat flux is 171.3Wm-2and average decrease is 145.2Wm-2at 14:00 LT over urban domain (Port Adelaide Enfield, Charies Sturt, Prospect, Norwood, Payneham & St Peters, West Torrens and Holdfast Bay). In the high-density residential urban area, the maximum and average reduction of sensible heat flux is about 179.5 Wm-2 and 153.0Wm-2 during 14:00 LT of summer month compare to control case. At 18:00LT, the maximum and average reduction of summer month of sensible heat flux is 79.4Wm-2and 64.7Wm-2over the urban domain **(Figure 5)**.

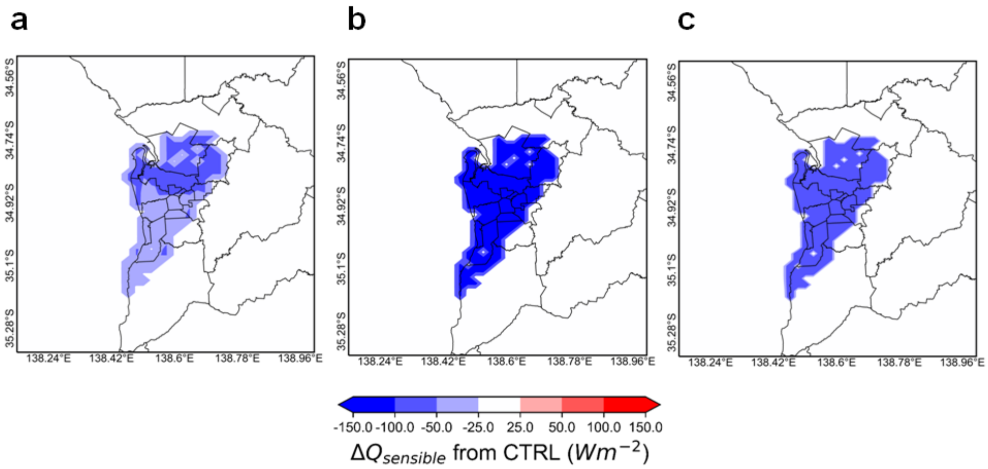

Figure 5 Reduction of sensible heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.4 Latent heat flux

The maximum and average latent heat flux (Qlatent)under cool roof scenario over city during 14:00 LT is 27.4Wm-2 and 20.2 Wm-2. At 18:00 LT and 06:00 LT, the average sensible heat flux is 7.8 Wm-2 and 4.8 Wm-2.The maximum decrease the latent heat flux is 15.0wm-2 and average decrease is 11.9 Wm-2at 14:00 LTnear the coast and central part (Port Adelaide, Charies Sturt and Adelaide, Unley, Burnside) of the city.But, in the high density residential urban area, the average decrease of latent heat flux is about 12.5 during 14:00LT of summer months. At 18:00 LT, the maximum and average reduction of summer month of latent heat flux is 6.0Wm-2and 4.3Wm-2over urban domain. At, 06:00 LT, the maximum reduction of latent heat flux is 4.7Wm-2and average reduction is 3.1Wm-2over urban domain **(Figure 6)**.

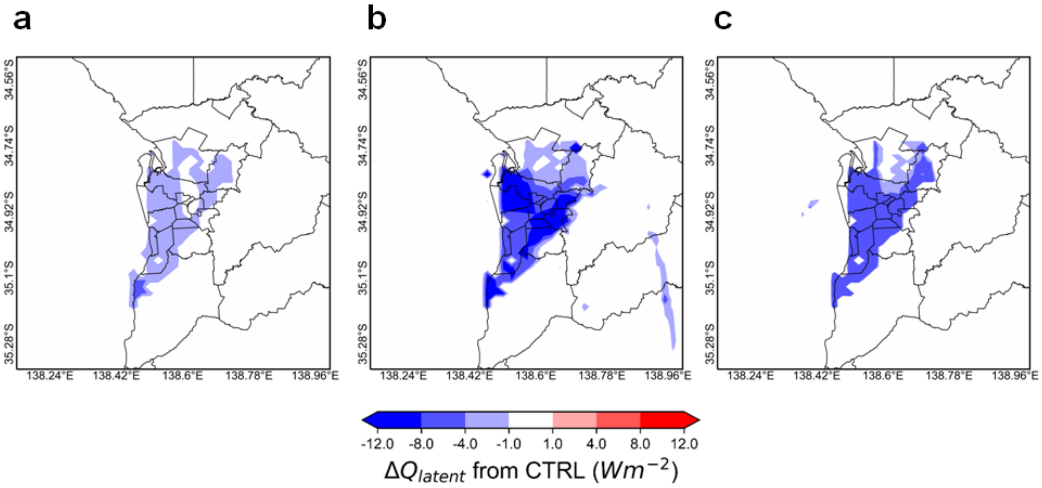

Figure 6 Reduction of latent heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT

1.5.5 Wind

Under the base case simulation, the average wind speed (Wspeed) are 2.7 ms-1, 6.4 ms-1 and 5.2 ms-1 during 06:00 LT, 14:00 LT and 18:00 LT respectively over the city. The maximum decrease of wind speed compared to control case is 1.4ms-1, 2.1ms-1 and 2.0ms-1 at 06:00 LT, 14:00 LT (central part of the city e.g Adelaide, Walkerville, Burnside, Unley and Mitcham) and 18:00 LT(Port Adelaide Enfield, Charies Sturt, Prospect, Adelaide and West Torrens) respectively over urban domain. The average decrease of wind speed of whole summer months is 1.5 ms-1 at 14:00 LT, 0.9 ms-1 at 06:00 LT and 1.3ms-1 at 18:00 LT over the city **(Figure 7)**.

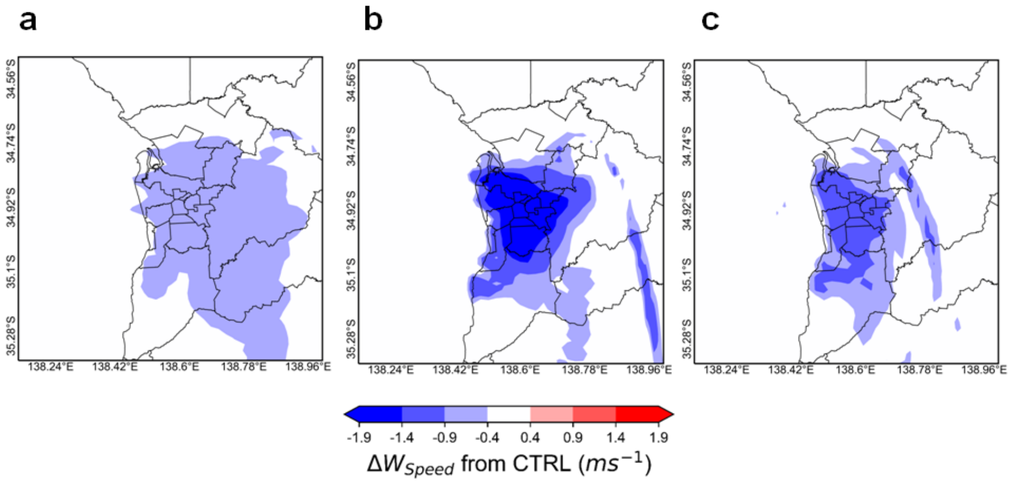

Figure 7 Reduction of wind speed at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.6 Regional Impact of Cool Roof: PBL Dynamics

The high-density urban building environment impacts on the lower atmospheric dynamics at the city to regional scale. The diurnal variability of the PBL, resulting from the impacts of cool materials at the city scale, was reported. The magnitude of the PBL height reduction is considerable higher when highly reflective cool materials rather than conventional materials are implemented at the city scale. **Figure 8** shows spatial distribution of the PBL height in the case of the cool roof implementation at different hours of a summer day at 6:00LT, 14:00LT, 18:00LT. The PBL height distribution and corresponding spatial changes in vertical wind speed. For instance, in core urban areas of the city (central part of the city e.g. Adelaide, Walkerville, Burnside, Unley, Mitcham, Port Adelaide Enfield, Charies Sturt, Prospect, and West Torrens), impacts on PBL depth reduction resulting from the use of highly reflective cool materials appear to extend beyond the scale of the implementation itself. The maximum reduction of PBL is 176.5 m, 694.0 m (near the coast and central part of the city), and 373.5 m for 6:00LT, 14:00LT, 18:00LT, respectively with average value is about 120.9m, 589.0 m and 275.0m. The minimum reduction of PBL is 61.2 m, 417.5 m, and 110.2m, for 6:00LT, 14:00LT, 18:00LT, respectively, **(Figure 8)**. The maximum reduction associated with peak hour

(14:00 LT) over central part of the Adelaide city. The prime causes of PBL depth reduction due to cut-off input solar radiation and subsequently decrease in sensible heat and associated turbulence in the lower atmosphere. It is also noted that the increase of the albedo is expected to accelerate the static stability at the diurnal scale of the PBL depth. Modification of the albedo reduces the impacts of urban induced warming and decreases the intensity of the convective mixing thereby reducing the PBL depth, with potential penalties for air pollutant dilution and dispersion over the city domain. The reduction of moisture transport from the urban surface to the vertical layer caused by the implementation of reflective materials can also be disadvantageous to cloud formation processes, and as a result, reduce the amount of precipitation in urban areas or their downwind environments.

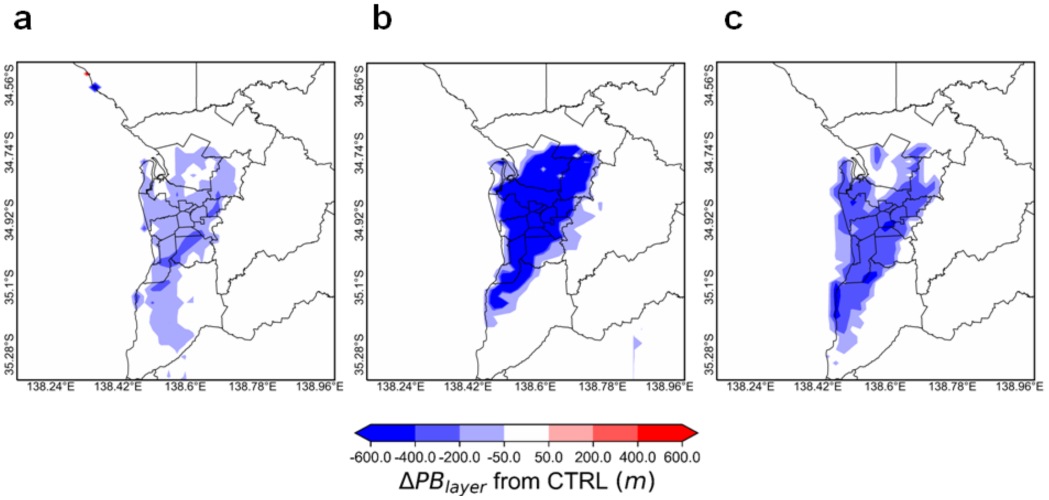

Figure 8 Reduction of PBL height at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT

1.6 Regional impact on sea breeze circulations

The strengthening of sea breeze circulation is dependent on the large-scale synoptic background, which plays an important role in modulating the prevailing wind at the near surface. In the vertical dimension, report revealed the height of the PBL in the Adelaide is linked closely with the advection of the sea breeze. The circulation can be modified when cool roof is implemented at city-scale **(Figure 9)**. The cool roof could alter the PBL height and potentially trigger localized circulation over the urban domain of Adelaide. Results also indicate that the onset of the sea breeze was delayed to afternoon (14:00 LT) due to the “regional high” effect within the lower PBL and offshore synoptic wind flow above the PBL. The denser cool air over the urban domain flows towards the suburban area to replenish the buoyant warm air. The cool roof materials can suppress the process of vertical lifting of urban thermals, transport and dispersion of low-level motions due to inversion in hot summer and decelerate the sea breeze front. Therefore, the decrease in the extent of vertical wind speed by 1 to 2 ms-1 induces a stronger subsidence over the urban domain where reflective materials are implemented. The surface roughness parameters are painstaking to be useful to pull the cool air of sea breezes down to the surface due to the mixing effects. Besides, the horizontal wind shear and frontal lifting owing to surface roughness parameters could setback the onset of sea breeze front in the urban core. The potency of the sea breeze advection is subjected to the dimension of the city which persuades the urban heating effect. Thus, cool roof for cities have greatly modified the thermal and dynamic profile in the urban boundary layer and sea breeze circulation. This synoptic flow prevails in the opposite direction of sea breeze and sea breeze front developed is more prone to the accumulation of secondary pollutant in the back of the front.

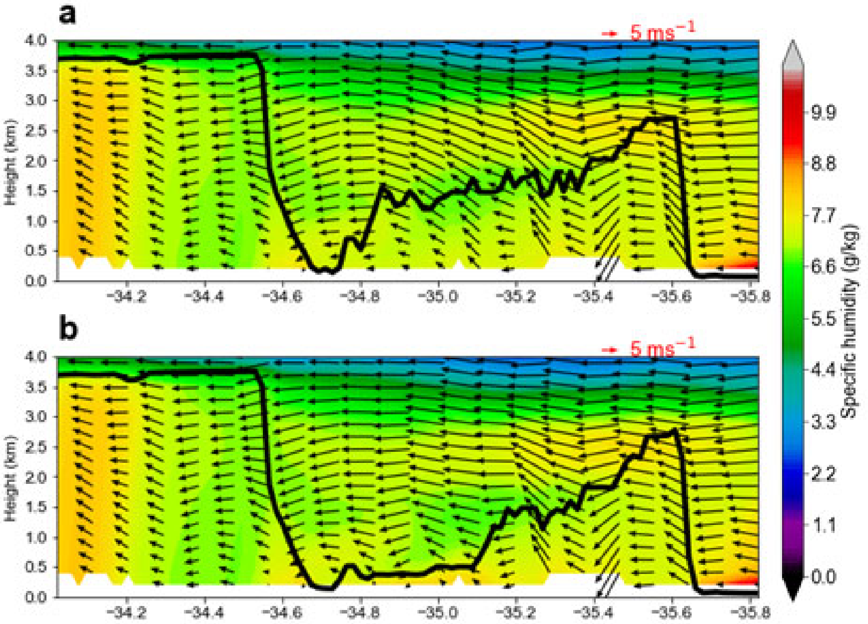

Figure 9 Cross-sectional profile of heat mitigations impacts on sea breeze during peak hour (14:00 LT) over Adelaide (a) control case, and (b) cool roof scenario. The vertical gradient of specific humidity determines the static stability of the lower atmosphere.

