SEPTEMBER 2021

Research plan & progress report

COOL ROOFS COST BENEFIT ANALYSIS

Volume 2 Brochures

Prof Mattheos Santamouris[1],
Dr Riccardo Paolini[1],
Dr Ansar Khan[2],
Dr Carlos Bartesaghi Koc[3],
Dr Shamila Haddad[1],
Dr Samira Garshasbi[1],
Dr Jie Feng[1]

UNSW SYDNEY

This report is submitted by the University of New South Wales

COOL ROOFS COST BENEFIT ANALYSIS

Background image front cover:
Ryonosuke KiKuno (Copyright free)

https://unsplash.com/@ryunosuke_kikuno

Authors

Prof Mattheos Santamouris[1], Dr Riccardo Paolini[1], Dr Ansar Khan[2], Dr Carlos Bartesaghi Koc[3], Dr Shamila Haddad[1], Dr Samira Garshasbi[1], Dr Jie Feng[1]

Research team

Prof Mattheos Santamouris[1], Prof Deo Prasad[1], A/Prof Lan Ding[1], A/Prof Paul Osmond[1], Dr Riccardo Paolini[1], Dr Carlos Bartesaghi Koc[3], Dr Shamila Haddad[1], Dr Samira Garshasbi[1], Dr Jie Feng[1], Kai Gao[1]

International contributors

Prof Denia Kolokotsa[4], Dr Afroditi Synnefa[4], Dr Ansar Khan[2], Stelios Diakrousis[4], Kurt Shickman[5]

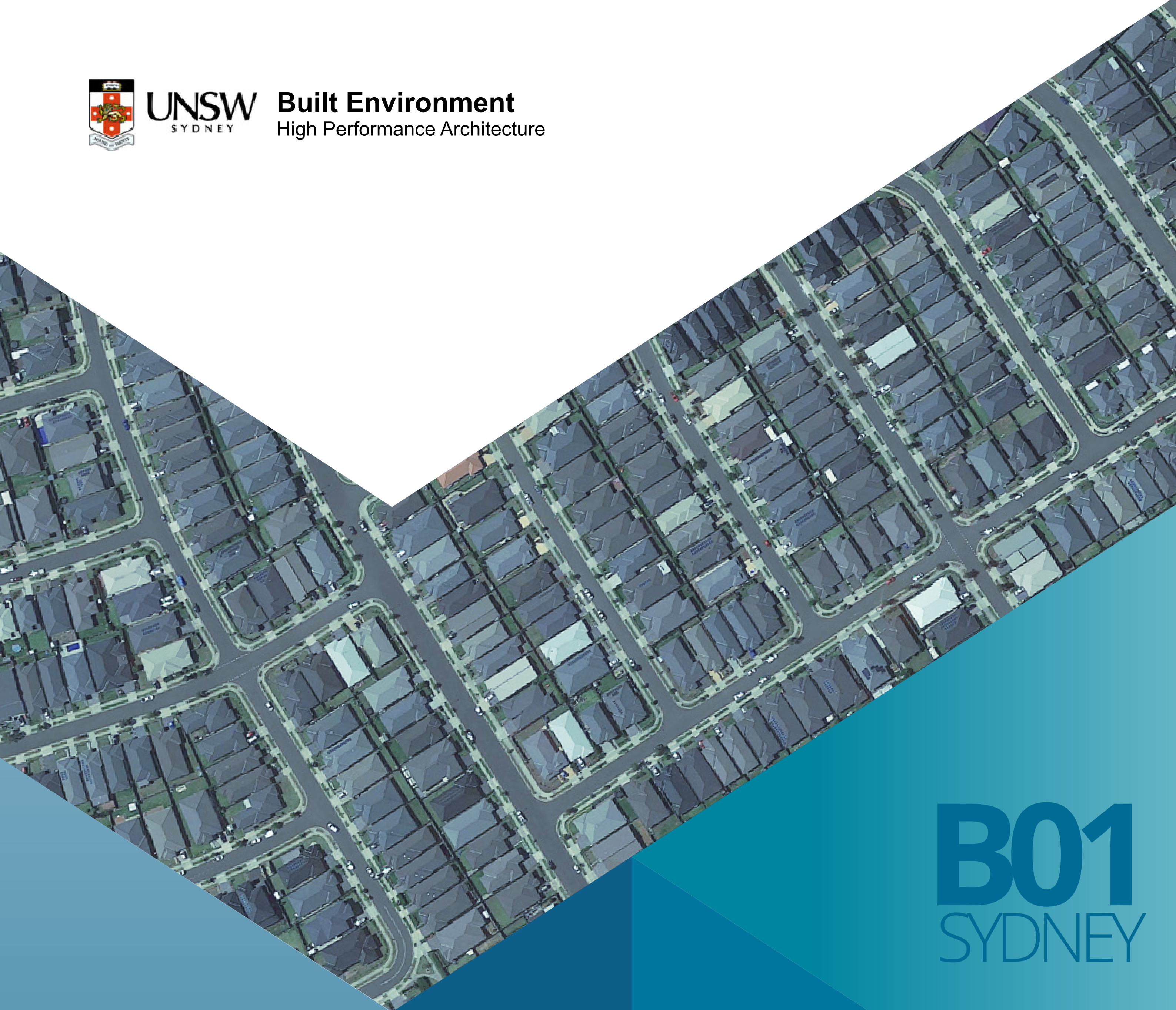
[1] School of Built Environment, University of New South Wales, Australia
[2] Department of Geography, Lalbaba College, University of Calcutta, India
[3] School of Architecture and Built Environment, Faculty of Engineering, Computer and Mathematical Sciences, The University of Adelaide, Australia
[4] Technical University of Crete, Greece
[5] Global Cool Cities Alliance, USA

Submission date: 20 September 2021.

UNSW SYDNEY, NSW 2052, AUSTRALIA
T +61 (2) 9385 1000 | F +61 (2) 9385 0000 |
ABN 57 195 873 179

UNSW SYDNEY

Built Environment
High Performance Architecture



B01
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

Low-rise office building without roof insulation
2021

BUILDING 01

LOW-RISE OFFICE BUILDING WITHOUT ROOF INSULATION

Floor area : 1200m^2
Number of stories : 2

Image source: Ecipark Office Building. https://jhmrad.com/21-delightful-two-story-building/ecipark-office-building-two-story/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a typical low-rise office building without roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building withour roof insulation from 33.1-44.5 kWh/m² to 17.6-23.7 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)
Sydney Airport	26.0	33.8	11.8	18.1	8.4	11.0
Terry Hill	30.7	36.4	13.7	18.5	11.9	14.9
Bankstown	31.5	38.1	15.6	21.2	12.5	14.9
Canterbury	27.5	34.6	12.8	18.8	10.0	13.0
Observatory	25.6	33.1	11.5	17.6	9.1	12.4
Richmond	39.7	44.5	19.6	23.7	17.7	19.5
Penrith	35.3	40.2	17.9	22.0	15.9	17.7
Horsley Park	34.3	39.5	17.0	21.4	14.1	16.2
Camden	35.7	40.0	18.3	21.9	16.2	17.5
Olympic Park	30.7	37.5	15.0	20.8	12.6	15.7
Campbelltown	33.7	38.8	16.7	21.0	14.4	16.2

Table 2. Sensible and total cooling load saving for a typical low-rise office building without roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 15.5-20.8 kWh/m² which is equivalent to 44.4-49.2 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 20.7-25.0 kWh/m² which is equivalent to 56-67.5 % of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Sydney Airport	14.2	54.6	15.7	46.4	17.6	67.7	22.8	67.5
Terry Hill	17.0	55.4	17.9	49.2	18.8	61.2	21.5	59.1
Bankstown	15.9	50.5	16.9	44.4	19.0	60.3	23.2	60.9
Canterbury	14.7	53.5	15.8	45.7	17.5	63.6	21.6	62.4
Observatory	14.1	55.1	15.5	46.8	16.5	64.5	20.7	62.5
Richmond	20.1	50.6	20.8	46.7	22.0	55.4	25.0	56.2
Penrith	17.4	49.3	18.2	45.3	19.4	55.0	22.5	56.0
Horsley Park	17.3	50.4	18.1	45.8	20.2	58.9	23.3	59.0
Camden	17.4	48.7	18.1	45.3	19.5	54.6	22.5	56.3
Olympic Park	15.7	51.1	16.7	44.5	18.1	59.0	21.8	58.1
Campbelltown	17.0	50.4	17.8	45.9	19.3	57.3	22.6	58.2

> *In the eleven weather stations in Sydney, it is estimated that both building-scale and combined building-scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical low-rise office building without insulation during the summer season.*

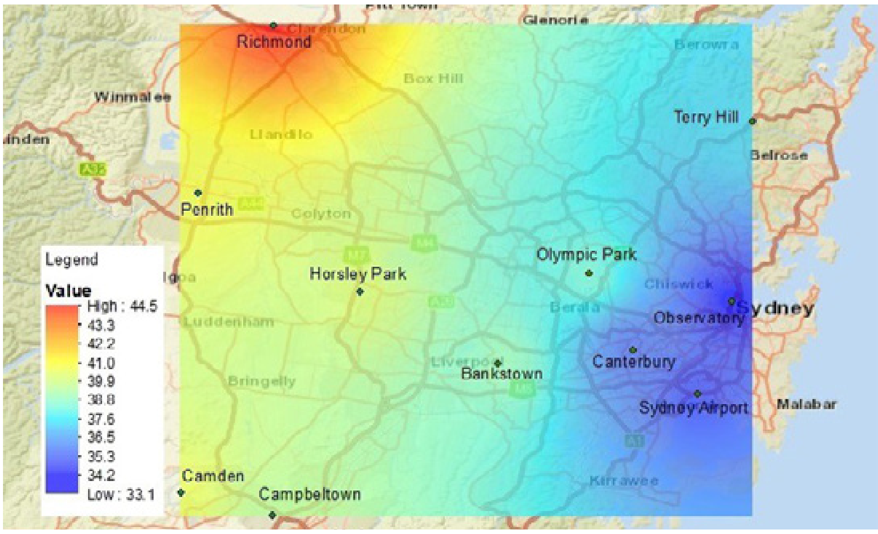


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

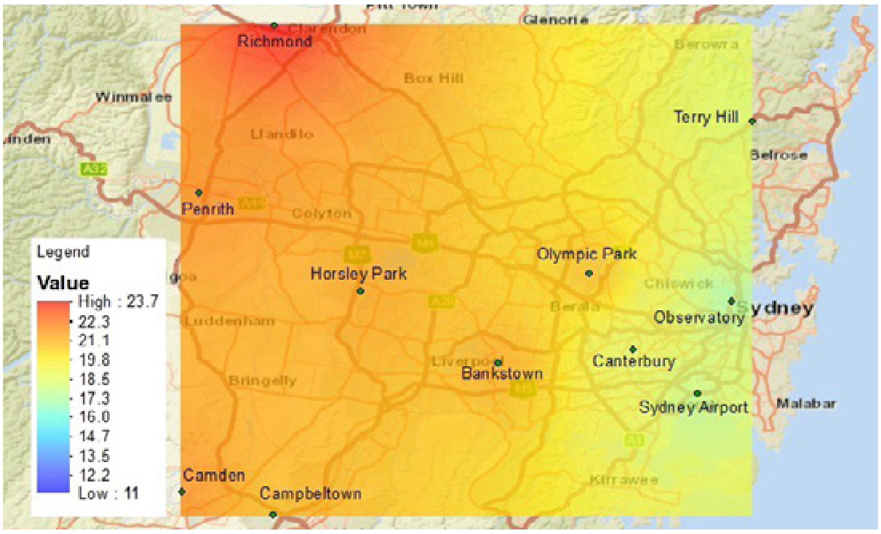


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

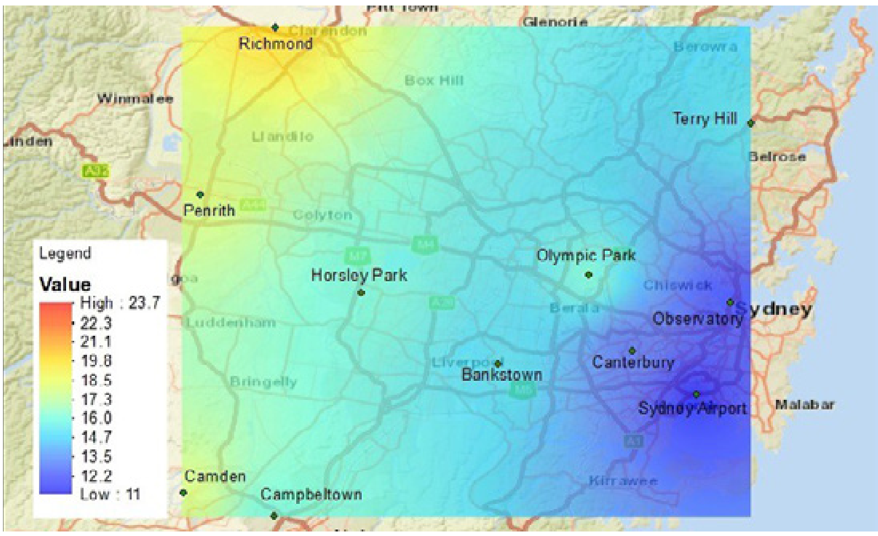


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a low-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (2.4-4.2 kWh/m²) is significantly lower than the annual cooling load reduction (24.6-43.1 kWh/m²).

