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COOL ROOFS COST BENEFIT ANALYSIS

Volume 3 - Climatic and Energy Performance of Cool Roofs in Melbourne

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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 Melbourne, Australia. Specifically, the purposes of this report are:

1) To evaluate the existing reference climatic conditions in the city of Melbourne, 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 Melbourne.
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 Melbourne 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.

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 11 weather stations in Melbourne 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 16 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 eleven weather stations across Melbourne. 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 Melbourne 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 Melbourne 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 Melbourne.

Collectively, the following conclusions have been drawn:

1) Increase of albedo fraction in Melbourne city can decrease the peak ambient temperature up to 2.1°C and surface temperature up to 11.1°C.
2) The maximum decrease of sensible heat and latent heat flux were 292.8 Wm-2 and 15.1 Wm-2, respectively.
5) The highest decrease of wind speeds up to 3.4 ms-1. Thus, higher urban albedo values decrease the advective flow between city and its surroundings surface improving the cooling potential of reflective materials. Modification of the urban albedo in Melbourne results in an average 1590.6m reduction up to of the PBL heights over city and may increase the concentration of pollutants at ground level and subsequently increase the health problems.
6) 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.
7) When cool roofs are used in the city, CDH ranges from 114.9 to 1059.8. The percentage of CDH reduction due to the implementation of the cool roof ranges from 20.2 % to 42.24 %.
8) 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.
9) 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, 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 8.3-11.7 kWh/m2.
10) 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 2.4-3.3 kWh/m2 in a typical new low-rise office building.
11) 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 0.6-0.9 kWh/m2 and 0.1-0.2 kWh/m2 for new low-rise and high-rise office buildings with insulation, respectively.

12) 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 2.1-3.2 kWh/m2 in an existing high-rise shopping mall centre, which is expected to increase to 7.5-9.7 kWh/m2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).
13) 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 8.8-14.4 kWh/m2, while the corresponding heating penalty is just 3.3-7.5 kWh/m2.
14) The annual heating penalty of cool roofs may exceed the cooling benefits in residential buildings in Melbourne. For instance, the heating penalty can be up to 6.8-8.5 kWh/m2 compared to the equivalent 5.6-8.3 KWh/m2 in an existing stand-alone house.
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) 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 8.1-10.0 °C.
16) 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 9-10.4 °C.
17) 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 334-395 hours to 193-253 hours and 152-197 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
18) 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 2.1-2.2 °C in a typical new low-rise office building.

19) 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 345-399 hours to 250-305 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
20) 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 8.1-10 °C in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 1.7-1.9 °C during a typical winter month.
21) 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 3.8 °C occurs when the indoor air temperature is 22.8 °C.
22) 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 179-200 hours to 200-229 hours in a typical existing low-rise office building with roof insulation.

Objectives

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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 Melbourne 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.

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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 Melbourne.

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

1.1 Introduction

Heatwave events exacerbate extreme urban heat and the frequency and intensity of heatwaves are escalating in southeast Australia. Localized synergies between heatwaves and extreme urban heat are imperative. Extreme urban heat with regional climate change can affect the health and wellbeing of humans, the environmental quality, and the socio-economic performance of cities. The higher magnitude of urban temperatures (and for longer periods) is considerably affecting citizen's quality of life and outdoor activities. Extreme urban heat is being augmented by local and regional climate change which leads to an increase in the magnitude, frequency, and duration of extreme temperature, prolonged thermal distress and heat stress, and increased heat-related mortality and morbidity (Santamouris et al., 2017). The extreme urban heat is driving a doubling in consumption of electricity for cooling and a three-fold increase in heat-related deaths. 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 performance of cool roof strategies at the city scale during an extreme heat condition.

1.2 Objectives of the study

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

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

1.3 Domain and method of simulation

We use a full mesoscale climatic model for the entire city of Melbourne using the 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 Melbourne under the existing heatwave conditions and one mitigation scenario. 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 the cool roof scenario and its cooling potential. One mitigation scenario is evaluated in this report. The mitigation strategy is examined in this study at a city scale.

Table 1 WRF/SLUCM Model configuration

Configuration	**Domain 01 (d_1)**	**Domain 02 (d_2)**	**Domain 03 (d_3)**
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 Melbourne. 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**.

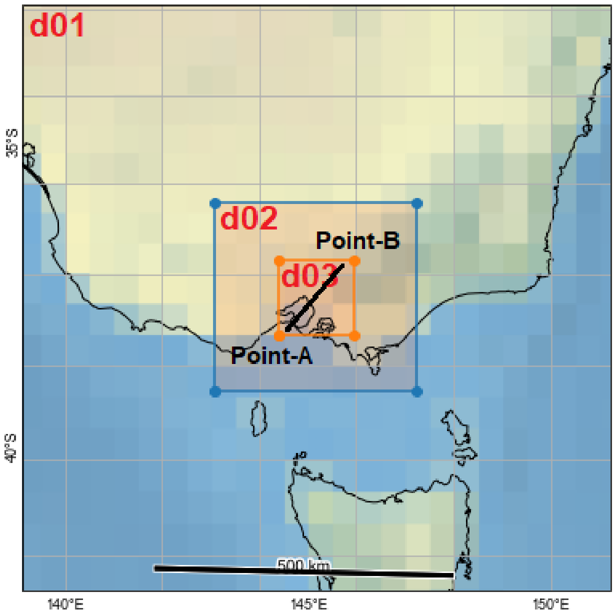


Table 2 Numerical design for cool roof for Melbourne

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 the 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=0.982; mean bias=0.569) for Avalon, Laverton, Moorabbin Airport, and Cerberus. 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 2.8°C to 5.7C 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 MAS of air temperature was 0.362°C to 0.625°C and 0.465°C to 0.596°C, respectively. The range of IOA was 0.905 to 0.985 with average values of 0.961 when considering all observation stations. The model slightly overestimated the daily average 2m 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 the utility of the UCM scheme. The well-simulated daytime warming is balanced by equally well-simulated night-time cooling, resulting in a diurnal range that is of a similar magnitude to observations. The comfort level of different dew points is >22.1°C for the stations represents the uncomfortable situation in the 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 dewpoint, and the model framework can be used to predict the regional meteorology and investigate the regional influence of cool roof strategy.

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

Parameters	**Local weather stations**			
	Avalon	Laverton	Moorabbin Airport	Cerberus
Correlation coefficient	0.985	0.975	0.978	0.976
Mean Bias error	0.362	0.625	0.524	0.576
Mean absolute error	0.596	0.562	0.465	0.534
Root mean square error	1.002	1.024	1.023	1.036
Index of Agreement	0.953	0.966	0.905	0.985
Correlation coefficient	0.901	0.924	0.880	0.905

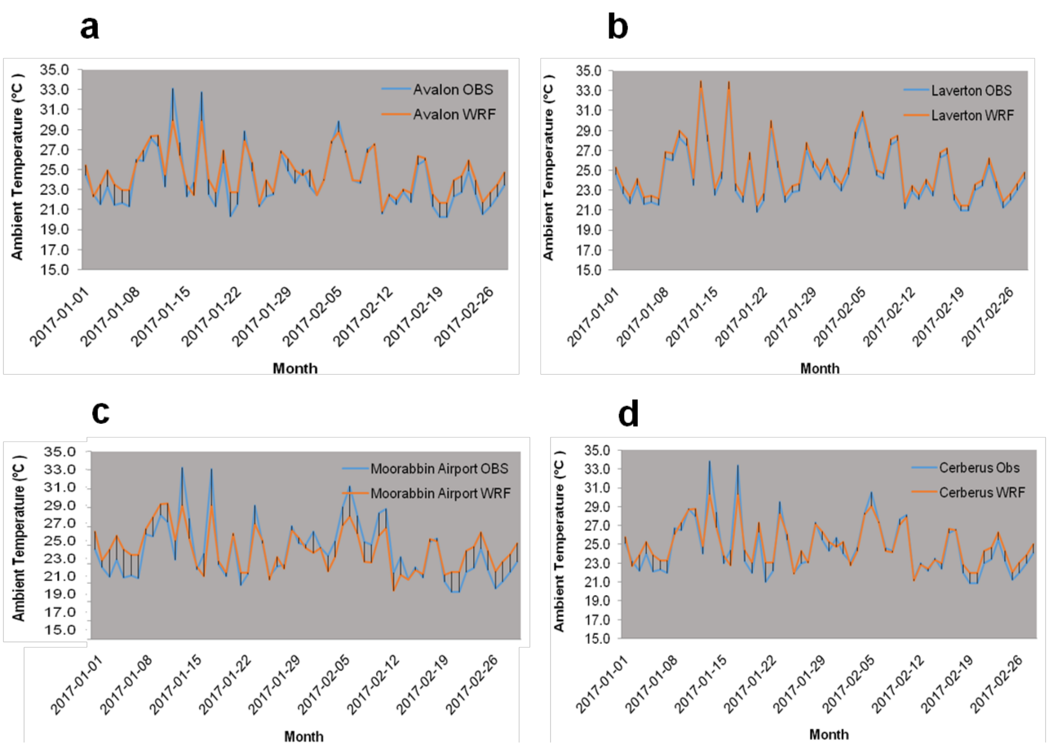


Figure 2 Validation of the WRF Model and the corresponding observed air temperature for the 24-hour average duration for four local meteorological stations: (a) Avalon, (b) Laverton, (c) Moorabbin Airport, and (d) Cerberus**.**

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 Melbourne to ensure the robustness and accuracy of the model. The results of the 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 the summer period for 59 days of two months (January and February). These two months were warmer than average during 2017 for both daytime and overnight temperatures in Greater Melbourne. For Greater Melbourne, the hottest temperature during January was 38.9°C at Essendon Airport, in a hot northerly airstream that preceded the approaching low-pressure trough on record, behind 2016 (Bureau of Meteorology, Australia, 2017a, b).

1.5.1 Ambient temperatures

Ambient temperatures can be calculated from the surface energy flux partitions in the WRF-SLUCM urban modeling system. Under the cool roof materials scenario, the ambient temperature at 14:00 ranges between 21.3 °C and 39.3 °C. At 06:00 LT, it varies between 20.3°C and 36.5°C. The results show that the use of cool roof materials maximum reduces the peak ambient temperature ($T_{ambient}$) by 2.1ºC over Melbourne and Kingstone compared to the control case. The average ambient temperature reduction at 14:00 over the whole summer is 0.90°C. The maximum decrease of the ambient temperature during 18:00 LT is 1.7°C over the eastern part of Melbourne and the average decrease of summer months is 0.6°C (**Figure 3**).

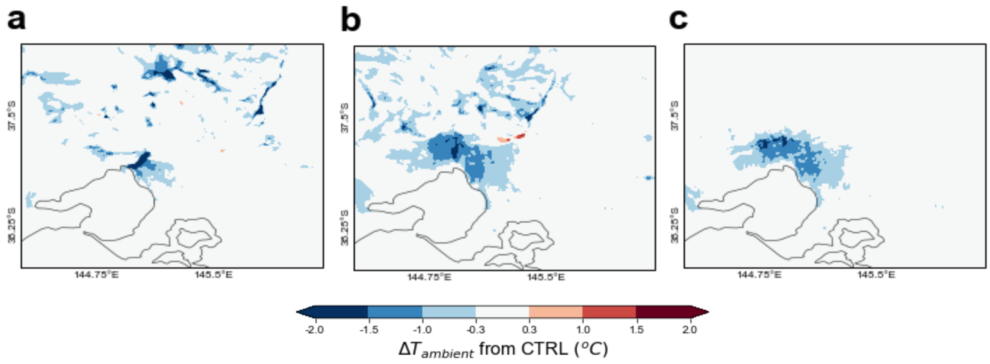


Figure 3 Reduction of ambient temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.2 Surface temperatures

Under the cool roof scenario, the surface temperature ($T_{surface}$) ranges between 22.5 °C to 44.9°C at 14:00, 20.2°C to 39.5°C at 18:00 LT, and 15.1 to 34.9 at 6:00 LT over the city. The maximum decrease of surface temperature during 14:00 LT is 11.1°C over Melbourne and Monash and 3.3°C at 18:00 LT near core Melbourne areas but in the early morning (06:00 LT) it is about 7.1°C over the urban domain. The average decrease of urban surface temperature is 6.1°C at 14:00 LT, 2.8°C at 18:00 LT, and 0.9°C in the city (**Figure 4**).

