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Research plan & progress report

COOL ROOFS COST BENEFIT ANALYSIS

Volume 5 - Climatic and Energy Performance of Cool Roofs in Brisbane

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Contents

Executive summary

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

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

<u>Phase 1: Mesoscale simulation of the current climatic conditions.</u> In the first phase, a full mesoscale climatic model for the entire city of Brisbane 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: <u>Mesoscale simulation of the climatic conditions when cool roofs are implemented at the city scale</u>. 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.

<u>Phase 3: Cooling degree hours calculation</u>. 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 31 weather stations in Brisbane 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 31 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 thirty-one weather stations across Brisbane. 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 Brisbane 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 Brisbane and the results have been compared. Specifically, for the seventeen building types, the linear regression has been generated between CDH and the sensible 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 Brisbane.

Collectively, the following conclusions have been drawn:

1) The use of a cool roof at the city scale reduces the maximum peak ambient temperature by 2.5ºC over CBD and eastern Brisbane compared to the existing conditions, reference case.
2) The maximum decrease the sensible heat flux is 175.0 Wm-2 over urban domain (Hamilton, Doboy, Morningside and the Central) and average decrease is 160.0 Wm-2 at 14:00 LT over central part of the city.
3) Alteration of the urban albedo in Brisbane results in a solemn average reduction up to 735.6 m of the PBL heights over city and may increase the concentration of pollutants at ground level
4) Cooling degree hours indicating the climatic severity during the summer period range from 956.6 to 4167.1 and about 40% of the data is concentrated in 1800 - 2000. CDH gradually increases from the east of the city to the west.
5) When cool roofs are used in the city, the percentage of CDH reduction due to the implementation of the cool roof ranges from 16% to 62% with an average value of 34.6%. The percentage of CDH reduction in the original control volume is relatively large in the east of the city, and gradually decreases toward the west.
6) In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in individual buildings (scenario 1) is quite significant. For instance, application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 11.3-15.6 kWh/m2.
7) In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in both individual buildings and at the whole urban area (scenario 2) is quite significant. For instance, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 18.7-21.3 kWh/m2.
8) In existing buildings without insulation/with low insulation level, the cooling load reduction of the cool roofs is remarkable even for the high-rise buildings. For instance, the application of cool roofs on the individual building (scenario 1) and both individual buildings and at the whole urban area (scenario 2) is expected to

decrease the cooling loads of a high-rise office building without roof insulation by 2.0-3.0 kWh/m2 and 8.6-10.4 kWh/m2, respectively.

9) 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 in both individual building and at the whole urban area (scenario 2) is predicted to be 7.3-9.2 kWh/m2 in a typical new low-rise office building.
10) In new high-rise buildings with high insulation level, application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.2-0.3 kWh/m2 for new high-rise office buildings with insulation.
11) In high-rise buildings, the cooling load reduction through application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.4-0.5 kWh/m2 in a new high-rise apartment building, which is expected to increase to 6.7-9.1 kWh/m2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).
12) The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in all types of buildings. For instance, the annual cooling load saving in a low-rise office building without insulation is 34.7-52.7 kWh/m2, while the corresponding heating penalty is just 0.5-0.9 kWh/m2.
13) 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 9.0-10.3 oC.
14) In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in both individual building and at the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and at the whole urban area (scenario 2) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 9.6-11.1 oC.
15) 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 1.7-2.1 oC in a typical new low-rise office building.

16) In residential buildings 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 existing stand-alone house is predicted to reduce from 573-592 hours to 530-565 hours and 463-490 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.
17) In non-residential buildings and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual buildings and at the whole urban area (scenario 2) has low or no impact on reducing 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 mid-rise shopping mall centre is predicted to remain unchanged after application of cool roofs.
18) The maximum indoor air temperature reduction by cool roofs in a typical winter period is significantly lower than the maximum indoor air temperature reduction during a typical summer period. For instance, the maximum indoor air temperature reduction by application cool roofs in individual buildings in low-rise office building without roof insulation is predicted to be 9-10.3 oC in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 3.4-3.6 oC during a typical winter month.
19) The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 oC and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.4 oC occurs when the indoor air temperature is 29.3 oC.
20) 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 18-29 hours to 26-31 hours in a typical existing low-rise office building with roof insulation.

Objectives

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

5) To evaluate the existing reference climatic conditions in the city of Brisbane, understand the characteristics of the urban overheating, and develop detailed climatic data through advanced mesoscale climatic modelling.
6) 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.
7) To investigates the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Brisbane.
8) To understand the way of how specific building characteristics affect the performance of cool roofs and the advantages of applying cool roofs in various stations.

Methodology

The whole study involved the following phases:

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

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

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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 Brisbane.

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

1.1 Introduction

Urbanization augments the risks associated with extreme events. Urbanization suppresses evaporative cooling from urban surface and amplifies heatwave intensity with a strong influence on minimum near surface temperatures. Heat waves are documented as a sober threat for human health worldwide; with urban areas being more vulnerable due to the urban warming effect. Extreme urban heatalong with regional climate changecan affect the health and wellbeing of human, the environmental quality, and the socio-economic performance of cities. Higher magnitude of urban temperatures (and for longer periods) isconsiderably 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, intensity, frequency, and duration of extreme temperature, prolonged thermal distress and heat stress, and increased heat-related mortality and morbidity (Santamouris et al., 2017). To undertake the extreme urban heat and perk up the quality and comfort levels of outdoor and indoor environments, it is imperative to investigate and evaluate the performance of cool roof strategies at city-scale during an extreme heat condition.

1.2 Objectives of the study

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

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

1.3 Domain and method of simulation

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

Table 1 WRF/SLUCM Model configuration

Configuration	**Domain 01 (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)		

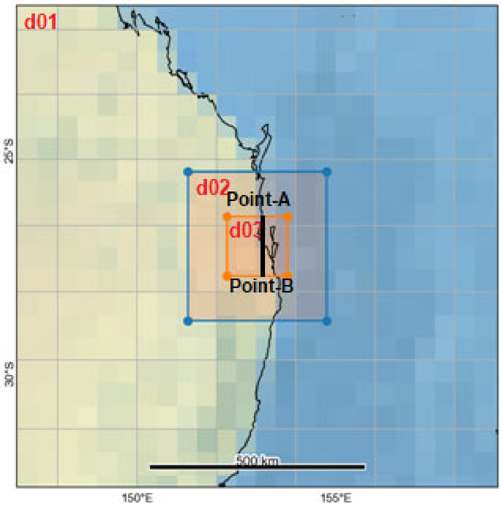


Figure 1 WRF domain shows (a) dynamical downscaling with domain 1 (d01) as outermost parent domain with 4500m grid spacing, domain 2 (d02) with 1500m grid spacing and, an innermost domain 3 (d03) with 500m grid spacing; (b) innermost d03 with 500m grid spacing which encompasses the Greater Brisbane. 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 the cool roof for Brisbane

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

1.4 Model evaluation

To evaluate the performance of the WRF-SLUCM system, we compared hourly simulated 2-m ambient air temperature against local measurements for the control case simulation over urban grid cells in the innermost domain. A statistical comparison of the mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE), correlation coefficient (r), and the index of agreement (IOA) for hourly 2m air temperature for the 24-hour duration are listed in **Table 3** and **Figure 2.** The model evaluation is based on correlation between the WRF model and observations for 2m-temperature across the diurnal cycle. The coupled WRF-SLUCM model accurately captures the temperature observed at different stations (mean R=0.902; mean bias=0.96) for Archerfield, Brisbane, Brisbane Airport and Cape Moreton. The base case simulation produced urban meteorological conditions well and statistically, agreed with local observation ($p<0.05$). The simulated average UHI intensity varied from 2.3°C to5.5°C in the high-density urban residential areas relative to rural (i.e., surrounding) landscapes, as a function of the prevailing local weather conditions. The range of MBE and RMSE of air temperature was 0.6°C to 1.4°C and 0.8°C to 2.7°C, respectively. The range of IOA was 0.8 to 0.9 with average values of 0.96 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 utility of the UCM scheme. The well-simulated daytime warming is balanced by equally well-simulated nighttime cooling, resulting in a diurnal range that is of similar magnitude to observations. The comfort level of different dew points is >19°C for the stations represents the uncomfortable situation in urban environment. The difference is identical when quantifying impacts on local meteorological stations. Although WRF does not display considerable warm (comfort) bias over urban locales, the representation of the 24-h averaged diurnal range of dew point temperature is well captured. In addition, model biases are most likely caused by: (a) lack of proper urban morphological representation, and (b) uncertainties in model physical schemes, input data used, and locally meaningful urban biophysical parameters. Nevertheless, our initial evaluation highlights that the model can replicate the urban environment realistically, including a well-simulated evolution of the diurnal cycle of both near-surface temperature and dew-point, and the model framework can be used to predict the regional meteorology and investigate the regional influence of cool roof strategies.

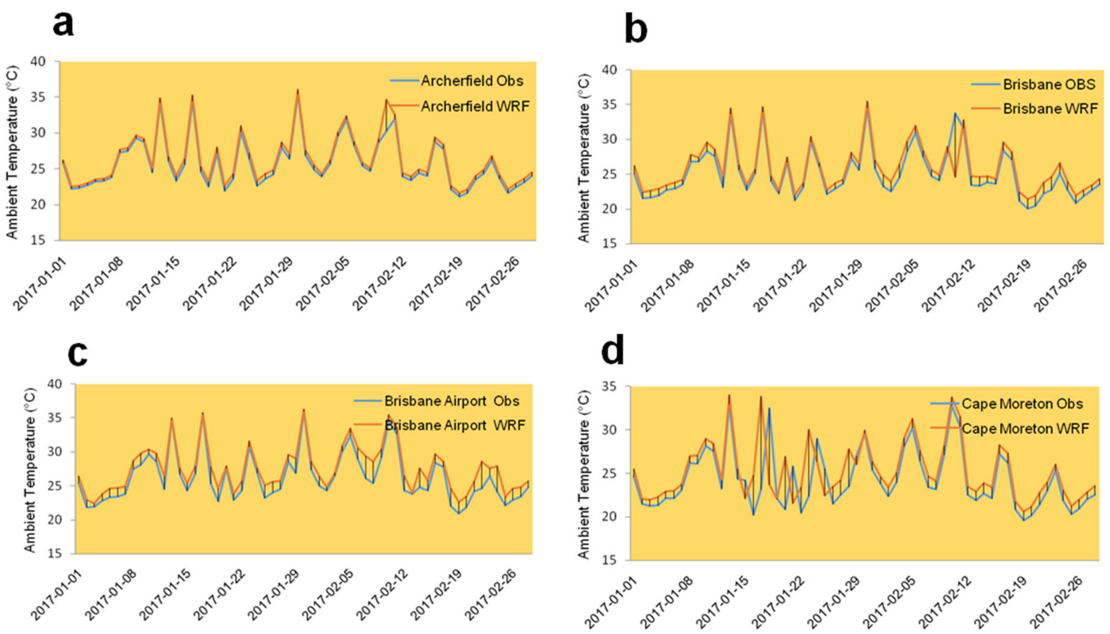


Figure 2 Validation of the WRF Model and the corresponding observed air temperature for the 24-hour average duration for four local meteorological stations: (a) Archerfield, (b) Brisbane, (c) Brisbane Airport, and (d) CapeMoreton.

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

Parameters	**Local weather stations**			
	Archerfield	Brisbane	Brisbane Airport	Cape Moreton
Correlation coefficient	0.989	0.922	0.973	0.721
Mean Bias error	-0.63	-0.84	-1.4	-1.0
Mean absolute error	-0.625	-0.825	-1.367	-1.021
Root mean square error	0.809	1.584	1.596	2.667
Index of Agreement	0.986	0.945	0.949	0.829

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 Brisbane to ensure the robustness and accuracy of the model. The results of base case are presented for two months of summer. The simulated summer period is from January 1st, 2017 to March, 2017. The mitigation scenario presented here has been analyzed during summer period for 59 days of two months (January and February). These two months was warmer than average during 2017 for both daytime and overnight temperatures in the Greater Brisbane. Temperatures in Greater Brisbane were very warm overall in 2017, with Brisbane's mean temperature the warmest on record. The mean maximum temperature equaled the record set in 2016 (Bureau of Meteorology, Australia, 2017a, b).

1.5.1 Ambient temperatures

Ambient temperatures can be calculated from the surface energy balance flux partitions in the WRF-SLUCM urban modeling system. Under the cool roof materials scenario, the ambient temperature at 14:00 ranges between 25.2 °C and 41.4 °C. At 06:00 LT, it varies between 20.7°C and 28.2°C .The results show that the use of cool roof materials maximum reduces the peak ambient temperature ($T_{ambient}$) by 2.5ºC over high density residential areas and 1.8°C for whole urban average compared to control case. The average ambient temperature reduction at 14:00 over the whole summer is 1.1°C. The maximum decrease of the ambient temperature during 18:00 LT is 1.3°C near coastal fringe (Manly Hamilton, and Wynnum) and average decrease of summer months is 0.9°C (**Figure 3**).