Report also shows the implementation of cool roof over city scale can affect the pressure gradient between city and surrounding surface due to significant drop ambient temperature up to 1.9°C and wind speed decrease up to 2.3 ms-1.Thus, changes in roof reflectivity, sensible heating, and wind result in feedbacks within local climate of the city during peak hour (14:00 LT).The higher urban albedo values decrease the advective flow between city and its surroundings improving the cooling potential of reflective materials. It creates 'regional high', which can reduce both horizontal and vertical wind speed over city. Consequently, the increase of albedo may prevent the warm air flow from the long fetch desert towards western Adelaide due to the effect of this regional high over the domain (Fig. 10). The sea breeze generated during the day reduced UHI effects by vertically mixing and warming the inland suburban area without affecting the urban area with no inversion. In addition, it is clearly proved that the impact of sea breeze considerably reduced over high-density residential areas.

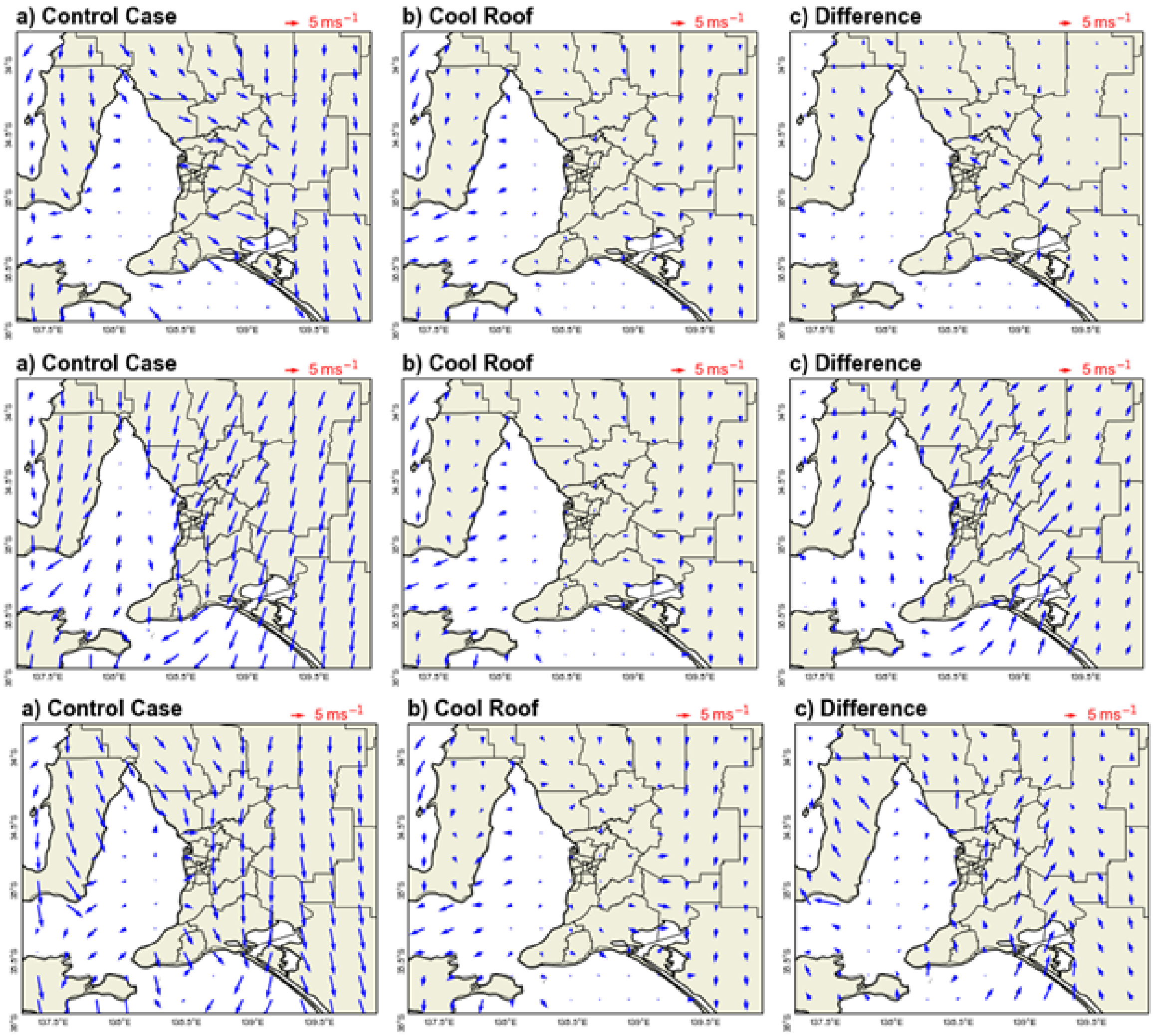

Figure 10 Surface characteristics of wind before and after cool roof implementation at city scale (a) control case (b) cool roof (c) scenarios minus control: difference at 06:00 LT (upper), 14:00 LT (middle), and 18:00 LT (lower panel) for the domain d03.

1.7 Main conclusions

- The most intense temperature differences occurred between city cores to surrounds. The maximum magnitude of the phenomena may exceed 5°C.The UHI effect would be added evenhandedly balanced spatially under the urban expansion. The intensity and the characteristics of the phenomena are strappingly influenced by the synoptic weather conditions and in particular the development of the sea breeze and the westerly winds from the long fetch desert area. The possible existence of an extra heating mechanism, like the advection of warm air from nearby desert spaces, may intensify the strength of the problem.

- High density parts of the city exhibit a higher temperature reduction than the urban average. The locations and magnitudes of urban heating in the high density urban areas vary spatially and diurnally.
- Increase of albedo in Adelaide can decrease the peak summer ambient temperature up to 1.9°C and surface temperature up to 6.6°C. Such cooling improves human comfort levels, and could be feasible for reducing cooling energy demand.
- It was found that important temperature differences exist near the coast and core part of the city. The patterns of the ambient temperature distribution in the city were found to depend highly on the synoptic climatic conditions and the magnitude of the horizontal thermal gradient.
- The city of Adelaide experiences an aggravate UHI at night during extreme urban heatwaves. In the daytime, a pocket of urban heat happen in the northwest part of the high density urban areas, while in the night, a hotspot occurs in the northern part of the city.
- The maximum decrease of sensible heat and latent heat flux were up to 179.5 Wm-2 and 15.8 Wm-2, respectively.
- The maximum decrease of wind speeds up to 2.3ms-1. Cool roofs increase the pressure over core urban at local-scale and decrease the wind advection from the adjacent bare surface of desert fetch.
- The results show that the increase in albedo fraction leads to decrease in wind speeds and the incidence of high wind speeds along with augmented turbulent energy in the planetary boundary layer (PBL) during heat wave scenario.
- Modification of the urban albedo in Adelaide city results in an average reduction up to 682.1 m of the PBL heights over high density parts of the city and may increase the concentration of bad pollutants at ground level during peak hour (14:00 LT) due to low level urban mixing.
- The sea breeze significantly affected by cool roof due to higher local pressure over city, which greatly reduces the sea breeze penetration.
- The amplitude of the UHI was linked with the subsistence of the sea breeze in the central parts of the city with a thermal gradient from Adelaide Hills to the Western Beach. And decreasing the temperature of the coastal zone, combined with wind effects from the inland and nearby surfaces.

2. Climatic design Parameters _ CDH distribution

In this study, cooling degree hours (CDH) base 26 °C, which measures how much, and for how long, outside air temperature is higher than 26 °C, has been calculated for 19 weather stations in Adelaide for the entire simulation period, serving as a rough indication of the regional climatic severity. Two scenarios: reference scenario (Solar reflectance_ roof, streets, and walls=0.15; thermal emissivity _ roof, streets, and walls =0.85) and cool roof scenario (Solar reflectance _ roof = 0.80; Solar reflectance _ walls and streets=0.15; thermal emissivity _ roof, streets, and walls =0.85) are simulated and analysed. CDH for reference cases, cool roof applied cases, their differences, as well as the percentage of CDH reduction due to the implementation of the cool roof in the 19 weather stations, has been calculated. The frequency and spatial distribution of the calculated CDH are analyzed as well.

2.1 Overview of the weather stations in Adelaide

Nineteen stations in Adelaide, as shown in **Table 4** and **Figure 11**, have been simulated for two months: January and Feburary, and the dry bulb temperatures generated by Weather Research Forecasting Model have been used in subsequent calculations.

No.	Station name	Lat	Long	Climate zone
1	ADELAIDE (WEST TERRACE / NGAYIRDAPIRA)	-34.93	138.58	5
2	ADELAIDE AIRPORT	-34.95	138.52	5
3	EDINBURGH RAAF	-34.71	138.62	5
4	HINDMARSH ISLAND AWS	-35.52	138.82	6
5	KUITPO FOREST RESERVE	-35.17	138.68	5
6	MOUNT BARKER	-35.07	138.85	6
7	MOUNT CRAWFORD AWS	-34.73	138.93	6
8	MOUNT LOFTY	-34.98	138.71	6
9	MURRAY BRIDGE	-35.12	139.26	6
10	NOARLUNGA	-35.16	138.51	5
11	NURIOOTPA PIRSA	-34.48	139.01	6
12	BLACK POLE	-34.73	138.47	5
13	PALLAMANA AERODROME	-35.06	139.23	6
14	PARAFIELD AIRPORT	-34.8	138.63	5
15	SECOND VALLEY FOREST AWS	-35.57	138.29	6
16	ROSEWORTHY AWS	-34.51	138.68	6
17	MOUNT TERRIBLE RADAR	-35.33	138.5	5
18	STRATHALBYN RACECOURSE	-35.28	138.89	6
19	ENCOUNTER BAY	-35.55	138.6	6

Table 4 Latitude, longitude, and the climate zone of the 19 stations in Adelaide.

Figure 11 Location of the 19 weather stations in Adelaide.

2.2 Calculation method and results

For all scenarios, Cooling Degree Hours (CDH) Base 26 °C has been calculated for the entire simulation period. It is a rough indication of the cooling load of a building, and it was calculated by firstly subtracting 26 from the hourly dry-bulb air temperature, and then adding all the positive differences in the two months. The calculated CDH for reference cases, cool roof applied cases, their differences, as well as the percentage of CDH reduction due to the implementation of the cool roof in the 19 weather stations, are shown in **Table 5** and **Figure 12**. Compared with the reference case, the largest percentage reduction is observed in SECOND VALLEY FOREST AWS and the smallest is found in NURIOOTPA PIRSA, with an average reduction of 23.1%. The mean CDH values of the 19 weather stations for the reference case, cool roof case are 1896.0, 1496.9 respectively, see **Table 6**. It can be observed that in most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in reference cases, indicating that a cool roof is generally more effective when applied in hotter regions. In contrary, the percentage reduction is larger in colder regions.

Table 5 The CDH of reference cases, cool roof applied cases, and the difference between these two, as well as the percentage of CDH reduction due to the implementation of the cool roof in 19 weather stations in Adelaide.

Weather Station	CDH_CTRL	CDH_COOL ROOF	CDH_ Difference (CTRL-COOL ROOF)	Percentage of the reduction_% (CDH_Difference/CDH_CTRL)
ADELAIDE (WEST TERRACE / NGAYIRDAPIRA)	2307.4	1762.2	545.2	23.6
ADELAIDE AIRPORT	2073.1	1617.9	455.2	22.0
EDINBURGH RAAF	2568.9	1984.6	584.3	22.7
HINDMARSH ISLAND AWS	1786.9	1417.0	370.0	20.7
KUITPO FOREST RESERVE	1417.0	1053.3	363.7	25.7
MOUNT BARKER	1846.2	1504.8	341.4	18.5
MOUNT CRAWFORD AWS	2174.6	1754.1	420.5	19.3
MOUNT LOFTY	1342.7	1052.3	290.4	21.6
MURRAY BRIDGE	2786.2	2249.7	536.5	19.3
NOARLUNGA	1085.4	823.2	262.2	24.2
NURIOOTPA PIRSA	3014.6	2526.0	488.6	16.2
BLACK POLE	1909.3	1364.1	545.2	28.6
PALLAMANA AERODROME	2514.7	2053.8	460.9	18.3
PARAFIELD AIRPORT	2441.7	1983.3	458.4	18.8
SECOND VALLEY FOREST AWS	261.5	145.7	115.8	44.3
ROSEWORTHY AWS	3551.5	2945.5	606.0	17.1
MOUNT TERRIBLE RADAR	527.3	377.6	149.7	28.4
STRATHALBYN RACECOURSE	1570.9	1205.2	365.7	23.3
ENCOUNTER BAY	844.4	620.1	224.3	26.6

Table 6 Mean and SD of the CDH of the 19 weather stations in reference cases and cool roof cases respectively.

	Mean	SD	Sample No.
CDH_CTRL	1896.0	855.0	19
CDH_COOL ROOF	1496.9	725.1	19
CDH_DIFFERENCE (CTRL-COOL ROOF)	399.2	142.9	19

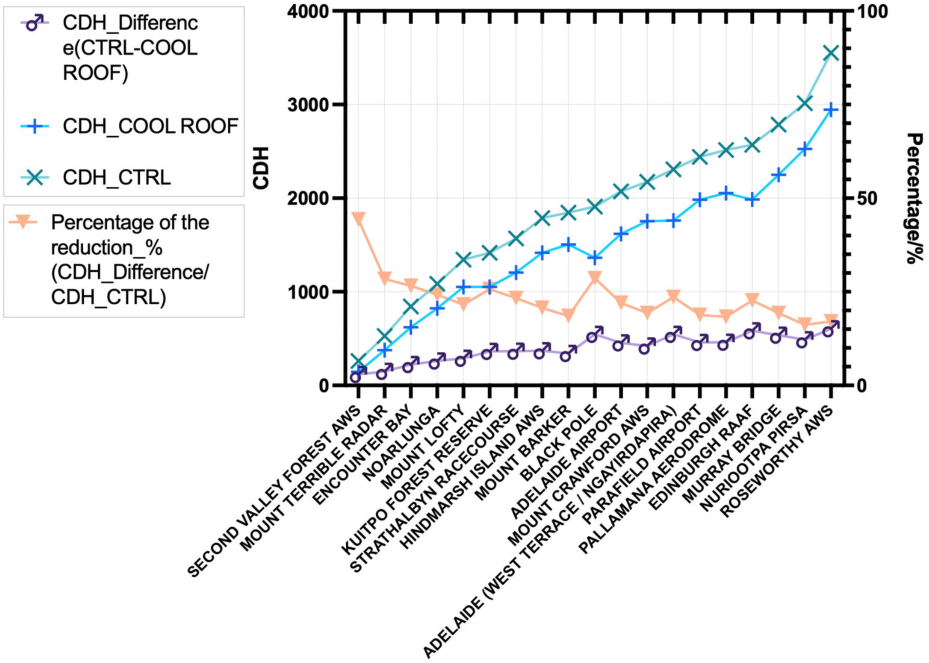

Figure 12 The CDH of reference cases, cool roof applied cases, the difference between these two, and the percentage of the CDH reduction due to the implementation of the cool roof in 19 weather stations in Adelaide.