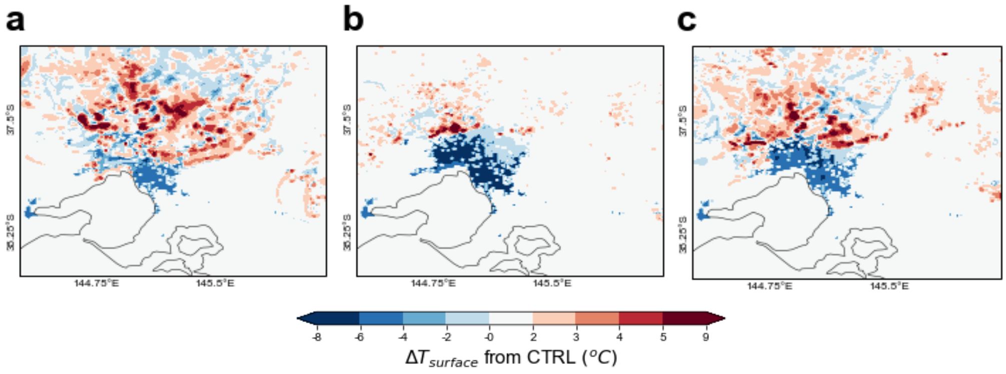


Figure 4 Reduction of surface temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.3 Sensible heat flux

The WRF-SLUCM reasonably computed the sensible heat flux from the urban surface. The maximum and average sensible heat flux ($Q_{sensible}$) over the city during 14:00 LT is 398.8 Wm^{-2} and 273.1 Wm^{-2}. At 06:00LT, the average sensible heat flux is 50.2 Wm-2. The maximum decrease in the sensible heat flux is 292.8 Wm^{-2}and the average decrease is 175.1 Wm^{-2} at 14:00 LT over CBD areas of Melbourne city and extends up to Maribyrnong, Moonee Valley, and Moreland. At 18:00LT, the maximum and average reduction of the summer month of sensible heat flux is 118.0 Wm^{-2}and 59.1 Wm^{-2}over the urban domain (**Figure 5**).

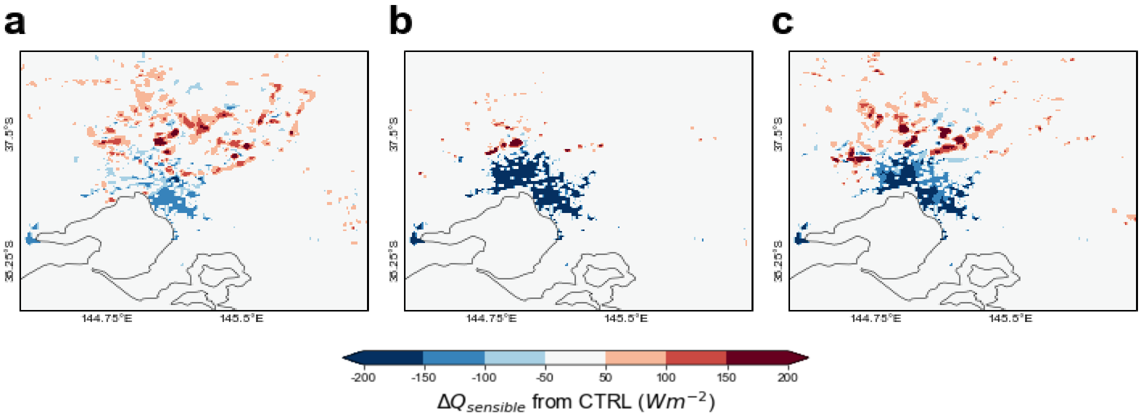


Figure 5 Reduction of sensible heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.4 Latent heat flux

The maximum and average latent heat flux (Q_{latent}) over the city during 14:00 LT is 33.3 Wm^{-2} and 21.2 Wm^{-2}. At 18:00 LT and 06:00 LT, the average sensible heat flux is 7.8 Wm^{-2}. The maximum decrease in the latent heat flux is 15.1 wm^{-2} and the average decrease is 12.3 Wm^{-2} at 14:00 LT over CBD and the outer part of Melbourne including Melton, Hume, Nillumbik, and lower part of Yarra Ranges. At 18:00 LT, the maximum and average reduction of the summer month of latent heat flux is 5.2 Wm^{-2}and 2.4 Wm^{-2} over Melbourne city. At, 06:00 LT, the maximum reduction of latent heat flux is 6.4 Wm-2and the average reduction is 4.0 Wm^{-2}over urban domain (**Figure 6**).

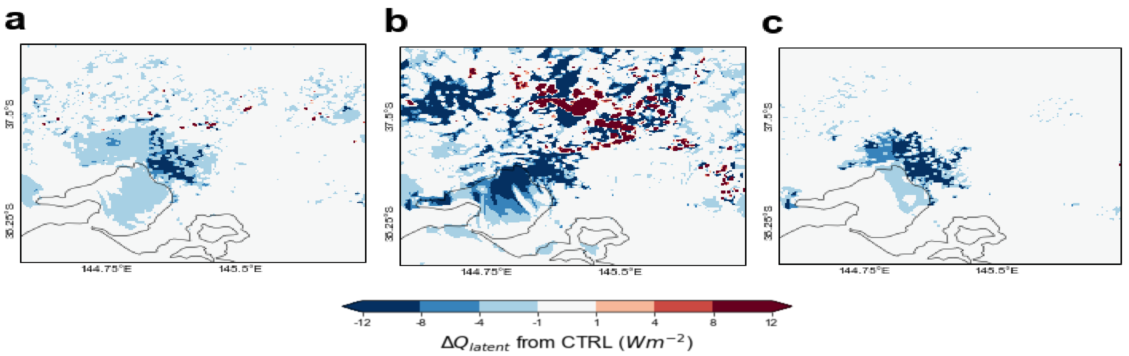


Figure 6 Reduction of latent heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.5 Wind

Under the base case simulation, the average wind speed (W_{speed}) is 8.9 ms^{-1}, 10.1 ms$^{-1,}$ and 9.2 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 the control case is 1.8 ms-1, 3.4 ms$^{-1,}$ and 2.2 ms^{-1} at 06:00 LT, 14:00 LT, and 18:00 LT respectively over Monash, Hume, Knox, and Casey. The average decrease of wind speed of whole summer months is 2 ms^{-1} at 14:00 and 1 ms^{-1} and 1.3 ms^{-1} at 06:00 LT and 18:00 LT over the city, respectively (**Figure 7**).

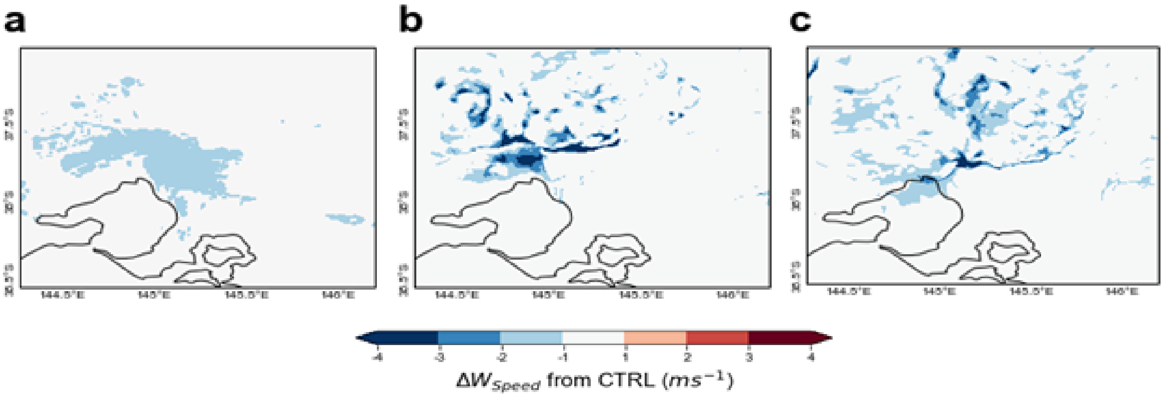


Figure 7 Reduction of wind speed at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.6 Regional Impact of Cool Roof: PBL Dynamics

The high-density urban building environment impacts 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 considerably higher when highly reflective cool materials rather than conventional materials are implemented at the city scale. Fig. 8 shows the 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, 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 275.7m, 1590.6m, and 986.5m, for 6:00LT, 14:00LT, 18:00LT, respectively with an average value is about 407.6m. The minimum reduction of PBL is 49.8m, 29.7m, and 29.6m, for 6:00LT, 14:00LT, 18:00LT, respectively with an average value is about 12.4m (**Figure 8**). The maximum reduction is associated with peak hours (14:00 LT) over Melbourne, Maribyrnong, Monney Valley, Monash, Knox, Whitehorse, Manningham, and Brimbank. On the other hand, during sunrise and sunset, the maximum reduction is reported for the outer west of the Melbourne domain. 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.

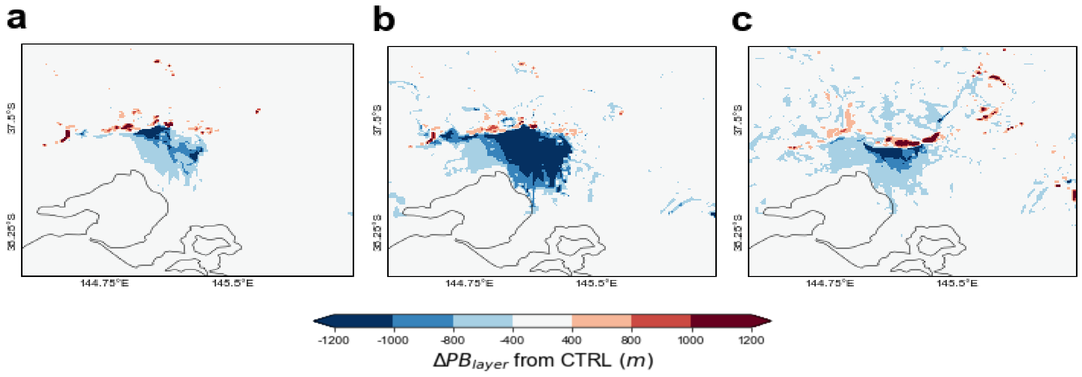


Figure 8 Reduction of PBL height at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.6 Regional impact on sea breeze circulations

The amplification of sea breeze circulation is more variable on the large-scale synoptic background, which plays an important role in modulating the prevailing wind at the near-surface. In the vertical dimension, the report revealed the height of the PBL in Melbourne is linked closely with the advection of the sea breeze from Port Philip and the local impact of cool materials. However, based on the numerical analysis of vertical profiles of winds and specific humidity of cool roofs, this report suggests that the advection of moist air from surrounding areas is unlikely to be the driving mechanism due to the extremely hot and dry conditions during the heatwave event. The circulation can be modified when the cool roof is implemented at the city scale (**Figure 9**). The cool roof could alter the PBL height and potentially trigger localized circulation over the urban domain of Melbourne. 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 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 1.5 to 3.5 ms^{-1} induces 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, a cool roof for cities has 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 the sea breeze front developed is more prone to the accumulation of secondary pollutants in the back of the front. The location of Port Philip and its geometrical horse-head-shaped enclosed bay on the central coast. This bay may change the wind pattern from the open fetch of the nearby ocean. The winds over the city of Melbourne are indicative of the synoptic pattern over the whole Bay, but there is a modification of the wind component as one moves southward due to the sea breeze effects of Port Phillip Bay itself. There is also an east-west funneling in the vicinity of Port Phillip which increases the frequency of easterlies and westerly components.