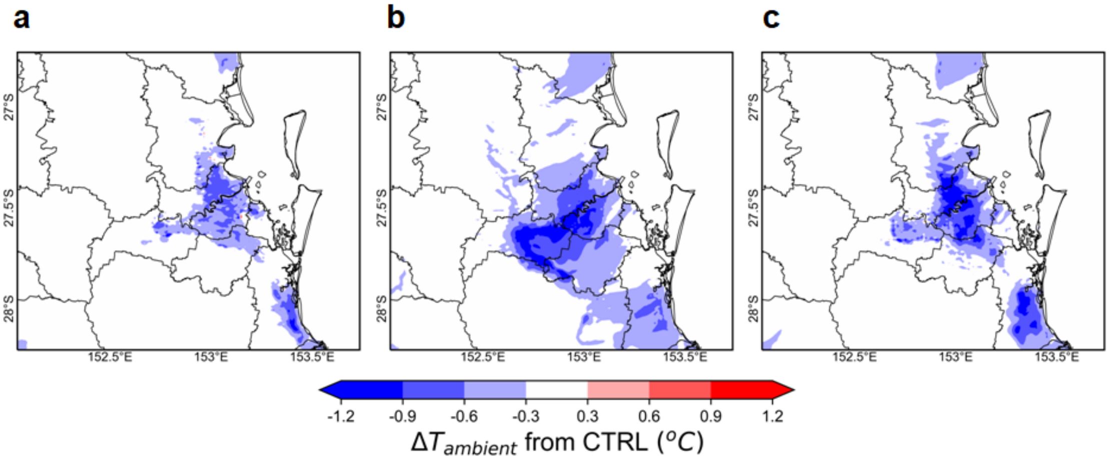


Figure 3 Reduction of ambient temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.2 Surface temperatures

Under the cool roof scenario, the surface temperature (Tsurface) ranges between 27.2°C to 46.8°C at 14:00, 22.7°C to 38.4°C at 18:00 LT and 21.5°C to 33.2°C at 6:00 LT over city. The maximum decrease of surface temperature during 14:00 LT is 6.1°C over urban surface with average reduction of whole summer is about 5.6 over urban domain. But, in the high-density residential urban area, the maximum decrease of surface temperature is about 6.8°C during 14:00 LT of summer months. The maximum surface temperature reduction at 18:00 LT is about 5.0°C near the coastal fringe areas of the city. The average decrease of urban surface temperature is 4.5°C at 18:00 LT and 1.9°C at 06:00 LT compare to control case for the whole summer month in city (**Figure 4**).

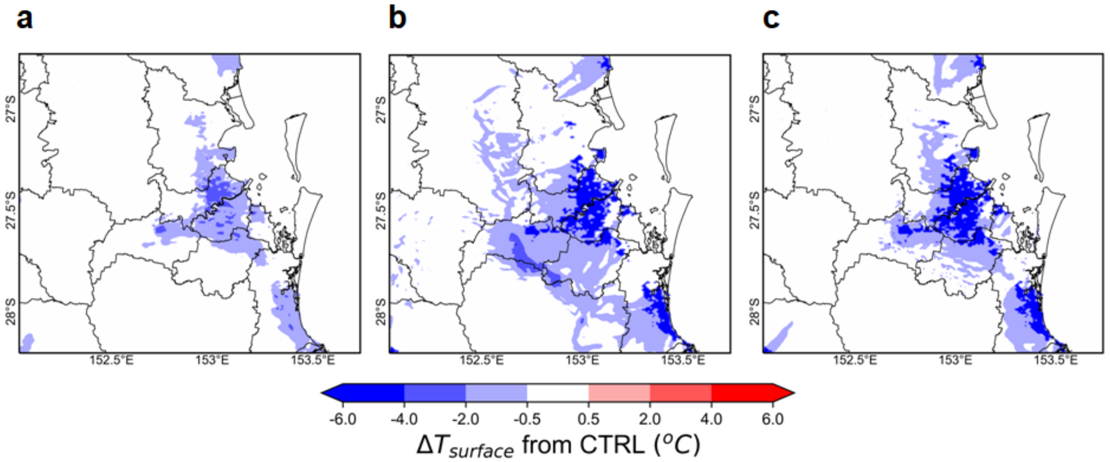


Figure 4 Reduction of surface temperature at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.3 Sensible heat flux

The WRF-SLUCM reasonable computed the sensible heat flux from the urban surface. Under the cool roof scenario, the maximum and average sensible heat flux (Qsensible) over city during 14:00 LT is 474.6 Wm^{-2} and 412.4 Wm-2,. At 18:00LT, the average sensible heat flux is 108.7 Wm-2. The maximum decrease the sensible heat flux is 175.0 Wm-2over urban domain (Hamilton, Doboy, Morningside and the Central) and average decrease is 160.0 Wm-2 at 14:00 LT over central part of the city. In the high density residential urban area, the maximum and average reduction of sensible heat flux is about 184.6 Wm-2 and 169.2 Wm-2 during 14:00 LT of summer month compare to control case. At 18:00LT, the maximum and average reduction of summer month of sensible heat flux is 69.9 Wm-2and 63.8 Wm-2over the urban domain **(Figure 5)**.

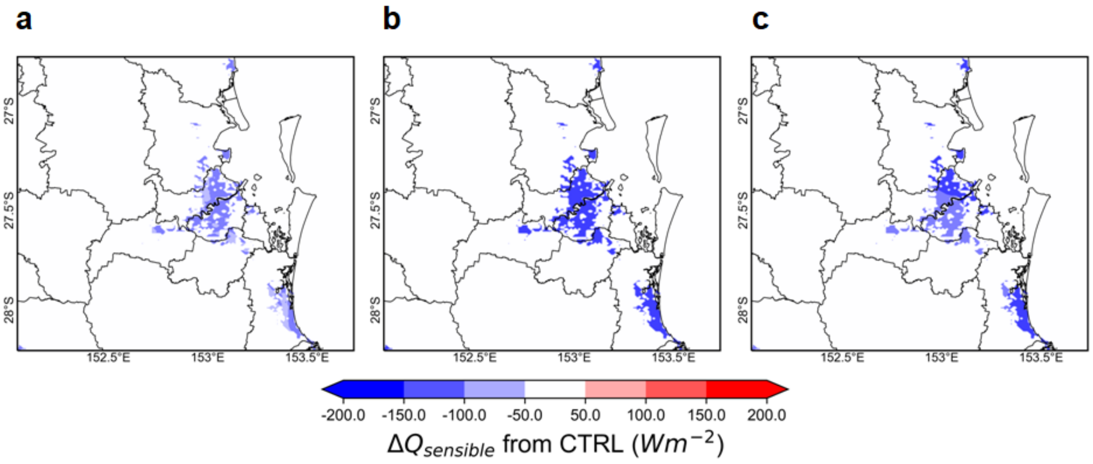


Figure 5 Reduction of sensible heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.4 Latent heat flux

The maximum and average latent heat flux (Qlatent) under cool roof scenario over city during 14:00 LT is 26.5 Wm-2 and 22.3Wm-2. At 18:00 LT and 06:00 LT, the average sensible heat flux is 7.8 Wm-2 and 4.9 Wm-2.The maximum decrease the latent heat flux is 15.5 wm-2 and average decrease is 13.1Wm-2at 14:00 LTnear central and eastern part (Hamilton, Doboy, and Morningside) of the city. But, in the high density residential urban area, the average decrease of latent heat flux is about 15.3 during 14:00LT of summer months. At 18:00 LT, the maximum and average reduction of summer month of latent heat flux is 5.6 Wm-2and 4.3Wm-2 over eastern Brisbane. At, 06:00 LT, the maximum reduction of latent heat flux is 4.0 Wm-2and average reduction is 3.1Wm-2over urban domain (**Figure 6**).

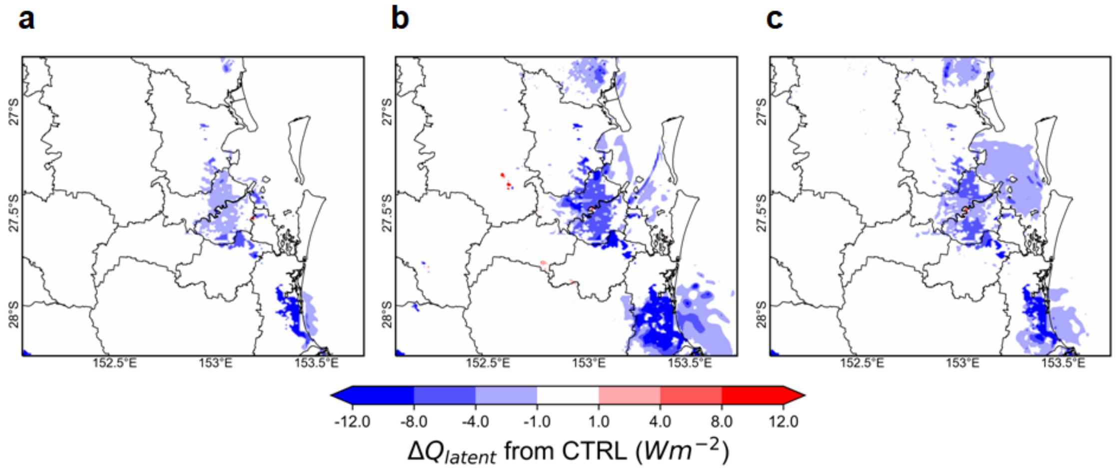


Figure 6 Reduction of latent heat flux at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.5 Wind

Under the base case simulation, the maximum wind speeds of urban average (Wspeed) are 3.9 ms-1, 6.7 ms-1 and 6.2 ms-1 during 06:00 LT, 14:00 LT and 18:00 LT respectively over the city. The maximum decrease of wind speed compared to control case is 1.1 ms-1, 2.4 ms-1 and 1.8 ms-1 at 06:00 LT, 14:00 LT and 18:00 LT respectively over inner west (The Gabba, and Walter Taylor) south west (Moorooka, and Tennyson) and near central (high density) part of the city. The average decrease of wind speed of whole summer months is 1.0 ms-1 at 14:00 LT, 0.6 ms-1 at 06:00 LT and 0.7 ms-1 at 18:00 LT over the city (**Figure 7**).

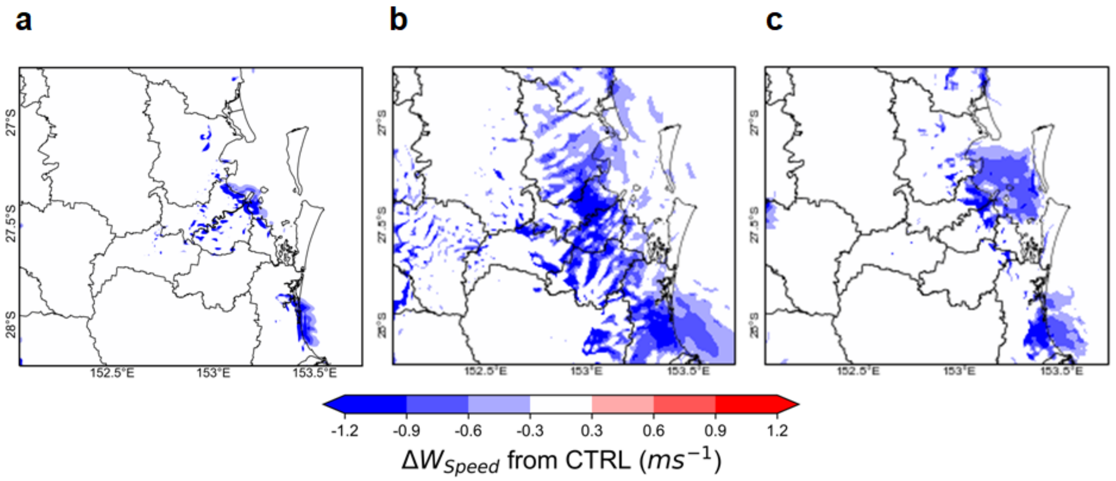


Figure 7 Reduction of wind speed at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.5.6 Regional Impact of Cool Roof: PBL Dynamics

The high-density urban building environment impacts on the lower atmospheric dynamics at the city to regional scale. The diurnal variability of the PBL resulting from the impacts of cool materials at the city scale, was reported. The magnitude of the PBL height reduction is considerable higher when highly reflective cool materials rather than conventional materials are implemented at the city scale. **Figure 8** shows spatial distribution of the PBL height in the case of the cool roof implementation at different hours of a summer day at6:00LT, 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 145.2 m (over some part of Northgate and Hamilton), 695.5 m (over the Central, The Gobba area, Coorparoo, some part of Holland Park and Moorooka), and 251.1m (near Moorooka, Doboyarea,and some parts of central of the city), for 6:00LT, 14:00LT, 18:00LT, respectively with average value is about 128.3m, 618.0m and 211.3m. The minimum reduction of PBL is 110.2m, 500.6m, and 189.5 m, for 6:00LT, 14:00LT, 18:00LT, respectively (**Figure 8**). The maximum reduction associated with peak hour (14:00 LT) over central part of the Brisbane city. The prime causes of PBL depth reduction due to cut-off input solar radiation and subsequently decrease in sensible heat and associated turbulence in the lower atmosphere. It is also noted that the increase of the albedo is expected to accelerate the static stability at the diurnal scale of the PBL depth. Modification of the albedo reduces the impacts of urban induced warming and decreases the intensity of the convective mixing thereby reducing the PBL depth, with potential penalties for air pollutant dilution and dispersion over the city domain. The reduction of moisture transport from the urban surface to the vertical layer caused by the implementation of reflective materials can also be disadvantageous to cloud formation processes, and as a result, reduce the amount of precipitation in urban areas or their downwind environments.

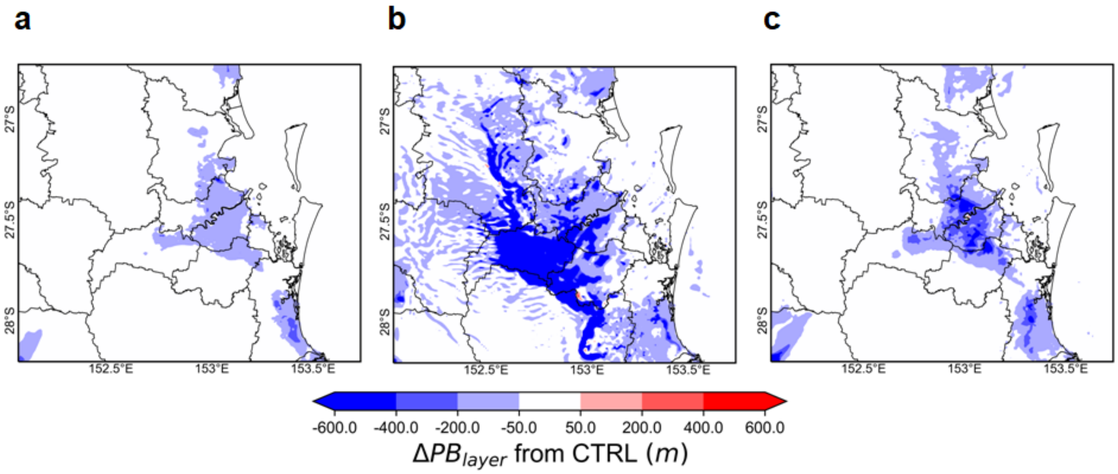


Figure 8 Reduction of PBL height at (a) 06:00 LT (b) 14:00 LT, and (c) 18:00 LT.