2.2.1 Frequency distribution of the results

The frequency distribution of the CDH values for the 19 weather stations in both the reference cases and the cool roof cases is shown in **Figure 3**. In the reference case, the CDH of the 19 stations in reference cases and cool roof cases are concentrating mianly in 1400-2600 and 1000-2000 respectively. The CDH distribution of reference case and cool roof cases share simmlar patterns with the former of around 400 (the average decrease of CDH after applying cool roof) higher than the latter.

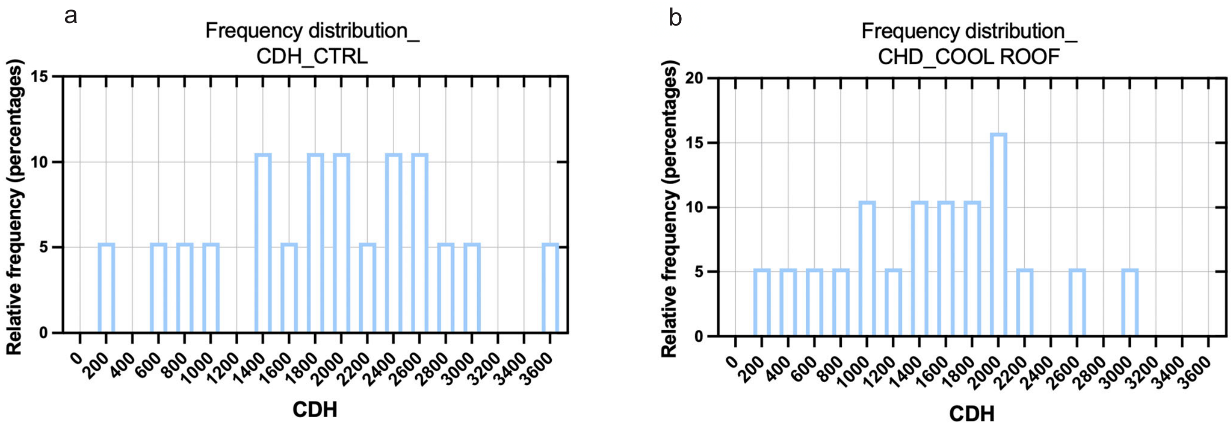

Figure 13 Frequency distribution of the CDH values for the 19 weather stations in reference cases (a) and cool roof cases (b).

2.2.2 Spatial distribution of the results

- **CHD_Reference scenario: (Figure 14)**

  The highest CDH of 3551.5 is observed in ROSEWORTHY AWS and SECOND VALLEY FOREST AWS has the lowest number. CDH gradually increases from southwest to northeast.

- **CDH_Cool roof scenario: (Figure 15)**

  When applied with a cool roof, the decrease of CDH is observed at every station. CDH still increases from southwest to northeast.

- **CDH_Reference scenario – cool roof scenario: (Figure 16)**

  The maximum decrease occurs in the northern regions of the city while the smallest is observed in the southweat. The average decrease after applying cool roof is 399.2 **(Table 6).**

- **CDH_(Reference scenario – cool roof scenario)/Reference scenario:**

  The proportion of CDH reduction in the original reference volume is relatively large in southwest and gradually decreases toward the northeast, as shown in **Figure 17**. Its spatial distribution is the opposite compared with that of the other three parameters.

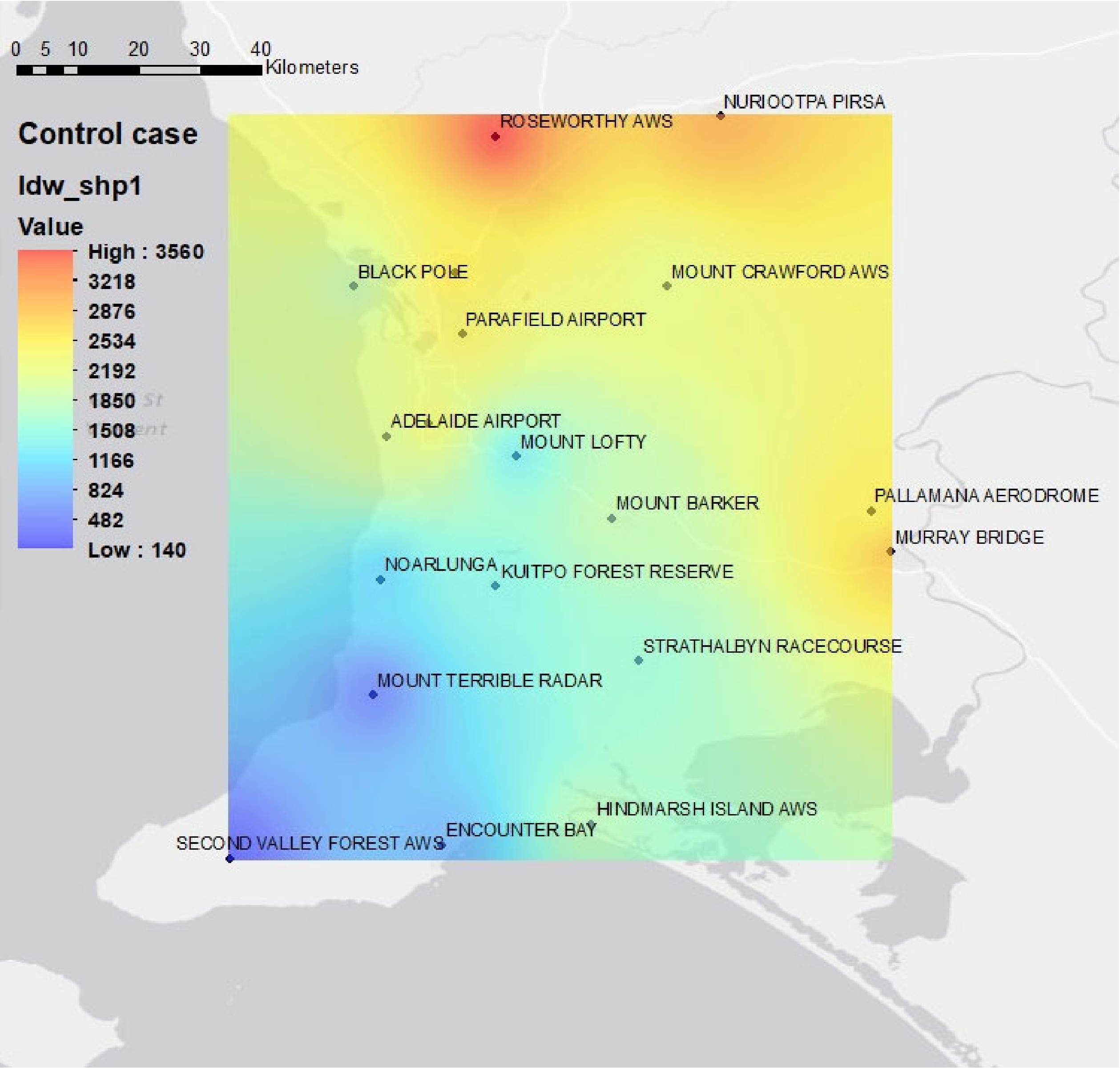

Figure 14 The sum of Cooling degree hours in Jan and Feb of the reference cases in the 19 stations in Adelaide.

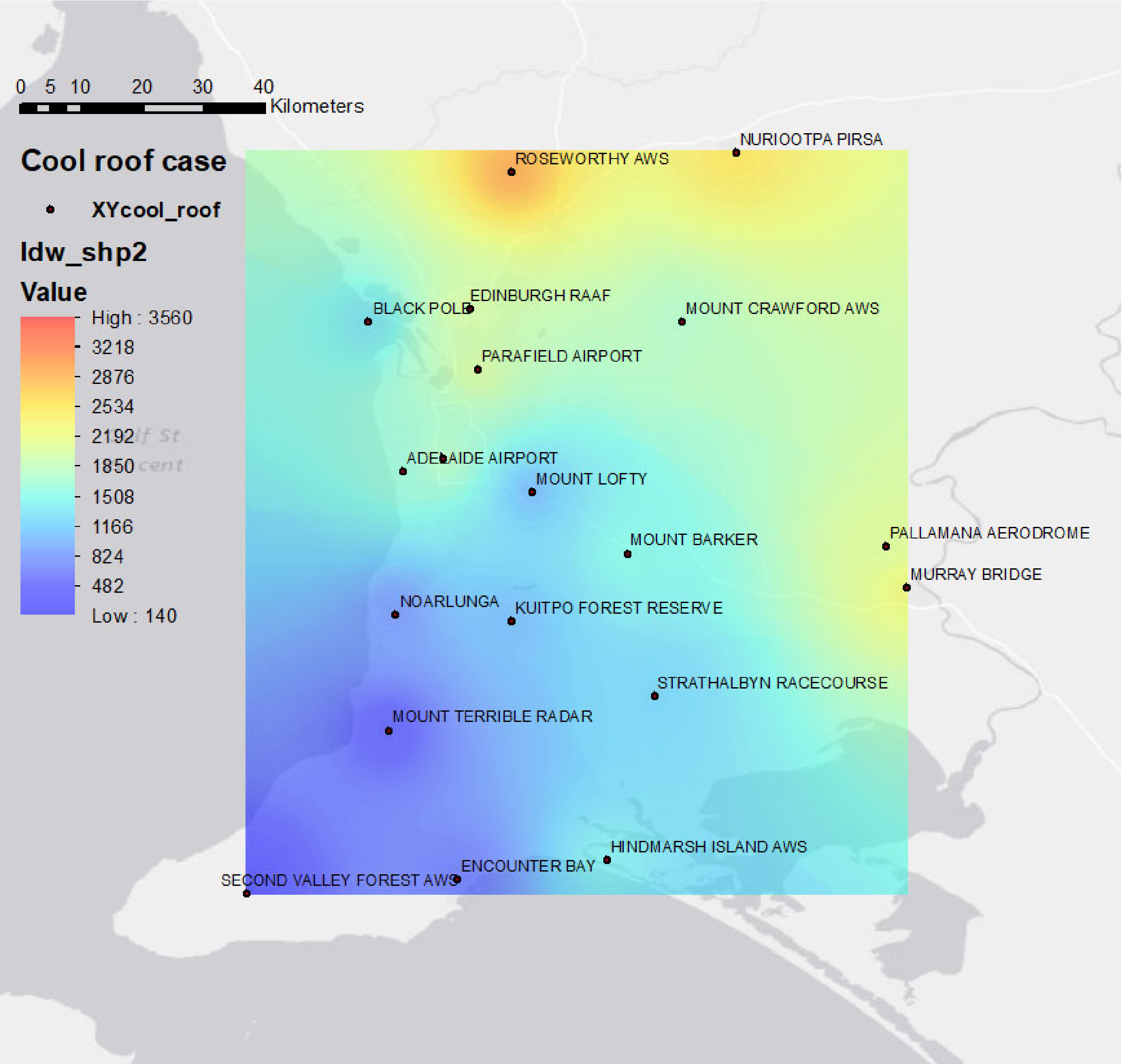

Figure 15 The sum of Cooling degree hours in Jan and Feb of the cool roof cases in the 19 stations in Adelaide.

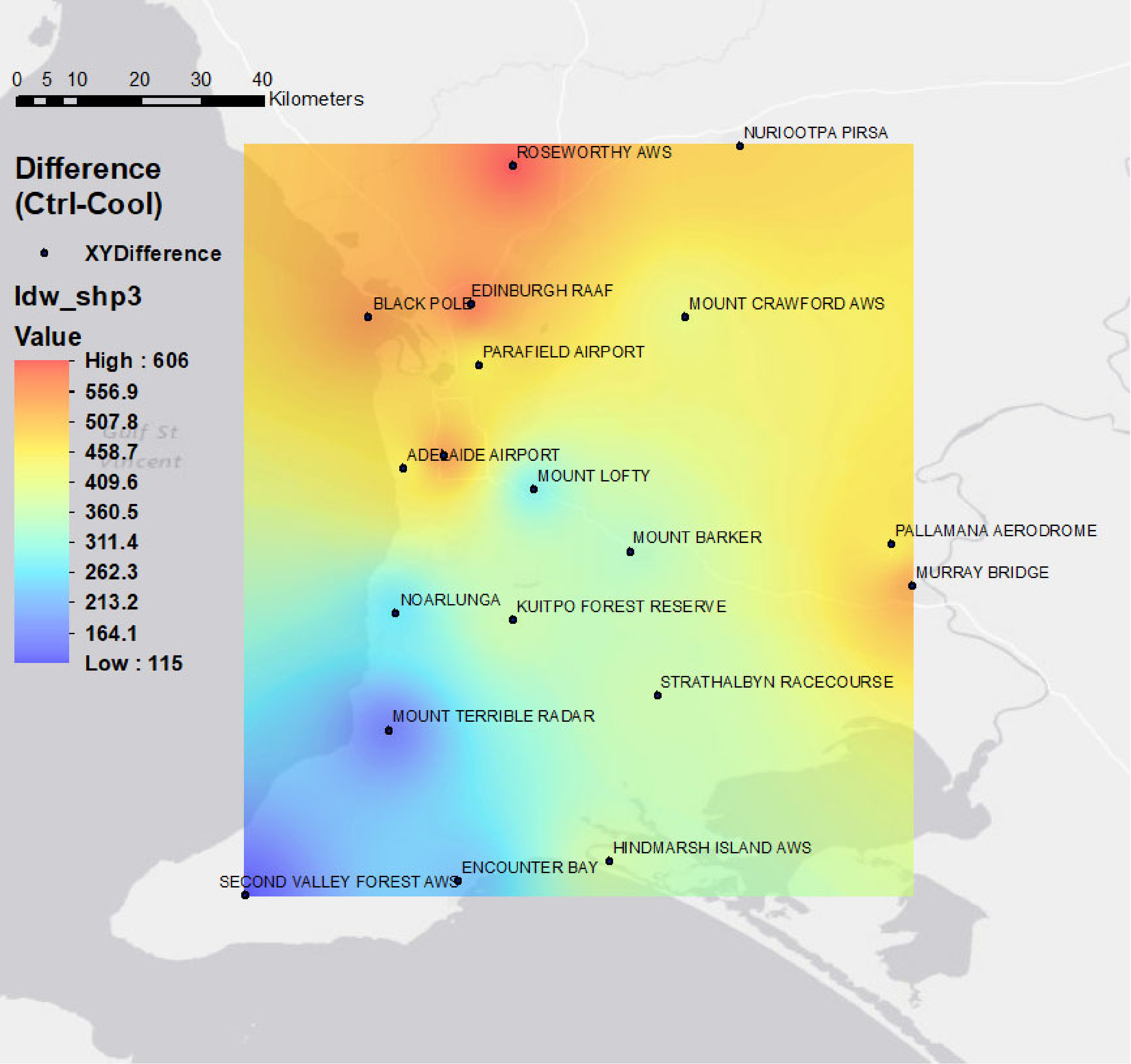

Figure 16 The difference of Cooling degree hours in Jan and Feb between the cool roof cases and reference ones in the 19 stations in Adelaide.