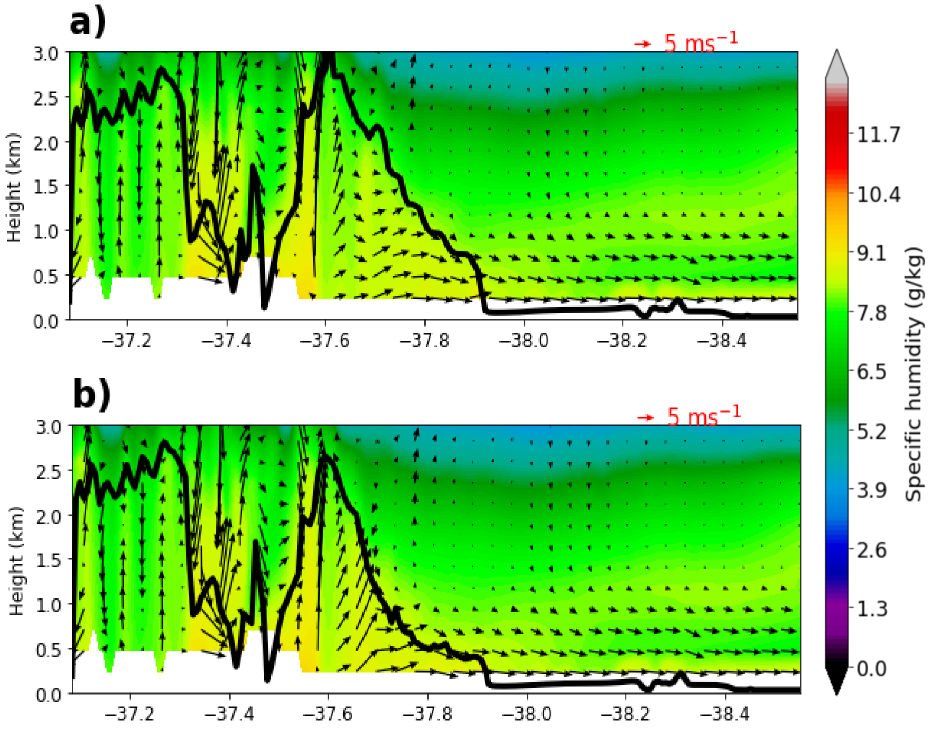


Figure 9 Cross-sectional profile of cool material impacts on sea breeze during peak hour (14:00 LT) over Melbourne (see **Figure 1**): (a) control case, and (b) cool roof scenario. The vertical gradient of specific humidity determines the static stability of the lower atmosphere. During the high solar hour, the convective boundary layer developed the very fastest way and progressively decreases with the implementation of cool materials.

It is also showed that the implementation of a cool roof over the city scale can affect the horizontal and vertical pressure gradient between the city and surrounding urban surface due to significant drop ambient temperature up to 2.1°C and wind speed reduced up to 3.4 ms^{-1}. Thus, changes in roof reflectivity, sensible heating, and wind result in feedbacks within a local climate of the city during peak hours (14:00 LT). The higher urban albedo values decrease the advective flow between the city and its surroundings improving the cooling potential of reflective materials. It creates a ‘regional high’, which can reduce both horizontal and vertical wind speed over the city. The average decrease of wind speed in NW and SW at 14:00 LT is 1.8 and 1.5 ms^{-1}, respectively. As a result, the increase of albedo may put off the flow of warm air from the contiguous desert towards the city of Melbourne due to the effect of this regional high over the urban domain (**Figure 10**). In addition, it is showed that the impact of sea breeze is considerably reduced over high-density residential areas where roof areas are high.

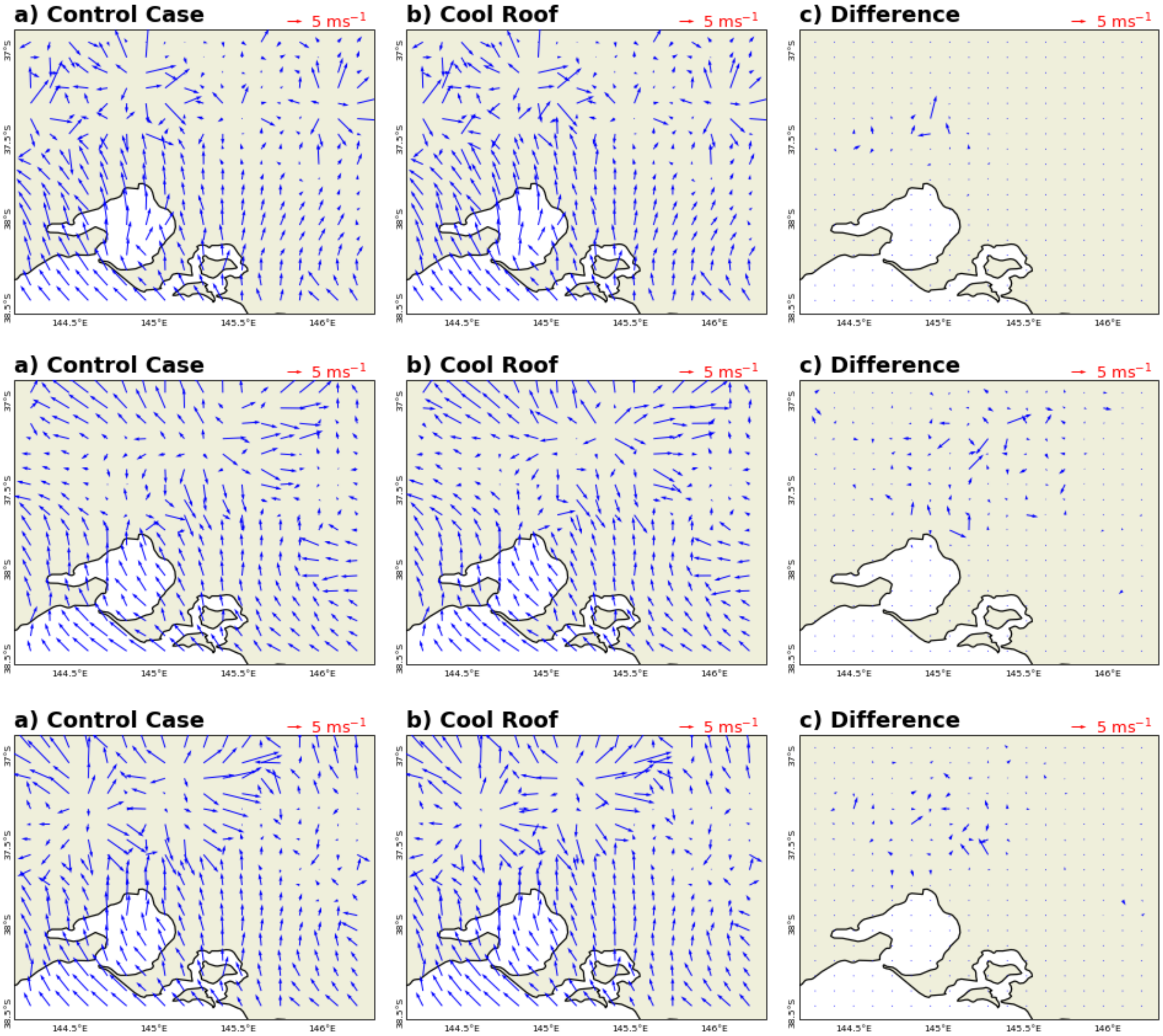


Figure 10 Surface characteristics of wind before and after cool roof implementation at city scale (a) control case (b) cool roof (c) control minus scenarios: difference at 06:00 LT (upper), 14:00 LT (middle), and 18:00 LT (lower panel) for the domain 03.

1.7 Main conclusions

- It is observed that a sturdy urban heat island (UHI) phenomenon is developed during heatwave over high-density residential areas of Melbourne city. The magnitude of the phenomena may exceed 5°C. The intensity and the spatio-temporal characteristics of the phenomena are strappingly influenced by the synoptic weather conditions and in particular the advance of the sea breeze and the westerly winds from the desert area. The potential existence of an additional heating mechanism, like the advection of warm air from nearby spaces, could intensify the strength of the problems of urban heating.

- An increase of albedo fraction in Melbourne city can decrease the peak ambient temperature up to 2.1°C and surface temperature up to 11.1°C. It was noted that significant temperature differences subsist between the eastern and western parts of the city. The spatio-temporal patterns of the ambient temperature distribution in the city were found to depend highly on the synoptic climatic conditions and the potency of the advection flows.
- The maximum decrease of sensible heat and latent heat flux was 292.8 Wm-2 and 15.1 Wm-2, respectively.
- The highest decrease of wind speeds up to -3.4 ms-1. Thus, higher urban albedo values decrease the advective flow between the city and its surroundings surface improving the cooling potential of reflective materials. Modification of the urban albedo in Melbourne results in an average 1590.6m reduction up to of the PBL heights over the city and may increase the concentration of pollutants at ground level and subsequently increase the health problems.
- High intensities of the UHI phenomenon were associated with the existence of a sea breeze in the seaward parts of the city, decreasing the temperature of the coastal zone, combined with westerly winds from the inland that warm up the western zones of the city.

2. Climatic design Parameters _ CDH distribution

2.1 Overview of the weather stations in Melbourne

Two scenarios, one as the control 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; thermal emittance = 0.85) are simulated and analyzed. 16 stations in Melbourne, as shown in Table 4 and **Figure 11**, have been simulated for two months: Jan and Feb, and the dry bulb temperatures generated by Weather Research Forecasting Model have been used in subsequent calculations.

Table 4 Latitude, longitude, and the climate zone of the 16 stations in Melbourne.

No.	Station name	Lat	Long	Height	Climate zone
1	GEELONG RACECOURSE	-38.17	144.38	12.9 m	6
2	POINT WILSON	-38.1	144.54	18.0 m	6
3	AVALON AIRPORT	-38.03	144.48	10.6 m	6
4	LAVERTON RAAF	-37.86	144.76	20.1 m	6
5	ESSENDON AIRPORT	-37.73	144.91	78.4 m	6
6	MELBOURNE AIRPORT	-37.67	144.83	113.4 m	6
7	LATROBE UNIVERSITY	-37.72	145.05	83.0 m	6
8	COLDSTREAM	-37.72	145.41	83.0 m	6
9	MELBOURNE (OLYMPIC PARK)	-37.83	144.98	7.53 m	6
10	FERNY CREEK	-37.87	145.35	512.9 m	6
11	FAWKNER BEACON	-37.95	144.93	17.0 m	6
12	MOORABBIN AIRPORT	-37.98	145.1	12.1 m	6
13	FRANKSTON BEACH	-38.15	145.12	6.0 m	6
14	FRANKSTON (BALLAM PARK)	-38.15	145.16	58.47 m	6
15	CRANBOURNE BOTANIC GARDENS	-38.13	145.26	85.0 m	6
16	CERBERUS	-38.36	145.18	12.69 m	6

Figure 11 Location of the 16 weather stations in Melbourne.

2.2 Calculation method and results

For all scenarios, Cooling Degree Hours (CDH) Base 26 °C, which measures how much (in degrees), and for how long (in hours), outside air temperature is higher than 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 control 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 16 weather stations, are shown in **Table 5** and **Figure 12**. Compared with the control case, the largest percentage reduction is observed in CRANBOURNE BOTANIC GARDENS and the smallest is found in FAWKNER BEACON, with an average reduction of 31.2%. The mean CDH values of the 16 weather stations for the control case, cool roof case are 876.0, 618.0 respectively, with standard deviations of 354.2 and 281.5 sequentially, see **Table 6**.

Table 5 The CDH of control 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 16 weather stations in Melbourne.

Weather Station	CDH_CTRL	CDH_COOL ROOF	CDH_ Difference (CTRL-COOL ROOF)	Percentage of the reduction_% (CDH_Difference/ CDH_CTRL)
GEELONG RACECOURSE	761.7	513.4	248.3	32.6
POINT WILSON	1037.9	761.4	276.5	26.6
AVALON AIRPORT	995.1	735.6	259.6	26.1
LAVERTON RAAF	1066.5	784.7	281.8	26.4
ESSENDON AIRPORT	1241.9	842.6	399.3	32.2
MELBOURNE AIRPORT	1328.5	910.5	418.0	31.5
LATROBE UNIVERSITY	1166.4	798.1	368.3	31.6
COLDSTREAM	1224.8	957.7	267.1	21.8
MELBOURNE (OLYMPIC PARK)	922.6	667.0	255.6	27.7
FERNY CREEK	532.2	360.1	172.1	32.3
FAWKNER BEACON	1328.5	1059.6	268.8	20.2
MOORABBIN AIRPORT	702.2	450.1	252.1	35.9
FRANKSTON BEACH	576.7	355.9	220.8	38.3
FRANKSTON (BALLAM PARK)	455.0	294.0	161.0	35.4
CRANBOURNE BOTANIC GARDENS	490.4	282.2	208.2	42.4
CERBERUS	185.8	114.9	70.9	38.2

Table 6 Mean and SD of the CDH of the 16 weather stations in control cases and cool roof cases respectively.