Table 3. Annual cooling and heating loads for a low-rise office building without roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	47.6	57.8	4.1	6.2	24.9	33.2	6.0	8.6
Terry Hill	43.1	56.6	5.0	7.9	18.2	25.4	7.9	11.8
Bankstown	60.9	72.2	4.5	7.5	31.3	40.4	7.1	10.9
Canterbury	49.6	60.3	4.7	8.0	23.7	31.7	7.6	11.9
Observatory	53.3	63.1	4.0	6.1	24.7	32.6	6.3	9.2
Richmond	68.1	81.1	4.9	8.4	34.7	44.4	7.4	11.8
Penrith	76.0	89.8	4.0	6.9	36.8	46.7	6.4	10.1
Horsley Park	65.6	74.9	4.7	7.7	30.1	37.3	7.5	11.5
Camden	61.6	70.2	5.3	9.2	29.4	35.9	8.4	13.3
Olympic Park	65.0	78.6	3.8	6.4	30.2	40.8	6.0	9.3
Campbelltown	62.0	69.6	5.1	8.8	28.4	34.2	8.3	13.0

The annual cooling load saving by building-scale application of cool roofs is around 42.6-55.1 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 22.2 and 39.9 kWh/m² (~34.7-42.3 %).

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without roof insulation using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	22.7	47.7	24.6	42.6	1.9	2.4	20.8	40.2	22.2	34.7
Terry Hill	24.9	57.8	31.2	55.1	2.9	3.9	22.0	45.7	27.3	42.3
Bankstown	29.6	48.6	31.8	44.0	2.6	3.4	27.0	41.3	28.4	35.6
Canterbury	25.9	52.2	28.6	47.4	2.9	3.9	23.0	42.4	24.7	36.2
Observatory	28.6	53.7	30.5	48.3	2.3	3.1	26.3	45.9	27.4	39.6
Richmond	33.4	49.0	36.7	45.3	2.5	3.4	30.9	42.3	33.3	37.2
Penrith	39.2	51.6	43.1	48.0	2.4	3.2	36.8	46.0	39.9	41.3
Horsley Park	35.5	54.1	37.6	50.2	2.8	3.8	32.7	46.5	33.8	40.9
Camden	32.2	52.3	34.3	48.9	3.1	4.1	29.1	43.5	30.2	38.0
Olympic Park	34.8	53.5	37.8	48.1	2.2	2.9	32.6	47.4	34.9	41.1
Campbelltown	33.6	54.2	35.4	50.9	3.2	4.2	30.4	45.3	31.2	39.8

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

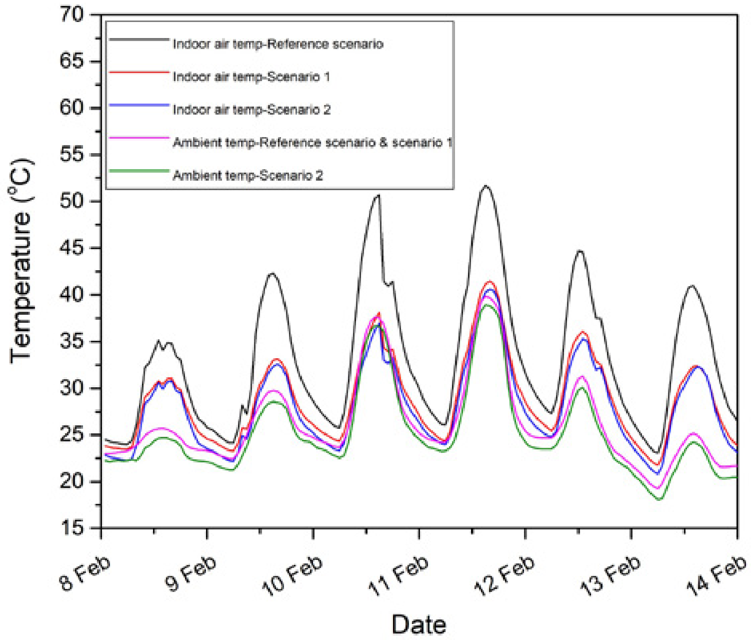


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

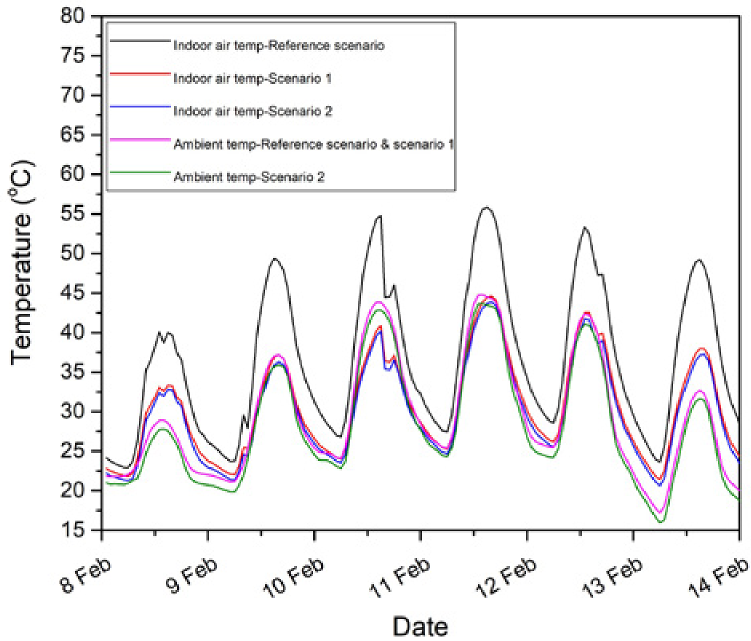


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 23.0-51.7 °C and 22.9-55.8 °C in Observatory and Richmond stations, respectively.

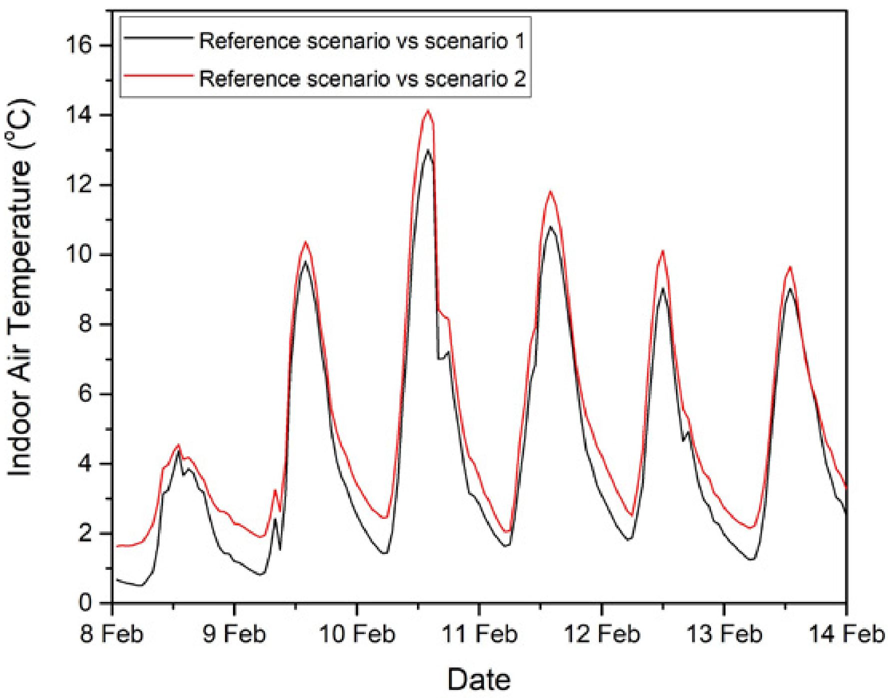


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 13 °C and 14 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 14.1°C and 14.7°C in Observatory and Richmond stations, respectively.

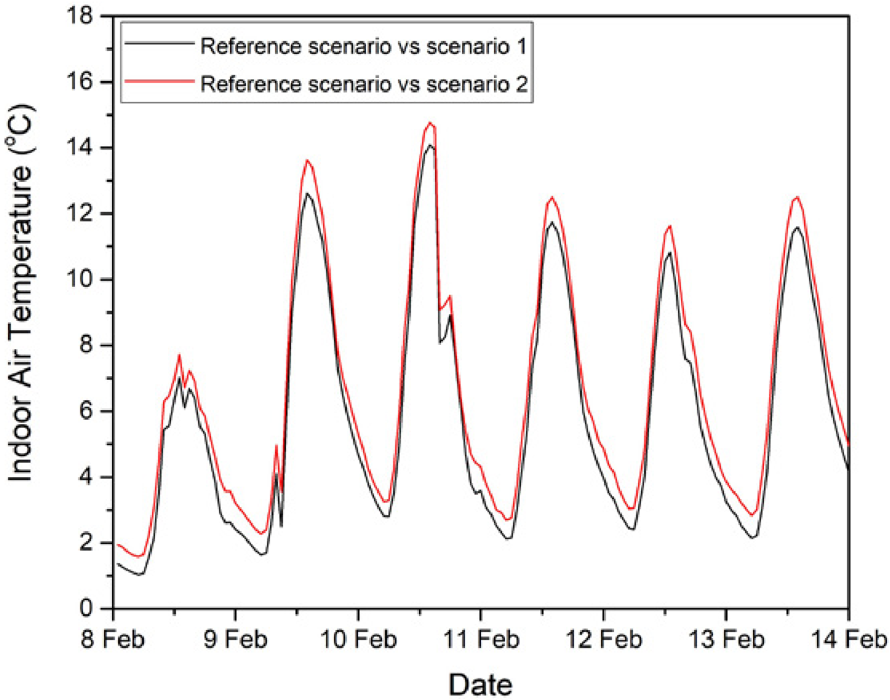


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a low-rise office building without insulation under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 8.7-26.6 °C in reference scenario to a range 8.3-23.9 °C in scenario 1 in Observatory Hill station.

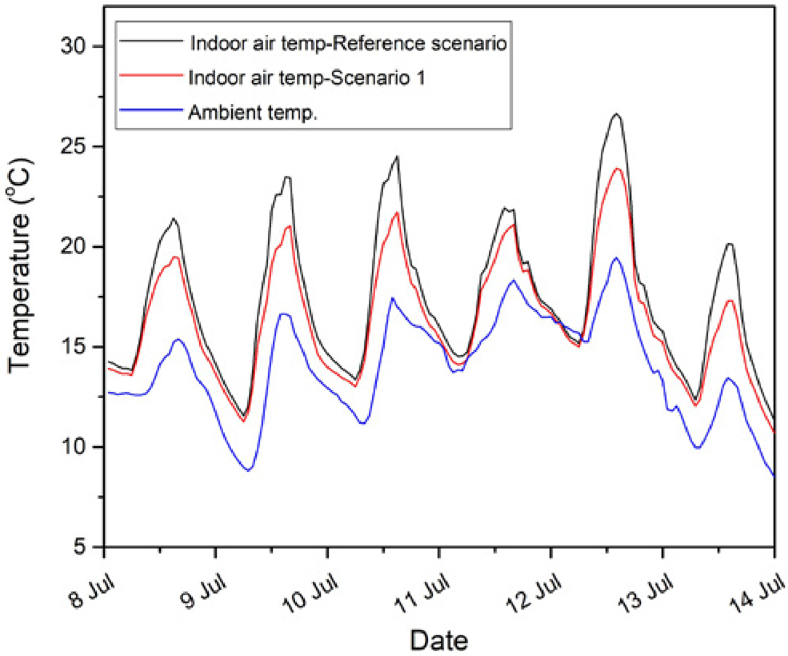


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 4.9-25.9 °C in reference scenario to a range 4.5-23.7 °C in scenario 1 in Richmond station.