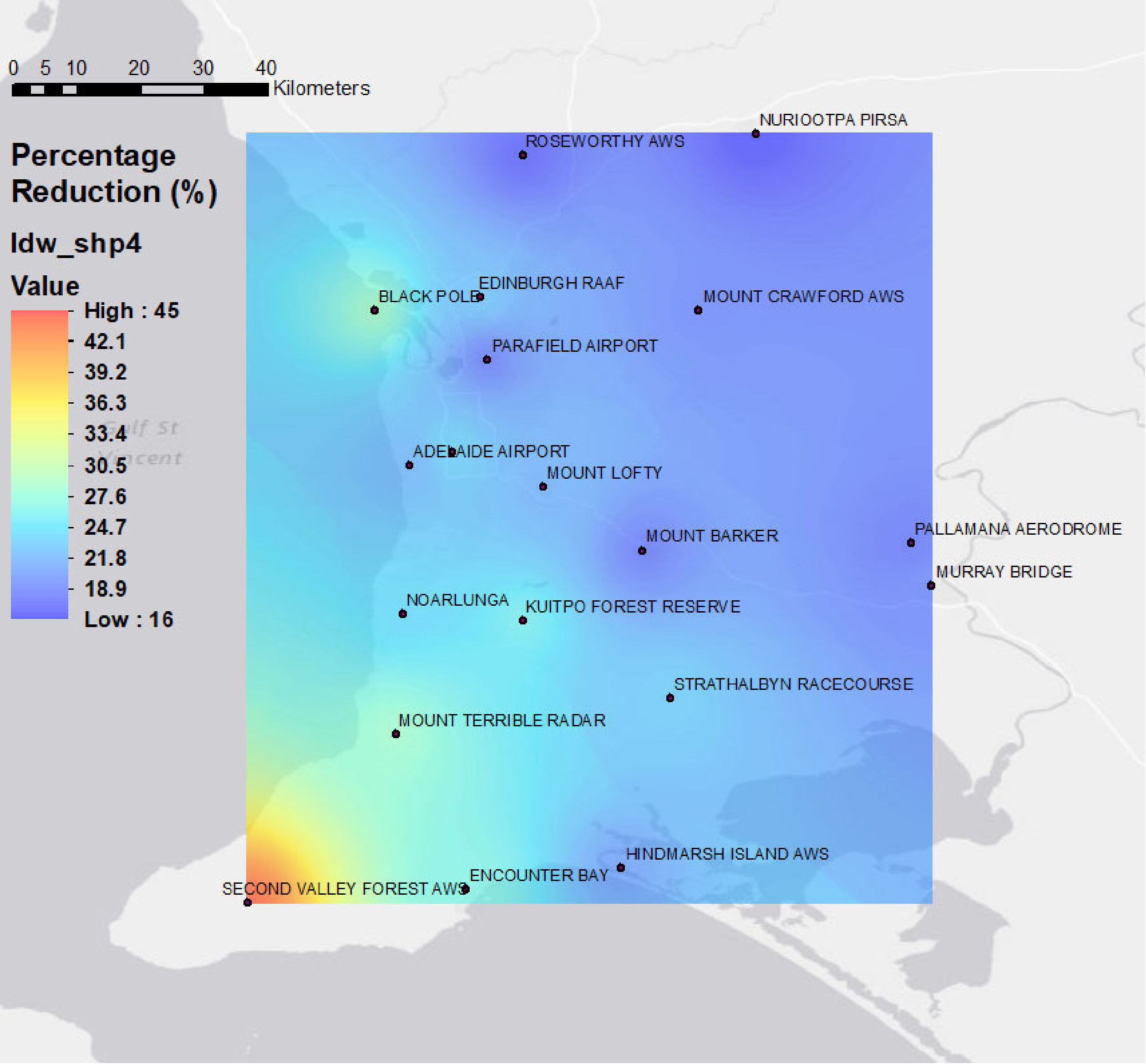

Figure 17 The percentage of CDH reduction due to the implementation of the cool roof in the 19 stations in Adelaide.

2.3 Conclusion

- In reference cases, CDH ranges from 261.5 to 3551.5 and the CDH values are mainly concentrating in 1400-2600. CDH gradually increases from southwest to northeast.
- When applied with a cool roof, the decrease of CDH is observed at every station. The average dearease is 399.2 in all stations. CDH still increases from southwest to northeast.

- In most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in reference cases, indicating that a cool roof is generally more effective when applied in hotter regions.
- The percentage of CDH reduction due to the implementation of the cool roof ranges from 16.2% to 44.3% with an average value of 23.1%. The percentage is smaller in the hotter regions.

3. Impact of cool roofs on the cooling/heating load and indoor air temperature of buildings

3.1 Introduction

This chapter investigates the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Adelaide. The cooling load simulations were performed for two summer months of January and February using weather data simulated by WRF. The annual cooling and heating load estimations were also performed to assess the annual cooling load savings of cool roofs against their corresponding annual heating penalty. The annual cooling and heating load simulations were then performed using the weather data obtained from the Bureau of Meteorology (BoM). Additionally, the impact of cool roofs on indoor air temperature was assessed under free-floating mode in weather stations presenting the lowest and highest ambient temperatures in Adelaide during a typical summer and winter period. Specifically, the simulations were performed for seventeen types of buildings and five weather stations across Adelaide (in climate zone 5 and 6). The seventeen typical buildings modeled in this study include the following and their characteristics are listed in **Appendix: Building characteristic**s:

1) A low-rise office building without roof insulation-existing building,
2) A high-rise office building without roof insulation-existing building,
3) A low-rise office building with roof insulation-new building,
4) A high-rise office building with roof insulation-new building,
5) A low-rise shopping mall center- new building,
6) A mid-rise shopping mall center- new building,
7) A high-rise shopping mall center-new building,
8) A low-rise apartment building-new building,
9) A mid-rise apartment building-new building,
10) A high-rise apartment building-new building,

11) A typical stand-alone house-existing building,

12) A typical school building-existing building,

13) A low-rise office building with roof insulation-existing building,

14) A high-rise office building with roof insulation-existing building,

15) A low-rise shopping mall center-existing building,

16) A high-rise shopping mall center-existing building,

17) A stand-alone house-new building.

The five weather stations modeled in Adelaide include (See Figure 18):

1) Adelaide Airport, Climate zone 5
2) Edinburgh Raaf, Climate zone 5
3) Kuitpo, Climate zone 5
4) Parafield Airport, Climate zone 5
5) Roseworthy, Climate zone 6.

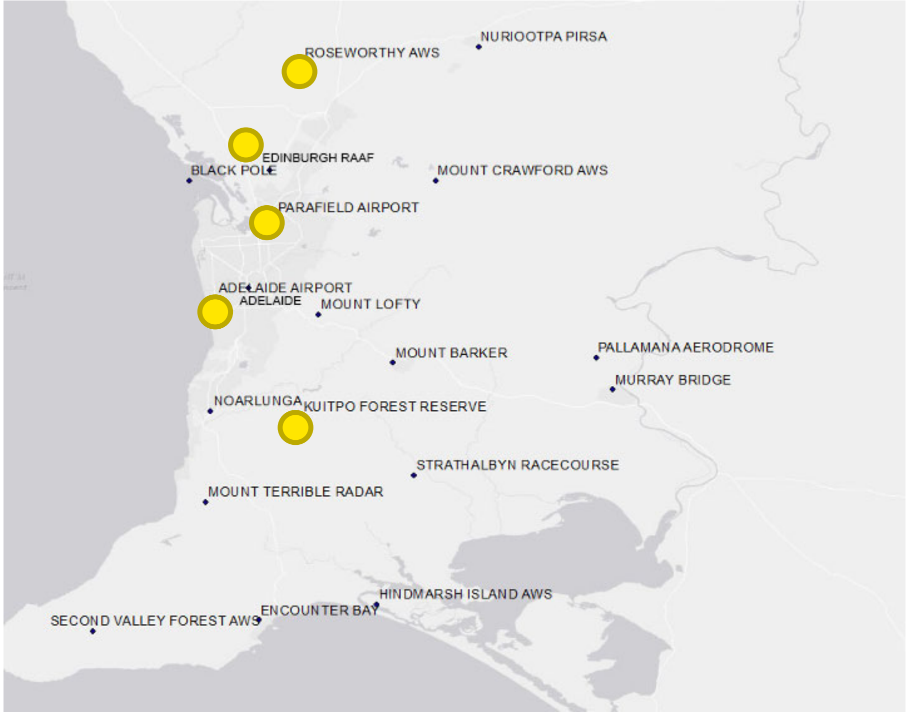

Figure 18 Weather stations in Adelaide including four weather stations in climate zone 5 (including Adelaide Airport, Edinburgh Raaf, Kuitpo, and Parafield Airport) and one weather stations in climate zone 6 (Roseworthy).

The corresponding building specifications for the buildings in climate zones 5 and 6 were considered. Three sets of simulations were performed in this study:

1) Cooling load simulations for two summer months:

The cooling load simulations were performed for two summer months of January and February. Two sets of weather data were used for the simulations including one climatic data for the current condition and one climatic data considering an extensive use of cool roofs in the city. The reference and cool weather data, including hourly values of all climatic variables, were generated from the results of WRF simulations for the two summer months of January and February, in Adelaide. The simulations were performed under three scenarios:

- **Reference scenario:** A reference building with a conventional roof using the climatic data simulated by WRF for the current condition.
- **Scenario 1 (Reference with cool roof scenario):** The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF for the current condition.
- **Scenario 2 (Cool roof with modified urban temperature scenario):** The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF considering an extensive use of cool roofs in the city.

The cooling load saving for the two summer months was then computed for the two cool roof scenarios (i.e. scenario 1 and 2) against the reference scenario. The spatial distribution maps of cooling loads for the three scenarios were presented to compare the impact of cool roofs on the cooling loads of each building type in different weather stations. The spatial distribution of the cooling load for two summer months was generated using ArcMap 10.6.

2) Annual cooling and heating load simulations

The annual cooling and heating load estimations were performed to assess the annual cooling load savings of cool roofs against their corresponding annual heating penalty. The annual cooling and heating load simulations were performed using the measured annual weather data obtained from the Bureau of Meteorology (BoM). The simulations were performed under two scenarios:

- **Reference scenario:** A reference building with a conventional roof using the BoM annual measured climatic data.

- **Scenario 1 (Reference with cool roof scenario):** The same building as in the reference scenario with a cool roof using the BoM annual measured climatic data.

3) Indoor air temperature simulations under free-floating mode

The impact of cool roofs on indoor air temperature was assessed under free-floating mode in weather stations presenting the lower and higher ambient temperatures in Adelaide (Kuitpo [coldest] and Roseworthy [hottest]) during a typical summer and winter period. The indoor air temperature simulations for the summer period were performed under three scenarios:

- **Reference scenario:** A reference building with a conventional roof using the climatic data simulated by WRF for the current condition.

- **Scenario 1 (Reference with cool roof scenario):** The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF for the current condition.

- **Scenario 2 (Cool roof with modified urban temperature scenario):** The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF considering an extensive use of cool roofs in the city.

The indoor air temperature reduction of the cool roof scenarios (i.e. scenarios 1 and 2) against the reference scenario was computed. In addition, the number of hours above 26 ºC for the three scenarios was computed to assess the impact of cool roofs on the number of hours the buildings can be functional without an air-conditioning system.

In parallel, the indoor air temperature estimations for the typical winter period were performed under two scenarios:

- **Reference scenario:** A reference building with a conventional roof using the BoM measured weather data.

- **Scenario 1 (Reference with cool roof scenario):** The same building as in the reference scenario with a cool roof using the BoM measured weather data.

The indoor air temperature difference between the cool roof scenario and the reference scenario was then computed. The indoor air temperature reduction in scenario 1 vs reference scenario was plotted against the indoor air temperature in the reference scenario to determine the periods when the undesired temperature reduction occurs. In addition, the number of hours below 19 ^{o}C during occupational/total (i.e. non-occupational and occupational) periods for the two scenarios were computed to assess the impact of cool roofs on the number of hours the buildings can be functional without an air-conditioning system.

3.2 Impact of cool roofs on the cooling/heating load and indoor air temperature of individual buildings

The impact of cool roofs on the cooling/heating load and indoor air temperature of the individual buildings is presented in detail in ***Volume 8***.

3.3 Summary of results

This report investigated the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Adelaide. In this chapter, a summary of the simulation results and detailed discussions are presented. A summary table of the impact of application of cool roofs in individual buildings (scenario 1) or both individual buildings and at the whole urban area (scenario 2) on total cooling load of different types of buildings in two summer months is given in **Table 7**.