1.6 Regional impact on sea breeze circulations

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

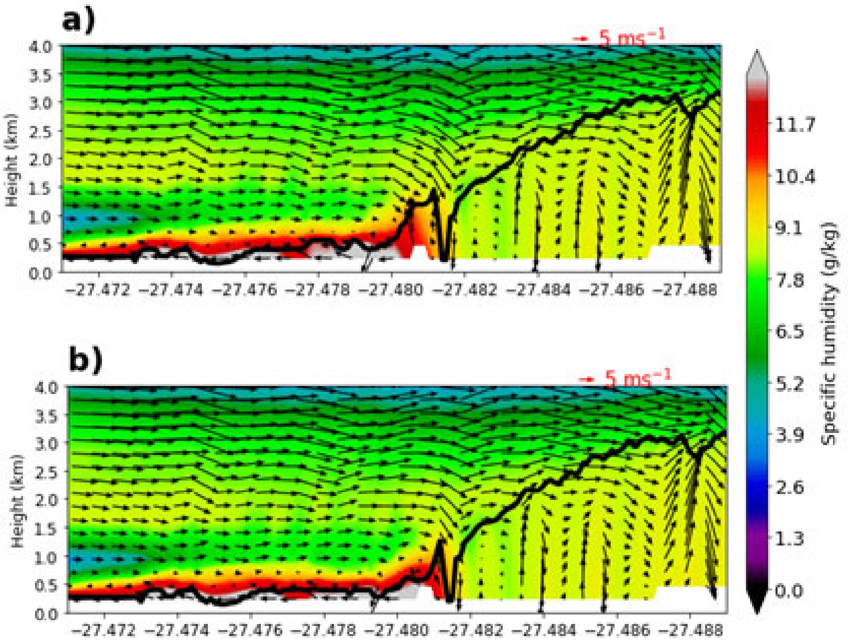


Figure 9 Cross-sectional profile of heat mitigations impacts on sea breeze during peak hour (14:00 LT) over Brisbane (a) control case, and (b) cool roof scenario. The vertical gradient of specific humidity determines the static stability of the lower atmosphere.

Report also shows the implementation of cool roof over city scale can affect the pressure gradient between city and surrounding surface due to significant drop ambient temperature up to 2.5°C and wind speed decrease up to 2.5 ms-1.Thus, changes in roof reflectivity, sensible heating, and wind result in feedbacks within local climate of the city during peak hour (14:00 LT).The higher urban albedo values decrease the advective flow between city and its surroundings improving the cooling potential of reflective materials. It creates 'regional high', which can reduce both horizontal and vertical wind speed over city. Consequently, the increase of albedo may prevent the warm air flow from the adjacent desert towards western Brisbane due to the effect of this regional high over the domain (**Figure 10**). The sea breeze generated during the day reduced UHI effects by vertically mixing and warming the inland sub-urban area without affecting the urban area with no inversion. In addition, it is clearly proved that the impact of sea breeze considerably reduced over high-density residential areas.

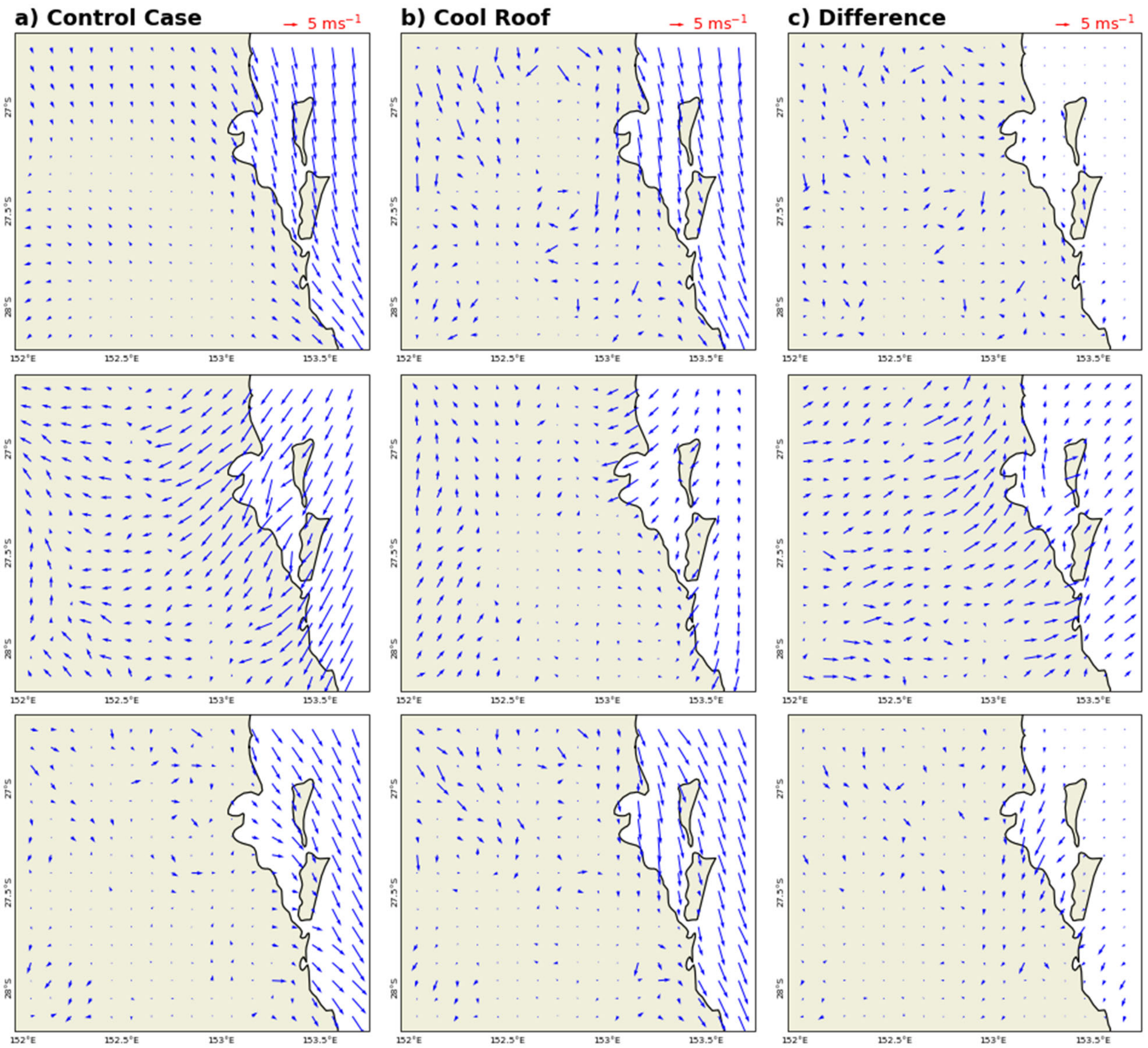


Figure 10 Surface characteristics of wind before and after cool roof implementation at city scale (a) reference case (b) cool roof (c) reference minus scenarios: difference at 06:00 LT (upper), 14:00 LT (middle), and 18:00 LT (lower panel) for the domain 03.

1.7 Impact of cool materials on the urban thermal gradient

The impact of cool materials on open-air surface and ambient temperature which is associated to urban heating and thermal flow condition has been well reported (**Figure 11**). Under the low wind speed, additional thermal gradient was observed over Brisbane city. The thermal wind describes the vertical change in the geostrophic wind in a baroclinic atmosphere at a synoptic scale. But, under the low inflow circumstance, the wind velocity was simply prejudiced by the geometry of buildings, thermal difference, and buoyancy flow. After heating the roof top and pavements, the wind velocity increased while turbulent concentration decreased due small scale thermal gradient.

This strength could make pollutant transporting more rapidly but withdrawn pollutants from mixing. The situations also occur over the some parts of Brisbane city (Marchant, Central, The Gabba, Paddington, Walter Taylor, Coorparoo, Holland Park, Tennyson, Jamboree, and Moorooka) when the wind speed is low and the ambient and surface temperature is very high. Under these conditions, there is a substantial temperature difference between the cool roofs and the warm pavements that generate some small local thermal winds at neighborhood scale. It is assumed, this could designate the influence of solar radiation alteration by cool materials on wind flow, and thus when the wind velocity is small; the effect of the roof and surface material is noticeably shown in the thermal wind environment at the vicinity of the roof surface to warm pavements with increase of the wind velocity and decrease of the turbulent energy.

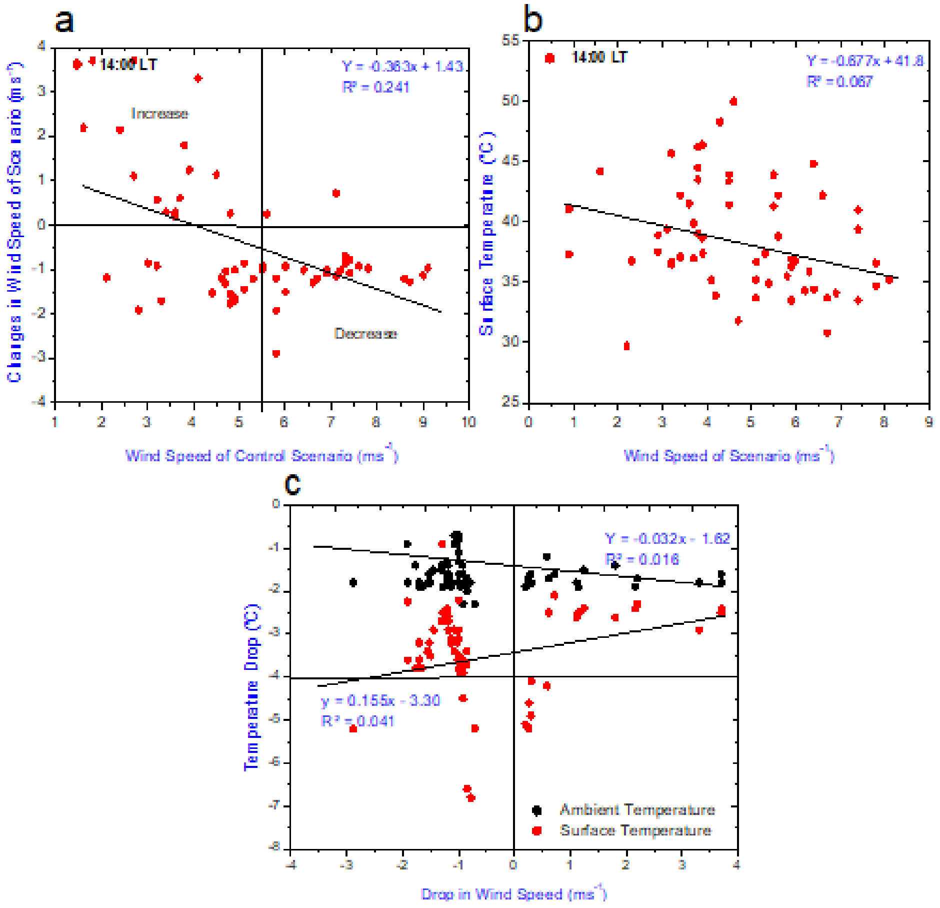


Figure 11 (a) Variability of the average wind speed in the simulated area as a function of the average control wind speeds for the albedo scenario at 14:00 LT, (b) Association of the wind speed and surface temperature at peak hour (14:00 LT), and (c) Association

1.8 Main conclusions

- It is found that a strong urban heat island (UHI) phenomenon is developed. The maximum magnitude of the phenomena may exceed 5°C.The UHI effect would be added evenhandedly balanced spatially under the urban expansion. The intensity and the characteristics of the phenomena are strongly influenced by the synoptic weather conditions and in particular the development of the sea breeze and the westerly winds from the desert area. The possible existence of an additional heating mechanism, like the advection of warm air from nearby spaces, may intensify the strength of the problem.
- High density parts of the city exhibit a much higher temperature drop than the urban average. Increase of albedo in Brisbane can decrease the peak summer ambient temperature up to 2.5°C and surface temperature up to 6.8°C. It was found that important temperature differences exist near the coast and central part of the city. The patterns of the ambient temperature distribution in the city were found to depend highly on the synoptic climatic conditions and the magnitude of the surface thermal gradient.
- The maximum decrease of sensible heat and latent heat flux were up to 184.6 Wm-2 and 17.4 Wm-2, respectively.
- The maximum decrease of wind speeds up to 2.5 ms-1. Cool roofs increase the pressure at local-scale and decrease the wind advection from the bare surface.
- The results of numerical experiments show that the increase in albedo fraction leads to decrease in wind speeds and the incidence of high wind speeds along with augmented turbulent energy in the planetary boundary layer (PBL) during heat wave scenario. Under the low wind speed, additional thermal gradient was observed over Brisbane city. When the wind speed is low and the ambient and surface temperature is very high. Under these conditions, there is a substantial temperature difference between the cool roofs and the warm pavements that generate some small local thermal winds at neighborhood scale.
- Alteration of the urban albedo in Brisbane results in a solemn average reduction up to 735.6 m of the PBL heights over city and may increase the concentration of pollutants at ground level,
- The urban–sea temperature difference approaching to sea-breeze effects. Cool roof that reduced daytime ambient temperatures, but higher winds over cool roof implemented city greatly reduce the sea breeze penetration.
- The magnitudes of the UHI phenomenon were associated with the existence of a sea breeze in the eastern parts of the city, decreasing the temperature of the coastal zone, combined with westerly winds from the inland that heat up the western zones of the city.

2. Climatic Design Parameters _ CDH distribution

In this study, cooling degree hours (CDH) base 26 °C, which measures how much, and for how long, outside air temperature is higher than 26 °C, has been calculated for 31 weather stations in Brisbane for the entire simulation period, serving as a rough indication of the regional climatic severity. 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.

2.1 Overview of the weather stations in Brisbane

31 stations in Brisbane, as shown in **Table 4** and **Figure 12** have been simulated for two months: Jan and Feb, by Weather Research Forecasting Model.