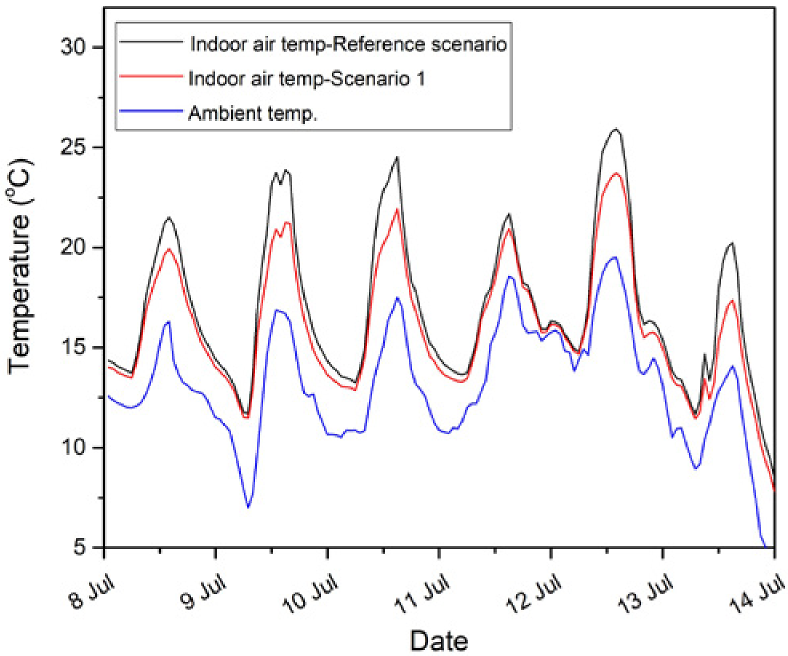


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

> *For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 3.2 °C and 3.4 °C in Observatory and Richmond stations, respectively.*

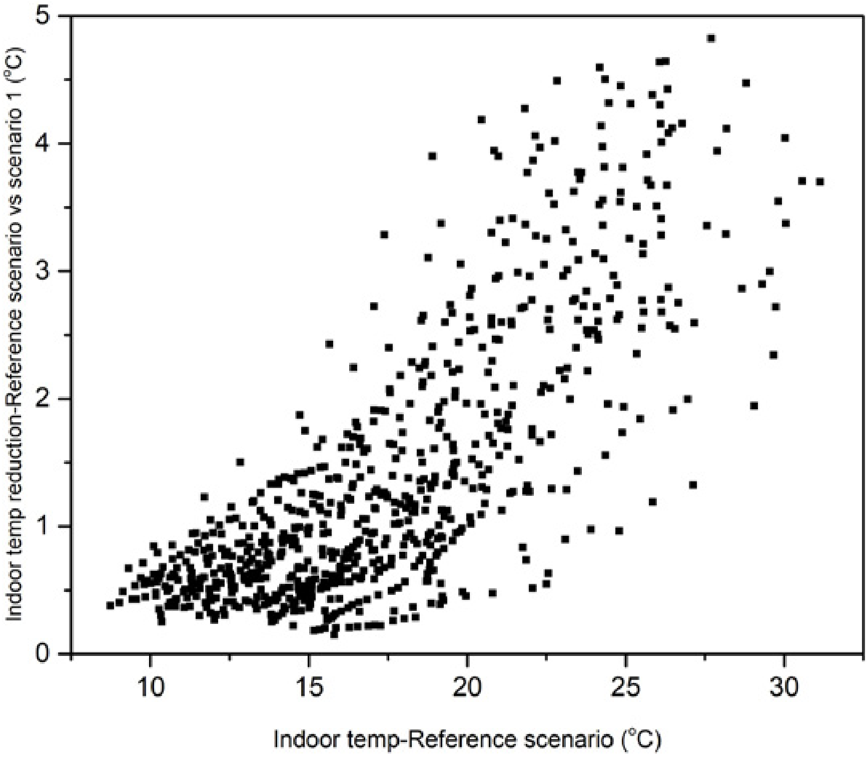


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

> *Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.*

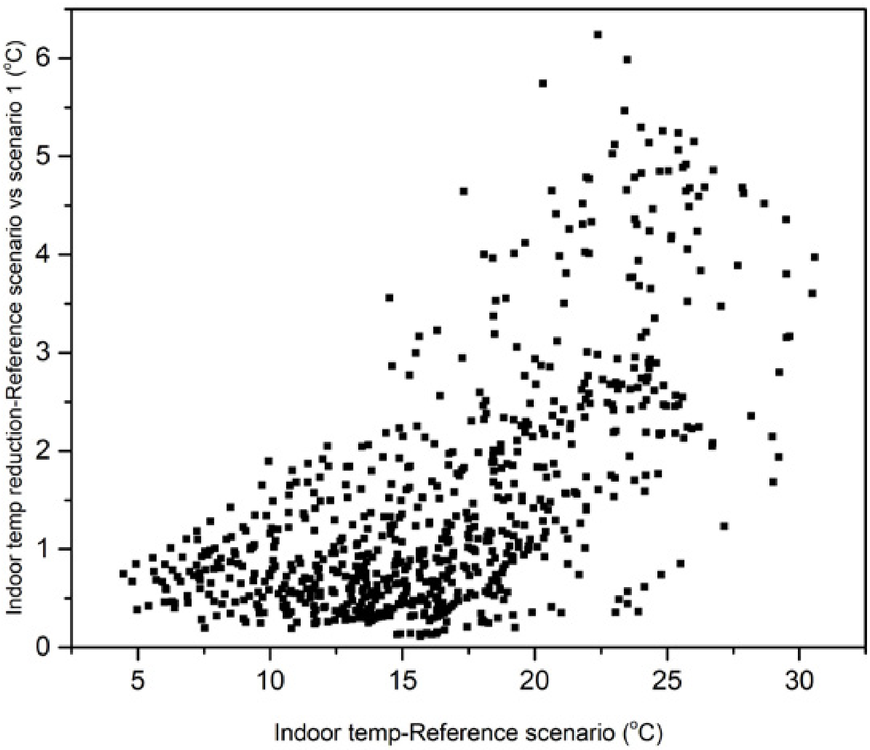


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a low-rise office building without insulation under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 489 hours in reference scenario to 581 and hours and from 516 to 594 hours in scenario 1 in Observatory and Richmond stations, respectively.

The number operational hours with air temperature <19 °C during is expected to increase from 146 hours in reference scenario to 226 hours; and from 165 to 236 hours in scenario 1 in Observatory and Richmond stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	146	489	226	581
Richmond	165	516	236	594

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decreased from 462 hours in reference scenario to 356 and 296 hours under scenario 1 and 2 in Observatory station; and from 499 hours in reference scenario to 385 and 346 hours under scenario 1 and 2 in Richmond station, respectively.

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	462	356	296
Richmond	499	385	346

6

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of the typical low-rise office building without insulation during the summer season.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 33.1-44.5 kWh/m2 to 17.6-23.7 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 15.5-20.8 kWh/m^2. This is equivalent to approximately 44.4-49.2% total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1& Table 2 and Figure 1 & Figure 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 20.7-25 kWh/m^2. This is equivalent to 56-67.5% total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 & Table 2 and Figure 2 & Figure 3).

• The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (2.4-4.2 kWh/m^2) is significantly lower than the annual cooling load reduction (24.6-43.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 42.6-55.1%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 22.2 and 39.9 kWh/m^2 (~34.7-42.3%) (Tables 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 23-51.7 °C and 22.9-55.8 °C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 13 and 14 °C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 14.1 and 14.7 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figure 4, Figure 5, Figure 6 and Figure 7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 °C in reference scenario to a range between 18.1 and 38.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 °C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 °C in reference scenario to 15.9-43.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 °C in Richmond station (See Figure 4 and Figure 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 8.7 and 26.6 °C in reference scenario to a range between 8.3 and 23.9 °C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 4.9 and 25.9 °C in reference scenario to a range between 4.5 and 23.7 °C in reference with cool roof scenario (scenario 1) in Richmond station (See Figure 8 and Figure 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 3.2 °C and 3.4 °C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figure 10 and Figure 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 489 hours in reference scenario to 581 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slight increase in total number of hours below 19 °C from 516 hours in reference scenario to 594 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to increase from 146 hours in reference scenario to 226 hours in reference with cool roof scenario (scenario 1) in Observatory station. Similarly, the calculation in Richmond station shows a slight increase of number of hours below 19 °C from 165 hours to 236 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 462 hours under the reference scenario in Observatory station, which decreases to 356 and 296 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 °C from 499 hours in reference scenario to 385 in reference with cool roof scenario (scenario 1) and 346 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B01

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

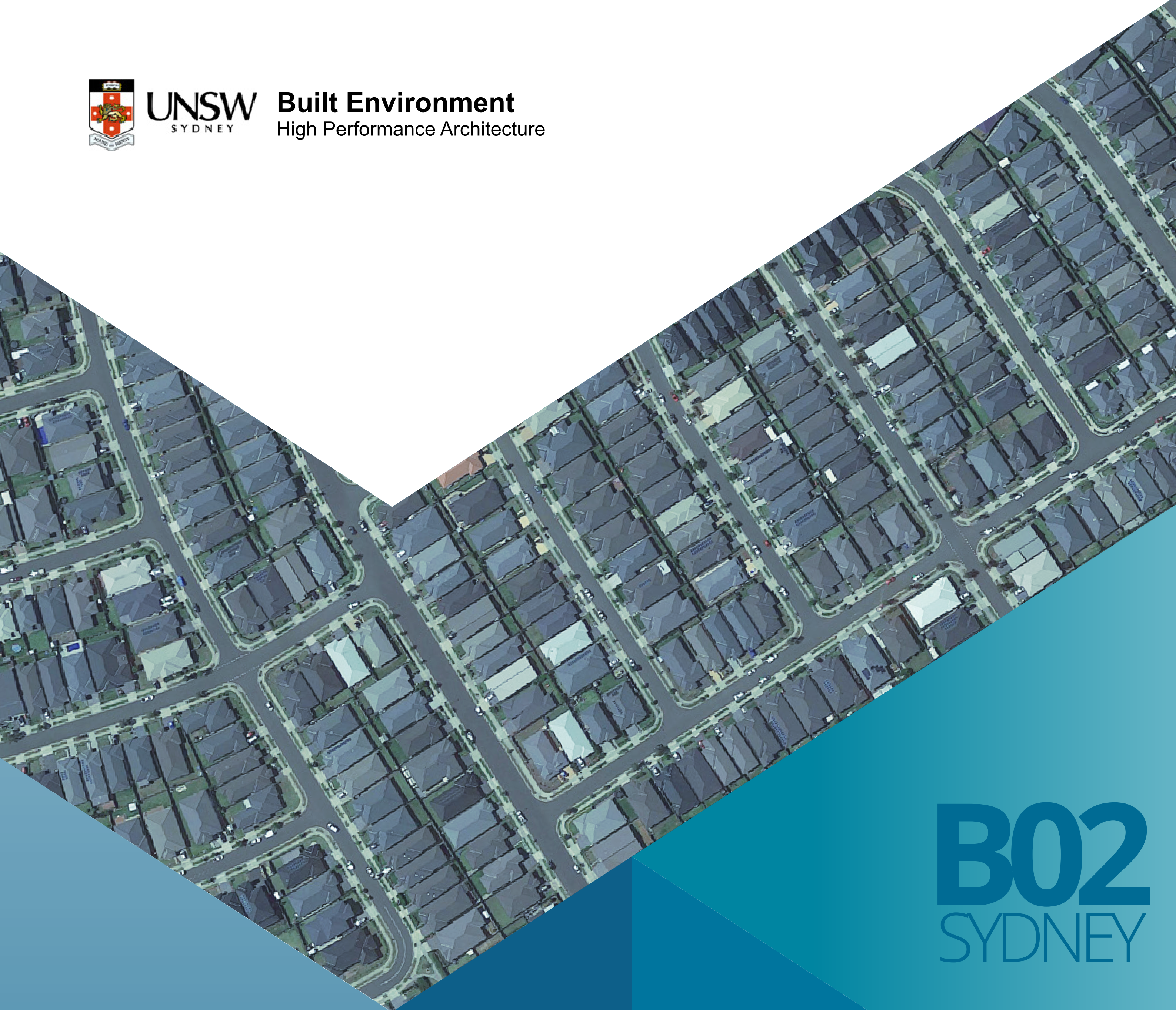
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY
Built Environment
High Performance Architecture



B02
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

High-rise office building without roof insulation
2021

BUILDING 02

HIGH-RISE OFFICE BUILDING WITHOUT ROOF INSULATION

Floor area : 1200m^2
Number of stories : 10

Image source: Ecipark Office Building. https://jerseydigs.com/bayonne-city-council-approves-10-story-building-975-broadway/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a typical high-rise office building without roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the high-rise office building withour roof insulation from 21.9-30.1 kWh/m² to 19.1-26.0 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	15.6	22.5	13.1	19.7	9.3	12.1
Terry Hill	18.1	23.3	14.9	20.0	13.1	16.2
Bankstown	19.8	25.9	17.0	22.9	13.7	16.2
Canterbury	16.7	23.2	14.1	20.4	11.0	14.2
Observatory	15.3	21.9	12.7	19.1	10.0	13.4
Richmond	25.7	30.1	21.6	26.0	19.3	21.4
Penrith	22.5	27.1	19.3	23.7	17.2	19.2
Horsley Park	21.6	26.4	18.4	23.1	14.3	16.6
Camden	22.9	26.9	19.7	23.5	17.3	18.8
Olympic Park	19.2	25.5	16.3	22.5	13.8	17.1
Campbelltown	21.2	26.0	18.1	22.7	15.6	17.6

Table 2. Sensible and total cooling load saving for a typical high-rise office building without roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 2.8-4.1 kWh/m² which is equivalent to 12.8-13.6% total cooling load reduction.