Table 7 Total cooling load under reference scenario and cooling load reductions by building-scale and combined building-scale and urban scale application of cool roofs for all building types for two summer months (i.e. Jan and Feb) with weather data simulated by WRF for COP=1 for heating and cooling

Building Type	Cooling load-reference	Reference with cool roof scenario (scenario 1) vs reference scenario		Cool roof with modified urban temperature scenario (scenario 2) vs reference scenario	
	kWh/m^2	kWh/m^2	%	kWh/m^2	%
A low-rise office building without roof insulation-existing building	20.9-28.5	9.6-11.3	39.6-45.9	12.5-13.9	47.7-59.8
A high-rise office building without roof	13.5-19.9	1.7-2.0	10.3-12.6	4.5-5.0	22.8-37.4

insulation-existing building					
A low-rise office building with roof insulation-new building	12.8-19.3	0.9-1.3	6.1-6.9	3.6-4.3	19.6-33.5
A high-rise office building with roof insulation-new building	12.2-18.4	0.2	1.2-1.3	2.8-3.6	15.1-29.7
A low-rise shopping mall centre-new building	56.3-66.3	1.6-1.8	2.5-2.9	7.3-10.2	11.0-18.1
A mid-rise shopping mall centre-new building	54.8-64.6	0.7-0.9	1.2-1.4	6.3-9.4	9.8-17.2
A high-rise shopping mall centre-new building	54.2-64.0	0.5-0.6	0.8-0.9	6.0-9.2	9.4-16.9
A low-rise apartment building-new building,	8.7-13.4	1.0-1.2	8.6-11.0	3.2-3.8	25.7-41.5
A mid-rise apartment building-new building	8.3-12.9	0.5-0.7	5.1-6.6	2.8-3.4	22.9-39.4
A high-rise apartment building-new building	8.1-12.6	0.3-0.4	3.1-4.0	2.6-3.2	21.3-38.2
A typical stand-alone house-existing building,	11.8-15.8	5.7-6.0	38.1-48.1	7.3-7.9	48.1-62.2
A typical school building-new building	17.0-26.5	0.7-0.9	3.4-4.2	4.4-5.2	17.1-29.1
A low-rise office building with roof insulation-existing building	16.0-23.0	4.5-5.5	24.1-28.3	7.7-8.3	34.6-48.0

A high-rise office building with roof insulation-existing building	12.7-19.0	0.8-1.0	5.3-6.3	3.5-4.2	18.5-33.2
A low-rise shopping mall centre-existing building	60.3-70.5	8.0-8.2	11.4-13.3	13.4-16.3	19.1-27.0
A high-rise shopping mall centre-existing building	55.2-65.1	2.4-2.5	3.7-4.3	7.9-11.0	12.1-19.9
A stand-alone house-new building.	9.0-12.3	2.9-3.3	23.7-33.9	4.6-5.2	37.1-54.9

Table 8 Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference with cool roof scenario (scenario 1) vs reference scenario for all building types using annual measured weather data for COP=1 for heating and cooling

Building Type	**Annual cooling load saving**		**Annual heating load penalty**	**Annual total cooling & heating load saving**	
	kWh/m²	**%**	**kWh/m²**	**kWh/m²**	**%**
A low-rise office building without roof insulation-existing building	11.0-19.2	39.3-46.9	1.4-3.6	7.4-17.7	21.3-32.5
A high-rise office building without roof insulation-existing building	1.8-3.2	9.6-12.9	0-0.9	0.9-2.9	4.6-9.7
A low-rise office building with roof insulation-new building	1.0-2.1	5.5-7.5	0-0.3	0.6-1.9	3.2-6.2
A high-rise office building with roof insulation-new building	0.2-0.3	1.0-1.3	0-0.1	0.1-0.3	0.6-1.1
A low-rise shopping mall centre-new building	4.1-5.0	2.9-3.9	0.1-0.2	3.9-4.8	2.7-3.5

A mid-rise shopping mall centre-new building	1.9-2.3	1.4-1.9	0-0.1	1.8-2.2	1.3-1.7
A high-rise shopping mall centre-new building	1.2-1.4	0.9-1.2	0-0.1	1.1-1.4	0.8-1.1
A low-rise apartment building-new building,	0.9-1.8	8.5-13.0	0.8-1.5	-0.6-0.9	-1.2-1.8
A mid-rise apartment building-new building	0.5-1.0	5.0-7.8	0.5-0.9	-0.4-0.5	-0.7-1.0
A high-rise apartment building-new building	0.3-0.6	3.0-4.8	0.3-0.5	-0.2-0.3	-0.5-0.6
A typical stand-alone house-existing building,	6.9-11.4	41.3-55.4	5.1-8.7	-1.8-5.9	-3.3-10.6
A typical school building-new building	0.8-1.5	3.3-4.3	0.3-0.8	0-1.1	0-1.8
A low-rise office building with roof insulation-existing building	4.9-9.0	23.1-28.5	0.6-1.6	3.3-8.3	13.2-19.5
A high-rise office building with roof insulation-existing building	0.8-1.5	4.8-6.3	0.1-0.3	0.5-1.4	2.9-4.2
A low-rise shopping mall centre-existing building	18.2-22.0	12.3-16.9	0.3-0.8	17.4-21.6	11.4-14.9
A high-rise shopping mall centre-existing building	5.1-6.3	3.8-5.4	0.1-0.2	4.9-6.2	3.5-4.8
A stand-alone house-new building.	3.3-5.9	25.8-40.0	1.4-2.7	0.6-4.3	1.7-10.5

Table 9 Maximum indoor air temperature in reference scenario, maximum indoor air temperature reduction between reference scenario vs reference with cool roof scenario (scenario 1) and reference scenario vs cool roof with modified urban temperature scenario (scenario 2) for all building types under free floating conditions during a typical summer week using weather data simulated by WRF, and number of hours with indoor air temperature above 26 ^{o}C in free-floating mode during a typical summer month using weather data simulated by WRF

Building type	**Maximum Indoor air temp in a typical summer week**	**Maximum indoor air temp reduction in a typical summer week**		**Number of hours above 26 ºC in a typical summer month**		
	Reference scenario (ºC)	**Reference with cool roof scenario (scenario 1) vs reference scenario (ºC)**	**Cool roof with modified urban temperature scenario (scenario 2) vs reference scenario (ºC)**	**Reference scenario (hours)**	**Reference with cool roof scenario (scenario 1) (hours)**	**Cool roof with modified urban temperature scenario (scenario 2) (hours)**
A low-rise office building without roof insulation-existing building	47.5-49.8	7.6-8.4	8.4-10.0	436-457	326-367	251-333
A high-rise office building without roof insulation-existing building	42.1-44.7	1.5-1.6	2.4-3.3	510-542	485-521	462-477
A low-rise office building with	42.8-45.8	1.0	2.1-3.0	494-510	471-493	388-456

roof insulation-new building						
A high-rise office building with roof insulation-new building	41.4-44.2	0.2	1.5-2.5	529-560	523-556	436-511
A low-rise shopping mall centre-new building	48.4-52.6	0.6	1.6-2.9	520-533	518-530	467-506
A mid-rise shopping mall centre-new building	47.6-52.1	0.4-0.6	1.7-2.7	543-552	542-549	493-532
A high-rise shopping mall centre-new building	47.4-51.9	0.4-0.5	1.6-2.7	548-556	547-555	498-536
A low-rise apartment building-new building,	35.3-39.5	0.7	1.6-2.7	556-593	555-593	532-536
A mid-rise apartment building-new building	34.9-39.4	0.4-0.5	1.3-2.5	328-421	311-409	219-355
A high-rise apartment	34.7-39.3	0.3-0.4	1.2-2.4	245-349	241-343	150-295

building-new building						
A typical stand-alone house-existing building	38.9-42.4	4.4-4.5	5.1-5.5	297-354	185-282	136-248
A typical school building-new building	38.7-42.6	0.6	1.6-2.6	285-371	275-358	200-316
A low-rise office building with roof insulation-existing building	44.9-47.4	3.9-4.5	4.8-6.1	459-493	373-428	308-385
A high-rise office building with roof insulation-existing building	41.7-44.4	0.8-0.9	1.7-2.9	518-552	501-541	412-495
A low-rise shopping mall centre-existing building	49.1-53.0	2.3-2.6	3.6-4.2	498-513	478-496	424-467

A high-rise shopping mall centre-existing building	47.5-51.9	0.8	1.8-3.0	538-546	538-541	485-525
A stand-alone house-new building.	36.9-40.2	2.2-2.4	3.1-4.0	284-356	203-300	139-264

Table 10 Minimum indoor air temperature in reference scenario during a typical winter week, average maximum indoor air temperature reduction between reference scenario vs reference with cool roof scenario (scenario 1) for all building types under free floating conditions during a typical winter month using annual measured weather data, and number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data

Building type	**Minimum Indoor air temp in a typical winter week**	**Average maximum indoor air temp reduction in a typical winter month**	**Number of hours below 19 °C in a typical winter month**			
	Reference scenario (°C)	**Reference with cool roof scenario (scenario 1) vs reference scenario (°C)**	**Reference scenario (hours)**		**Reference with cool roof scenario (scenario 1) (hours)**	
			Operational hours	**Total**	**Operational hours**	**Total**
A low-rise office building	9.2-9.6	0.4-1.8	215-272	574-635	261-317	622-681

without roof insulation-existing building						
A high-rise office building without roof insulation-existing building	12.5-12.7	0.1-0.3	156-221	460-551	165-234	473-569
A low-rise office building with roof insulation-new building	12.0-12.5	0.4-1.3	135-195	437-525	165-205	472-541
A high-rise office building with roof insulation-new building	13.1-13.4	0.1	136-199	416-505	137-202	417-510
A low-rise shopping mall centre-new building	12.0-12.1	0.2-0.3	64-79	345-388	65-81	348-392
A mid-rise shopping mall centre-new building	12.5-12.8	0.1-0.2	62-81	325-369	63-82	327-372
A high-rise shopping mall	12.6-13.0	0.1	62-81	316-365	62-85	318-370

centre-new building						
A low-rise apartment building-new building,	10.2-11.1	0.2	N/A	316-365	N/A	318-370
A mid-rise apartment building-new building	10.3-11.3	0.1	N/A	714-732	N/A	718-732
A high-rise apartment building-new building	10.3-11.3	0.1	N/A	721-732	N/A	721-732
A typical stand-alone house-existing building,	9.1-9.4	1.2-1.3	N/A	691-721	N/A	720-732
A typical school building-new building	8.1-8.9	0.1-0.2	257-313	642-707	262-316	647-712
A low-rise office building with roof insulation-existing building	10.6-10.9	1.0	176-239	516-595	210-274	560-636
A high-rise office building with roof insulation-	12.8-13.0	0.2	143-212	435-531	146-216	442-540

existing building						
A low-rise shopping mall centre-existing building	10.9-11.1	0.6	84-112	392-452	86-116	398-457
A high-rise shopping mall centre-existing building	12.3-12.6	0.2	70-104	340-404	71-104	342-405
A stand-alone house-new building.	10.2-10.4	0.7-0.8	N/A	680-718	N/A	703-727

3.4 Conclusion

The conclusions drawn from this study are:

- In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in individual buildings (scenario 1) is quite significant. For instance, application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 9.6-11.3 kWh/m2.
- In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in both individual buildings and at the whole urban area (scenario 2) is quite significant. For instance, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 12.5-13.9 kWh/m2.
- In new low-rise buildings with high insulation level, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) has a noticeable impact on cooling load reduction. For instance, cooling loads savings by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 3.6-4.3 kWh/m2 in a typical new low-rise office building.

- In high-rise buildings, application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.2 kWh/m2 for a new high-rise office building with insulation.
- In high-rise buildings, the cooling load reduction through application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.5-0.6 kWh/m2 in an existing high-rise shopping mall centre, which is expected to increase to 6.0-9.2 kWh/m2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).
- The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in majority of building types. For instance, the annual cooling load saving in a low-rise office building without insulation is 11.0-19.2 kWh/m2, while the corresponding heating penalty is just 1.4-3.6 kWh/m2.
- The annual heating penalty of cool roofs may exceed the cooling benefits in residential buildings in Adelaide. For instance, the heating penalty can be up to 6.9-11.4 kWh/m2 compared to the equivalent 5.1-8.7 KWh/m2 in an existing stand-alone house.
- In existing low-rise buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in individual buildings (scenario 1) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 7.6-8.4 ^{o}C.
- In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in both individual building and at the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and at the whole urban area (scenario 2) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 8.4-10.0 ^{o}C.
- In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual building and at the whole urban area (scenario 2) can significantly decrease the number of hours with an indoor air temperature above 26 ^{o}C. For instance, the number of hours with an indoor air temperature above 26 ^{o}C in a typical low-rise office building without insulation is predicted to reduce from 436-457 hours to 326-367

hours and 251-333 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.

- In new low-rise buildings with high insulation level and under free-floating condition in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the maximum indoor air temperature during a typical summer period. For instance, the maximum indoor air temperature reduction by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 2.1-3.0 ^{o}C in a typical new low-rise office building.
- In new low-rise buildings with high insulation level and under free-floating condition in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the number of hours with an indoor air temperature above 26 ^{o}C during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 ^{o}C in new low-rise office building with insulation is predicted to reduce from 494-510 hours to 388-456 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
- The maximum indoor air temperature reduction by cool roofs in a typical winter period is significantly lower than the maximum indoor air temperature reduction during a typical summer period. For instance, the maximum indoor air temperature reduction by application cool roofs in individual buildings in low-rise office building without roof insulation is predicted to be 7.6-8.4 ^{o}C in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 0.4-1.8 ^{o}C during a typical winter month.
- The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 ^{o}C and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.3 ^{o}C occurs when the indoor air temperature is 24.0 ^{o}C.
- The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 ^{o}C especially during the operational hours of the buildings in a typical winter period. For instance, it is predicted that the application of cool roofs in individual buildings (scenario 1) can increase the total number of operational hours with ambient temperature below 19 ^{o}C from 176-239 hours to 210-274 hours in a typical existing low-rise office building with roof insulation.