	Mean	**SD**	**Sample No.**
CDH_CTRL	876.0	354.2	16
CDH_COOL ROOF	618.0	281.5	16
CDH_DIFFERENCE (CTRL-COOL ROOF)	258.0	87.4	16

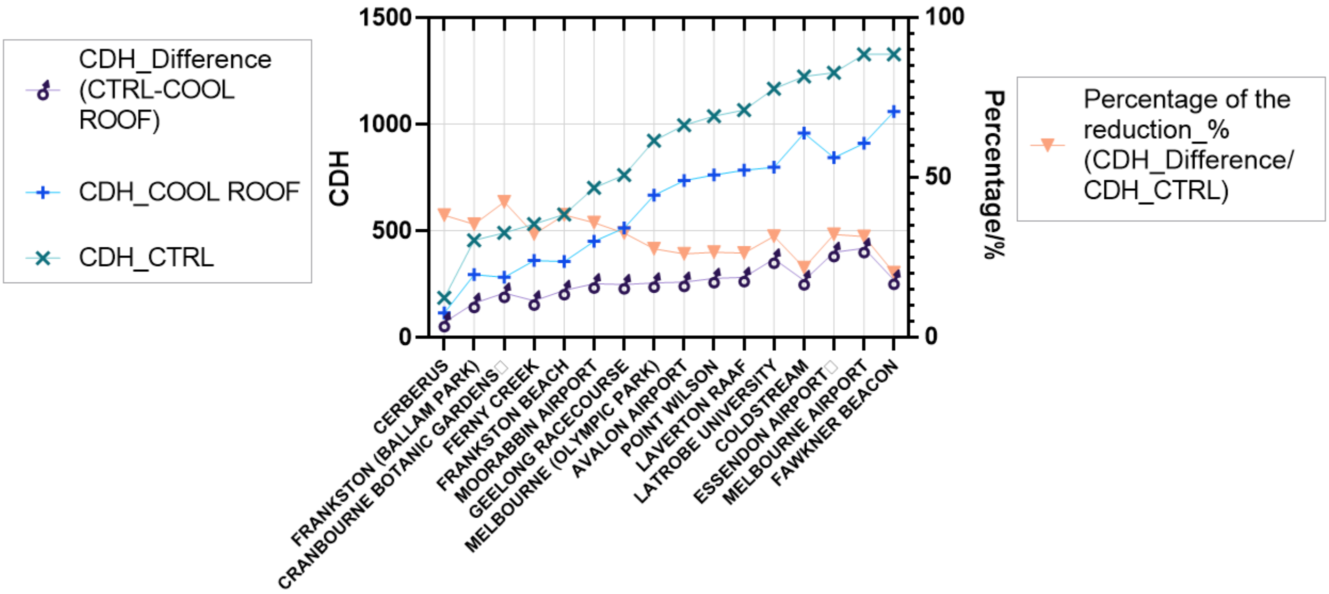


Figure 12 The CDH of control cases, cool roof applied cases, the difference between these two, and the percentage of the CDH reduction due to the implementation of the cool roof in 16 weather stations in Melbourne.

2.2.1 Frequency distribution of the results

The frequency distribution of the CDH values for the 16 weather stations in both the control cases and the cool roof cases is shown in **Figure 13**. In control cases, the CDH centered around 500 and 1200 has the largest proportion: each accounting for 18.8% of the total. Data centered around 1000 and 1300 each account for 12.5% of the total, while all the remaining intervals have the same proportions. In cool roof cases, the CDH centered around 800 has the largest proportion of 25%. The data of all remaining intervals account for less than 15%

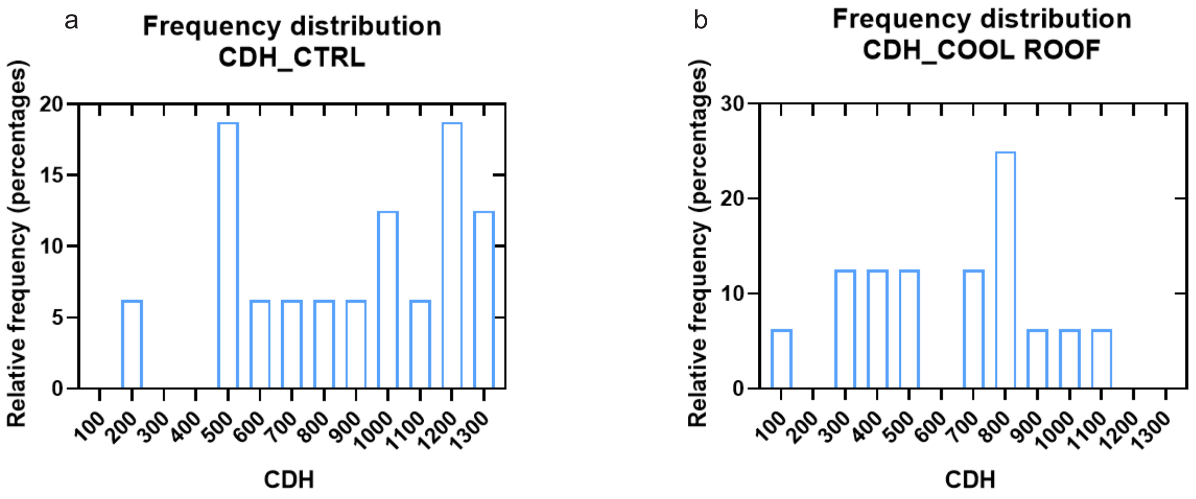
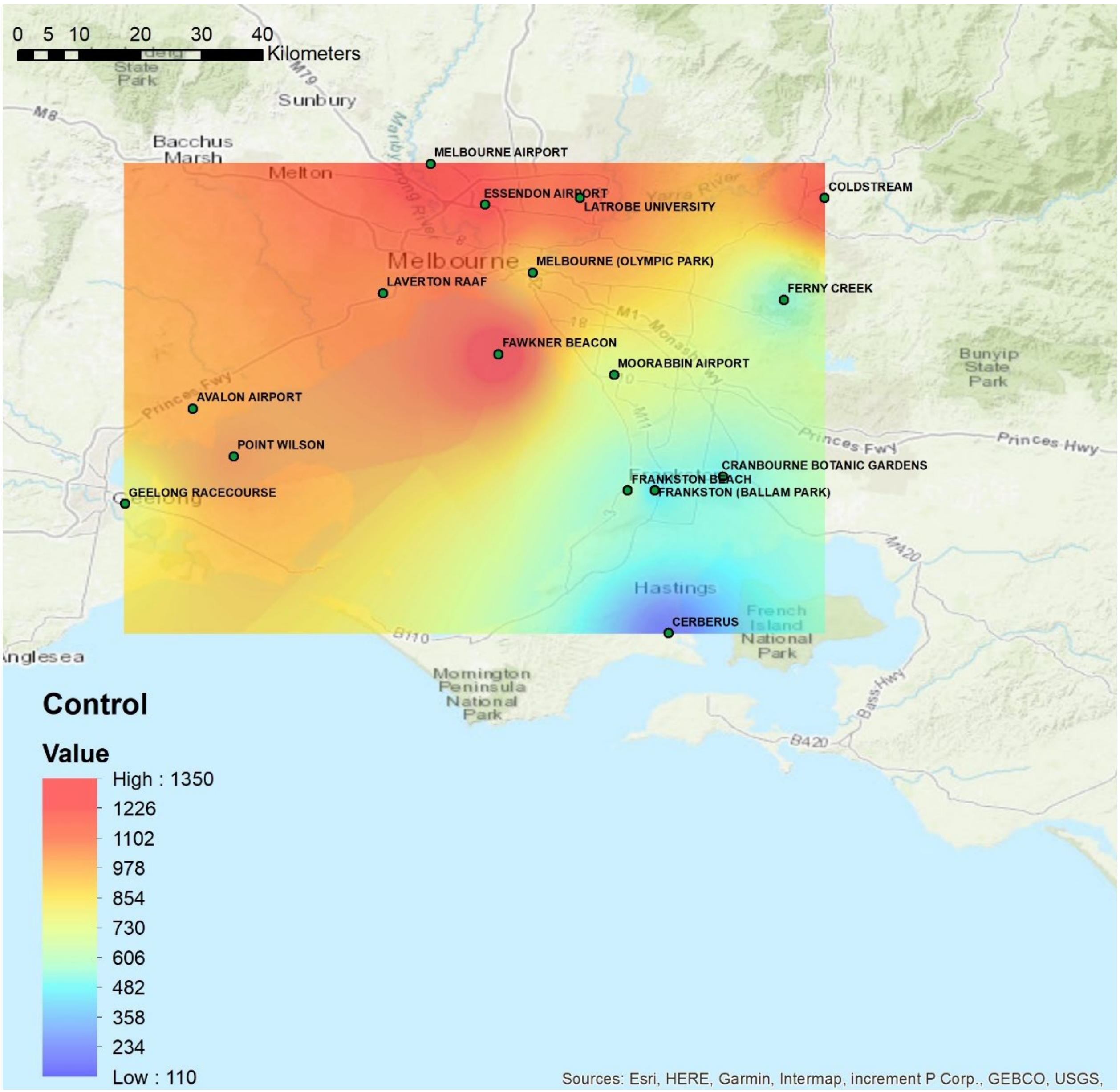


Figure 13 Frequency distribution of the CDH values for the 16 weather stations in control cases (a) and cool roof cases (b).

2.2.2 Spatial distribution of the results

Figure 14 shows the spatial distribution of CDH in Jan and Feb of the control cases in the 16 stations. The highest CDH of 1328.5 is observed in FAWKNER BEACON and MELBOURNE AIRPORT. CERBERUS has the lowest number. CDH gradually increases from southeast to northwest. When applied with a cool roof, the decrease of CDH is observed at every station, as shown in **Figure 15**. The highest CDH of 1059.6 is still observed in FAWKNER BEACON and CERBERUS again has the lowest number. The spatial distribution pattern is very similar to that of the control cases: CDH increases from southeast to northwest. **Figure 16** shows the spatial distribution of the decrease of cooling degree hours in the two simulated months after the cool roof is applied. The maximum decrease occurs in the north (MELBOURNE AIRPORT:418.0) of the city. The smallest decrease is observed in the southeast part of the city (CERBERUS: 70.9). The average decrease due to the implementation of a cool roof is 258.0 (**Table 6**) across the 16 stations. The proportion of CDH reduction in the original control volume is relatively large in the southeast corner of the city and gradually decreases toward the northwest and northeast, as shown in **Figure 17**.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS,

Figure 14 The sum of Cooling degree hours in Jan and Feb of the control cases in the 16 stations in Melbourne.