Table 4 Latitude, longitude, and the climate zone of the 31 stations in Brisbane.

No.	Station name	Lat	Long	Climate zone
1	BRISBANE	-27.48	153.04	2
2	BRISBANE AERO	-27.39	153.13	2
3	AMBERLEY AMO	-27.63	152.71	2
4	ARCHERFIELD AIRPORT	-27.57	153.01	2
5	BANANA BANK NORTH BEACON	-27.53	153.33	2
6	BEERBURRUM FOREST STATION	-26.96	152.96	2
7	BEAUDESERT DRUMLEY STREET	-27.97	152.99	2
8	CANUNGRA (DEFENCE)	-28.04	153.19	2
9	CAPE MORETON LIGHTHOUSE	-27.03	153.47	2
10	COOLANGATTA	-28.17	153.51	2
11	DOUBLE ISLAND POINT LIGHTHOUSE	-25.93	153.19	2
12	UNIVERSITY OF QUEENSLAND GATTON	-27.54	152.34	2
13	GOLD COAST SEAWAY	-27.94	153.43	2
14	GREENBANK (DEFENCE)	-27.69	152.99	2
15	GYMPIE	-26.18	152.64	2
16	HOPE BANKS BEACON	-27.43	153.29	2
17	INNER RECIPROCAL MARKER	-27.26	153.24	2
18	KINGAROY AIRPORT	-26.57	151.84	5

19	LOGAN CITY WATER TREATMENT PLANT	-27.68	153.19	2
20	NAMBOUR DAFF - HILLSIDE	-26.64	152.94	2
21	NORTH WEST 10 BEACON	-27	153.24	2
22	OAKEY AERO	-27.4	151.74	5
23	RAINBOW BEACH	-25.9	153.09	2
24	REDCLIFFE	-27.22	153.09	2
25	REDLAND (ALEXANDRA HILLS)	-27.54	153.24	2
26	SUNSHINE COAST AIRPORT	-26.6	153.09	2
27	TEWANTIN RSL PARK	-26.39	153.04	2
28	TIN CAN BAY (DEFENCE)	-25.94	152.96	2
29	TOOWOOMBA AIRPORT	-27.54	151.91	5
30	WARWICK	-28.21	152.1	5
31	WELLCAMP AIRPORT	-27.55	151.78	5

Figure 12 Location of the 31 weather stations in Brisbane.

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 31 weather stations are shown in **Table 5** and **Figure 13**. Compared with the control case, the largest percentage reduction (62%) is observed in BANANA BANK NORTH BEACON and the smallest (16%) is found in OAKEY AERO, with an average reduction of 34.6%. The mean CDH values of the 31 weather stations for the control case, cool roof case are 2363.7, 1653.7 respectively, with standard deviations of 932.7 and 934.3 sequentially, see **Table 5**.

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 31 weather stations in Brisbane.

Weather Station	**CDH_CTRL**	**CDH_COOL ROOF**	**CDH_ Difference (CTRL-COOL ROOF)**	**Percentage of the reduction_% (CDH_Difference/CDH_CTRL)**
BRISBANE	2243.8	1451.4	792.4	35
BRISBANE AERO	2225	1319.9	905.2	41
AMBERLEY AMO	3754.5	2988.1	766.4	20
ARCHERFIELD AIRPORT	2380	1641.2	738.8	31
BANANA BANK NORTH BEACON	1119.1	428.3	690.8	62
BEERBURRUM FOREST STATION	1736.4	1010.8	725.6	42
BEAUDESERT DRUMLEY STREET	2993.7	2223.4	770.3	26
CANUNGRA (DEFENCE)	2507.5	1831.1	676.4	27
CAPE MORETON LIGHTHOUSE	956.6	377.7	578.9	61

COOLANGATTA	1380.3	727.4	652.9	47
DOUBLE ISLAND POINT LIGHTHOUSE	1584.1	958.4	625.7	39
UNIVERSITY OF QUEENSLAND GATTON	4167.1	3446.5	720.7	17
GOLD COAST SEAWAY	1760.5	1038	722.5	41
GREENBANK (DEFENCE)	1872.7	1091.8	780.9	42
GYMPIE	3369.8	2665.4	704.4	21
HOPE BANKS BEACON	2146.8	1419.2	727.6	34
INNER RECIPROCAL MARKER	1052	460	592	56
KINGAROY AIRPORT	3821.1	3168.4	652.7	17
LOGAN CITY WATER TREATMENT PLANT	2131.8	1399.5	732.3	34
NAMBOUR DAFF - HILLSIDE	2135.2	1467.2	668	31
NORTH WEST 10 BEACON	1634.8	950.2	684.6	42
OAKEY AERO	4096.4	3431.3	665.1	16
RAINBOW BEACH	1764.7	998.3	766.4	43
REDCLIFFE	2207.1	1424.1	783	35

REDLAND (ALEXANDRA HILLS)	2016.8	1390.8	626	31
SUNSHINE COAST AIRPORT	1809.4	943.8	865.6	48
TEWANTIN RSL PARK	1962	1200.4	761.6	39
TIN CAN BAY (DEFENCE)	1773.6	1053.9	719.7	41
TOOWOOMBA AIRPORT	3280.2	2706.2	574	17
WARWICK	3462.7	2855.7	607	18
WELLCAMP AIRPORT	3927.6	3196	731.6	19

Table 6 Mean and SD of the CDH of the 31 weather stations in control cases and cool roof cases respectively.

	Mean	**SD**	**Sample No.**
CDH_CTRL	2363.7	932.7	31
CDH_COOL ROOF	1653.7	934.3	31
CDH_DIFFERENCE (CTRL-COOL ROOF)	710.0	77.8	31
PERCENTAGE OF THE REDUCTION (%) (CDH_DIFFERENCE/CDH_CTRL)	34.6	12.9	31

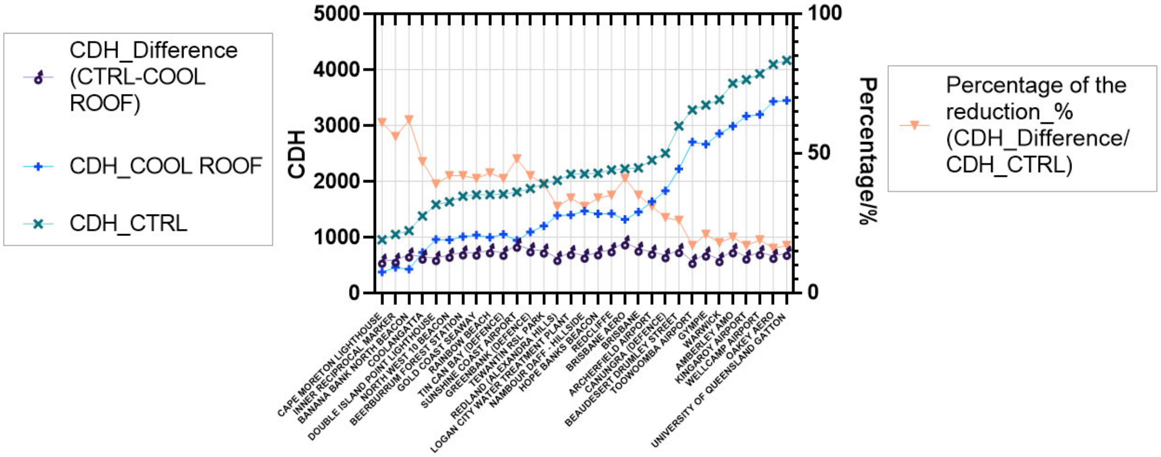


Figure 13 The CDH of control cases, cool roof applied cases, the difference between these two and the percentage of the CDH reduction due to the implementation of cool roof in 31 weather stations in Brisbane.

2.2.1 Frequency distribution of the results

The frequency distribution of the CDH values for the 31 weather stations in both the control cases and the cool roof cases is shown in **Figure 14**. In control cases, the CDH centered around 1800 and 2000 has the largest proportion: each accounting for 19.4 % of the total, while all the remaining intervals have the proportions of less than 10%. In cool roof cases, the CDH centered around 1000 and 1400 has the two largest proportions of 25.8% and 22.6% respectively. The data of all remaining intervals accounts for less than 10%.

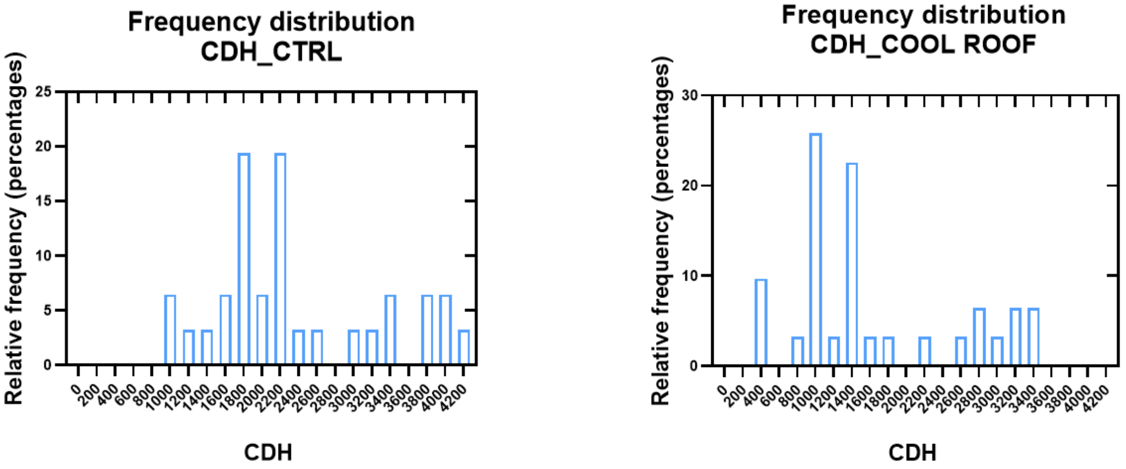


Figure 14 Frequency distribution of the CDH values for the 31 weather stations in control cases (a) and cool roof cases (b).

2.2.2 Spatial distribution of the results

- **CDH_Reference scenario: (Figure 15)**

  The highest CDH of 4167.1 is observed in University of Queensland Gatton and Cape Moreton Lighthouse has the lowest number. CDH gradually increases from east to west.

- **CDH_Cool roof scenario**: **(Figure 16)**.

  When applied with a cool roof, the decrease of CDH is observed at every station. The highest CDH of 3446.5 is still observed in University of Queensland Gatton and Cape Moreton Lighthouse again has the lowest number **(Figure 15**). The spatial distribution pattern is very similar to that of the control cases: CDH increases from east to west.

- **CDH_Reference scenario – cool roof scenario: (Figure 17)**

  The maximum decrease occurs along the coastline (BRISBANE AERO:905.2) of the city. The smallest decrease is observed in the western part of the city (TOOWOOMBA AIRPORT: 574). The average decrease due to the implementation of a cool roof is 710.0 (**Table 6**) across the 31 stations.

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

  The proportion of CDH reduction in the original control volume is relatively large in the east region of the city, and gradually decreases toward west, as shown in **Figure 18**.

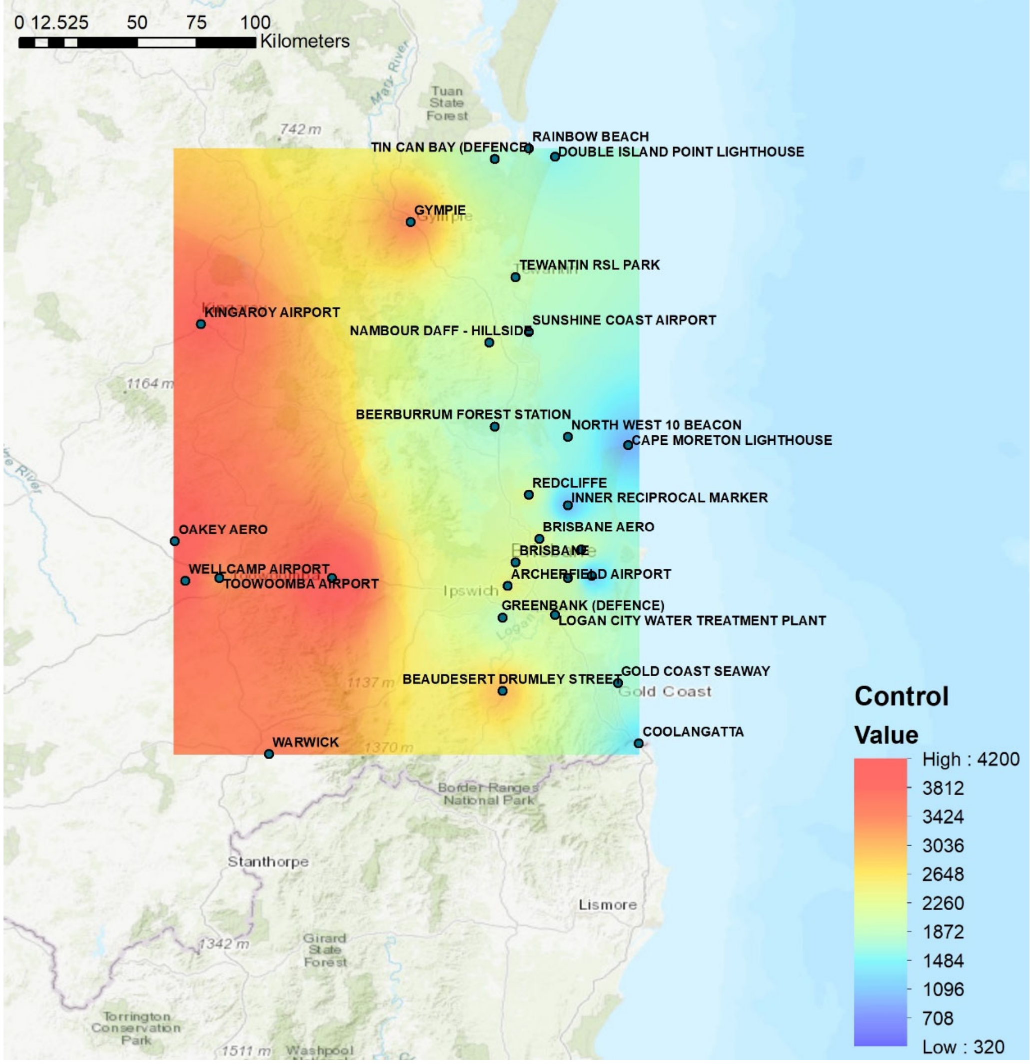


Figure 15 The sum of Cooling degree hours in Jan and Feb of the control cases in the 31 stations in Brisbane.