4. Energy loss through building envelopes in various stations in Adelaide _ The correlation between cooling load (reduction) and CDH

4.1 Introduction

In this report, the impact of building characteristics and in particular of the energy loss through building envelopes on the performance of cool roofs in various stations in Adelaide has been investigated. Specifically, for the 17 building types, the correlation between cooling degree hours (Base 26) and the sensible cooling load in **reference scenarios** (A reference building with conventional roof using the climatic data simulated by WRF for the current condition), and the cooling load reduction in **scenario 1** (The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF for the current condition) and **scenario 2** (The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF considering an extensive use of cool roofs in the city) has been plotted using the simulated data in 5 weather stations in Adelaide for two summer months. For each plot, the linear regression line has been generated in the format of

$$Y=a X + b$$

Y is the cooling load (reduction) (kWh/m2);

X is the cooling degree hours (K);

For reference scenarios:

a is the slope of the regression line, indicating the approximate heat loss magnitude of the overall envelope including ventilation

b is the Y-intercept of the regression line, indicating the approximate cooling load caused by miscellaneous heat gain when the cooling degree hour is zero (K).

For the cooling load reduction in scenarios 1 and 2:

a is the slope of the regression line, indicating the rate of variation in cooling load reduction when cooling degree hours change, indirectly expressing the effectiveness of cool roofs under different climatic conditions.

b is the Y-intercept of the regression line, indicating the cooling load reduction when cooling degrees hour is zero.

4.2 Office buildings

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, and the cooling load reduction in scenario 1 and scenario 2 for the 5 office building types (B01_Existing_Low-rise_no insulation; B02_Existing_High-rise_no insulation; B03_New_Low-rise_insulated; B04_New_High-rise_insulated; B13_Existing_Low-rise_insulated; B14_Existing_High-rise_insulated) is shown in **Figure 19** and **Table 11**.

1) Regarding the sensible cooling load of reference scenarios, it can be observed that new buildings (B03 VS B13; or B04 VS B14) have lower heat loss coefficient of the overall envelope; the envelope of an insulated building loses less heat (B01 VS B13 or B02 VS B14).
2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all office building types, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors, no insulation, and older construction years, which often have higher heat loss coefficients in envelopes.
3) For the cooling load reduction in scenario 2 compared with the reference scenario, except B01 and B13 which presents an increased cooling load reduction with the increase of cooling degree hours, all other building types have an opposite trend. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in colder areas for most of the buildings.

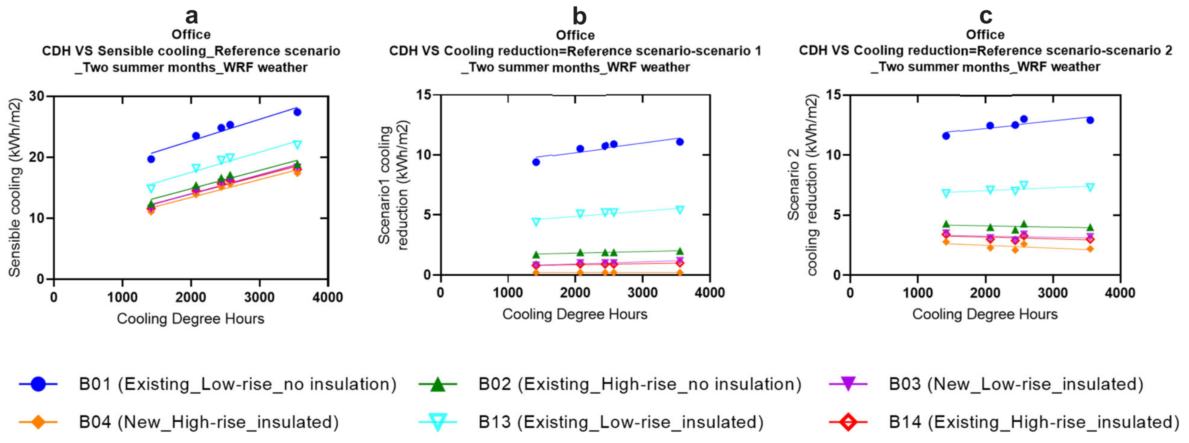

Figure 19 For office building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared to the reference scenario.

Table 11 Slope, Y intercept and equation of linear regression lines in a) reference scenario; b) scenario 1 cooling reduction; 3) scenario 2 cooling reduction.

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B01 (Existing_Low-rise_no insulation)	0.003521	15.65	Y = 0.003521*X + 15.65
B02 (Existing_High-rise_no insulation)	0.002998	8.85	Y = 0.002998*X + 8.85
B03 (New_Low-rise_insulated)	0.003099	7.81	Y = 0.003099*X + 7.81
B04 (New_High-rise_insulated)	0.002916	7.59	Y = 0.002916*X + 7.59
B13 (Existing_Low-rise_insulated)	0.003304	10.92	Y = 0.003304*X + 10.92
B14 (Existing_High-rise_insulated)	0.002957	8.07	Y = 0.002957*X + 8.07

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B01 (Existing_Low-rise_no insulation)	0.0007479	8.76	Y = 0.0007479*X + 8.756
B02 (Existing_High-rise_no insulation)	0.0001288	1.57	Y = 0.0001288*X + 1.57

B03 (New_Low-rise_insulated)	0.0001758	0.58	Y = 0.0001758*X + 0.58
B04 (New_High-rise_insulated)	0.000	0.20	Y = 0.20
B13 (Existing_Low-rise_insulated)	0.0004351	4.01	Y = 0.0004351*X + 4.01
B14 (Existing_High-rise_insulated)	0.00008788	0.69	Y = 0.00008788*X + 0.69

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B01 (Existing_Low-rise_no insulation)	0.0005887	11.08	Y = 0.0005887*X + 11.08
B02 (Existing_High-rise_no insulation)	-0.0001057	4.34	Y = -0.0001057*X + 4.34
B03 (New_Low-rise_insulated)	-0.0000996	3.46	Y = -0.0000996*X + 3.46
B04 (New_High-rise_insulated)	-0.0002345	2.97	Y = -0.0002345*X + 2.97
B13 (Existing_Low-rise_insulated)	0.0002415	6.56	Y = 0.0002415*X + 6.56
B14 (Existing_High-rise_insulated)	-0.0001453	3.47	Y = -0.0001453*X + 3.47

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, scenario 1 and scenario 2 for the 5 office building types (B01_Existing_Low-rise_no insulation; B02_Existing_High-rise_no insulation; B03_New_Low-rise_insulated; B04_New_High-rise_insulated; B13_Existing_Low-rise_insulated; B14_Existing_High-rise_insulated) is also shown in **Figure 20**.

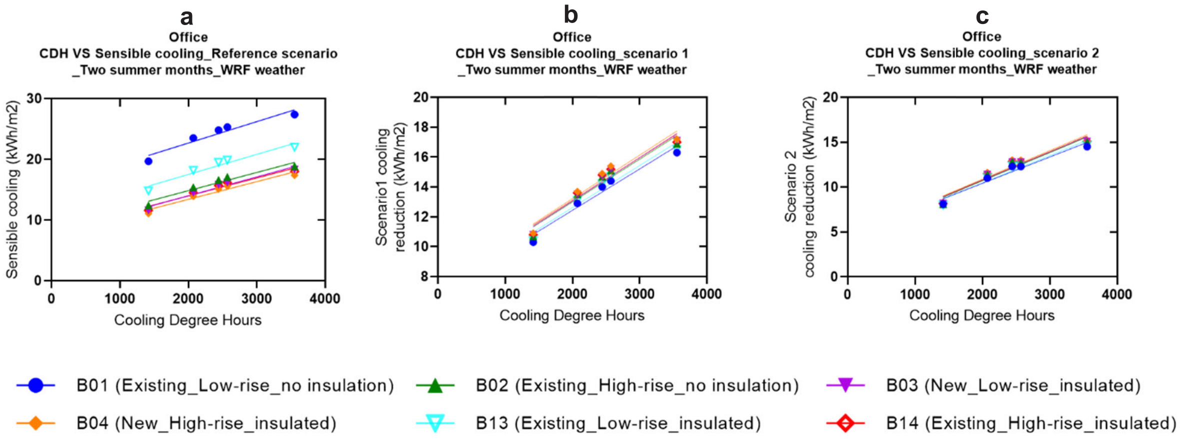

Figure 20 For office building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

4.3 Shopping mall centers

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, and the cooling load reduction in scenario 1 and scenario 2 for the 5 shopping mall center building types (B05_New_Low-rise; B06_New_Mid-rise; B07_New_High-rise; B15_Existing_Low-rise; B16_Existing_High-rise) is shown in **Figure 21** and **Table 12**.

1) Regarding the sensible cooling load of reference scenarios, it can be observed that new buildings (B05 VS B15; or B07 VS B16) have lower heat loss coefficient of the overall envelope.

2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all shopping mall center building types, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions.

3) For the cooling load reduction in scenario 2 compared with the reference scenario, all buildings present a decreasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in colder areas for all buildings.

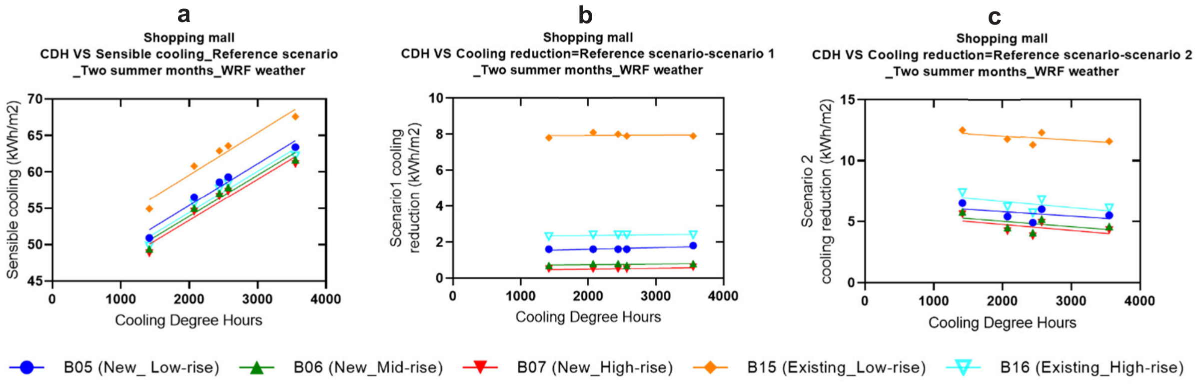

Figure 21 For shopping mall center a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared to the reference scenario.

Table 12 Slope, Y intercept and equation of linear regression lines in a) reference scenario; b) scenario 1 cooling reduction; 3) scenario 2 cooling reduction.

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.005742	43.9	Y = 0.005742*X + 43.90
B06 (New_Mid-rise)	0.005654	42.59	Y = 0.005654*X + 42.59
B07 (New_High-rise)	0.005642	42.06	Y = 0.005642*X + 42.06
B15 (Existing_Low-rise)	0.005818	47.94	Y = 0.005818*X + 47.94
B16 (Existing_High-rise)	0.005683	43.04	Y = 0.005683*X + 43.04

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.00009396	1.41	Y = 0.00009396*X + 1.41
B06 (New_Mid-rise)	0.00003438	0.68	Y = = 0.00003438*X + 0.68
B07 (New_High-rise)	0.00004698	0.41	Y = 0.00004698*X + 0.41
B15 (Existing_Low-rise)	0.00001441	7.91	Y = 0.00001441*X + 7.91

B16 (Existing_High-rise)	0.00004090	2.28	Y = 0.00004090*X + 2.28

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	-0.0003702	6.55	Y = -0.0003702*X + 6.55
B06 (New_Mid-rise)	-0.0004442	5.91	Y = -0.0004442*X + 5.91
B07 (New_High-rise)	-0.0004851	5.73	Y = -0.0004851*X + 5.73
B15 (Existing_Low-rise)	-0.0003541	12.75	Y = -0.0003541*X + 12.75
B16 (Existing_High-rise)	-0.0005051	7.66	Y = -0.0005051*X + 7.66

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, scenario 1 and scenario 2 for the 5 office building types (B01_Existing_Low-rise_no insulation; B02_Existing_High-rise_no insulation; B03_New_Low-rise_insulated; B04_New_High-rise_insulated; B13_Existing_Low-rise_insulated; B14_Existing_High-rise_insulated) is also shown in **Figure 22**.

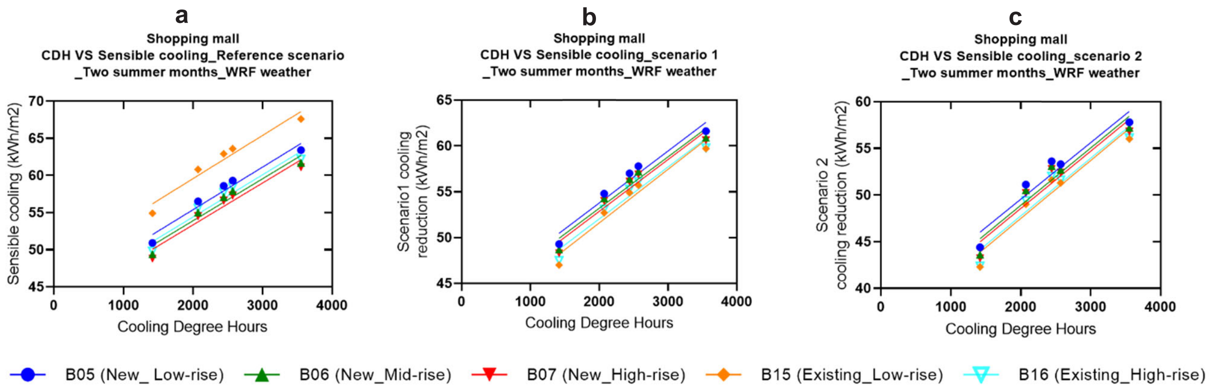

Figure 22 For shopping mall center a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

4.4 Residential building

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, and the cooling load reduction in scenario 1 and scenario 2 for the 5 residential building types (B08_Existing_Low-rise_apartment; B09_New_Mid-rise_apartment; B10_New_High-rise_apartment; B11_Existing_Standalone house; B17_New_Standalone house) is shown in **Figure 23** and **Table 13**.

1) Regarding the sensible cooling load of reference scenarios, it can be observed that new buildings (B11 VS B17) have a lower heat loss coefficient of the overall envelope. As a one-story new standalone house, B17 has the lowest heat loss coefficient among all 5 building types, being the most stable one when the external environment changes.