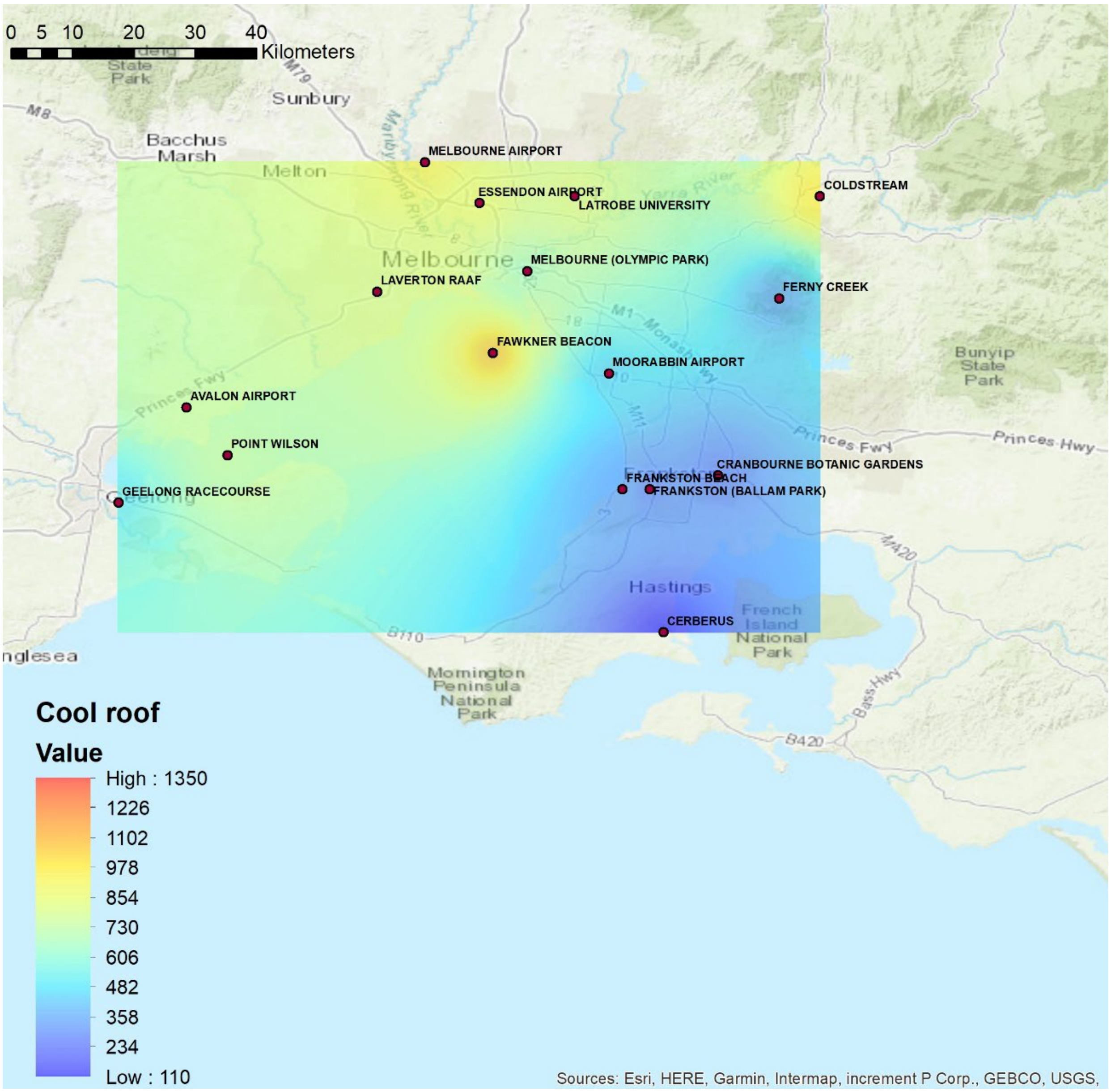


Figure 15 The sum of Cooling degree hours in Jan and Feb of the cool roof cases in the 16 stations in Melbourne.

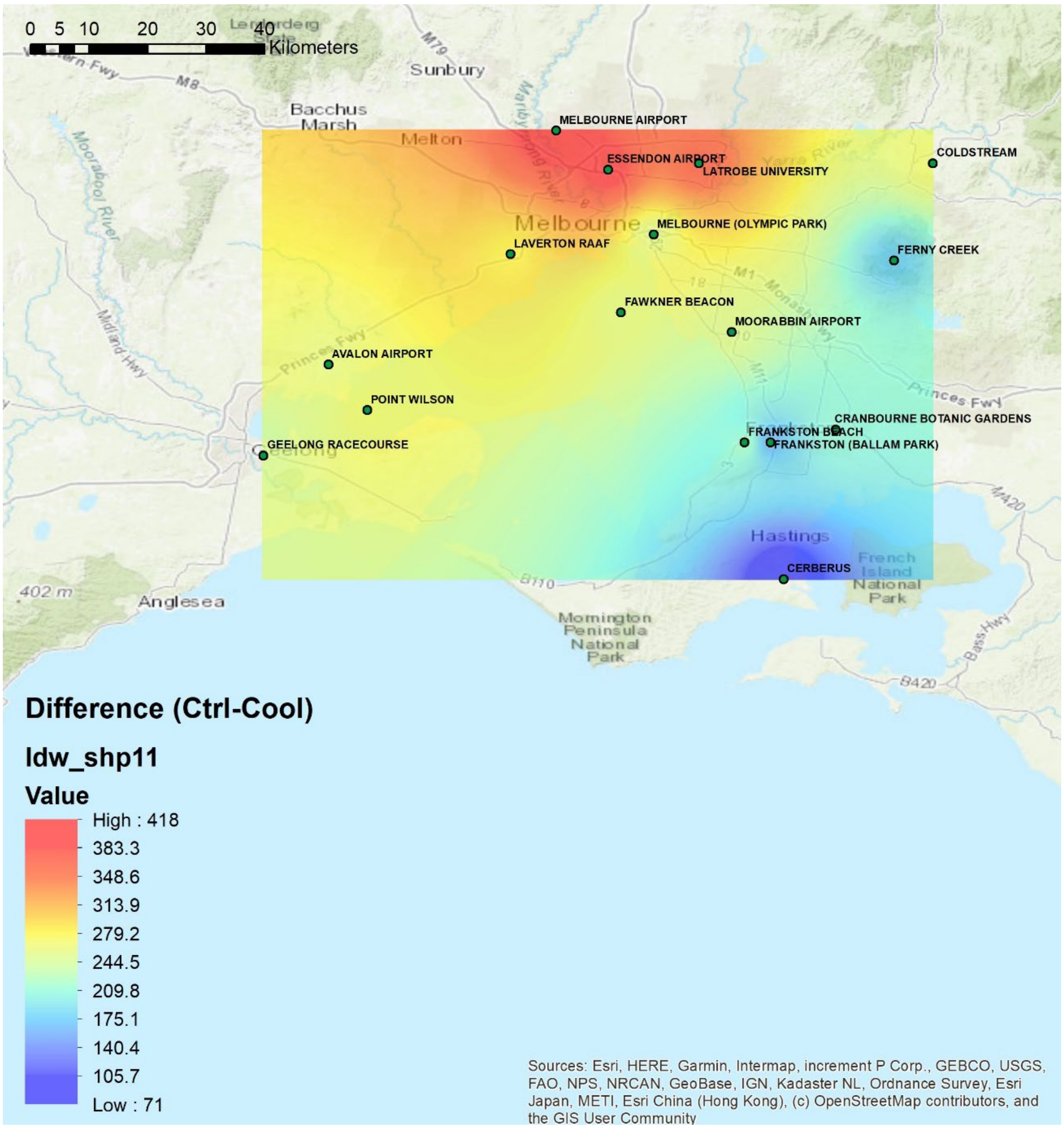
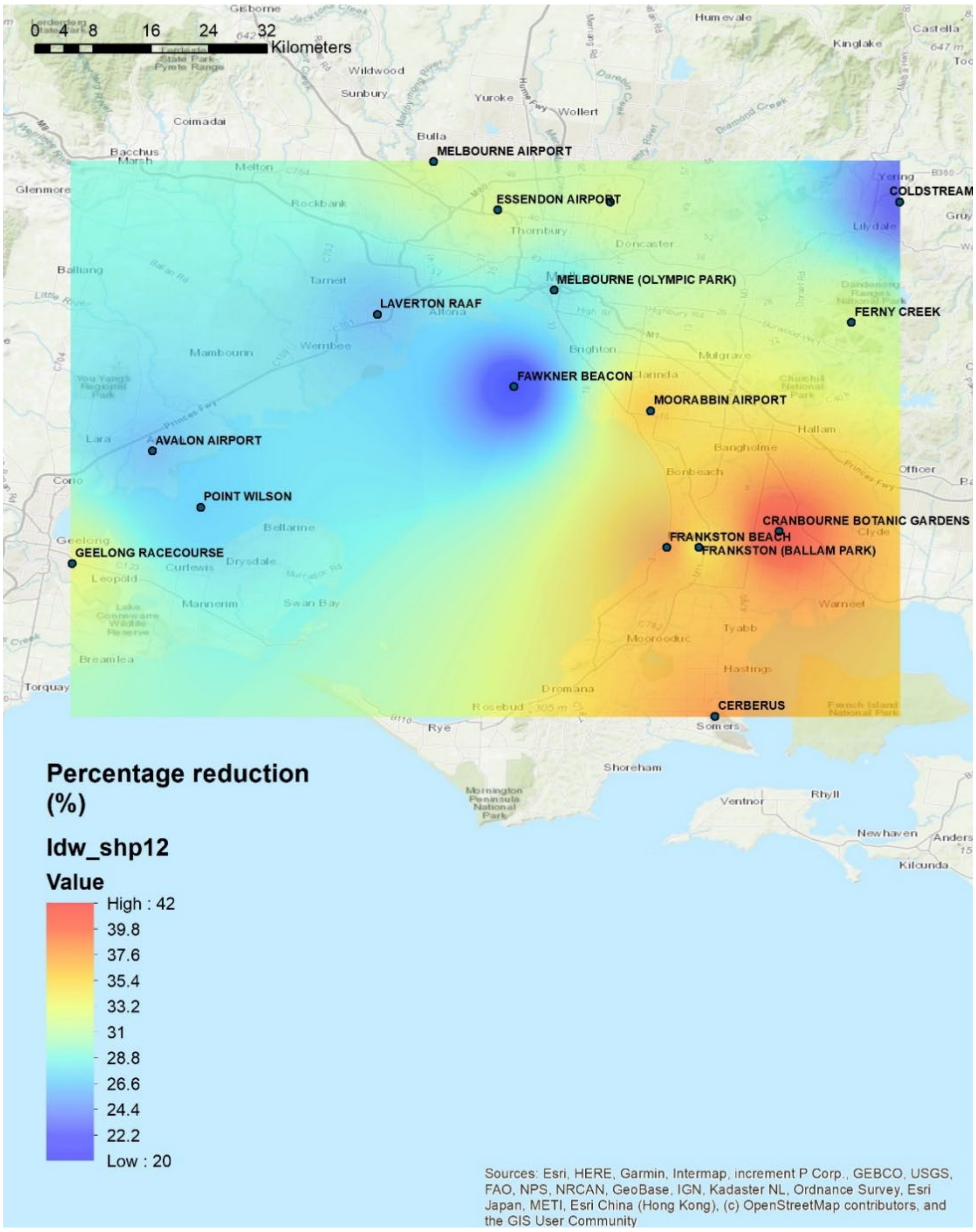


Figure 16 The difference of Cooling degree hours in Jan and Feb between the cool roof cases and control ones in the 16 stations in Melbourne.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 17 The percentage of CDH reduction due to the implementation of the cool roof in the 16 stations in Melbourne.

2.3 Conclusions

- In control cases, CDH ranges from 185.8 to 1328.5, and about half of the data is concentrated in 1000-1300. CDH gradually increases from the southeast of the city to the northwest.
- In cool roof cases, CDH ranges from 114.9 to 1059.8 and about 75% of the data is concentrated in 300-800. Its spatial distribution is also similar to that of the control case.
- In most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in control 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 20.2% to 42.4% with an average value of 31.2%. The percentage of CDH reduction in the original control volume is relatively large in the southeast corner of the city and gradually decreases toward the northwest and northeast.

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 Melbourne. 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 Melbourne during a typical summer and winter period. Specifically, the simulations were performed for seventeen types of buildings and Seven weather stations across Melbourne (in climate zone 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 seven weather stations modeled in Melbourne include (See **Figure 18**):

1) Avalon Airport-Climate zone 6,

2) Essendon Airport-Climate zone 6,

3) Melbourne Airport-Climate zone 6,

4) Coldstream-Climate zone 6,

5) Melbourne (Olympic Park)-Climate zone 6,

6) Moorabbin Airport-Climate zone 6,

7) Frankston Beach-Climate zone 6.