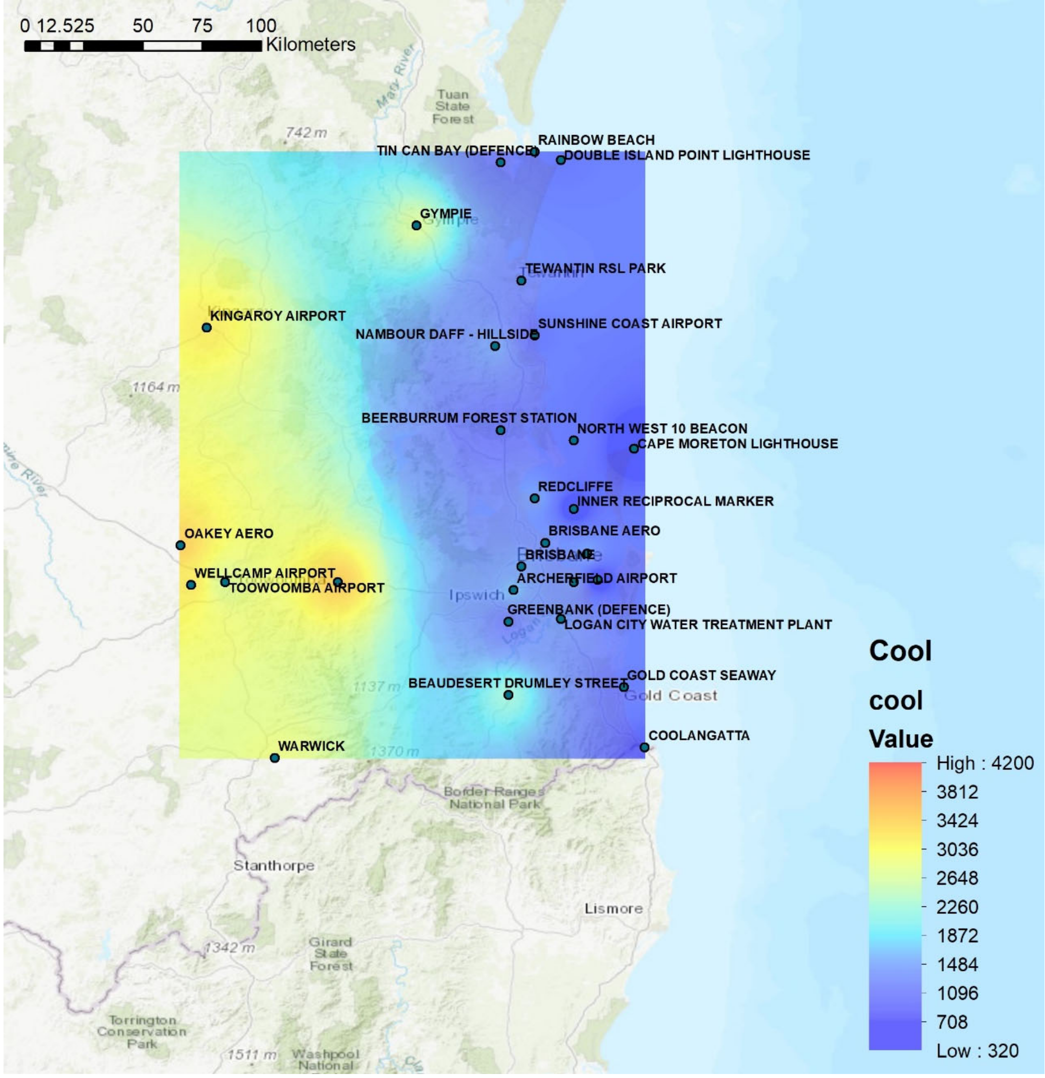


Figure 16 The sum of Cooling degree hours in Jan and Feb of the cool roof cases in the 31 stations in Brisbane.

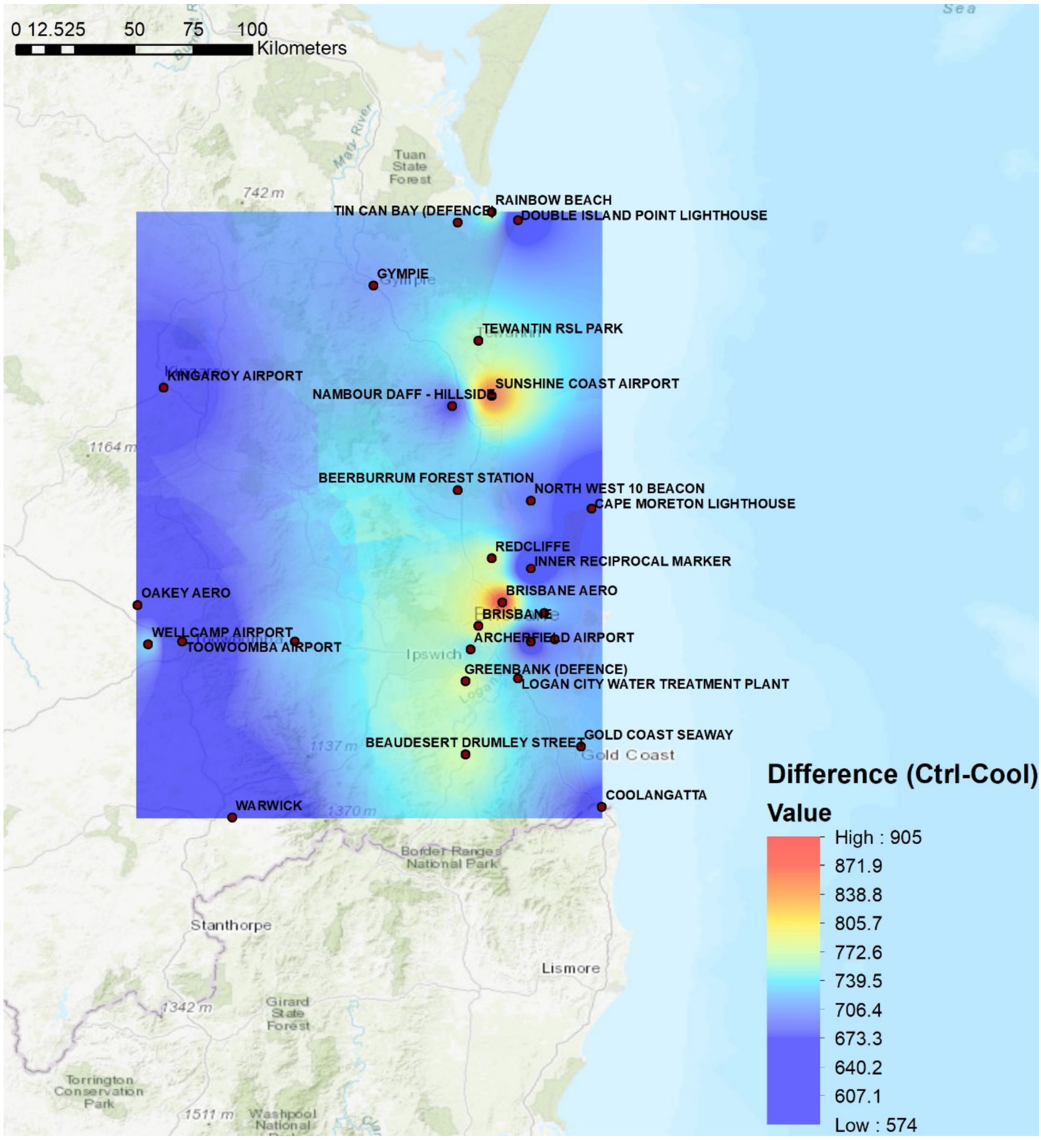


Figure 17 The difference of Cooling degree hours in Jan and Feb between the cool roof cases and control ones in the 31 stations in Brisbane.

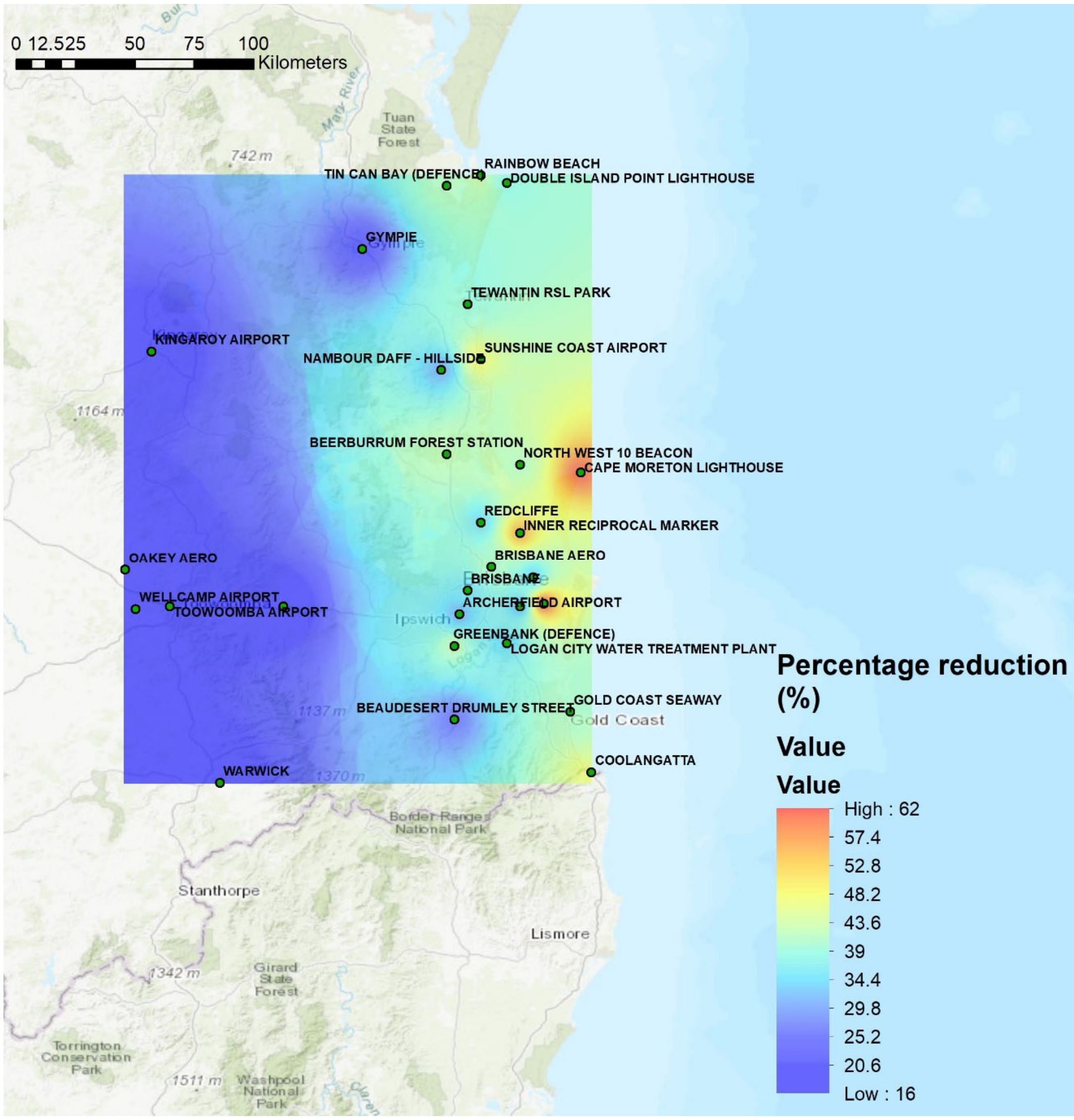


Figure 18 The percentage of CDH reduction due to the implementation of the cool roof in the 31 stations in Brisbane.

2.3 Conclusions

- In control cases, CDH ranges from 956.6 to 4167.1 and about 40% of the data is concentrated in 1800 - 2000. CDH gradually increases from the east of the city to the west.
- In cool roof cases, CDH ranges from 377.7 to 3446.5 and about 50% of the data is concentrated in 1000 - 1400. Its spatial distribution is also similar to that of the control case.
- The percentage of CDH reduction due to the implementation of the cool roof ranges from 16% to 62% with an average value of 34.6%. The percentage of CDH reduction in the original control volume is relatively large in the east of the city, and gradually decreases toward the west.

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

3.1 Introduction

This report investigated the impact of cool roofs on the cooling/heating load and indoor air temperature of different types of buildings in Brisbane. 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 Brisbane during a typical summer and winter period. Specifically, the simulations were performed for seventeen types of buildings and seven weather stations across Brisbane (in climate zone 2). 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 Brisbane include (See **Figure 19**):

1) Brisbane Airport -Climate zone 2,

2) Amberley-Climate zone 2,

3) Archerfield-Climate zone 2,

4) Gold Coast Seaway- Climate zone 2,

5) Greenbank (Defence)-Climate zone 2,

6) Redcliffe-Climate zone 2,

7) Redland (Alexandra Hills)-Climate zone 2,

Figure 19 Weather stations in Brisbane

The corresponding building specifications for the buildings in climate zones 2 was 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 Brisbane. 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 Brisbane (i.e. Redland and Amberley) 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 6***.