2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all residential building types except for B17, indicating that in most cases, under unmodified climatic conditions, a cool roof is more effective reducing cooling load in hotter regions. Moreover, a higher increase rate is mostly observed in buildings with fewer floors, and older construction years, which often have higher heat loss coefficients in envelopes.

3) For the cooling load reduction in scenario 2 compared with the reference scenario, all residential building types present an increased cooling load reduction with the increase of cooling degree hours. Moreover, a higher increase rate is mostly observed in buildings with fewer floors, and older construction years, which often have higher heat loss coefficients in envelopes.

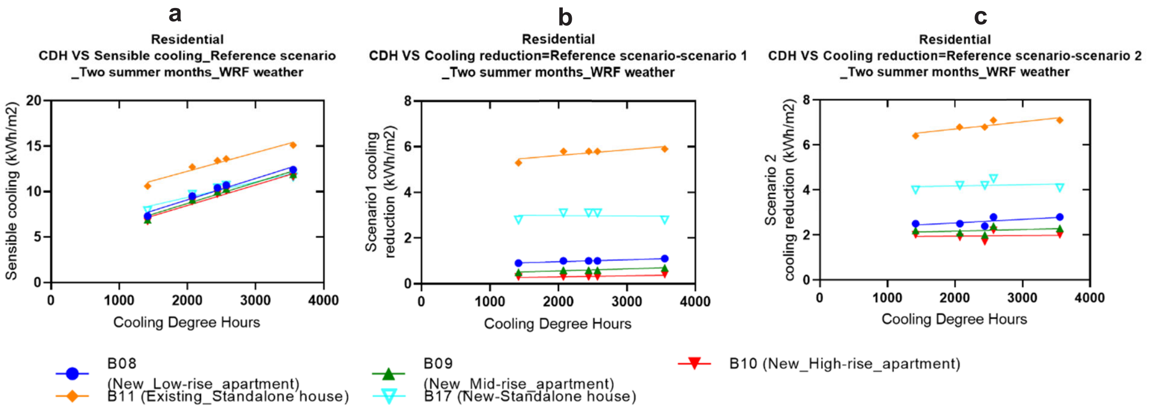

Figure 23 For residential building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference

scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared to the reference scenario.

Table 13 Slope, Y intercept and equation of linear regression lines in a) reference scenario; b) scenario 1 cooling reduction; 3) scenario 2 cooling reduction.

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.002352	4.39	Y = 0.002352*X + 4.39
B09 (New_Mid-rise_apartment)	0.002305	4.08	Y = 0.002305*X + 4.08
B10 (New_High-rise_apartment)	0.002257	3.96	Y = 0.002257*X + 3.96
B11 (Existing_Standalone house)	0.002054	8.13	Y = 0.002054*X + 8.13
B17 (New-Standalone house)	0.001703	5.96	Y = 0.001703*X + 5.96

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.0000879	0.79	Y = 0.0000879*X + 0.79
B09 (New_Mid-rise_apartment)	0.0000879	0.39	Y = 0.0000879*X + 0.39
B10 (New_High-rise_apartment)	0.0000470	0.21	Y = 0.0000470*X + 0.21
B11 (Existing_Standalone house)	0.0002515	5.11	Y = 0.0002515*X + 5.11
B17 (New-Standalone house)	-0.0000182	3.02	Y = -0.0000182*X + 3.02

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.0001592	2.22	Y = 0.0001592*X + 2.22
B09 (New_Mid-rise_apartment)	0.0000713	2.03	Y = 7.134e-005*X + 2.03
B10 (New_High-rise_apartment)	0.0000231	1.90	Y = 2.308e-005*X + 1.90
B11 (Existing_Standalone house)	0.0003241	6.06	Y = 0.0003241*X + 6.06

B17 (New-Standalone house)	0.0000544	4.07	Y = 5.440e-005*X + 4.07

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, scenario 1 and scenario 2 for the 5 office building types (B01_Existing_Low-rise_no insulation; B02_Existing_High-rise_no insulation; B03_New_Low-rise_insulated; B04_New_High-rise_insulated; B13_Existing_Low-rise_insulated; B14_Existing_High-rise_insulated) is also shown in **Figure 24**.

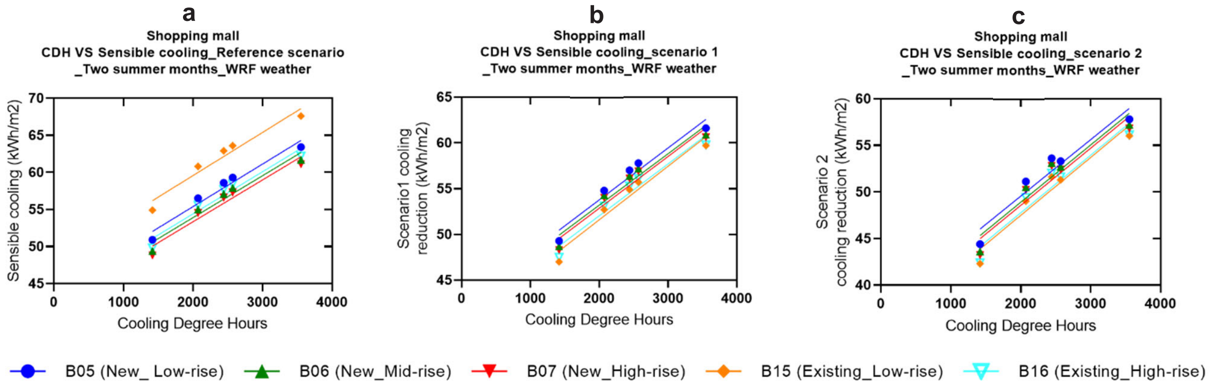

Figure 24 For residential building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2.

4.5 School

School load reduction in scenario 1 and scenario 2 for the one building type (B12_Existing) is shown in **Figure 25** and **Table 14.** As only one building type is simulated under the category of school, no conclusions can be drawn from internal comparisons like other building categories. For this existing school alone, its sensible cooling load increases with the increase of cooling degree hours. Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree, indicating that in most cases, under unmodified climatic conditions, a cool roof is more effective reducing the cooling load in hotter regions. For the cooling load reduction in scenario 2 compared with the reference scenario, B12 presents a decreasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in colder areas.

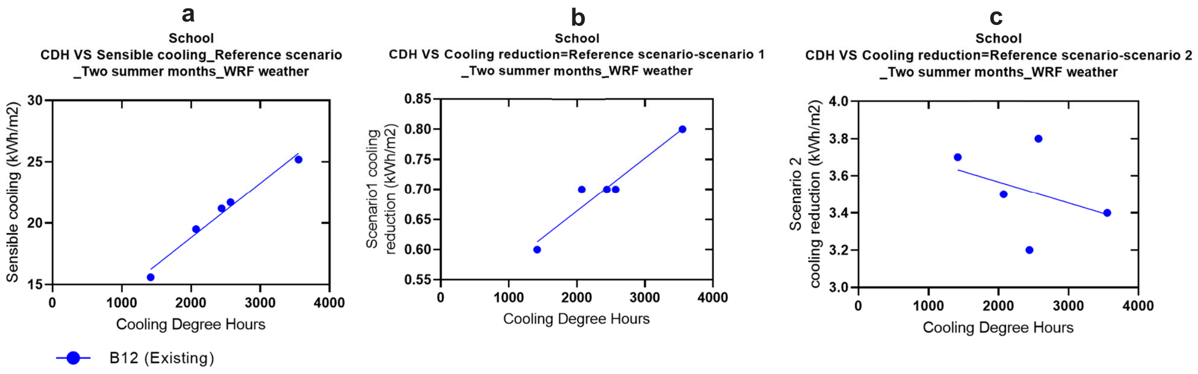

Figure 25 For school a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared to the reference scenario.

Table 14 Slope, Y intercept and equation of linear regression lines in a) reference scenario; b) scenario 1 cooling reduction; 3) scenario 2 cooling reduction.

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	0.004438	9.94	Y = 0.004438*X + 9.94

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	0.0000879	0.49	Y = 8.788e-005*X + 0.49

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B12 (Existing)	-0.0001131	3.79	Y = -0.0001131*X + 3.79

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, scenario 1 and scenario 2 for the 5 office building types (B01_Existing_Low-rise_no insulation; B02_Existing_High-rise_no insulation; B03_New_Low-rise_insulated; B04_New_High-rise_insulated; B13_Existing_Low-rise_insulated; B14_Existing_High-rise_insulated) is also shown in **Figure 26**.

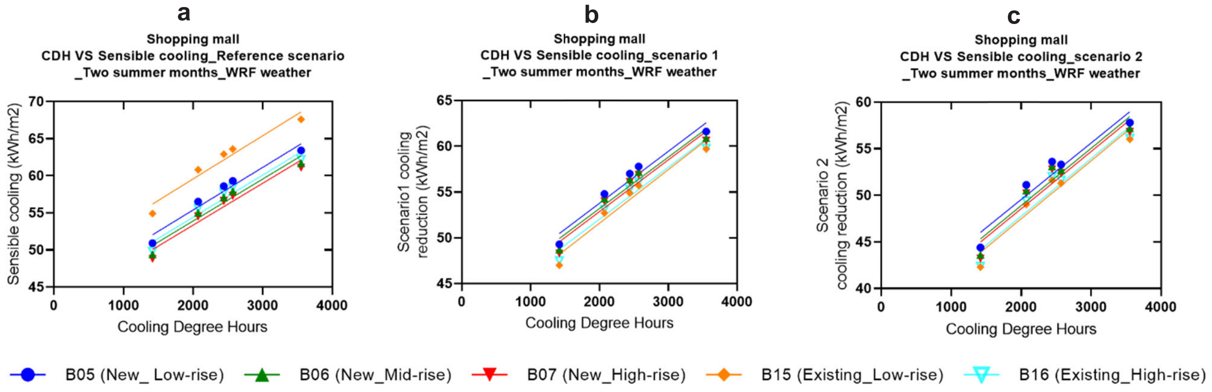

Figure 26 For school a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the sensible cooling of the scenario 1; c) The correlation between CDH and the sensible cooling of the scenario 2

4.6 Conclusion

- Regarding the total cooling load of reference scenarios, new buildings, or buildings with higher levels, or those with insulated envelopes have a lower heat loss coefficient of the overall envelope and therefore have a more stable cooling load when cooling degree hours change.

- Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors, and older construction years, which often have higher heat loss coefficients in envelopes.
- For the cooling load reduction in scenario 2 compared with the reference scenario, most buildings present an increasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in hotter areas for all buildings except for three residential buildings and two shopping centers.
- A general ranking of the heat loss coefficients of these buildings from low to high is office, school, residential buildings, and shopping mall center (Table 15).

Table 15 A general ranking of the heat loss coefficients of these buildings from low to high.

Building No.	Heat loss coefficient
B04 (Office_New_High-rise_insulated)	0.0007687
B03 (Office_New_Low-rise_insulated)	0.0009024
B12 (School_Existing)	0.000917
B14 (Office_Existing_High-rise_insulated)	0.0009647
B10 (Apartment_New_High-rise)	0.001095
B09 (Apartment_New_Mid-rise)	0.001138
B08 (Apartment_New_Low-rise)	0.001146
B02 (Office_Existing_High-rise_no insulation)	0.001263
B17 (Standalone house_New)	0.001277
B11 (Standalone house_Existing)	0.001478
B13 (Office_Existing_Low-rise_insulated)	0.001747
B07 (Shopping mall_New_High-rise)	0.002416
B06 (Shopping mall_New_Mid-rise)	0.002507
B05 (Shopping mall_New_ Low-rise)	0.002691
B16 (Shopping mall_Existing_High-rise)	0.002864
B01 (Office_Existing_Low-rise_no insulation)	0.003031
B15 (Shopping mall_Existing_Low-rise)	0.003888

5. Conclusions

This study is performed to assess the extreme urban heat and cooling potential of cool materials in the city of Adelaide, Australia. Specifically, it has

1) Evaluated the existing climatic conditions (reference case) in the city of Adelaide.

2) Assessed the magnitude and spatial variation of cooling potential generated by the cool roof, as well as how its application affects the climate in multiple ways when it is implemented in the city of Adelaide.
3) Compared the impacts of cool roof strategies at diurnal and monthly scales over the urban domain.
4) Investigated the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Adelaide.
5) Compared the energy loss through building envelopes in various building types and the advantages applying cool roof in various stations.

Specifically, the following conclusions have been drawn:

1) The most intense temperature differences occurred between city cores to surrounds. The maximum magnitude of the phenomena may exceed 5°C.The UHI effect would be added evenhandedly balanced spatially under the urban expansion. The intensity and the characteristics of the phenomena are strappingly influenced by the synoptic weather conditions and in particular the development of the sea breeze and the westerly winds from the long fetch desert area. The possible existence of an extra heating mechanism, like the advection of warm air from nearby desert spaces, may intensify the strength of the problem.
2) High density parts of the city exhibit a higher temperature reduction than the urban average. The locations and magnitudes of urban heating in the high density urban areas vary spatially and diurnally.
3) Increase of albedo in Adelaide can decrease the peak summer ambient temperature up to 1.9°C and surface temperature up to 6.6°C. Such cooling improves human comfort levels, and could be feasible for reducing cooling energy demand.
4) It was found that important temperature differences exist near the coast and core part of the city. The patterns of the ambient temperature distribution in the city were found to depend highly on the synoptic climatic conditions and the magnitude of the horizontal thermal gradient.

5) The city of Adelaide experiences an aggravate UHI at night during extreme urban heatwaves. In the daytime, a pocket of urban heat happen in the northwest part of the high density urban areas, while in the night, a hotspot occurs in the northern part of the city.

6) The maximum decrease of sensible heat and latent heat flux were up to 179.5 Wm-2 and 15.8 Wm-2, respectively.

7) The maximum decrease of wind speeds up to 2.3ms-1. Cool roofs increase the pressure over core urban at local-scale and decrease the wind advection from the adjacent bare surface of desert fetch.

8) The results show that the increase in albedo fraction leads to decrease in wind speeds and the incidence of high wind speeds along with augmented turbulent energy in the planetary boundary layer (PBL) during heat wave scenario.

9) Modification of the urban albedo in Adelaide city results in an average reduction up to 682.1 m of the PBL heights over high density parts of the city and may increase the concentration of bad pollutants at ground level during peak hour (14:00 LT) due to low level urban mixing.