For Scenario 2, the total cooling load saving is around 7.1-10.4 kWh/m² which is equivalent to 30.5-46.2% of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	2.5	16.0	2.8	12.4	6.3	40.4	10.4	46.2
Terry Hill	3.2	17.7	3.3	14.2	5.0	27.6	7.1	30.5
Bankstown	2.8	14.1	3.0	11.6	6.1	30.8	9.7	37.5
Canterbury	2.6	15.6	2.8	12.1	5.7	34.1	9.0	38.8
Observatory	2.6	17.0	2.8	12.8	5.3	34.6	8.5	38.8
Richmond	4.1	16.0	4.1	13.6	6.4	24.9	8.7	28.9
Penrith	3.2	14.2	3.4	12.5	5.3	23.6	7.9	29.2
Horsley Park	3.2	14.8	3.3	12.5	7.3	33.8	9.8	37.1
Camden	3.2	14.0	3.4	12.6	5.6	24.5	8.1	30.1
Olympic Park	2.9	15.1	3.0	11.8	5.4	28.1	8.4	32.9
Campbelltown	3.1	14.6	3.3	12.7	5.6	26.4	8.4	32.3

In the eleven weather stations in Sydney, it is estimated that both building-scale and combined building-scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical high-rise office building without roof insulation during the summer season.

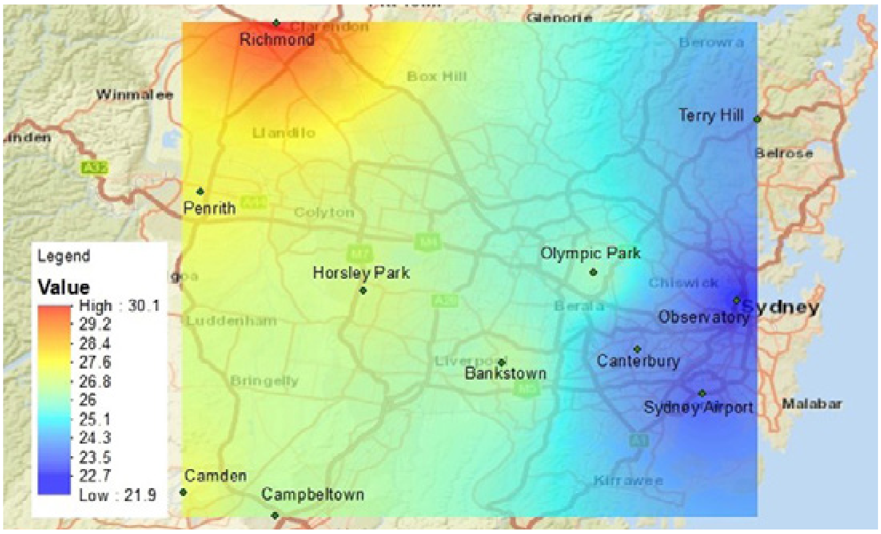


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

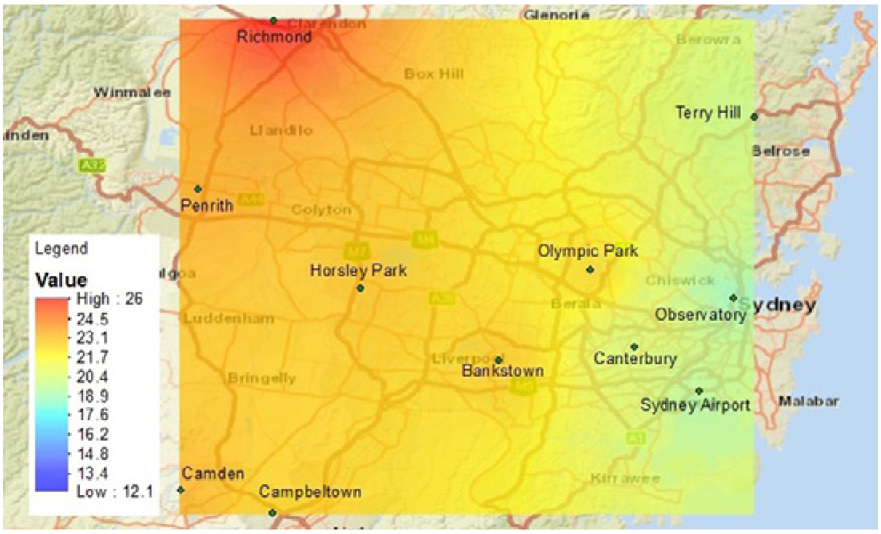


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

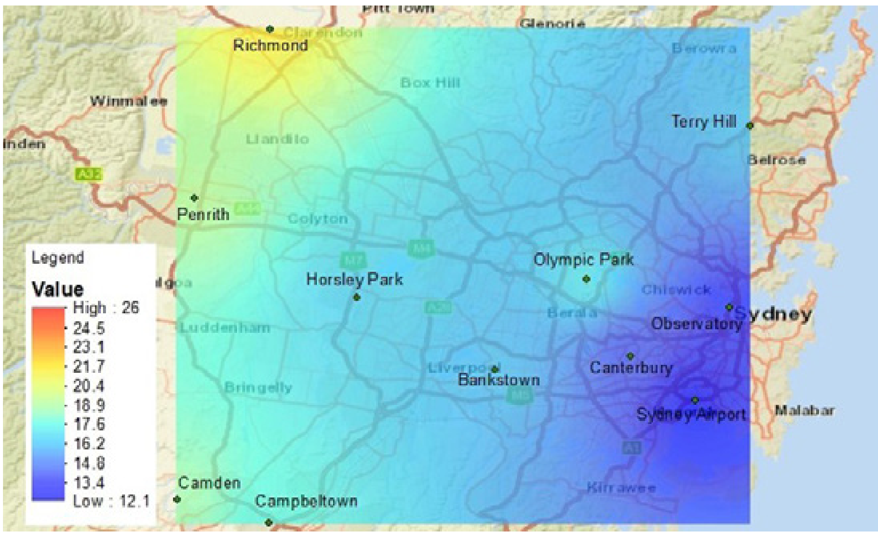


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a high-rise office building without insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.5-0.8 kWh/m²) is significantly lower than the annual cooling load reduction (3.7-7.7 kWh/m²).

Table 3. Annual cooling and heating loads for a high-rise office building without roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	29.8	38.8	1.8	3.2	26.3	35.1	2.2	3.7
Terry Hill	22.8	31.1	2.6	4.9	18.6	25.9	3.2	5.7
Bankstown	36.3	46.2	2.6	4.9	31.3	40.7	3.1	5.6
Canterbury	29.1	38.0	2.6	5.3	25.0	33.4	3.2	6
Observatory	31.3	39.9	1.6	3.0	26.7	35.0	2.0	3.6
Richmond	41.1	52.0	3.2	6.2	35.5	45.7	3.7	6.9
Penrith	44.6	55.9	2.3	4.6	37.8	48.2	2.8	5.2
Horsley Park	37.1	45.1	2.6	5.0	30.9	38.5	3.2	5.8
Camden	35.6	42.9	3.5	7.0	30.3	37.1	4.1	7.8
Olympic Park	37.0	48.7	2.2	4.2	31.2	42.3	2.6	4.8
Campbelltown	34.6	41.0	3.4	6.5	29.0	35.0	4.0	7.3

The annual cooling load saving by building-scale application of cool roofs is around 9.5-16.7 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.2 and 7.1 kWh/m² (~7.6-12.2 %).

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without roof insulation using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	3.5	11.7	3.7	9.5	0.4	0.5	3.1	9.8	3.2	7.6
Terry Hill	4.2	18.4	5.2	16.7	0.6	0.8	3.6	14.2	4.4	12.2
Bankstown	5.0	13.8	5.5	11.9	0.5	0.7	4.5	11.6	4.8	9.4
Canterbury	4.1	14.1	4.6	12.1	0.6	0.7	3.5	11.0	3.9	9.0
Observatory	4.6	14.7	4.9	12.3	0.4	0.6	4.2	12.8	4.3	10.0
Richmond	5.6	13.6	6.3	12.1	0.5	0.7	5.1	11.5	5.6	9.6
Penrith	6.8	15.2	7.7	13.8	0.5	0.6	6.3	13.4	7.1	11.7
Horsley Park	6.2	16.7	6.6	14.6	0.6	0.8	5.6	14.1	5.8	11.6
Camden	5.3	14.9	5.8	13.5	0.6	0.8	4.7	12.0	5.0	10.0
Olympic Park	5.8	15.7	6.4	13.1	0.4	0.6	5.4	13.8	5.8	11.0
Campbelltown	5.6	16.2	6.0	14.6	0.6	0.8	5.0	13.2	5.2	10.9

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 °C in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

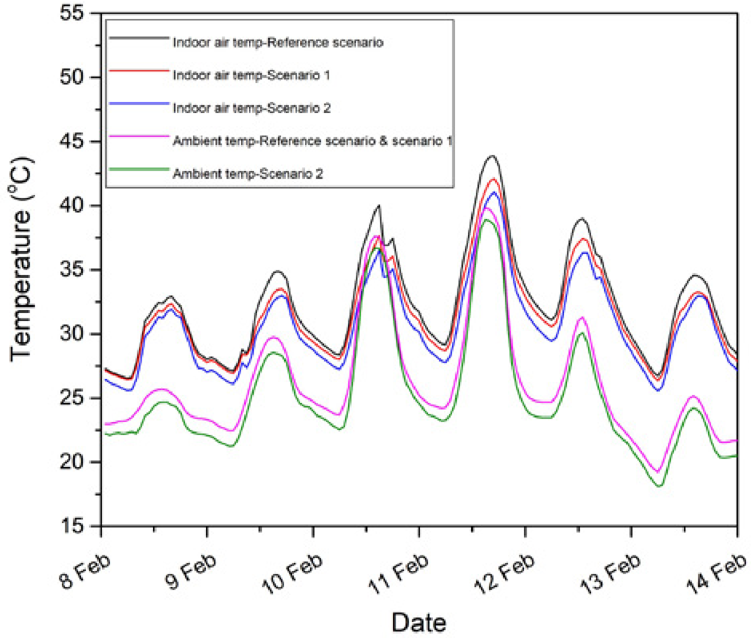


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

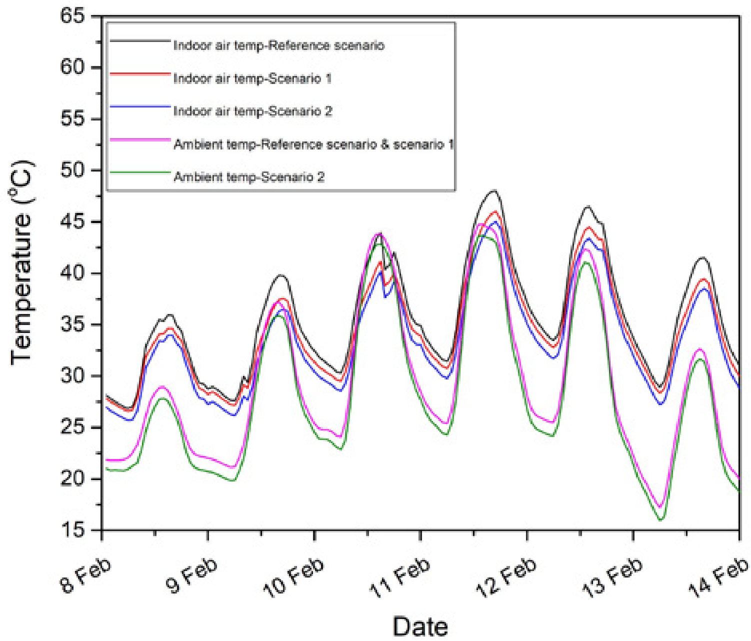


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 26.3-43.8 °C and 26.8-48.0 °C in Observatory and Richmond stations, respectively.