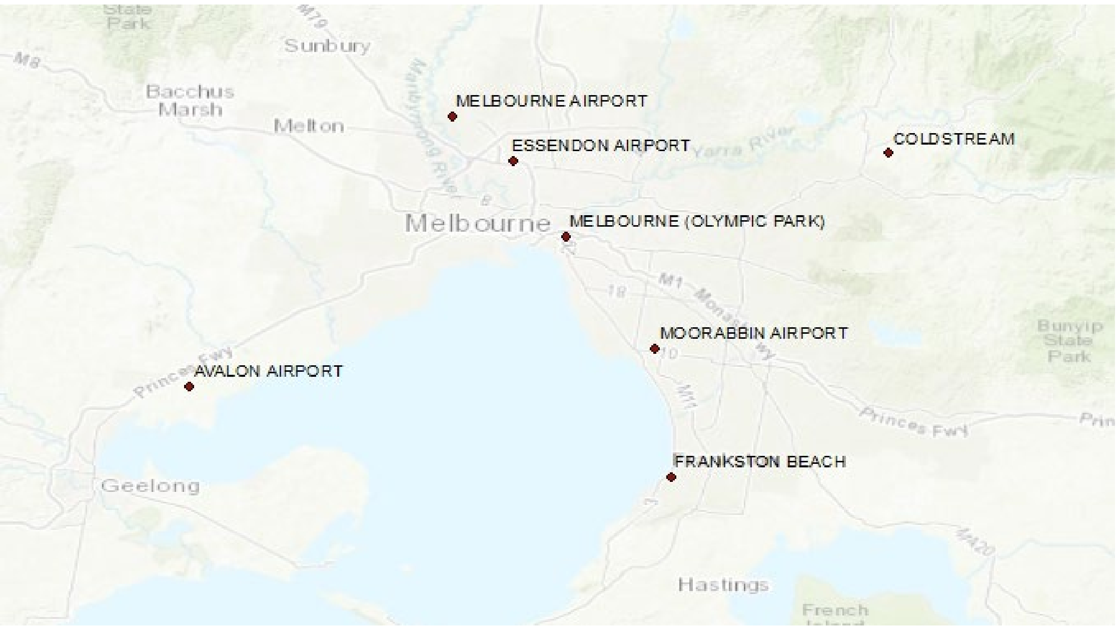


Figure 18 Weather stations in Melbourne in climate zone 6 including Avalon Airport, Essendon Airport, Melbourne Airport, Coldstream, Melbourne (Olympic Park), Moorabbin Airport and Frankston Beach.

The corresponding building specifications for the buildings in climate zones 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 Melbourne. 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 Melbourne (Frankston beach [coldest] and Coldstream [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 °C 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 °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 4***.

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 Melbourne. 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/m²	**kWh/m²**	**%**	**kWh/m²**	**%**
A low-rise office building without roof insulation-existing building	12.6-18.3	6.3-10	47.6-54.9	8.3-11.7	59.3-65.7
A high-rise office building without roof insulation-existing building	7.9-10.9	1.1-2.0	13-18.1	3.0-4.0	32-40.9
A low-rise office building with roof insulation-new building	7.5-10.3	0.6-0.9	7.1-9.4	2.4-3.3	26.8-35.7
A high-rise office building with roof insulation-new building	7.1-9.7	0.1-0.2	1.3-1.9	1.8-2.7	21.5-31.8
A low-rise shopping mall centre-new building	41.8-47.7	1.4-2.0	3.2-4.2	6.9-9.1	15.5-21.4
A mid-rise shopping mall centre-new building	40.2-45.9	0.7-1.0	1.6-2.1	6.2-8.4	14.4-20.4
A high-rise shopping mall centre-new building	39.6-45.3	0.4-0.6	1-1.4	5.9-8.1	14.0-20.0
A low-rise apartment building-new building,	3.4-6.1	0.6-1.0	13.3-18.3	1.8-2.5	40.3-54.0
A mid-rise apartment building-new building	3.1-5.7	0.4-0.6	8.3-11.7	1.5-2.2	36.9-49.5
A high-rise apartment building-new building	2.9-5.4	0.2-0.4	5.2-7.4	1.0-1.4	34.8-47.3
A typical stand-alone house-existing building,	6.6-10.0	3.4-7.5	51.9-75.3	5.1-6.8	67.4-77.4

A typical school building-new building	9.3-13.7	0.5-0.7	4.1-5.6	2.9-3.9	22.6-32.4
A low-rise office building with roof insulation-existing building	9.4-13.3	2.9-4.8	29.4-36.0	4.9-6.4	45.2-52.4
A high-rise office building with roof insulation-existing building	7.4-10.1	0.5-0.9	6.5-9.4	2.3-3.2	26.5-35.9
A low-rise shopping mall centre-existing building	44.7-52.9	6.9-9.8	14.7-18.6	12.2-15.6	25.8-32.4
A high-rise shopping mall centre-existing building	40.2-46.8	2.1-3.2	4.8-6.8	7.5-9.7	17.4-23.7
A stand-alone house-new building.	4.6-7.1	2.1-3.0	37.5-46.9	3.2-4.1	57.1-69.9

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/m^2	**%**	**kWh/m^2**	**kWh/m^2**	**%**

A low-rise office building without roof insulation-existing building	8.8-14.4	40.1-58.5	3.3-7.5	4.0-9.7	12.3-27.6
A high-rise office building without roof insulation-existing building	1.5-2.5	9.4-20.2	0.6-1.5	0.7-1.6	3.1-7.5
A low-rise office building with roof insulation-new building	0.8-1.3	5.6-10.5	0.2-0.8	0.2-1.0	1.2-4.6
A high-rise office building with roof insulation-new building	0.1-0.2	1.0-2.2	0-0.2	0-0.2	0.2-0.9
A low-rise shopping mall centre-new building	3.7-5.0	3.3-4.5	0.1-0.3	3.5-4.9	2.9-4.2
A mid-rise shopping mall centre-new building	1.6-2.3	1.6-2.2	0-0.1	1.6-2.3	1.4-2.1
A high-rise shopping mall centre-new building	1.0-1.5	1.0-1.4	0-0.1	1.0-1.4	0.9-1.3
A low-rise apartment building-new building,	0.8-1.3	10.8-16.7	1.1-1.5	-0.3-0.1	-0.9-0.2
A mid-rise apartment building-new building	0.6-1.2	8.3-14.5	0.6-0.9	-0.1-0.5	-0.3-1.1
A high-rise apartment building-new building	0.2-0.6	4.1-8.6	0.4-0.5	-0.1-0.3	-0.3-0.5
A typical stand-alone house-existing building,	5.6-8.3	48.8-63.5	6.8-8.5	-1.6-1.2	-3.1-2.5
A typical school building-new building	0.8-1.1	3.4-7.0	0.5-0.8	0.2-0.6	0.4-1.3
A low-rise office building with roof insulation-existing building	4.1-6.6	23.4-32.2	1.0-1.7	2.9-4.9	12.4-18.2
A high-rise office building with roof insulation-existing building	0.7-1.2	4.7-7.5	0.2-0.3	0.5-0.8	2.5-4.1
A low-rise shopping mall centre-existing building	25.5-22.1	14.1-19.2	0.4-0.9	12.6-15.0	12.5-18.0

A high-rise shopping mall centre-existing building	4.3-6.4	4.3-6.2	0.1-0.3	4.2-6.2	3.8-5.9
A stand-alone house-new building.	2.9-4.2	33.4-46.7	1.9-2.9	0.8-2.1	2.2-6.5

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 oC 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 °C in a typical summer month**		
	Reference scenario (°C)	**Reference with cool roof scenario (scenario 1) vs reference scenario (°C)**	**Cool roof with modified urban temperature scenario (scenario 2) vs reference scenario (°C)**	**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-	41.1-44.4	8.1-10.0	9-10.4	334-395	193-253	152-197

existing building						
A high-rise office building without roof insulation-existing building	36.4-38.0	1.4-2.1	2.6-2.8	297-424	249-372	186-310
A low-rise office building with roof insulation-new building	37.3-38.6	0.9-1.3	2.1-2.2	345-399	317-359	250-305
A high-rise office building with roof insulation-new building	36.0-37.0	0.2	1.5-1.7	382-427	375-419	286-353
A low-rise shopping mall centre-new building	42.2-45.9	0.5-0.6	2.0	430-455	418-444	382-408
A mid-rise shopping mall centre-new building	41.8-45.4	0.4-0.5	1.8	455-479	451-473	398-425
A high-rise shopping	41.6-45.2	0.4	1.7-1.8	460-482	459-482	404-431

mall centre-new building						
A low-rise apartment building-new building,	31.4-33.8	0.6-0.8	1.7-1.9	135-212	114-191	64-138
A mid-rise apartment building-new building	31.1-33.4	0.3-0.5	1.5-1.6	125-210	108-197	64-133
A high-rise apartment building-new building	30.9-33.1	0.2-0.3	1.4-1.5	114-205	106-198	63-132
A typical stand-alone house-existing building	34.3-37.4	4.1-4.7	5.0-5.6	192-250	96-151	62-121
A typical school building-new building	33.2-34.4	0.5-0.7	1.7-1.8	159-226	154-211	120-173
A low-rise office building with roof insulation-existing building	39.0-41.1	4.3-5.4	5.4-6.0	340-393	236-276	185-240

A high-rise office building with roof insulation-existing building	36.2-37.5	0.8-1.2	2.0-2.1	375-424	341-395	262-332
A low-rise shopping mall centre-existing building	42.7-46.7	2.1-2.7	3.1-3.7	401-436	378-401	333-364
A high-rise shopping mall centre-existing building	41.7-45.4	0.6-0.9	2.0-2.1	448-474	440-465	383-416
A stand-alone house-new building.	32.6-35.4	2.3-2.7	3.3-3.7	171-230	107-161	64-129

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 oC 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 without roof insulation-existing building	9.1-11.1	1.7-1.9	217-230	580-597	276-285	645-656
A high-rise office building without roof insulation-existing building	13.2-14.4	0.3-0.4	69-185	430-517	71-194	439-531
A low-rise office building with roof insulation-new building	12.2-14.6	0.3-0.4	132-163	415-492	138-173	432-509
A high-rise office building	13.6-14.8	0.1	124-164	353-461	124-164	367-461

with roof insulation-new building						
A low-rise shopping mall centre-new building	11.7-13.3	0.2-0.3	32-65	283-355	34-68	287-361
A mid-rise shopping mall centre-new building	12.7-14.1	0.1-0.2	26-63	244-331	27-64	247-334
A high-rise shopping mall centre-new building	13.0-14.3	0.1	26-63	236-325	26-64	236-326
A low-rise apartment building-new building,	11.2-12.3	0.2	N/A	729-731	N/A	735-737
A mid-rise apartment building-new building	11.5-12.6	0.1	N/A	736-738	N/A	737-741
A high-rise apartment building-new building	11.6-12.7	0.1	N/A	737-743	N/A	738-743
A typical stand-alone house-existing building,	8.7-10.5	1.2-1.4	N/A	708-717	N/A	735-743

A typical school building-new building	8.8-11.3	0.1	186-206	664-684	190-210	672-680
A low-rise office building with roof insulation-existing building	10.5-13.0	0.9-1.1	179-200	520-558	200-229	556-595
A high-rise office building with roof insulation-existing building	13.4-14.6	0.2	137-175	398-488	140-179	405-501
A low-rise shopping mall centre-existing building	10.6-12.2	0.5-0.0.7	48-84	350-407	54-86	364-412
A high-rise shopping mall centre-existing building	12.6-13.9	0.2	36-71	269-349	38-72	275-354
A stand-alone house-new building.	9.8-11.6	0.7-0.8	N/A	702-704	N/A	720-728

3.4 Conclusion

The conclusions drawn from this study are:

- 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.
- 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, 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 8.3-11.7 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 2.4-3.3 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 0.1-0.2 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 2.1-3.2 kWh/m2 in an existing high-rise shopping mall centre, which is expected to increase to 7.5-9.7 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 8.8-14.4 kWh/m2, while the corresponding heating penalty is just 3.3-7.5 kWh/m2.
- The annual heating penalty of cool roofs may exceed the cooling benefits in residential buildings in Melbourne. For instance, the heating penalty can be up to 6.8-8.5 kWh/m2 compared to the equivalent 5.6-8.3 KWh/m2 in an existing stand-alone house.
- 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) 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 8.1-10.0 oC.

- 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 9-10.4 oC.
- 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 oC. For instance, the number of hours with an indoor air temperature above 26 oC in a typical low-rise office building without insulation is predicted to reduce from 334-395 hours to 193-253 hours and 152-197 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 2.1-2.2 oC 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 oC during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 oC in new low-rise office building with insulation is predicted to reduce from 345-399 hours to 250-305 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 8.1-10 oC in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 1.7-1.9 oC 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 oC and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.8 oC occurs when the indoor air temperature is 22.8 oC.
- The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 oC 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 oC from 179-200 hours to 200-229 hours in a typical existing low-rise office building with roof insulation.