3.3 Summary of results

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	43.6-46.3	11.3-15.6	25.6-33.7	18.7-21.3	42.9-46.2
A high-rise office building without roof insulation-existing building	34.2-35.2	2.0-3.0	5.7-8.8	8.6-10.4	24.9-29.6
A low-rise office building with roof insulation-new building	32.1-33.7	1.2-1.6	3.6-5.0	7.3-9.2	22.3-27.5
A high-rise office building with roof insulation-new building	31.6-33.8	0.2-0.3	0.6-0.9	6.3-8.5	19.9-25.4
A low-rise shopping mall centre-new building	96.4-99.4	1.3-1.9	1.3-2.0	15.4-19.4	15.8-19.6
A mid-rise shopping mall centre-new building	95.3-98.5	0.7-0.8	0.7-0.8	14.6-18.7	15.1-19.0
A high-rise shopping mall centre-new building	94.8-98.1	0.4-0.6	0.4-0.6	14.4-18.4	15.0-18.8
A low-rise apartment building-new building,	25.5-27	1.3-1.6	4.8-6.3	7.7-9.9	30.2-37.1
A mid-rise apartment building-new building	25.2-26.9	0.7-0.9	2.6-3.6	7.1-9.4	28.2-35.5

A high-rise apartment building-new building	24.9-26.7	0.4-0.5	1.5-2.0	6.7-9.1	26.9-34.6
A typical stand-alone house-existing building,	21.8-22.6	3.9-4.2	17.3-18.8	8.6-10.1	38.8-44.9
A typical school building-existing building	44.4-46	1.5-1.7	3.3-3.8	12.6-17.5	27.9-38.0
A low-rise office building with roof insulation-existing building	37.1-37.8	6.0-7.5	15.9-19.8	12.2-14.0	32.9-37.0
A high-rise office building with roof insulation-existing building	32.6-34.3	0.9-1.4	2.6-4.3	7.4-9.3	22.4-27.3
A low-rise shopping mall centre-existing building	102.1-103.6	7.4-9.6	7.2-9.3	21.6-25.6	21.2-24.7
A high-rise shopping mall centre-existing building	96.6-99.1	2.1-2.9	2.1-3.0	16.2-20.2	16.6-20.4
A stand-alone house-new building.	22.5-23.5	4.1-4.4	17.4-19.3	8.8-10.4	39.1-44.6

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

Building Type	**Annual cooling load saving**		**Annual heating load penalty**	**Annual total cooling & heating load saving**	
	kWh/m2	**%**	**kWh/m2**	**kWh/m2**	**%**
A low-rise office building without roof insulation-existing building	34.7-52.7	34.6-40.0	0.5-0.9	34.2-52.2	33.8-39.4

A high-rise office building without roof insulation-existing building	5.7-9.7	7.5-10.6	0-0.2	5.6-9.7	7.4-10.6
A low-rise office building with roof insulation-new building	3.5-5.2	4.8-6.0	0-0.1	3.4-5.2	4.6-6.0
A high-rise office building with roof insulation-new building	0.6-1.0	0.8-1.2	0-0.1	0.6-1.0	0.8-1.2
A low-rise shopping mall centre-new building	6.6-9.2	1.9-2.5	0-0.1	6.6-9.2	1.9-2.5
A mid-rise shopping mall centre-new building	3.0-4.4	0.9-1.2	0	3.0-4.4	0.9-1.2
A high-rise shopping mall centre-new building	2.0-2.8	0.6-0.8	0	2.0-2.8	0.6-0.8
A low-rise apartment building-new building,	3.8-5.6	7.4-9.5	0.2-0.4	3.6-5.4	6.4-8.6
A mid-rise apartment building-new building	2.2-3.3	4.3-5.6	0.1-0.2	2.1-3.2	3.7-5.1
A high-rise apartment building-new building	1.2-2.0	2.4-3.4	0.1	1.1-1.9	2.1-3.0
A typical stand-alone house-existing building,	11.5-13.6	21.7-29.3	0.4-0.6	11.1-13.1	19.4-25.3
A typical school building-existing building	4.1-5.8	4.0-5.3	0-0.1	4.1-5.7	3.8-5.0
A low-rise office building with roof insulation-existing building	16.6-25.1	19.8-24.1	0.1-0.4	16.5-24.9	19.6-23.8
A high-rise office building with roof insulation-existing building	2.8-4.6	3.8-5.3	0-0.1	2.8-4.6	3.8-5.3
A low-rise shopping mall centre-existing building	30.8-44.2	8.8-11.5	0-0.2	30.8-44.1	8.8-11.4
A high-rise shopping mall centre-existing building	8.7-13.5	2.6-3.7	0-0.1	8.7-13.5	2.6-3.7

A stand-alone house-new building.	12.3-16.4	24.6-30.2	0.4-0.7	11.9-15.9	20.3-26.2

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 °C in free-floating mode during a typical summer month using weather data simulated by WRF

Building type	**Maximum Indoor air temp in a typical summer week**	**Maximum indoor air temp reduction in a typical summer week**		**Number of hours above 26 °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-existing building	46.4-53.3	9.0-10.3	9.6-11.1	649-664	591-629	558-592
A high-rise office building without roof	41.5-46.3	1.6-2.0	2.4-2.8	672	672	668-672

insulation-existing building						
A low-rise office building with roof insulation-new building	41.8-46.4	1.0-1.2	1.7-2.1	670-672	668-672	662-672
A high-rise office building with roof insulation-new building	41.0-45.1	0.2-0.3	1.2-1.3	672	672	672
A low-rise shopping mall centre-new building	45.9-51.7	0.5-0.7	1.6-1.8	672	671-672	666-672
A mid-rise shopping mall centre-new building	45.3-50.9	0.4	1.4-1.8	672	672	672
A high-rise shopping mall centre-new building	45.1-50.7	0.3-0.4	1.3-1.8	672	672	672
A low-rise apartment building-new building,	34.9-38.9	0.6-0.8	1.4-1.7	635-656	624-651	581-614
A mid-rise apartment	34.6-38.4	0.4-0.5	1.2-1.4	639-664	637-660	598-631

building-new building						
A high-rise apartment building-new building	34.4-38.1	0.2-0.3	1.1-1.2	642-665	640-664	606-637
A typical stand-alone house-existing building	37.0-41.6	2.4-2.8	3.1-3.6	573-592	530-565	463-490
A typical school building-existing building	36.7-42.1	0.6-0.7	1.4-1.6	623-650	616-645	569-607
A low-rise office building with roof insulation-existing building	43.7-49.4	4.6-5.6	5.3-6.4	664-672	644-666	617-657
A high-rise office building with roof insulation-existing building	41.2-45.6	0.8-1.1	1.7-2.0	672	672	672
A low-rise shopping mall centre-	46.7-53.2	2.5-2.8	3.3-3.7	664-672	662-672	648-672

existing building						
A high-rise shopping mall centre-existing building	45.3-51.1	0.9-1.0	1.7-1.9	672	672	672
A stand-alone house-new building.	36.9-41.1	2.5-2.9	3.2-3.7	558-618	552-583	485-566

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 ºC in a typical winter month**			
	Reference scenario (ºC)	**Reference with cool roof scenario (scenario 1) vs reference scenario (ºC)**	**Reference scenario (hours)**		**Reference with cool roof scenario (scenario 1) (hours)**	
			Operational hours	**Total**	**Operational hours**	**Total**
A low-rise office building without roof	11.7-15.5	3.4-3.6	30-37	158-229	42-56	221-294

insulation-existing building						
A high-rise office building without roof insulation-existing building	16.7-19.5	0.6	0-15	6-80	4-16	10-91
A low-rise office building with roof insulation-new building	15.5-18.9	0.6	7-24	21-109	15-27	24-116
A high-rise office building with roof insulation-new building	17.6-20.3	0.1-0.2	0-10	1-57	0-14	1-59
A low-rise shopping mall centre-new building	14.0-18.5	0.4	15-31	43-116	17-31	44-121
A mid-rise shopping mall centre-new building	15.2-19.5	0.2	8-25	15-87	9-26	16-89
A high-rise shopping mall centre-new building	15.5-19.8	0.2	5-25	9-83	5-25	9-84

A low-rise apartment building-new building,	14.4-17.5	0.4	N/A	120-240	N/A	129-248
A mid-rise apartment building-new building	14.8-17.8	0.2	N/A	108-236	N/A	112-242
A high-rise apartment building-new building	15.0-17.9	0.2	N/A	102-234	N/A	107-238
A typical stand-alone house-existing building,	11.8-15.6	1.3.1.4	N/A	235-330	N/A	270-360
A typical school building-existingbuilding	11.2-15.5	0.2	35-50	156-248	37-52	165-253
A low-rise office building with roof insulation-existing building	13.4-17.1	1.9-2.0	18-29	85-173	26-31	119-207
A high-rise office building with roof insulation-	17.1-19.9	0.4	1-14	3-71	2-19	5-75

existing building						
A low-rise shopping mall centre-existing building	12.6-17.3	1.1-1.2	20-42	79-171	25-45	91-182
A high-rise shopping mall centre-existing building	15.0-19.3	0.4	9-29	19-95	11-30	20-97
A stand-alone house-new building.	12.4-16.1	1.4-1.5	N/A	189-296	N/A	234-333

3.4 Conclusion

The conclusions drawn from this study are:

- In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in individual buildings (scenario 1) is quite significant. For instance, application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 11.3-15.6 kWh/m2.
- In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in both individual buildings and at the whole urban area (scenario 2) is quite significant. For instance, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 18.7-21.3 kWh/m2.
- In existing buildings without insulation/with low insulation level, the cooling load reduction of the cool roofs is remarkable even for the high-rise buildings. For instance, the application of cool roofs on the individual

building (scenario 1) and both individual buildings and at the whole urban area (scenario 2) is expected to decrease the cooling loads of a high-rise office building without roof insulation by 2.0-3.0 kWh/m2 and 8.6-10.4 kWh/m2, respectively.

- 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 in both individual building and at the whole urban area (scenario 2) is predicted to be 7.3-9.2 kWh/m2 in a typical new low-rise office building.
- In new high-rise buildings with high insulation level, application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.2-0.3 kWh/m2 for new high-rise office buildings with insulation.
- In high-rise buildings, the cooling load reduction through application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.4-0.5 kWh/m2 in a new high-rise apartment building, which is expected to increase to 6.7-9.1 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 all types of buildings. For instance, the annual cooling load saving in a low-rise office building without insulation is 34.7-52.7 kWh/m2, while the corresponding heating penalty is just 0.5-0.9 kWh/m2.
- 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 9.0-10.3 ^{o}C.
- In existing buildings without insulation/with low level of insulation and under free-floating condition in a typical summer period, application of cool roofs in both individual building and at the whole urban area (scenario 2) can significantly decrease the maximum indoor air temperature. For instance, the implementation of cool roofs in both individual building and at the whole urban area (scenario 2) is expected to decrease the maximum indoor air temperature of a low-rise office building without roof insulation by 9.6-11.1 ^{o}C.

- 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 1.7-2.1 ^{o}C in a typical new low-rise office building.
- In residential buildings and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual building and at the whole urban area (scenario 2) can significantly decrease the number of hours with an indoor air temperature above 26 ^{o}C. For instance, the number of hours with an indoor air temperature above 26 ^{o}C in a typical existing stand-alone house is predicted to reduce from 573-592 hours to 530-565 hours and 463-490 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 non-residential buildings and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual buildings and at the whole urban area (scenario 2) has low or no impact on reducing the number of hours with an indoor air temperature above 26 ^{o}C during a typical summer period. For instance, the number of hours with an indoor air temperature above 26 ^{o}C in mid-rise shopping mall centre is predicted to remain unchanged after application of cool roofs.
- 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 9-10.3 ^{o}C in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 3.4-3.6 ^{o}C during a typical winter month.
- The indoor air temperature reduction by cool roofs in a typical winter period occurs during the periods when the indoor air temperature is higher than 19 ^{o}C and heating is not required. For instance, in an existing office building with low insulation level, the maximum absolute temperature reduction of around 3.4 ^{o}C occurs when the indoor air temperature is 29.3 ^{o}C.
- The implementation of cool roofs in individual buildings has a low impact on the number of hours below 19 ^{o}C especially during the operational hours of the buildings in a typical winter period. For instance, it is predicted that the application of cool roofs in individual buildings (scenario 1) can increase the total

number of operational hours with ambient temperature below 19 °C from 18-29 hours to 26-31 hours in a typical existing low-rise office building with roof insulation.

4. Energy loss through building envelopes in various stations in Brisbane_ 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 Brisbane has been investigated. Specifically, for the 17 building types, the correlation between cooling degree hours (Base 26) and the sensible cooling load in **reference scenarios** (A reference building with conventional roof using the climatic data simulated by WRF for the current condition), and the cooling load reduction in **scenario 1** (The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF for the current condition) and **scenario 2** (The same building as in the reference scenario with a cool roof using the climatic data simulated by WRF considering an extensive use of cool roofs in the city) has been plotted using the simulated data in 7 weather stations in Brisbane for two summer months. For each plot, the linear regression line has been generated in the format of

$$Y=a X + b$$

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

X is the cooling degree hours (K);

For reference scenarios:

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

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

For the cooling load reduction in scenarios 1 and 2:

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

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

4.2 Office buildings

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, and the cooling load reduction in scenario 1 and scenario 2 for the 5 office building types (B01_Existing_Low-rise_no insulation; B02_Existing_High-rise_no insulation; B03_New_Low-rise_insulated; B04_New_High-rise_insulated; B13_Existing_Low-rise_insulated; B14_Existing_High-rise_insulated) is shown in **Figure 20** and **Table 11.**

1) Regarding the sensible cooling load of reference scenarios, it can be observed that new buildings (B03 VS B13; or B04 VS B14) have lower heat loss coefficient of the overall envelope; the envelope of an insulated building loses less heat (B01 VS B13 or B02 VS B14).
2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all office building types, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors, no insulation, and older construction years, which often have higher heat loss coefficients in envelopes.
3) For the cooling load reduction in scenario 2 compared with the reference scenario, all office building types present an increased cooling load reduction with the increase of cooling degree hours. Similar 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.