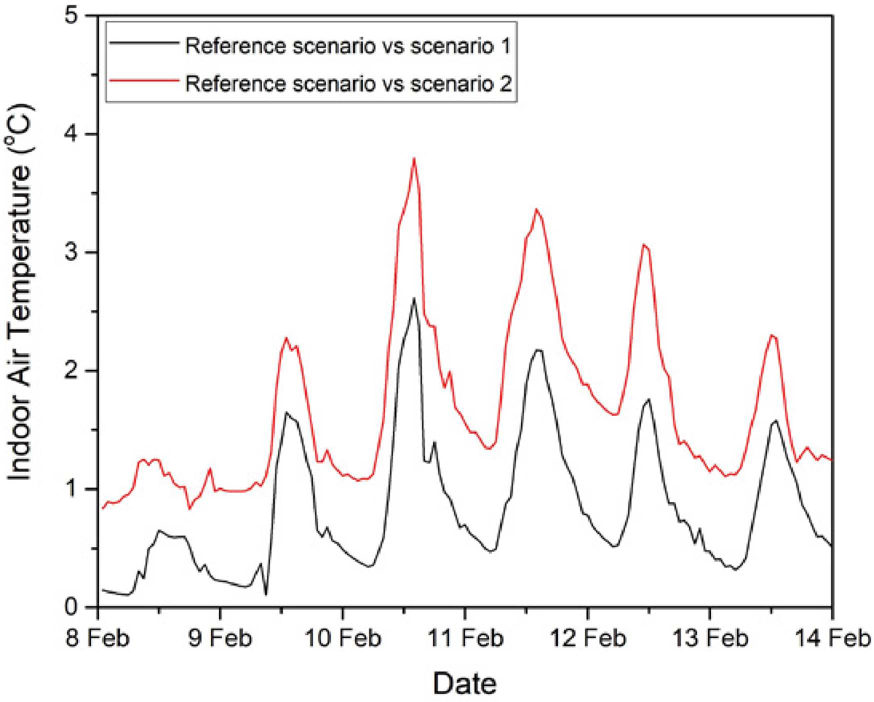


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.6 °C and 2.9 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 3.8 and 3.9 °C in Observatory and Richmond stations, respectively.

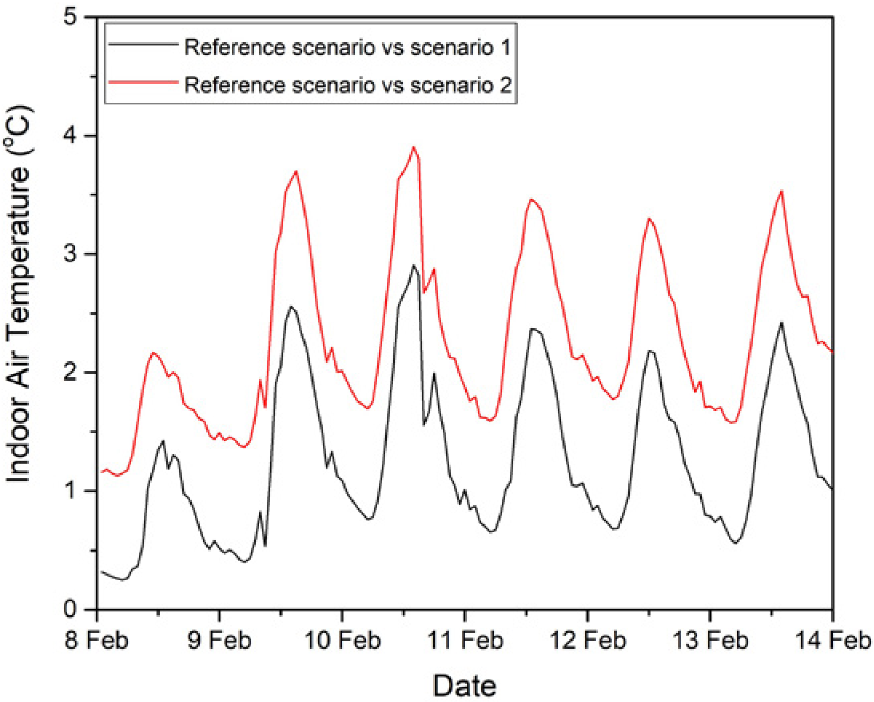


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a high-rise office building without insulation under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 14.3 and 27.1 °C in reference scenario to a range between 14.2 and 26.7 °C in scenario 1 in Observatory Hill station.

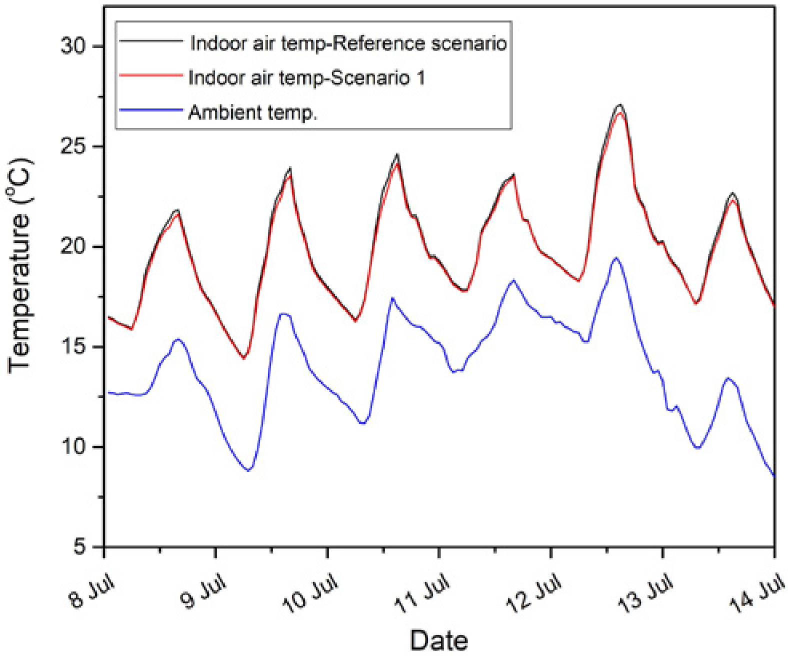


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to slighly reduce from a range between 10.6 and 26.3 °C in reference scenario to a range between 10.6 and 26.0 °C in scenario 1 in Richmond station.

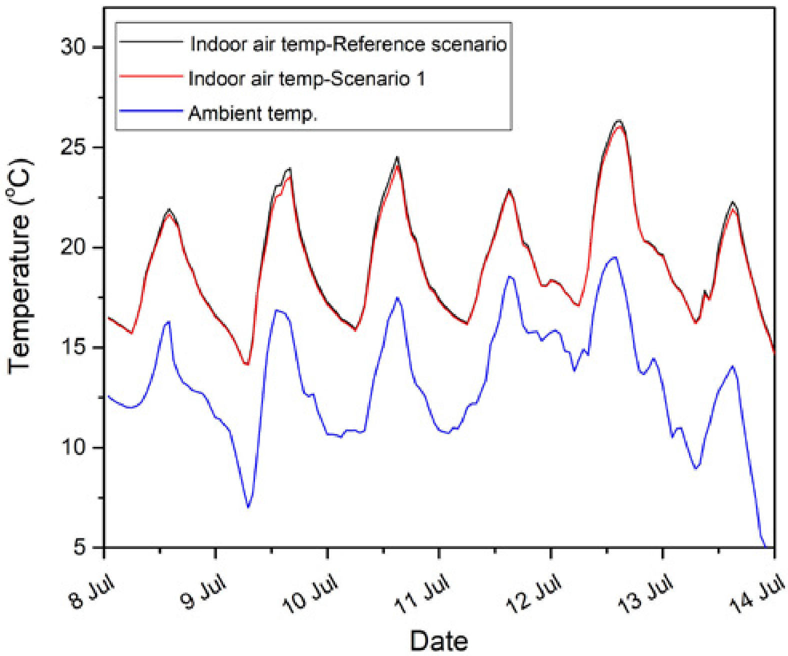


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.6 °C and 0.6 °C in Observatory and Richmond stations, respectively.

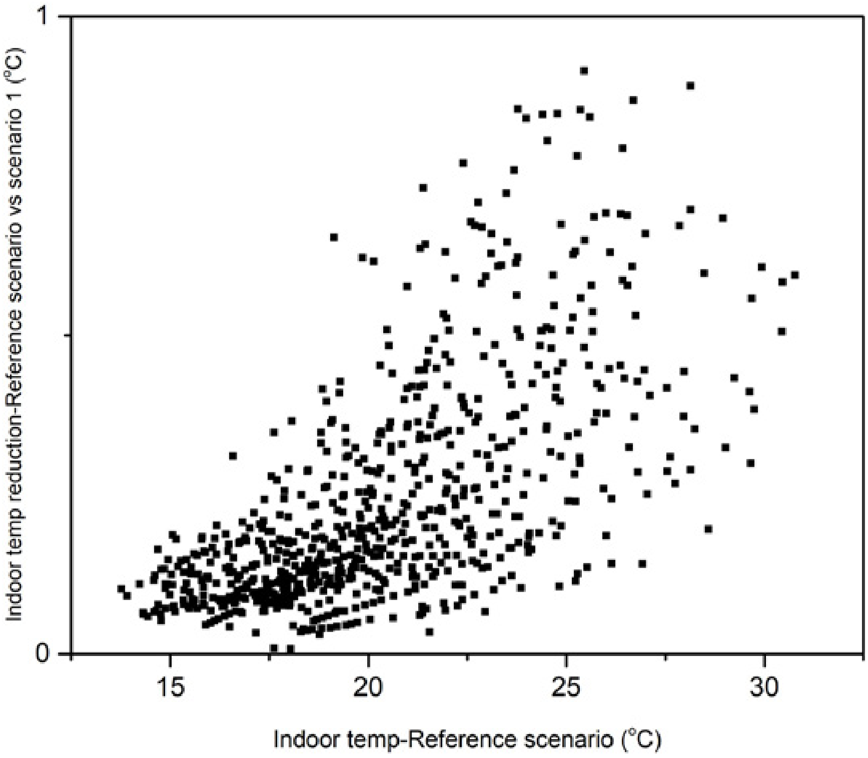


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

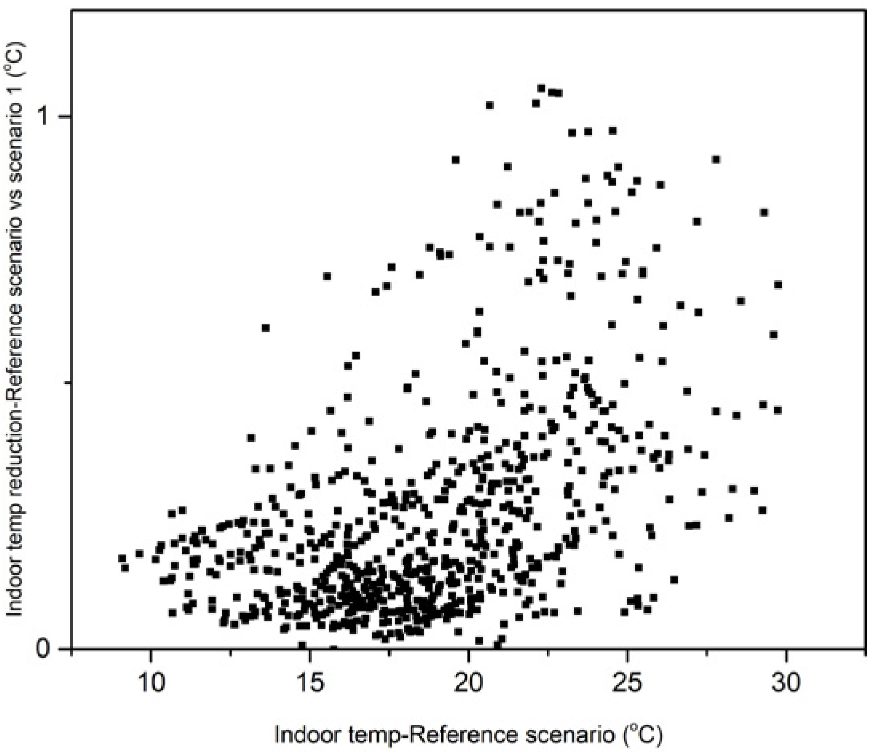


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 289 hours in reference scenario to 301 and hours and from 391 to 400 hours in scenario 1 in Observatory and Richmond stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 82 hours in reference scenario to 88 hours; and from 109 to 112 hours in scenario 1 in Observatory and Richmond stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	82	289	88	301
Richmond	109	391	112	400

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	607	591	532
Richmond	623	612	570

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 607 hours in reference scenario to 591 and 832 hours under scenario 1 and 2, in Observatory station; and from 623 hours in reference scenario to 612 and 570 hours under scenario 1 and 2 in Richmond station, respectively.