4. Energy loss through building envelopes in various stations in Melbourne _ 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 Melbourne has been investigated. Specifically, for the 17 building types, the correlation between cooling degree hours (Base 26) and the total 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 7 weather stations in Melbourne 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 total 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 7**.

1) Regarding the total 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, all office building types present an increased cooling load reduction with the increase of cooling degree hours. Similat to the scenario 1, 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.

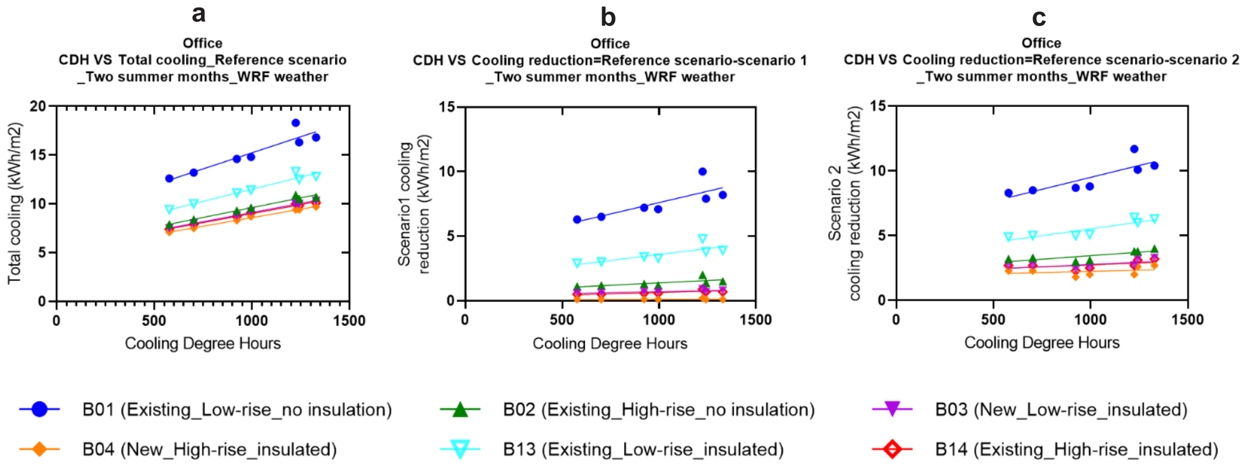


Figure 19 For office building a) The correlation between CDH and the total cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared 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)	0.006588	8.649	Y = 0.006588*X + 8.649
B02 (Existing_High-rise_no insulation)	0.004017	5.602	Y = 0.004017*X + 5.602
B03 (New_Low-rise_insulated)	0.003753	5.366	Y = 0.003753*X + 5.366
B04 (New_High-rise_insulated)	0.003504	5.086	Y = 0.003504*X + 5.086
B13 (Existing_Low-rise_insulated)	0.004972	6.533	Y = 0.004972*X + 6.533
B14 (Existing_High-rise_insulated)	0.003682	5.322	Y = 0.003682*X + 5.322

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B01 (Existing_Low-rise_no insulation)	0.003505	4.099	Y = 0.003505*X + 4.099
B02 (Existing_High-rise_no insulation)	0.0007393	0.6473	Y = 0.0007393*X + 0.6473
B03 (New_Low-rise_insulated)	0.0003057	0.409	Y = 0.0003057*X + 0.409
B04 (New_High-rise_insulated)	0.00004604	0.068	Y = 4.604e-005*X + 0.068
B13 (Existing_Low-rise_insulated)	0.001851	1.737	Y = 0.001851*X + 1.737
B14 (Existing_High-rise_insulated)	0.0004012	0.242	Y = 0.0004012*X + 0.242

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B01 (Existing_Low-rise_no insulation)	0.003680	5.824	Y = 0.003680*X + 5.824
B02 (Existing_High-rise_no insulation)	0.001082	2.376	Y = 0.001082*X + 2.376
B03 (New_Low-rise_insulated)	0.0006987	2.088	Y = 0.0006987*X + 2.088
B04 (New_High-rise_insulated)	0.0003590	1.884	Y = 0.0003590*X + 1.884

B13 (Existing_Low-rise_insulated)	0.002098	3.433	Y = 0.002098*X + 3.433
B14 (Existing_High-rise_insulated)	0.0005976	2.146	Y = 0.0005976*X + 2.146

4.3 Shopping mall centers

The correlation between cooling degree hours and the total 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 20** and **Table 8**.

1) Regarding the total 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. A higher increase rate is 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, except B15 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.

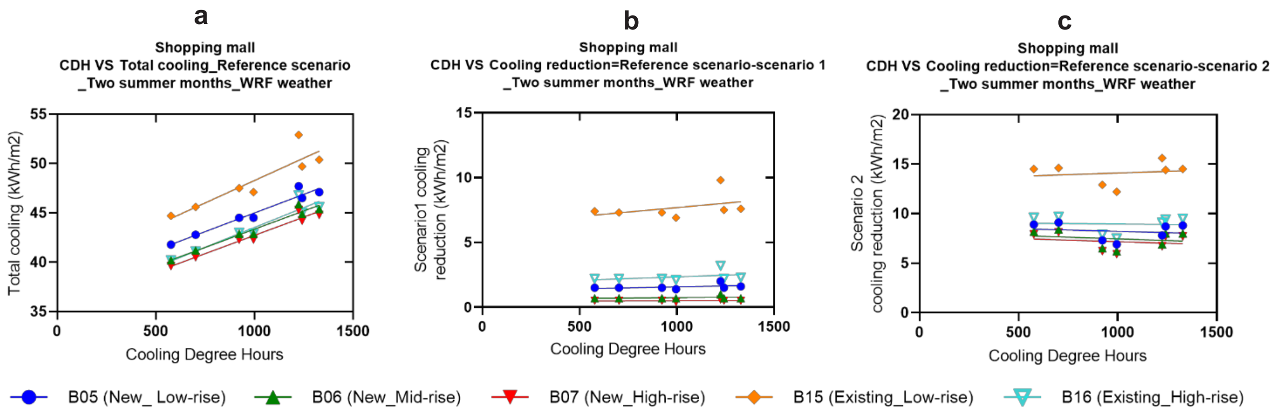


Figure 20 For shopping mall center a) The correlation between CDH and the total cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 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)	0.007559	37.44	Y = 0.007559*X + 37.44
B06 (New_Mid-rise)	0.007400	35.95	Y = 0.007400*X + 35.95
B07 (New_High-rise)	0.007411	35.31	Y = 0.007411*X + 35.31
B15 (Existing_Low-rise)	0.009083	39.20	Y = 0.009083*X + 39.20
B16 (Existing_High-rise)	0.008043	35.48	Y = 0.008043*X + 35.48

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.0002981	1.274	Y = 0.0002981*X + 1.274
B06 (New_Mid-rise)	0.0001381	0.605	Y = 0.0001381*X + 0.605
B07 (New_High-rise)	0.0000468	0.453	Y = 4.680e-005*X + 0.453
B15 (Existing_Low-rise)	0.001369	6.319	Y = 0.001369*X + 6.319
B16 (Existing_High-rise)	0.0005283	1.815	Y = 0.0005283*X + 1.815

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	-0.0005298	8.743	Y = -0.0005298*X + 8.743
B06 (New_Mid-rise)	-0.0006735	8.130	Y = -0.0006735*X + 8.130

B07 (New_High-rise)	-0.0006275	7.798	Y = -0.0006275*X + 7.798
B15 (Existing_Low-rise)	0.0006624	13.44	Y = 0.0006624*X + 13.44
B16 (Existing_High-rise)	-0.0001769	9.134	Y = -0.0001769*X + 9.134

4.4 Residential building

The correlation between cooling degree hours and the total 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 21** and **Table 9**.

1) Regarding the total 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 indicating that 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. 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.

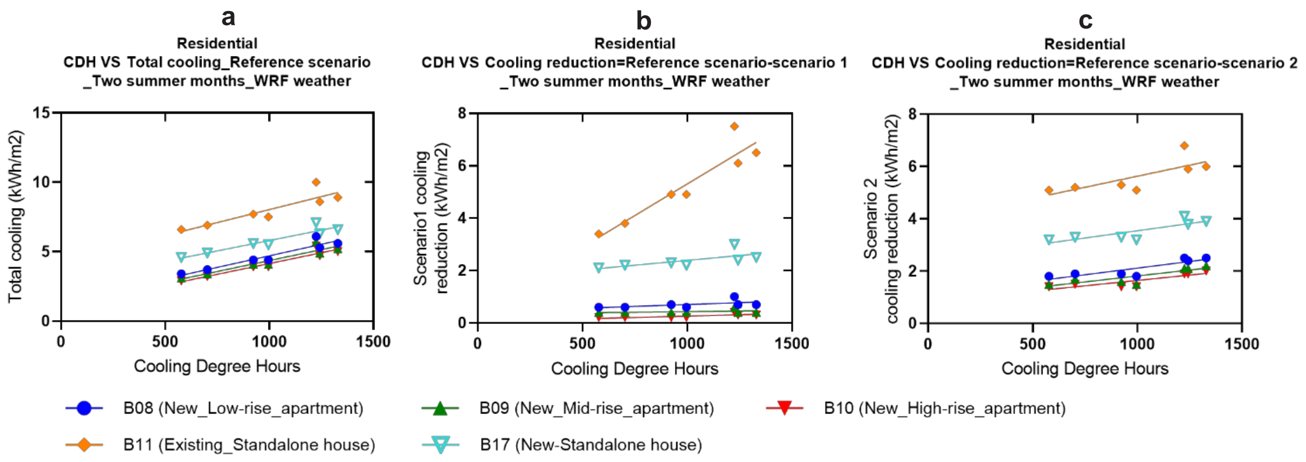


Figure 21 For residential building a) The correlation between CDH and the total cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 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)	0.003317	1.387	Y = 0.003317*X + 1.387
B09 (New_Mid-rise_apartment)	0.003155	1.206	Y = 0.003155*X + 1.206
B10 (New_High-rise_apartment)	0.003109	1.038	Y = 0.003109*X + 1.038
B11 (Existing_Standalone house)	0.003742	4.291	Y = 0.003742*X + 4.291
B17 (New-Standalone house)	0.002993	2.811	Y = 0.002993*X + 2.811

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.0002853	0.415	Y = 0.0002853*X + 0.4150
B09 (New_Mid-rise_apartment)	0.00009208	0.337	Y = 9.208e-005*X + 0.337
B10 (New_High-rise_apartment)	0.0002088	0.049	Y = 0.0002088*X + 0.049
B11 (Existing_Standalone house)	0.004821	0.485	Y = 0.004821*X + 0.485

B17 (New-Standalone house)	0.0007393	1.647	Y = 0.0007393*X + 1.647

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.001014	1.102	Y = 0.001014*X + 1.102
B09 (New_Mid-rise_apartment)	0.0009071	0.908	Y = 0.0009071*X + 0.908
B10 (New_High-rise_apartment)	0.0008204	0.824	Y = 0.0008204*X + 0.824
B11 (Existing_Standalone house)	0.001692	3.939	Y = 0.001692*X + 3.939
B17 (New-Standalone house)	0.001106	2.438	Y = 0.001106*X + 2.438

4.5 School

School load reduction in scenario 1 and scenario 2 for the one building type (B12_Existing) is shown in **Figure 22** and **Table 10**. 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 total 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 an increased cooling load reduction with the increase of cooling degree hours.