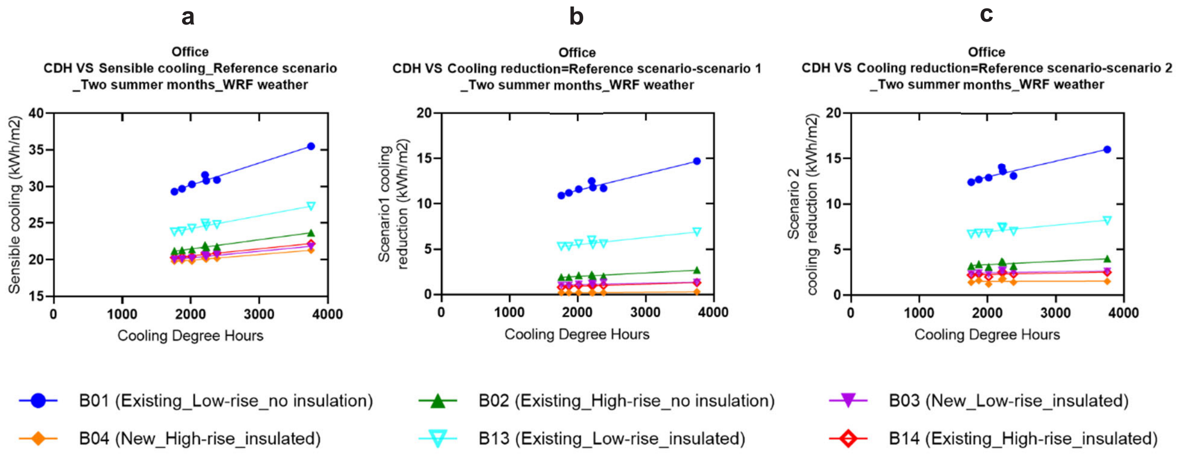


Figure 20 For office building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2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

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

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B01 (Existing_Low-rise_no insulation)	0.003031	24.13	Y = 0.003031*X + 24.13
B02 (Existing_High-rise_no insulation)	0.001263	18.95	Y = 0.001263*X + 18.95
B03 (New_Low-rise_insulated)	0.0009024	18.45	Y = 0.0009024*X + 18.45
B04 (New_High-rise_insulated)	0.0007687	18.40	Y = 0.0007687*X + 18.40
B13 (Existing_Low-rise_insulated)	0.001747	20.77	Y = 0.001747*X + 20.77
B14 (Existing_High-rise_insulated)	0.0009647	18.59	Y = 0.0009647*X + 18.59

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B01 (Existing_Low-rise_no insulation)	0.001828	7.823	Y = 0.001828*X + 7.823
B02 (Existing_High-rise_no insulation)	0.0003923	1.205	Y = 0.0003923*X + 1.205
B03 (New_Low-rise_insulated)	0.0001448	0.8074	Y = 0.0001448*X + 0.8074
B04 (New_High-rise_insulated)	0.00005349	0.09037	Y = 0.00005349*X + 0.09037
B13 (Existing_Low-rise_insulated)	0.0007941	3.903	Y = 0.0007941*X + 3.903
B14 (Existing_High-rise_insulated)	0.0002184	0.4941	Y = 0.0002184*X + 0.4941

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B01 (Existing_Low-rise_no insulation)	0.001727	9.543	Y = 0.001727*X + 9.543
B02 (Existing_High-rise_no insulation)	0.0003720	2.595	Y = 0.0003720*X + 2.595

B03 (New_Low-rise_insulated)	0.0001187	2.225	Y = 0.0001187*X + 2.225
B04 (New_High-rise_insulated)	0.00001690	1.475	Y = 1.690e-005*X + 1.475
B13 (Existing_Low-rise_insulated)	0.0007253	5.520	Y = 0.0007253*X + 5.520
B14 (Existing_High-rise_insulated)	0.0001462	1.990	Y = 0.0001462*X + 1.990

4.3 Shopping mall centers

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

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

2) Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours in all shopping mall center building types, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. 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 B06 and B07 presenting a decreased cooling load reduction with the increase of cooling degree hours, all other buildings show an increased cooling load reduction with the increase of cooling degree hours. A higher increase rate is observed in buildings with fewer floors, and older construction years, which often have higher heat loss coefficients in envelopes.

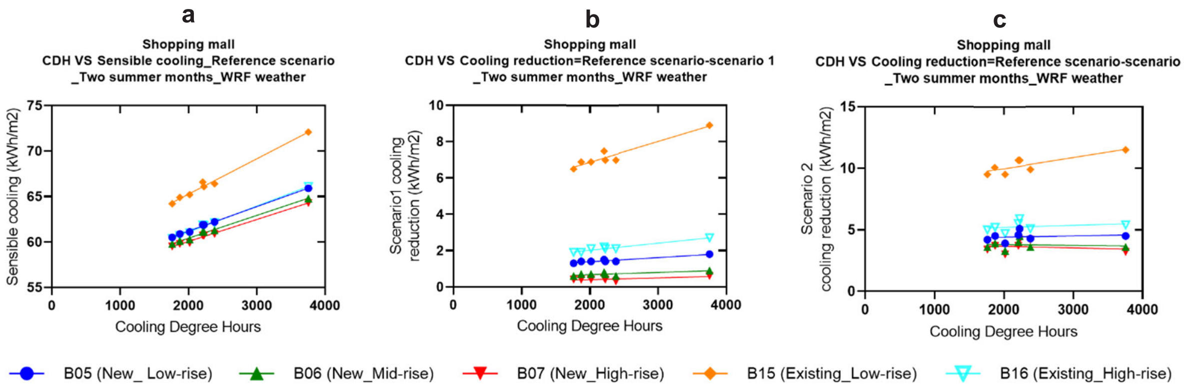


Figure 21 For shopping mall center a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario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

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

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.002691	55.82	Y = 0.002691*X + 55.82
B06 (New_Mid-rise)	0.002507	55.41	Y = 0.002507*X + 55.41
B07 (New_High-rise)	0.002416	55.23	Y = 0.002416*X + 55.23
B15 (Existing_Low-rise)	0.003888	57.49	Y = 0.003888*X + 57.49
B16 (Existing_High-rise)	0.002864	55.37	Y = 0.002864*X + 55.37

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B05 (New_ Low-rise)	0.0002306	0.9230	Y = 0.0002306*X + 0.9230
B06 (New_Mid-rise)	0.0001212	0.4334	Y = 0.0001212*X + 0.4334
B07 (New_High-rise)	0.0001005	0.1956	Y = 0.0001005*X + 0.1956
B15 (Existing_Low-rise)	0.001127	4.632	Y = 0.001127*X + 4.632

B16 (Existing_High-rise)	0.0003913	1.236	Y = 0.0003913*X + 1.236

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B05 (New_ Low-rise)	0.00009975	4.212	Y = 0.00009975*X + 4.212
B06 (New_Mid-rise)	-0.00006307	3.932	Y = -0.00006307*X + 3.932
B07 (New_High-rise)	-0.0001326	3.936	Y = -0.0001326*X + 3.936
B15 (Existing_Low-rise)	0.0008903	8.209	Y = 0.0008903*X + 8.209
B16 (Existing_High-rise)	0.0001657	4.873	Y = 0.0001657*X + 4.873

4.4 Residential building

The correlation between cooling degree hours and the sensible cooling load in reference scenarios, and the cooling load reduction in scenario 1 and scenario 2 for the 5 residential building types (B08_Existing_Low-rise_apartment; B09_New_Mid-rise_apartment; B10_New_High-rise_apartment; B11_Existing_Standalone house; B17_New_Standalone house) is shown in **Figure 22** and **Table 13**.

1) Regarding the sensible cooling load of reference scenarios, it can be observed that new buildings (B11 VS B17) have a lower heat loss coefficient of the overall envelope.

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, except B11 and B17 which present 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.

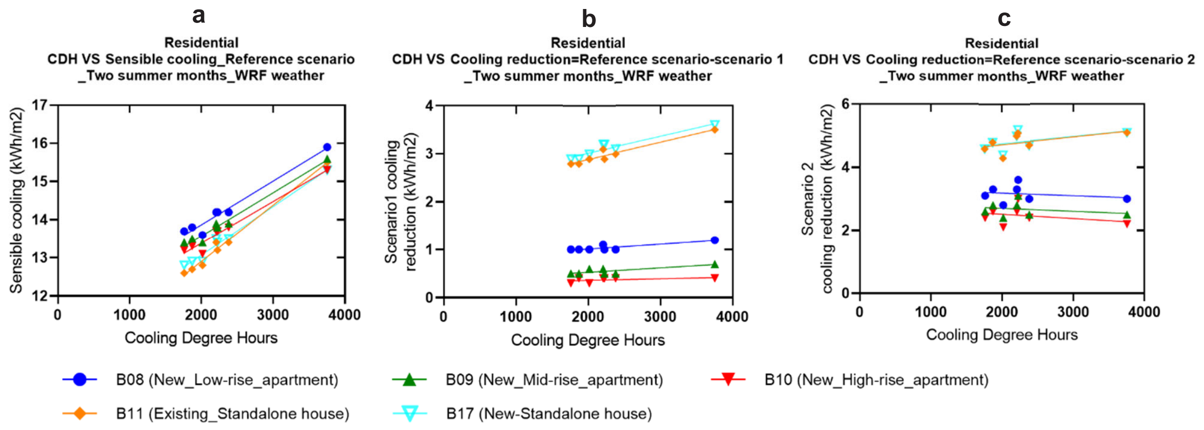


Figure 22 For residential building a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared to the reference scenario.

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

a. Reference scenario	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.001146	11.57	Y = 0.001146*X + 11.57
B09 (New_Mid-rise_apartment)	0.001138	11.29	Y = 0.001138*X + 11.29
B10 (New_High-rise_apartment)	0.001095	11.19	Y = 0.001095*X + 11.19
B11 (Existing_Standalone house)	0.001478	9.947	Y = 0.001478*X + 9.947
B17 (New-Standalone house)	0.001277	10.51	Y = 0.001277*X + 10.51

b. Scenario 1 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	0.0001029	0.8045	Y = 0.0001029*X + 0.8045
B09 (New_Mid-rise_apartment)	0.00009175	0.3446	Y = 9.175e-005*X + 0.3446
B10 (New_High-rise_apartment)	0.00003184	0.2977	Y = 3.184e-005*X + 0.2977

B11 (Existing_Standalone house)	0.0003523	2.184	Y = 0.0003523*X + 2.184
B17 (New-Standalone house)	0.0003455	2.328	Y = 0.0003455*X + 2.328

c. Scenario 2 cooling reduction	**Slope**	**Y-intercept**	**Equation**
B08 (New_Low-rise_apartment)	-0.00008061	3.344	Y = -0.00008061*X + 3.344
B09 (New_Mid-rise_apartment)	-0.00009177	2.884	Y = -0.00009177*X + 2.884
B10 (New_High-rise_apartment)	-0.0001352	2.785	Y = -0.0001352*X + 2.785
B11 (Existing_Standalone house)	0.0002369	4.251	Y = 0.0002369*X + 4.251
B17 (New-Standalone house)	0.0002223	4.314	Y = 0.0002223*X + 4.314

4.5 School

School load reduction in scenario 1 and scenario 2 for the one building type (B12_Existing) is shown in **Figure 23** and **Table 14.** As only one building type is simulated under the category of school, no conclusions can be drawn from internal comparisons like other building categories. For this existing school alone, its sensible cooling load increases with the increase of cooling degree hours. Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree, indicating that in most cases, under unmodified climatic conditions, a cool roof is more effective reducing the cooling load in hotter regions. For the cooling load reduction in scenario 2 compared with the reference scenario, B12 presents an increased cooling load reduction with the increase of cooling degree hours.

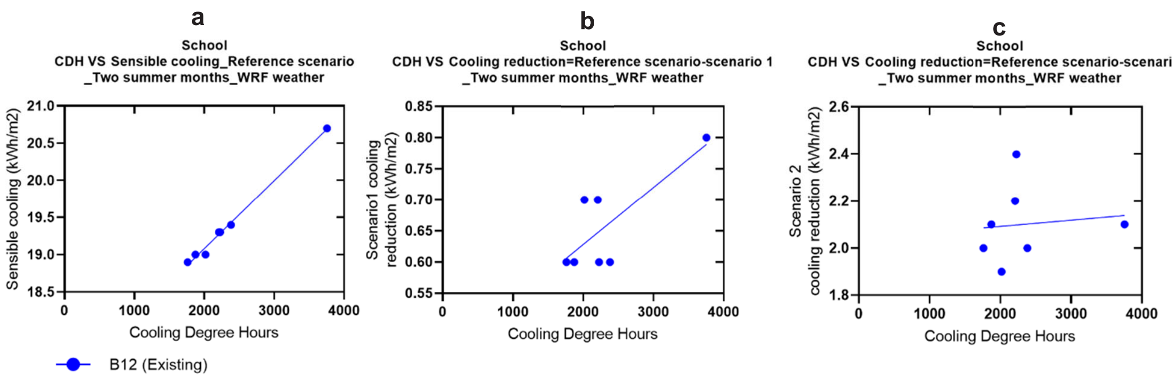


Figure 23 For school a) The correlation between CDH and the sensible cooling of the reference scenario; b) The correlation between CDH and the cooling load reduction of scenario 1 compared to the reference scenario; c) The correlation between CDH and the cooling load reduction of scenario 2 compared to the reference scenario.

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

a. Reference scenario	Slope	Y-intercept	Equation
B12 (Existing)	0.0009170	17.25	Y = 0.0009170*X + 17.25

b. Scenario 1 cooling reduction	Slope	Y-intercept	Equation
B12 (Existing)	0.00009175	0.4446	Y = 0.00009175*X + 0.4446

c. Scenario 2 cooling reduction	Slope	Y-intercept	Equation
B12 (Existing)	0.00002634	2.039	Y = 0.00002634*X + 2.039

4.6 Conclusion

- Regarding the sensible cooling load of reference scenarios, new buildings, or buildings with higher levels, or those with insulated envelopes, have a lower heat loss coefficient of the overall envelope and therefore have a more stable cooling load when cooling degree hours change.
- Cooling load reduction in scenario 1 compared with the reference scenario increases with the increase of cooling degree hours, indicating that under unmodified climatic conditions, a cool roof is more effective in reducing the cooling load in hotter regions. A higher increase rate is observed in buildings with fewer floors, and older construction years, which often have higher heat loss coefficients in envelopes.
- For the cooling load reduction in scenario 2 compared with the reference scenario, most buildings present an increasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving

advantage of a cool roof is higher in hotter areas for all buildings except for three residential buildings and two shopping centers.

- A general ranking of the heat loss coefficients of these buildings from low to high is office, school, residentail buildings and shopping mall center **(Table 15)**.