6

CONCLUSIONS

• In the eleven weather stations in Sydney, the total cooling load saving by building-scale application of cool roofs is around 2.8-4.1 kWh/m^2 for a typical high rise office building without roof insulation. This is equal to 12.8-13.6% cooling load reduction in reference with cool roof scenario (scenario 1) compared to reference scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is projected to have significantly higher impact on cooling load reduction of the high-rise office building without roof insulation. As estimated, the combined building-scale and urban-scale implementation of cool roofs can reduce the total cooling load of the high-rise office building without roof insulation by 7.1-10.4 kWh/m^2. This is equivalent to roughly 30.5-46.2% lower total cooling load under cool roof and modified urban temperature scenario (scenario 2) with respect to the reference scenario. Overall, the cooling load reduction by both building and combined building-scale and urban scale application of cool roofs is noticeable for the typical high-rise office building without roof insulation (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.5-0.8 kWh/m^2) is significantly lower than the annual cooling load reduction (3.7-7.7 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 9.5-16.7%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 3.2 and 7.1 kWh/m^2 (~7.6-12.2%) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 26.3-43.8 °C and 26.8-48 °C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 2.6 and 2.9 °C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 3.8 and 3.9 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 °C in reference scenario to a range between 18.1 and 38.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 °C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 °C in reference scenario to 15.9-43.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 °C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 14.3 and 27.1 °C in reference scenario to a range between 14.2 and 26.7 °C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 10.6 and 26.3 ^{o}C in reference scenario to a range between 10.6 and 26 ^{o}C in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.6 ^{o}C and 0.6 ^{o}C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase slightly from 289 hours in reference scenario to 301 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slight increase in total number of hours below 19 ^{o}C from 391 hours in reference scenario to 400 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 ^{o}C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 ^{o}C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to increase from 82 hours in reference scenario to 88 hours in reference with cool roof scenario (scenario 1) in Observatory station.

Similarly, the calculation in Richmond station shows a slight increase of number of hours below 19 ^{o}C from 109 hours to 112 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 ^{o}C is 607 hours under the reference scenario in Observatory station, which decreases to 591 and 532 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 ^{o}C from 623 hours in reference scenario to 612 in reference with cool roof scenario (scenario 1) and 570 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B02

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

Sydney, NSW 2052
Australia

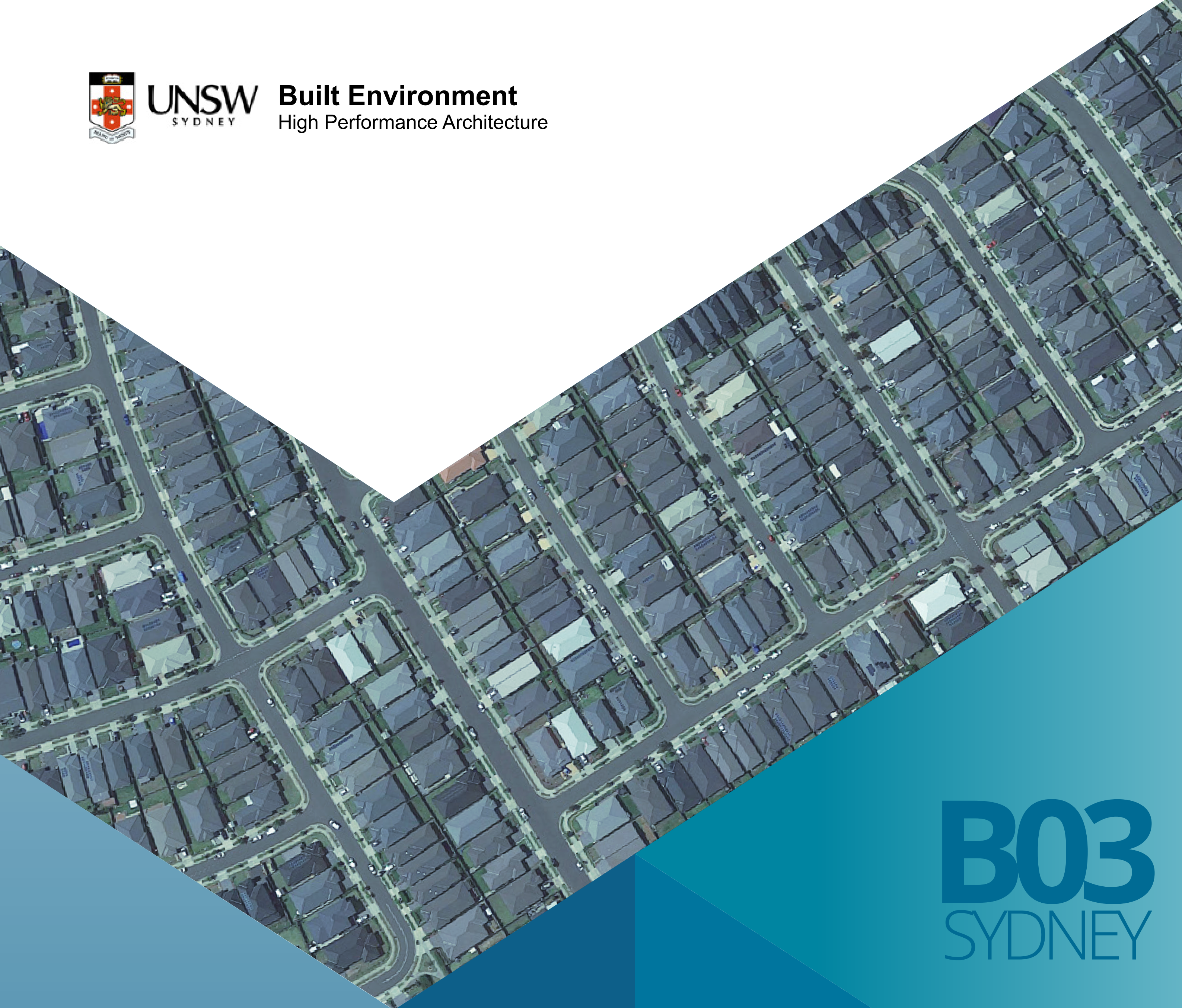
Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY

Built Environment
High Performance Architecture



B03
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

New low-rise office building with roof insulation
2021

BUILDING 03

NEW LOW-RISE OFFICE BUILDING WITH ROOF INSULATION

Floor area : $1200m^2$
Number of stories : 2

Image source: Ecipark Office Building. https://jhmrad.com/21-delightful-two-story-building/ecipark-office-building-two-story/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a new low-rise office building with roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the new low-rise office building eith roof insulation from 18.6-24.6 kWh/m² to 17.5-22.9 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	12.7	19.1	11.7	18.0	8.3	11.0
Terry Hill	14.1	19.3	13.0	18.1	11.4	14.5
Bankstown	16.2	22.1	15.1	20.9	12.4	14.8
Canterbury	13.6	19.9	12.5	18.7	9.9	13.0
Observatory	12.4	18.6	11.4	17.5	9.0	12.3
Richmond	20.3	24.6	18.7	22.9	17.0	19.0
Penrith	18.4	22.7	17.1	21.3	15.4	17.3
Horsley Park	17.5	22.2	16.3	20.8	14.5	16.7
Camden	18.7	22.5	17.5	21.1	15.4	16.8
Olympic Park	15.7	21.9	14.5	20.6	12.4	15.6
Campbelltown	17.3	21.8	15.9	20.4	13.8	15.7

Table 2. Sensible and total cooling load saving for a new low-rise office building with roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 1.1-1.7 kWh/m² which is equivalent to 5.4-6.9 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 4.8-8.1 kWh/m² which is equivalent to 24.9-42.2% of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	1.0	7.9	1.1	5.8	4.4	34.6	8.1	42.4
Terry Hill	1.1	7.8	1.2	6.2	2.7	19.1	4.8	24.9
Bankstown	1.1	6.8	1.2	5.4	3.8	23.5	7.3	33.0
Canterbury	1.1	8.1	1.2	6.0	3.7	27.2	6.9	34.7
Observatory	1.0	8.1	1.1	5.9	3.4	27.4	6.3	33.9
Richmond	1.6	7.9	1.7	6.9	3.3	16.3	5.6	22.8
Penrith	1.3	7.1	1.4	6.2	3.0	16.3	5.4	23.8
Horsley Park	1.2	6.9	1.4	6.3	3.0	17.1	5.5	24.8
Camden	1.2	6.4	1.4	6.2	3.3	17.6	5.7	25.3
Olympic Park	1.2	7.6	1.3	5.9	3.3	21.0	6.3	28.8
Campbelltown	1.4	8.1	1.4	6.4	3.5	20.2	6.1	28.0

In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to have higher impact on the total cooling load reduction of the new low-rise office building with roof insulation.

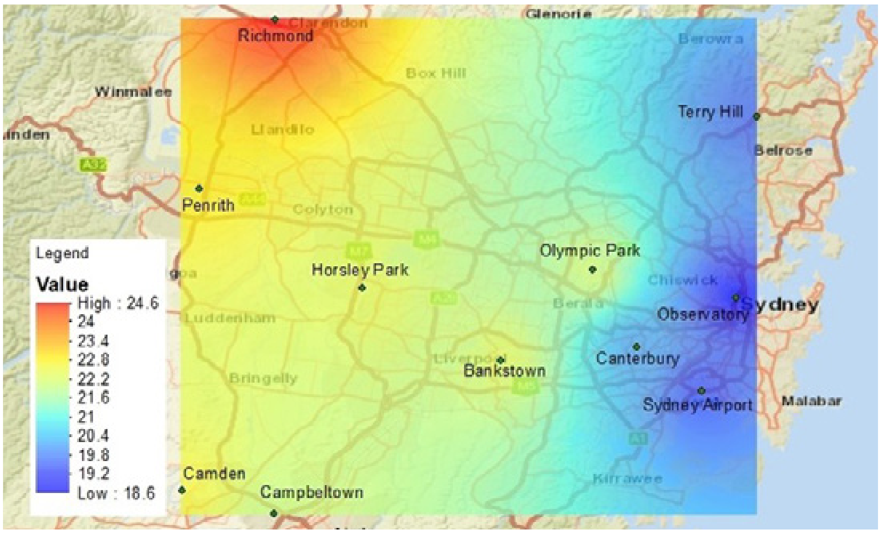


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs has a lower but still noticeable impact on the cooling load reduction of the new low-rise office building with roof insulation.

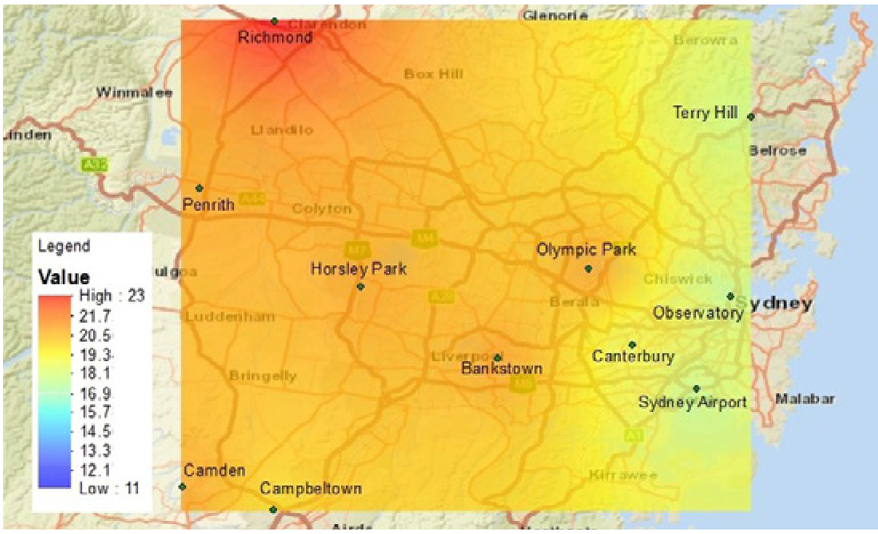


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

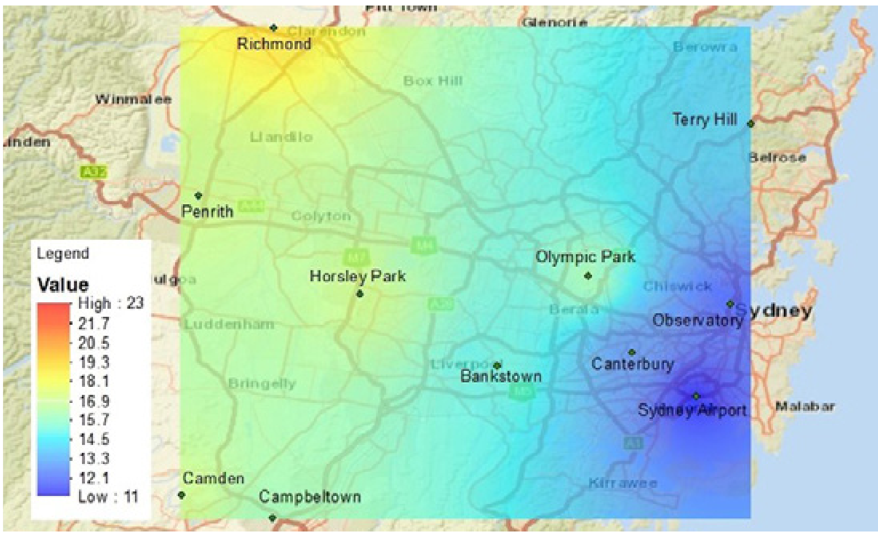


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a new low-rise office building with roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.3 kWh/m²) is significantly lower than the annual cooling load reduction (1.8-8.5 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	27.0	35.6	0.6	1.4	25.4	33.8	0.6	1.4
Terry Hill	18.1	25.3	1.1	2.5	16.7	23.5	1.2	2.7
Bankstown	31.2	40.5	1.4	3.0	29.2	38.3	1.4	3.2
Canterbury	25.1	33.5	1.3	3.1	23.5	31.6	1.3	3.3
Observatory	27.2	35.4	0.6	1.4	25.3	33.4	0.6	1.6
Richmond	35.5	45.7	1.9	4.2	33.0	42.8	2.0	4.5
Penrith	36.8	47.0	1.4	3.1	34.0	43.7	1.5	3.3
Horsley Park	30.5	38.0	1.5	3.3	28.0	35.3	1.6	3.5
Camden	30.0	36.9	2.2	5.0	27.8	34.4	2.4	5.3
Olympic Park	30.8	41.6	1.2	2.7	28.4	38.8	1.3	2.9
Campbelltown	34.6	41.0	2.0	4.5	26.7	32.5	2.2	4.7