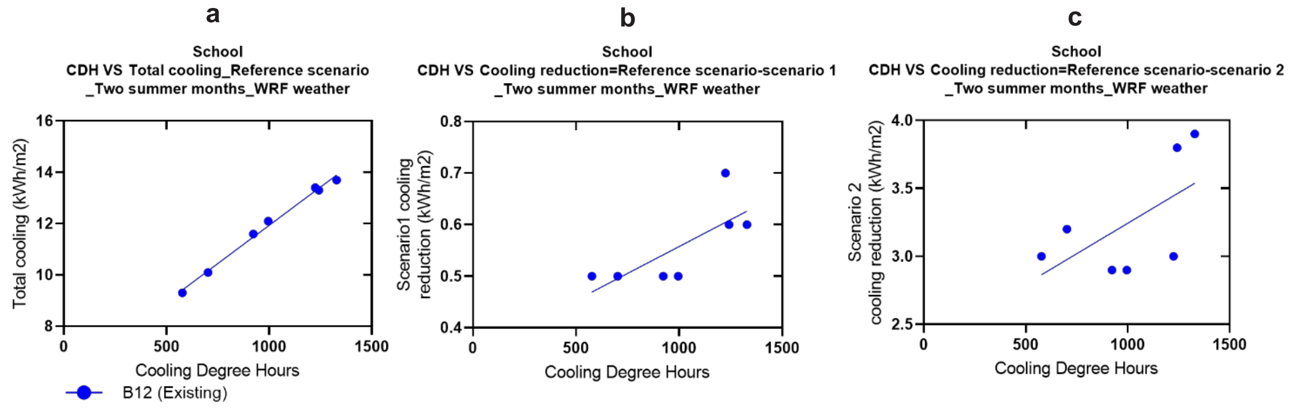


Figure 22 For school a) The correlation between CDH and the total cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared to 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)	0.005962	5.974	Y = 0.005962*X + 5.974

b. Scenario 1 cooling reduction	Slope	Y-intercept	Equation
B12 (Existing)	0.0002088	0.3486	Y = 0.0002088*X + 0.3486

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B12 (Existing)	0.0008961	2.348	Y = 0.0008961*X + 2.348

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, 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.

- A general ranking of the heat loss coefficients of these buildings from low to high is shopping mall center, standalone house, apartment, and office (**Table 11**).

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

Building No.	Heat loss coefficient
B17 (New-Standalone house)	0.002993
B10 (New_High-rise_apartment)	0.003109
B09 (New_Mid-rise_apartment)	0.003155
B08 (New_Low-rise_apartment)	0.003317
B04 (New_High-rise_insulated)	0.003504
B14 (Existing_High-rise_insulated)	0.003682
B11 (Existing_Standalone house)	0.003742
B03 (New_Low-rise_insulated)	0.003753
B02 (Existing_High-rise_no insulation)	0.004017
B13 (Existing_Low-rise_insulated)	0.004972
B12 (Existing)	0.005962
B01 (Existing_Low-rise_no insulation)	0.006588
B06 (New_Mid-rise)	0.0074
B07 (New_High-rise)	0.007411
B05 (New_ Low-rise)	0.007559
B16 (Existing_High-rise)	0.008043
B15 (Existing_Low-rise)	0.009083

5. Conclusions

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

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

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 Melbourne.
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 Melbourne.
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) It is observed that a sturdy urban heat island (UHI) phenomenon is developed during heatwave over high-density residential areas of Melbourne city. The magnitude of the phenomena may exceed 5°C. The intensity and the spatio-temporal characteristics of the phenomena are strappingly influenced by the synoptic weather conditions and in particular the advance of the sea breeze and the westerly winds from the desert area. The potential existence of an additional heating mechanism, like the advection of warm air from nearby spaces, could intensify the strength of the problems of urban heating.
2) An increase of albedo fraction in Melbourne city can decrease the peak ambient temperature up to 2.1°C and surface temperature up to 11.1°C. It was noted that significant temperature differences subsist between the eastern and western parts of the city. The spatio-temporal patterns of the ambient temperature distribution in the city were found to depend highly on the synoptic climatic conditions and the potency of the advection flows.
3) The maximum decrease of sensible heat and latent heat flux was 292.8 Wm-2 and 15.1 Wm-2, respectively.
4) The highest decrease of wind speeds up to -3.4 ms-1. Thus, higher urban albedo values decrease the advective flow between the city and its surroundings surface improving the cooling potential of reflective materials. Modification of the urban albedo in Melbourne results in an average 1590.6m reduction up to of

the PBL heights over the city and may increase the concentration of pollutants at ground level and subsequently increase the health problems.

5) High intensities of the UHI phenomenon were associated with the existence of a sea breeze in the seaward parts of the city, decreasing the temperature of the coastal zone, combined with westerly winds from the inland that warm up the western zones of the city.
6) In control cases, CDH ranges from 185.8 to 1328.5, and about half of the data is concentrated in 1000-1300. CDH gradually increases from the southeast of the city to the northwest.
7) In cool roof cases, CDH ranges from 114.9 to 1059.8 and about 75% of the data is concentrated in 300-800. Its spatial distribution is also similar to that of the control case.
8) In most instances, the decrease of CDH due to the implementation of a cool roof increases with the increase of CDH in control cases, indicating that a cool roof is generally more effective when applied in hotter regions.
9) The percentage of CDH reduction due to the implementation of the cool roof ranges from 20.2% to 42.4% with an average value of 31.2%. The percentage of CDH reduction in the original control volume is relatively large in the southeast corner of the city and gradually decreases toward the northwest and northeast.
10) 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.
11) 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, 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 8.3-11.7 kWh/m2.
12) 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 2.4-3.3 kWh/m2 in a typical new low-rise office building.
13) 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 0.1-0.2 kWh/m2 for a new high-rise office building with insulation.

14) 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 2.1-3.2 kWh/m2 in an existing high-rise shopping mall centre, which is expected to increase to 7.5-9.7 kWh/m2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).
15) 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 8.8-14.4 kWh/m2, while the corresponding heating penalty is just 3.3-7.5 kWh/m2.
16) The annual heating penalty of cool roofs may exceed the cooling benefits in residential buildings in Melbourne. For instance, the heating penalty can be up to 6.8-8.5 kWh/m2 compared to the equivalent 5.6-8.3 KWh/m2 in an existing stand-alone house.
17) 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) 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 8.1-10.0 oC.
18) 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 9-10.4 oC.
19) 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 oC. For instance, the number of hours with an indoor air temperature above 26 oC in a typical low-rise office building without insulation is predicted to reduce from 334-395 hours to 193-253 hours and 152-197 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
20) 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 2.1-2.2 oC in a typical new low-rise office building.

21) 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 oC during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 oC in new low-rise office building with insulation is predicted to reduce from 345-399 hours to 250-305 hours when cool roofs are implemented in both individual building and at the whole urban scale (scenario 2).
22) 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 8.1-10 oC in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 1.7-1.9 oC during a typical winter month.
23) 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 oC and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.8 oC occurs when the indoor air temperature is 22.8 oC.
24) The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 oC 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 oC from 179-200 hours to 200-229 hours in a typical existing low-rise office building with roof insulation.
25) 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.
26) 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.

27) 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.
28) A general ranking of the heat loss coefficients of these buildings from low to high is shopping mall center, standalone house, apartment, and office.

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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	-1.9	-2.1	-1.7	-1.8
Minimum	-0.2	-0.1	-0.3	-0.2
Average of January	-0.4	-0.9	-0.5	-0.7
Average of February	-0.4	-0.8	-0.7	-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	-7.1	-11.1	-3.3	-3.2
Minimum	-0.4	-0.7	-0.2	-0.5
Average of January	-1.0	-6.3	-3.0	-2.9
Average of February	-0.9	-5.8	-2.6	-2.7

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	-58.8	-292.8	-118.0	-105.8
Minimum	-8.6	-67.1	-22.2	-31.2
Average of January	-50.4	-178.6	-62.2	-74.6
Average of February	-49.7	-171.6	-56.9	-69.2

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	-6.4	-15.1	-5.2	-7.1
Minimum	-2.1	-1.1	-1.6	-1.2
Average of January	-3.8	-12.8	-2.3	-5.2
Average of February	-4.2	-11.9	-2.5	-4.3

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	-1.8	-3.4	-2.2	-2.6
Minimum	-0.7	-1.1	-1.6	-0.3
Average of January	-0.8	-1.4	-0.9	-1.6
Average of February	-1.2	-2.6	-1.6	-1.9

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	-235.7	-1590.6	-986.5	-407.6
Minimum	-49.8	-29.7	-29.6	-12.4
Average of January	-34.9	-228.7	-124.7	-102.6
Average of February	-16.1	-284.1	-112.4	-95.6

8. Appendix: Building characteristics_ Cool roofs project simulations inputs _ Climate zone 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
Building ID	**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**
Building Type	Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing
Floor area (m2)	1200			1100		1100
Aspect ratio	1:1			2:1		2:1
Window to Wall Ratio (WWR)	0.6			0.3		0.32
Year Built	1990		2018	1990	2018	1990
Number of stories	2 (L)			2 (L)	2 (L)	3
	-			4 (M)	-	

Low rise (L), mid-rise (M), high-rise (H)		10 (H)	6 (H)	4 (H)	
Building height (m) ***Low rise (L), mid-rise (M), high-rise (H)***		7.2 (L)	13.8 (L)	13.8 (L)	12.6
			27.6 (M)		
		36 (H)	41.4 (H)	41.4 (H)	
Lighting power density (W/m2) **(before operation profile and radiant fraction)**		4.5	14		4.5
Lighting internal gains (W/m2) ***(radiant fraction 0.42)***	Hourly Max	2.61	8.12		2.76
	Hourly Mean	1.45	4.77		1.13
	Hourly Min	0.39	0.81		0.15
Equipment gains ***(before operation profile)***		11	5		5
Equipment internal gains (W/m2)	Hourly Max	11	3.5		4.75
	Hourly Mean	6.16	2.31		1.86
	Hourly Min	2.75	0.5		0.25
Occupancy density (person/m2)		0.1	0.2		0.5

Continues

Table 23 Operation schedules

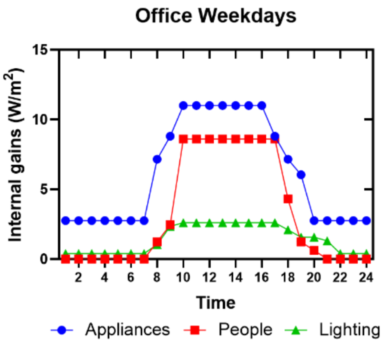
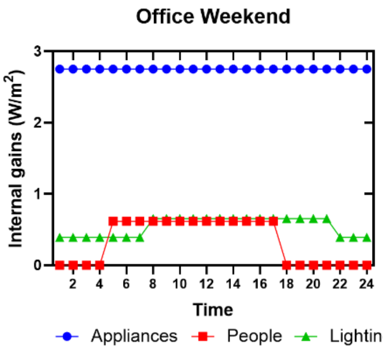
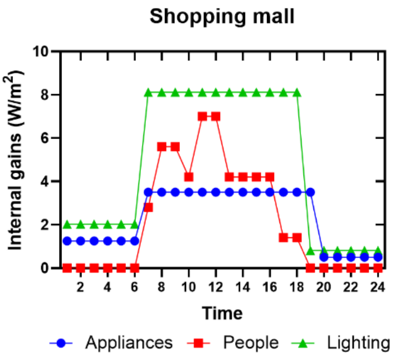
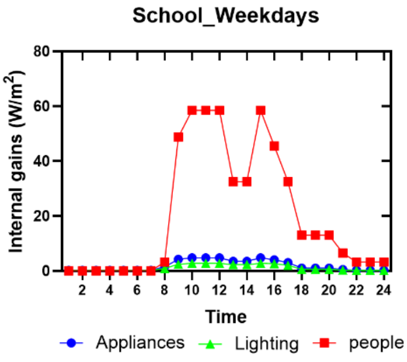
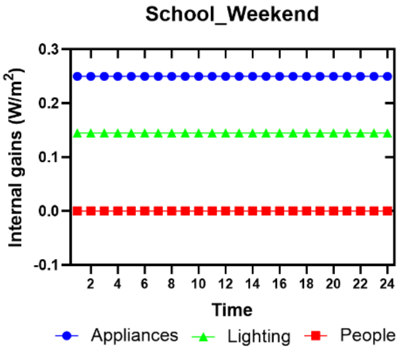
	Office			Shopping mall		School
Building ID	**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**
Building Type	Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing
Intensity of internal heat gains (W/m2) **(from NatHERS and NCC 2019)**	 					 

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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	3.2	0.5	3.2	0.5	3.2	2	4.6	3.2
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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