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

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

5. Conclusions

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

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

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 Brisbane.
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 Brisbane.
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 found that a strong urban heat island (UHI) phenomenon is developed. The maximum magnitude of the phenomena may exceed 5°C.The UHI effect would be added evenhandedly balanced spatially under the urban expansion. The intensity and the characteristics of the phenomena are strongly influenced by the synoptic weather conditions and in particular the development of the sea breeze and the westerly winds from the desert area. The possible existence of an additional heating mechanism, like the advection of warm air from nearby spaces, may intensify the strength of the problem.
2) High density parts of the city exhibit a much higher temperature drop than the urban average. Increase of albedo in Brisbane can decrease the peak summer ambient temperature up to 2.5°C and surface temperature up to 6.8°C. It was found that important temperature differences exist near the coast and central part of the city. The patterns of the ambient temperature distribution in the city were found to depend highly on the synoptic climatic conditions and the magnitude of the surface thermal gradient.
3) The maximum decrease of sensible heat and latent heat flux were up to 184.6 Wm-2 and 17.4 Wm-2, respectively.

4) The maximum decrease of wind speeds up to 2.5 ms-1. Cool roofs increase the pressure at local-scale and decrease the wind advection from the bare surface.
5) The results of numerical experiments show that the increase in albedo fraction leads to decrease in wind speeds and the incidence of high wind speeds along with augmented turbulent energy in the planetary boundary layer (PBL) during heat wave scenario. Under the low wind speed, additional thermal gradient was observed over Brisbane city. When the wind speed is low and the ambient and surface temperature is very high. Under these conditions, there is a substantial temperature difference between the cool roofs and the warm pavements that generate some small local thermal winds at neighborhood scale.
6) Alteration of the urban albedo in Brisbane results in a solemn average reduction up to 735.6 m of the PBL heights over city and may increase the concentration of pollutants at ground level,
7) The urban–sea temperature difference approaching to sea-breeze effects. Cool roof that reduced daytime ambient temperatures, but higher winds over cool roof implemented city greatly reduce the sea breeze penetration.
8) The magnitudes of the UHI phenomenon were associated with the existence of a sea breeze in the eastern parts of the city, decreasing the temperature of the coastal zone, combined with westerly winds from the inland that heat up the western zones of the city.
9) In control cases, CDH ranges from 956.6 to 4167.1 and about 40% of the data is concentrated in 1800 - 2000. CDH gradually increases from the east of the city to the west.
10) In cool roof cases, CDH ranges from 377.7 to 3446.5 and about 50% of the data is concentrated in 1000 - 1400. Its spatial distribution is also similar to that of the control case.
11) The percentage of CDH reduction due to the implementation of the cool roof ranges from 16% to 62% with an average value of 34.6%. The percentage of CDH reduction in the original control volume is relatively large in the east of the city, and gradually decreases toward the west.
12) In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in individual buildings (scenario 1) is quite significant. For instance, application of cool roofs in individual building (scenario 1) in an existing low-rise office building without insulation is projected to reduce the cooling load by 11.3-15.6 kWh/m2.
13) In existing buildings without insulation/with low level of insulation, the cooling load saving by implementation of cool roofs in both individual buildings and at the whole urban area (scenario 2) is quite significant. For instance, application of cool roofs in both individual buildings and at the whole urban area (scenario 2) in an existing low-rise office building without insulation is projected to reduce the cooling load by 18.7-21.3 kWh/m2.

14) In existing buildings without insulation/with low insulation level, the cooling load reduction of the cool roofs is remarkable even for the high-rise buildings. For instance, the application of cool roofs on the individual building (scenario 1) and both individual buildings and at the whole urban area (scenario 2) is expected to decrease the cooling loads of a high-rise office building without roof insulation by 2.0-3.0 kWh/m2 and 8.6-10.4 kWh/m2, respectively.

15) 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 in both individual building and at the whole urban area (scenario 2) is predicted to be 7.3-9.2 kWh/m2 in a typical new low-rise office building.

16) In new high-rise buildings with high insulation level, application of cool roofs in individual buildings (scenario 1) is predicted to have relatively low impact on the cooling load reduction. As per simulations results, the cooling load reduction by application of cool roofs in individual buildings (scenario 1) is predicted to be just 0.2-0.3 kWh/m2 for new high-rise office buildings with insulation.

17) In high-rise buildings, the cooling load reduction through application of cool roofs in both individual building and at the whole urban area (scenario 2) is significantly higher than the cooling load savings by implementation of cool roofs in individual buildings (scenario 1). For instance, the cooling load reduction by application of cool roofs in individual building (scenario 1) is projected to be just 0.4-0.5 kWh/m2 in a new high-rise apartment building, which is expected to increase to 6.7-9.1 kWh/m2 when cool roofs are applied both in individual buildings and at the whole urban area (scenario 2).

18) The annual heating penalty of cool roofs is significantly lower than the annual cooling load savings in all types of buildings. For instance, the annual cooling load saving in a low-rise office building without insulation is 34.7-52.7 kWh/m2, while the corresponding heating penalty is just 0.5-0.9 kWh/m2.

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) 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 9.0-10.3 ^{o}C.

20) 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 9.6-11.1 °C.

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 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 1.7-2.1 °C in a typical new low-rise office building.

22) In residential buildings 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 existing stand-alone house is predicted to reduce from 573-592 hours to 530-565 hours and 463-490 hours by application of cool roofs in individual building (scenario 1) and both individual building and at the whole urban scale (scenario 2), respectively.

23) In non-residential buildings and under free-floating condition in a typical summer period, application of cool roofs in individual buildings (scenario 1) or both individual buildings and at the whole urban area (scenario 2) has low or no impact on reducing 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 mid-rise shopping mall centre is predicted to remain unchanged after application of cool roofs.

24) 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 9-10.3 °C in a typical summer week, while the maximum indoor air temperature reduction of the same building is expected to be just 3.4-3.6 °C during a typical winter month.

25) 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 3.4 °C occurs when the indoor air temperature is 29.3 °C.

26) 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 ºC from 18-29 hours to 26-31 hours in a typical existing low-rise office building with roof insulation.

27) Regarding the sensible 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.

28) 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.

29) For the cooling load reduction in scenario 2 compared with the reference scenario, most buildings present an increasing cooling load reduction with the increase of cooling degree hours. It highlights that when extensive use of cool roofs in the city has been considered in the climatic data, the energy-saving advantage of a cool roof is higher in hotter areas for all buildings except for three residential buildings and two shopping centers.

6. Reference

Bureau of Meteorology (2017a). Humidity, heavy rain and heat in central and southern Australia, Australia. http://www.bom.gov.au/climate/current/statements/scs59.pdf. Accessed 28 July, 2021.

Bureau of Meteorology (2017b). Exceptional heat in southeast Australia in early 2017, Australia. http://www.bom.gov.au/climate/current/statements/scs61.pdf. Accessed 28 July, 2021.

Chen, F., & Dudhia, J. (2001). Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling system. Part I: Model implementation and sensitivity. Monthly Weather Review, 129(4), 569-585.

Dudhia, J. (1989). Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. Journal of Atmospheric Sciences, 46(20), 3077-3107.

Kain, J. S. (2004). The Kain–Fritsch convective parameterization: an update. Journal of Applied Meteorology, 43(1), 170-181.

Kusaka, H., Kondo, H., Kikegawa, Y., & Kimura, F. (2001). A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. Boundary-layer Meteorology, 101(3), 329-358.

Mellor, G. L., & Yamada, T. (1974). A hierarchy of turbulence closure models for planetary boundary layers. Journal of Atmospheric Sciences, 31(7), 1791-1806.

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., & Clough, S. A. (1997). Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated ‐ k model for the longwave. Journal of Geophysical Research: Atmospheres, 102(D14), 16663-16682.

Pleim, J. E. (2007). A combined local and nonlocal closure model for the atmospheric boundary layer. Part II: Application and evaluation in a mesoscale meteorological model. Journal of Applied Meteorology and Climatology, 46(9), 1396-1409.

Santamouris, M., Ding, L., Fiorito, F., Oldfield, P., Osmond, P., Paolini, R., ...&Synnefa, A. J. S. E. (2017). Passive and active cooling for the outdoor built environment–Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. Solar Energy, 154, 14-33.

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	-0.6	-1.8	-1.3	-1.2
Minimum	-0.1	-0.9	-0.6	-0.5
Average of January	-0.4	-1.1	-0.9	-0.8
Average of February	-0.4	-1.2	-1.9	-0.9

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

Parameters	Surface Temperature (°C)			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-2.2	-6.1	-5.0	-4.5
Minimum	-1.3	-5.1	-3.9	-3.7
Average of January	-1.9	-5.6	-4.5	-4.1
Average of February	-1.9	-5.6	-4.5	-4.0

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

Parameters	**Sensible Heat Flux (W/m2)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-59.7	-175.0	-69.9	-80.1
Minimum	-42.1	-135.4	-56.4	-66.6
Average of January	-51.6	-158.0	-63.4	-74.0
Average of February	-53.2	-162.3	-64.3	-74.5

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

Parameters	**Latent Heat Flux (W/m2)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-4.0	-15.1	-5.6	-7.6
Minimum	-2.0	-9.9	-2.4	-5.2
Average of January	-2.8	-12.9	-4.0	-6.1
Average of February	-3.4	-13.4	-4.6	-6.9

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

Parameters	**Wind Speed (m/s)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-1.1	-2.4	-1.8	-1.9

Minimum	-0.1	-0.2	-0.1	-0.2
Average of January	-0.7	-1.1	-0.8	-0.9
Average of February	-0.8	-1.0	-0.6	-0.7

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

Parameters	**PBL Height (m)**			
	06:00 LT	**14:00 LT**	**18:00 LT**	**24-h avg.**
Maximum	-145.2	-695.5	-251.1	-264.0
Minimum	-110.2	-500.6	-189.5	-199.4
Average of January	-131.1	-615.4	-212.6	-226.1
Average of February	-125.2	-621.0	-209.9	-230.0

8. Appendix: Building characteristics_ Cool roofs project simulations inputs _ Climate zone 2

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

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

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

Table 23 Operation schedules

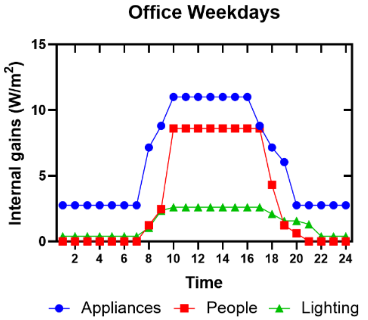
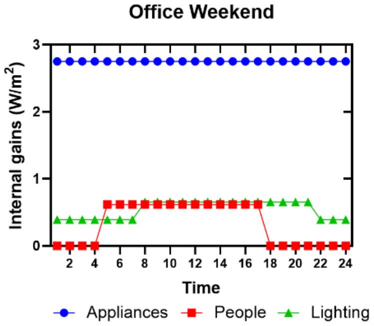
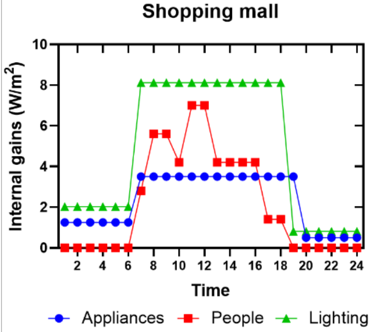
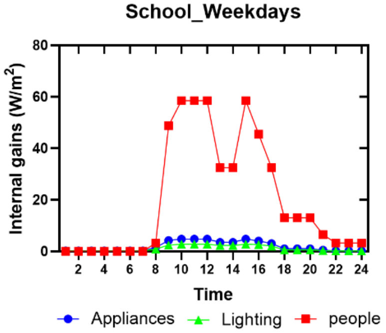
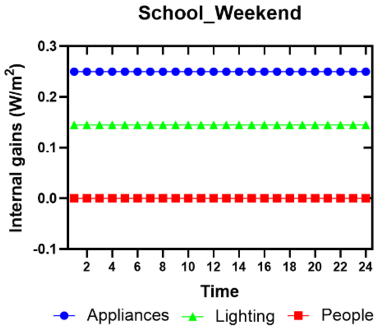
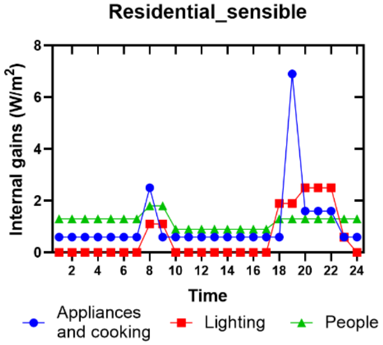
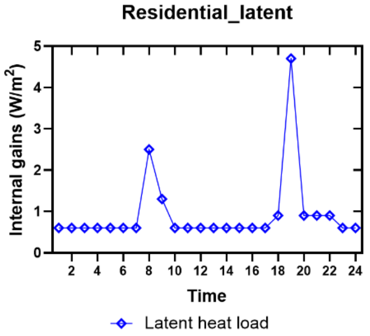
	Office			Shopping mall		School	Standalone House		Apartment
Building ID	**B01, B02**	**B03, B04**	**B13, B14**	**B05, B06, B07**	**B15, B16**	**B12**	**B11**	**B17**	**B08, B09, B10**
Building Type	Existing uninsulated	New	Existing w/ roof ins.	New	Existing	Existing	Existing	New	New
Intensity of internal heat gains (W/m2) **(from NatHERS and NCC 2019)**	 **Office Weekdays**  **Office Weekend** 			 **Shopping mall** 		 **School_Weekdays**  **School_Weekend** 	 **Residential_sensible**  **Residential_latent** 		

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)-calculated	0.26	3.84	0.64	3.84	0.64	3.84	0.26	4.24	3.84
Roof solar reflectance	0.15_CTRL								
	0.80_COOL								
Roof thermal emittance	0.85								
Wall R-value (m2·K/W)-calculated	1.17	1.17	1.17	1.17		1.17	2.97		1.17
Wall solar reflectance	0.15								
Wall thermal emittance	0.85								
Window U-value (W/m^{2}K)	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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