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 5.1-20.7 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.6 and 8.3 kWh/m² (~4.6-18.2 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	1.6	5.9	1.8	5.1	0.0	0.0	1.6	5.8	1.8	4.9
Terry Hill	1.4	7.7	1.8	7.1	0.1	0.2	1.3	6.8	1.6	5.8
Bankstown	2.0	6.4	2.2	5.4	0.0	0.2	2.0	6.1	2.0	4.6
Canterbury	1.6	6.4	1.9	5.7	0.0	0.2	1.6	6.1	1.7	4.6
Observatory	1.9	7.0	2.0	5.6	0.0	0.1	1.9	6.7	1.9	5.2
Richmond	2.5	7.0	2.9	6.3	0.1	0.3	2.4	6.4	2.6	5.2
Penrith	2.8	7.6	3.3	7.0	0.1	0.2	2.7	7.1	3.1	6.2
Horsley Park	2.5	8.2	2.7	7.1	0.1	0.2	2.4	7.5	2.5	6.1
Camden	2.2	7.3	2.5	6.8	0.2	0.3	2.0	6.2	2.2	5.3
Olympic Park	2.4	7.8	2.8	6.7	0.1	0.2	2.3	7.2	2.6	5.9
Campbelltown	7.9	22.8	8.5	20.7	0.2	0.2	7.7	21.0	8.3	18.2

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 °C in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

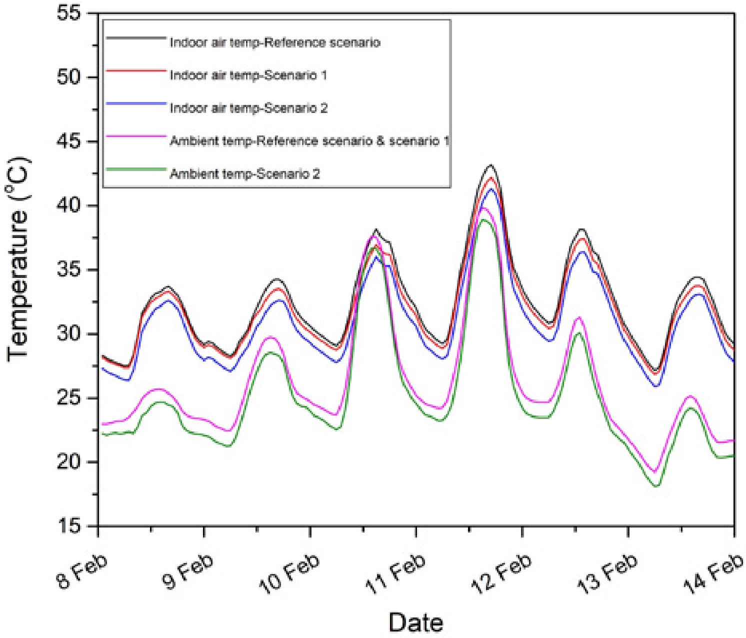


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

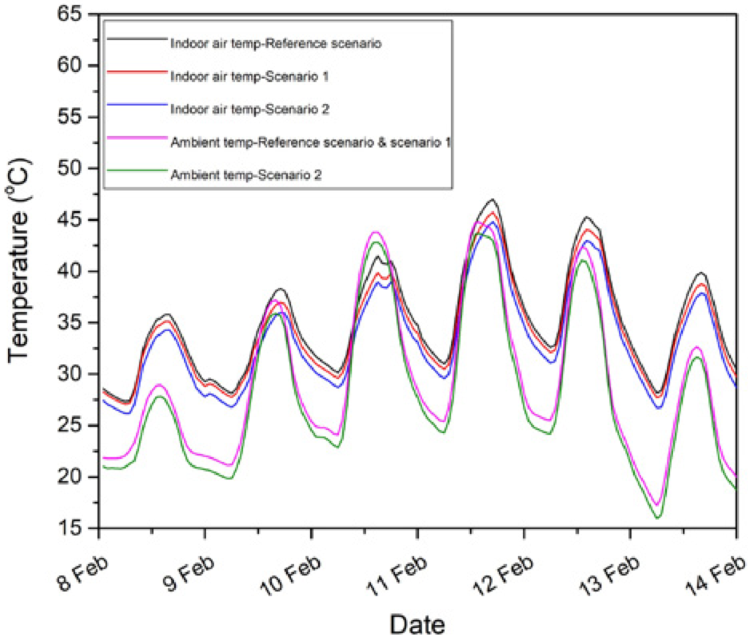


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 27.1-43.1 °C and 27.3-47.0 °C in Observatory and Richmond stations, respectively.

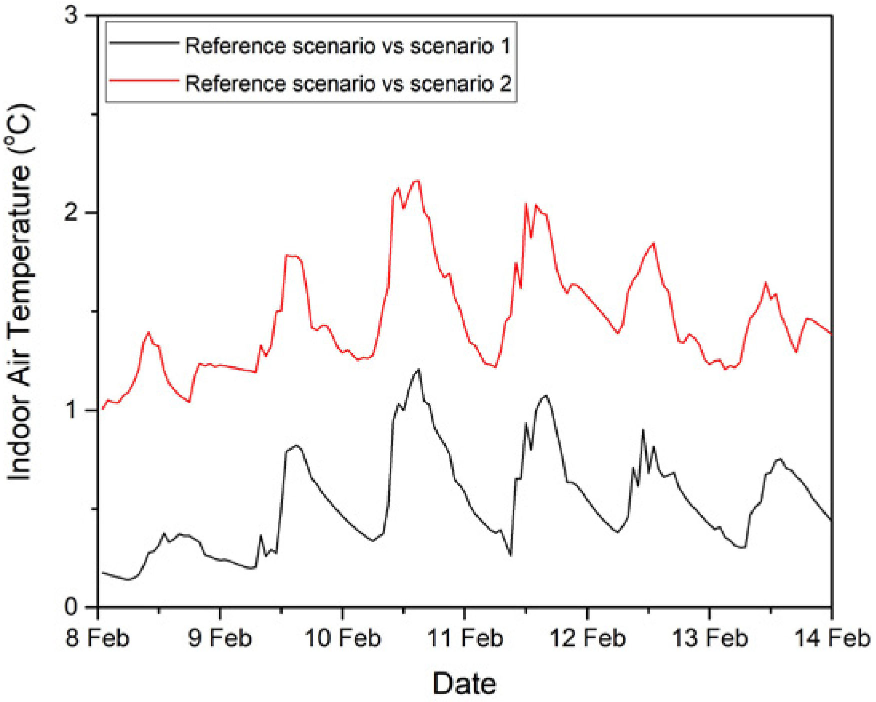


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 1.2 °C and 1.6 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.1 and 2.5 °C in Observatory and Richmond stations, respectively.

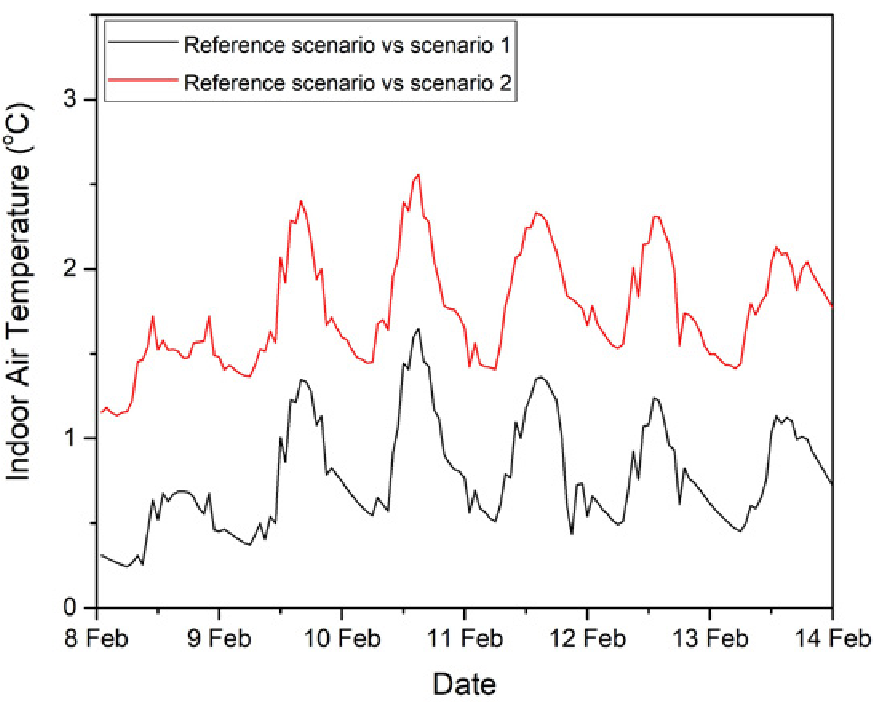


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise office building with roof insulation under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 15.6 and 29.2 °C in reference scenario to a range between 15.6 and 28.9 °C in scenario 1 in Observatory Hill station.

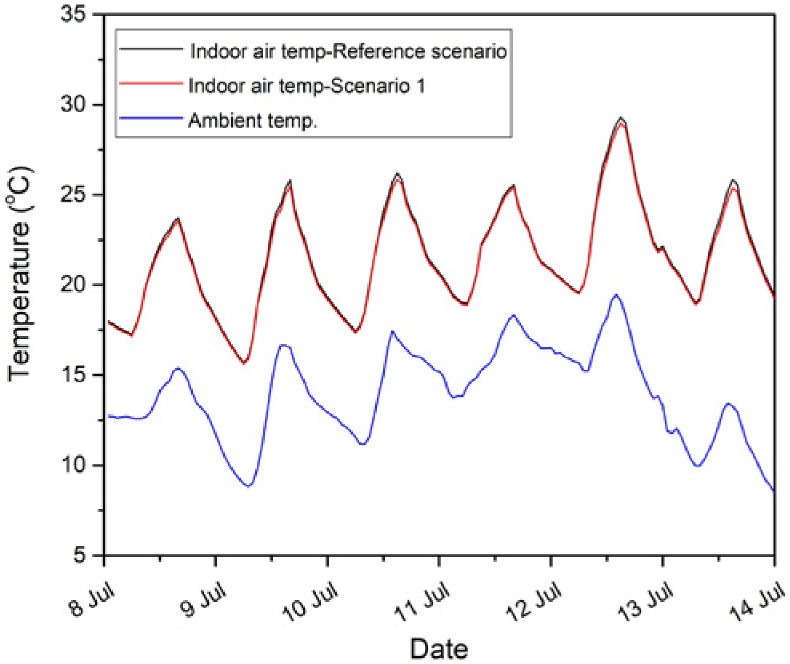


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range between 12.6 and 28.7 °C in reference scenario to a range between 12.5 and 28.4 °C in scenario 1 in Richmond station.