10) The sea breeze significantly affected by cool roof due to higher local pressure over city, which greatly reduces the sea breeze penetration.

11) The amplitude of the UHI was linked with the subsistence of the sea breeze in the central parts of the city with a thermal gradient from Adelaide Hills to the Western Beach. And decreasing the temperature of the coastal zone, combined with wind effects from the inland and nearby surfaces.

12) In reference cases, CDH ranges from 261.5 to 3551.5 and the CDH values are mainly concentrating in 1400-2600. CDH gradually increases from southwest to northeast.

13) When applied with a cool roof, the decrease of CDH is observed at every station. The average dearease is 399.2 in all stations. CDH still increases from southwest to northeast.

14) In most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in reference cases, indicating that a cool roof is generally more effective when applied in hotter regions.

15) The percentage of CDH reduction due to the implementation of the cool roof ranges from 16.2% to 44.3% with an average value of 23.1%. The percentage is smaller in the hotter regions.

16) In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in individual buildings (scenario 1) is quite significant. For instance, application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 9.6-11.3 kWh/m2.

17) In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in both individual buildings and at the whole urban area (scenario 2) is quite significant. For instance, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 12.5-13.9 kWh/m2.
18) In new low-rise buildings with high insulation level, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) has a noticeable impact on cooling load reduction. For instance, cooling loads savings by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 3.6-4.3 kWh/m2 in a typical new low-rise office building.
19) In high-rise buildings, application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.2 kWh/m2 for a new high-rise office building with insulation.
20) In high-rise buildings, the cooling load reduction through application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.5-0.6 kWh/m2 in an existing high-rise shopping mall centre, which is expected to increase to 6.0-9.2 kWh/m2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).
21) The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in majority of building types. For instance, the annual cooling load saving in a low-rise office building without insulation is 11.0-19.2 kWh/m2, while the corresponding heating penalty is just 1.4-3.6 kWh/m2.
22) The annual heating penalty of cool roofs may exceed the cooling benefits in residential buildings in Adelaide. For instance, the heating penalty can be up to 6.9-11.4 kWh/m2 compared to the equivalent 5.1-8.7 KWh/m2 in an existing stand-alone house.
23) In existing low-rise buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in individual buildings (scenario 1) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 7.6-8.4 ^{o}C.
24) In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in both individual building and at the whole urban area

(scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and at the whole urban area (scenario 2) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 8.4-10.0 °C.

25) In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual building and at the whole urban area (scenario 2) can significantly decrease the number of hours with an indoor air temperature above 26 °C. For instance, the number of hours with an indoor air temperature above 26 °C in a typical low-rise office building without insulation is predicted to reduce from 436-457 hours to 326-367 hours and 251-333 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
26) In new low-rise buildings with high insulation level and under free-floating condition in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the maximum indoor air temperature during a typical summer period. For instance, the maximum indoor air temperature reduction by application of cool roofs in both individual building and at the whole urban area (scenario 2) is predicted to be 2.1-3.0 °C in a typical new low-rise office building.
27) In new low-rise buildings with high insulation level and under free-floating condition in a typical summer period, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) can significantly reduce the number of hours with an indoor air temperature above 26 °C during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 °C in new low-rise office building with insulation is predicted to reduce from 494-510 hours to 388-456 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
28) The maximum indoor air temperature reduction by cool roofs in a typical winter period is significantly lower than the maximum indoor air temperature reduction during a typical summer period. For instance, the maximum indoor air temperature reduction by application cool roofs in individual buildings in low-rise office building without roof insulation is predicted to be 7.6-8.4 °C in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 0.4-1.8 °C during a typical winter month.
29) The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 °C and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.3 °C occurs when the indoor air temperature is 24.0 °C.

30) The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 °C especially during the operational hours of the buildings in a typical winter period. For instance, it is predicted that the application of cool roofs in individual buildings (scenario 1) can increase the total number of operational hours with ambient temperature below 19 °C from 176-239 hours to 210-274 hours in a typical existing low-rise office building with roof insulation.

31) Regarding the total cooling load of reference scenarios, new buildings, or buildings with higher levels, or those with insulated envelopes have a lower heat loss coefficient of the overall envelope and therefore have a more stable cooling load when cooling degree hours change.

32) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors, and older construction years, which often have higher heat loss coefficients in envelopes.

33) For the cooling load reduction in scenario 2 compared with the reference scenario, except four shopping mall center building types (B05, B06, B07, B16), most buildings present an increasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in hotter areas for most buildings.

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7. Appendix: Meso-scale simulation results

Table 16 Reduction of ambient temperature: cool roof minus control scenario

Parameters	**Ambient Temperature at 2m (°C)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-1.1	-1.6	-1.3	-1.1
Minimum	-0.2	-0.6	-0.3	-0.4
Average of January	-0.6	-1.1	-0.8	-0.8
Average of February	-0.6	-1.2	-0.9	-0.9

Table 17 Reduction of surface temperature: cool roof minus control scenario

Parameters	**Surface Temperature (°C)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-2.1	-6.1	-4.9	-4.7
Minimum	-1.1	-4.5	-3.3	-3.1
Average of January	-1.5	-5.4	-4.2	-4.0
Average of February	-1.6	-5.7	-4.4	-4.2

Table 18 Reduction of sensible heat flux: cool roof minus control scenario

Parameters	**Sensible Heat Flux (Wm^{-2})**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-61.2	-171.3	-79.4	-104.3
Minimum	-12.4	-110.0	-48.7	-58.1
Average of January	-30.9	-136.4	-60.9	-74.7
Average of February	-43.2	-155.0	-69.0	-76.1

Table 19 Reduction of latent heat flux: cool roof minus control scenario

Parameters	**Latent Heat Flux (Wm^{-2})**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-4.7	-15.0	-6.0	-7.1
Minimum	-1.7	-9.0	-2.4	-3.6
Average of January	-2.6	-11.1	-3.8	-5.1
Average of February	-3.7	-12.8	-4.9	-6.3

Table 20 Reduction of wind speed: cool roof minus control scenario

Parameters	**Wind Speed (ms^{-1})**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-1.4	-2.1	-2.0	-1.7
Minimum	-0.4	-1.1	-0.9	-0.7
Average of January	-0.8	-1.4	-1.2	-1.0
Average of February	-1.1	-1.7	-1.4	-1.2

Table 21 Reduction of PBL height: cool roof minus control scenario

Parameters	**PBL Height (m)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-176.5	-694.0	-373.5	-355.4
Minimum	-61.2	-417.5	-110.2	-141.3
Average of January	-109.7	-540.2	-244.6	-263.2
Average of February	-133.3	-643.0	-308.7	-242.8

8. Appendix: Building characteristics_ Cool roofs project simulations inputs _ Climate zone 5 and 6

The following **Table 22** to **Table 25** have presented the general building parameters, internal gains, and ventilation; operation schedules; ventilation, HVAC, and setpoints parameters and building envelope parameters employed in the simulations in **Chapter 3.**

Table 22 General building parameters, internal gains, and ventilation.

		Office			Shopping mall		School	Standalone House		Apartment
Building ID		**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type		Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Floor area (m2)		1200			1100		1100	242		624
Aspect ratio		1:1			2:1		2:1	1:2		1:4.3
Window to Wall Ratio (WWR)		0.6			0.3		0.32	0.14	0.15	0.24
Year Built		1990		2018	1990	2018	1990	1990	2018	1990
Number of stories		2 (L)			2 (L)	2 (L)	3	1		3 (L)
Low rise (L), mid-rise (M), high-rise (H)		-			4 (M)	-				5 (M)
		10 (H)			6 (H)	4 (H)				8 (H)
Building height (m)		7.2 (L)			13.8 (L)	13.8 (L)	12.6	2.8		8.4 (L)
Low rise (L), mid-rise (M), high-rise (H)					27.6 (M)					14 (M)
		36 (H)			41.4 (H)	41.4 (H)				22.4 (H)
Lighting power density (W/m2) **(before operation profile and radiant fraction)**		4.5			14		4.5	4.5		
Lighting internal gains (W/m2) ***(radiant fraction 0.42)***	Hourly Max	2.61			8.12		2.76	2.5		
	Hourly Mean	1.45			4.77		1.13	0.6		
	Hourly Min	0.39			0.81		0.15	0		
Equipment gains ***(before operation profile)***		11			5		5	6.88		
Equipment internal gains (W/m2)	Hourly Max	11			3.5		4.75	6.88		
	Hourly Mean	6.16			2.31		1.86	1.1		
	Hourly Min	2.75			0.5		0.25	0.6		
Occupancy density (person/m2)		0.1			0.2		0.5	0.02	0.025	0.04

Continues

Table 23 Operation schedules

<table>
<tr><td></td><td colspan="3">Office</td><td colspan="2">Shopping mall</td><td>School</td><td colspan="2">Standalone House</td><td>Apartment</td></tr>
<tr><td>Building ID</td><td>B01, B02</td><td>B03, B04</td><td>B13, B14</td><td>B05, B06, B07</td><td>B15, B16</td><td>B12</td><td>B11</td><td>B17</td><td>B08, B09, B10</td></tr>
<tr><td>Building Type</td><td>Existing uninsulated</td><td>New</td><td>Existing w/ roof ins.</td><td>New</td><td>Existing</td><td>Existing</td><td>Existing</td><td>New</td><td>New</td></tr>
<tr><td>Intensity of internal heat gains (W/m2) (from NatHERS and NCC 2019)</td>
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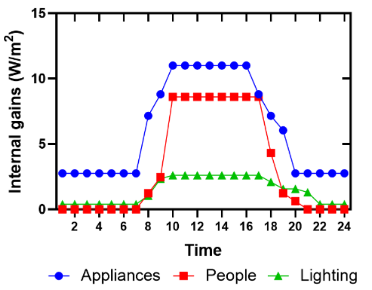
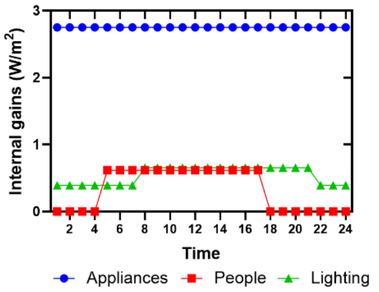


Office Weekend


</td>
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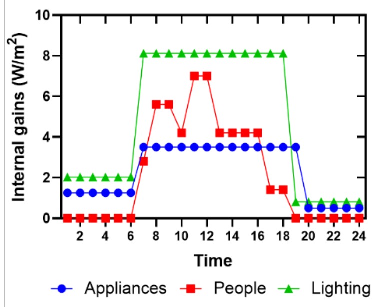
Shopping mall


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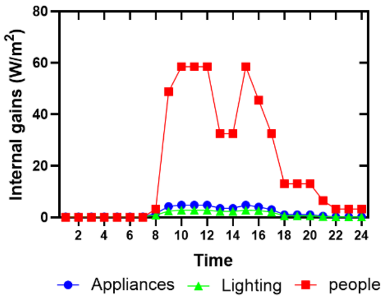
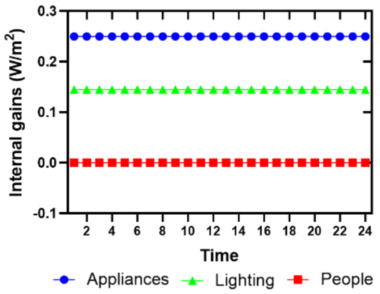
School_Weekdays


School_Weekend


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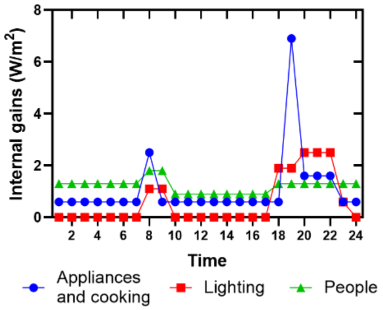
Residential_sensible


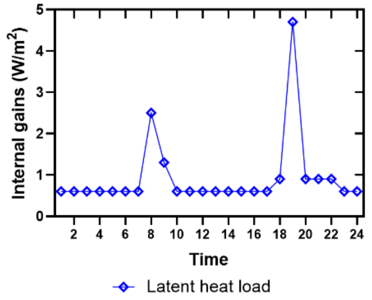
Residential_latent


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Table 24 Ventilation, HVAC, and setpoints parameters

	Office			Shopping mall		School	Standalone House		Apartment
Building ID	**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type	Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Ventilation op. hours (l/s. p)	7.5 (same for all buildings)								
Infiltration (op. hours) (ac/h)	1 (same for all buildings)								
Infiltration (non-op. hours) (ac/h)	1.5								
HVAC system type	VAV, AHU, Central plant			Heat pump air-cooled reverse cycle PAC		Non-ducted reverse cycle split units	Split-system central AC		Split-system central AC
HVAC cooling COP	1								
HVAC heating COP	1								
HVAC fan efficiency	1								
Heating setpoint (°C)	20 (same for all buildings)								
Heating setback (°C)	NA (system off out of working ours for commercial buildings, following NCC)								
Cooling setpoint (°C)	25 (same for all buildings)								
Cooling setback (°C)	NA (system off out of working ours for commercial buildings, following NCC)								

Continues

In the study by Delta Q (the one provided by Kavya for the archetypes) they used 22.5 °C setpoint, which is considering the current worst practice used in the industry, as pointed out by AIRAH (https://www.airah.org.au/Content_Files/HVACRNation/2015/08-15-HVACR-003.pdf).

Table 25 Building envelope parameters

	Office			Shopping mall		School	Standalone House		Apartment
Building ID	**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type	Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Roof R-value (m2·K/W)	0	3.7 in climate zone 5 and 3.2 in climate zone 6	0.5	3.7 in climate zone 5 and 3.2 in climate zone 6	0.5	3.7 in climate zone 5 and 3.2 in climate zone 6	2	4.1 in climate zone 5 and 4.6 in climate zone 6	3.7 in climate zone 5 and 3.2 in climate zone 6
Roof solar reflectance	0.15_CTRL								
	0.80_COOL								
Roof thermal emittance	0.85								
Wall R-value (m2·K/W)	0	1	1	1		1	2.8		1
Wall solar reflectance	0.15								
Wall thermal emittance	0.85								
Window U-value (W/m²K)	2.4			4.2		2.4	5.6	2.5	5.6
Window SHGC (summer)	0.25 (same for all buildings)								
Window SHGC (winter)	0.70 (same for all buildings)								

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