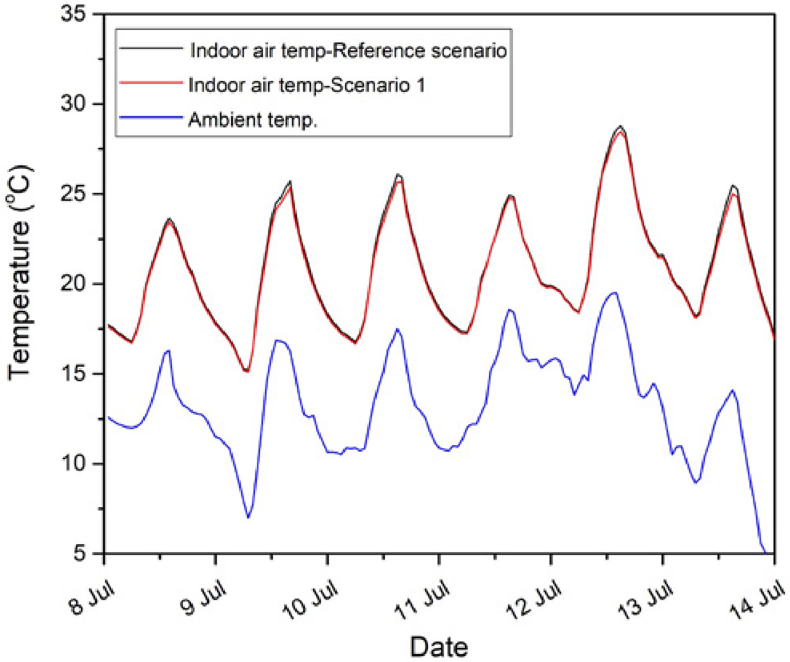


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

> *For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.5 °C and 0.5 °C in Observatory and Richmond stations, respectively.*

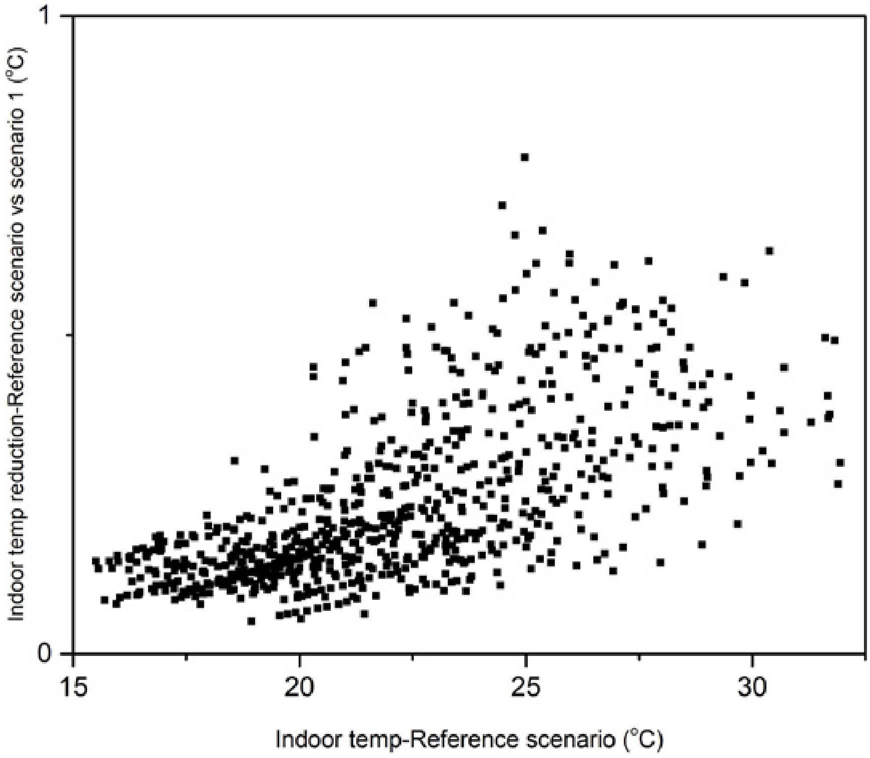


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

> *Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.*

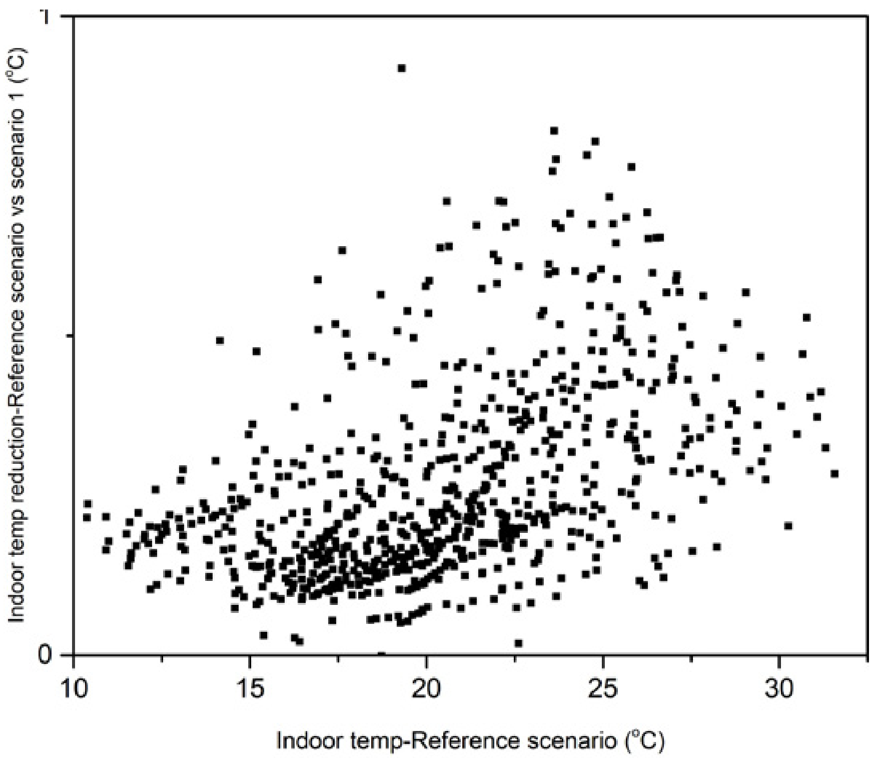


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase from 147 hours in reference scenario to 245 and hours and from 276 to 287 hours in scenario 1 in Observatory and Richmond stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 41 hours in reference scenario to 45 hours; and from 74 to 116 hours in scenario 1 in Observatory and Richmond stations, respectively.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	41	147	45	245
Richmond	74	276	116	287

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

Table 6. 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.

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 630 hours in reference scenario to 622 and 595 hours under scenario 1 and 2, in Observatory station; and from 658 hours in reference scenario to 652 and 613 hours under scenario 1 and 2 in Richmond station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	630	622	595
Richmond	658	652	613

6

CONCLUSIONS

• In the eleven weather stations in Sydney, the building scale application of cool roofs can reduce the total cooling load of a new low-rise office building with roof insulation by 1.1-1.7 kWh/m^2 (~5.4-6.9%) (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to have higher impact on the total cooling load reduction of the new low-rise office building with roof insulation. As projected, the combined building-scale and urban-scale implementation of cool roofs will reduce the cooling load of a typical low-rise office building with roof insulation by up to 4.8-8.1 kWh/m^2. This is equal to around 24.9-42.2% cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• Overall, the simulation results demonstrate that the combined building-scale and urban scale implementation of cool roofs is an efficient method to lower the cooling loads of the new low-rise office building with roof insulation. The building-scale application of cool roofs has a lower but still noticeable impact on the cooling load reduction of the new low-rise office building with roof insulation.

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0-0.3 kWh/m^2) is significantly lower than the annual cooling load reduction (1.8-8.5 kWh/m2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 5.1-20.7 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.6 and 8.3 kWh/m^2 (~4.6-18.2%) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 27.1-43.1 ^{o}C and 27.3-47 ^{o}C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 1.2 and 1.6 ^{o}C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.1 and 2.5 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 ^{o}C in reference scenario to a range between 18.1 and 38.9 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 ^{o}C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 ^{o}C in reference scenario to 15.9-43.6 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 ^{o}C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 15.6 and 29.2 ^{o}C in reference scenario to a range between 15.6 and 28.9 ^{o}C in reference with cool roof scenario (scenario 1) in

Observatory Hill station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 12.6 and 28.7 °C in reference scenario to a range between 12.5 and 28.4 °C in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.5 °C and 0.5 °C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 147 hours in reference scenario to 245 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slight increase in total number of hours below 19 °C from 276 hours in reference scenario to 287 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to increase from 41 hours in reference scenario to 45 hours in reference with cool roof scenario (scenario 1) in Observatory station. Similarly, the calculation in Richmond station shows a slight increase of number of hours below 19 °C from 74 hours to 116 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 630 hours under the reference scenario in Observatory station, which decreases to 622 and 595 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 °C from 658 hours in reference scenario to 652 in reference with cool roof scenario (scenario 1) and 613 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B03

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

Sydney, NSW 2052
Australia

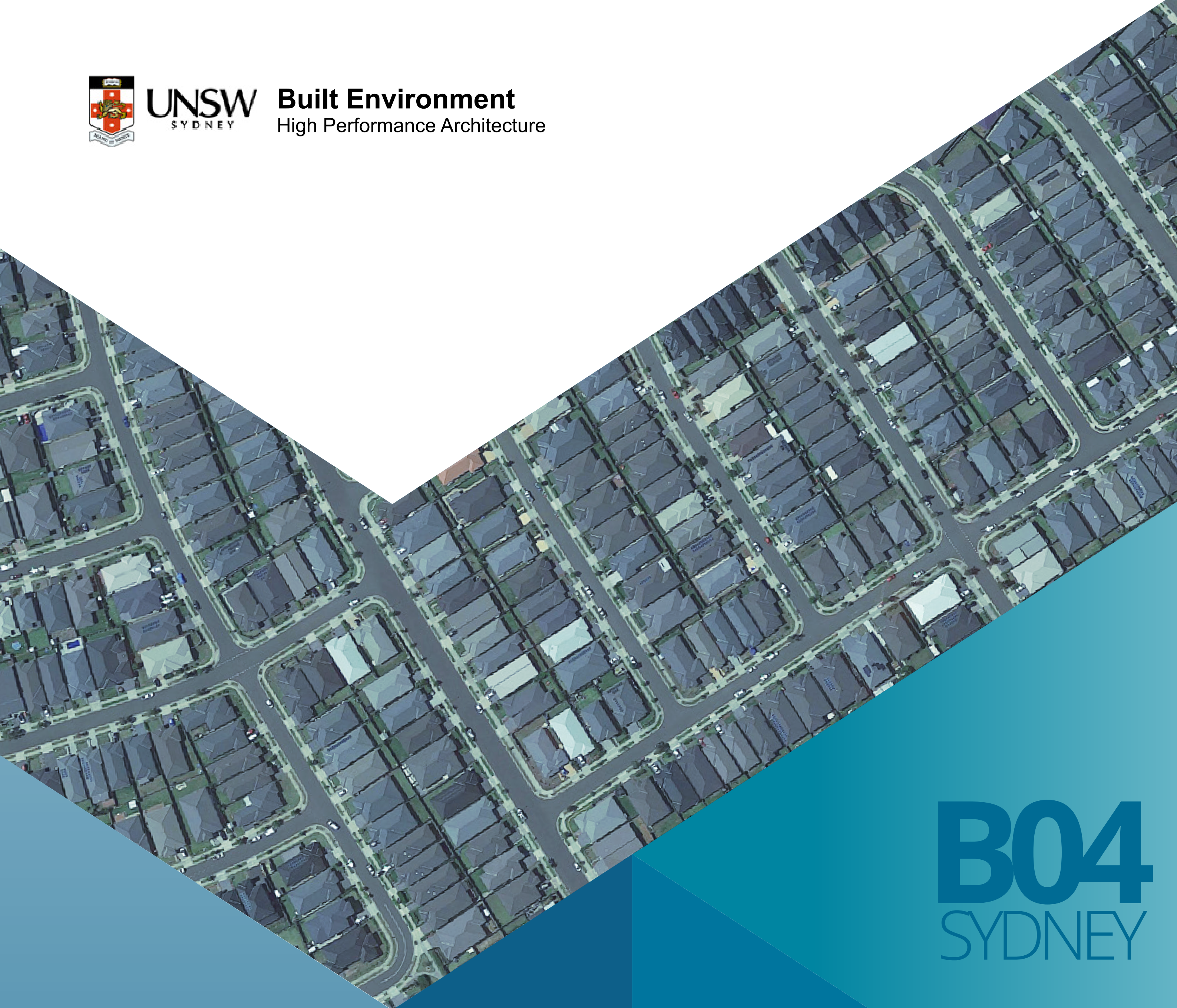
Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY

Built Environment
High Performance Architecture



B04
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

New high-rise office building with roof insulation
2021

BUILDING 04

NEW HIGH-RISE OFFICE BUILDING WITH ROOF INSULATION

Floor area : 1200m^2
Number of stories : 10

Image source: Ecipark Office Building. https://jerseydigs.com/bayonne-city-council-approves-10-story-building-975-broadway/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a typical new high-rise office building with roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the new high-rise office building with roof insulation from 18.1-23.7 kWh/m² to 17.8-23.4 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	12.4	18.6	12.2	18.4	8.6	11.3
Terry Hill	13.7	18.6	13.4	18.3	11.8	14.9
Bankstown	15.9	21.5	15.6	21.2	12.8	15.2
Canterbury	13.2	19.3	13.0	19.1	10.3	13.4
Observatory	12.0	18.1	11.8	17.8	9.3	12.6
Richmond	19.8	23.7	19.5	23.4	17.5	19.5
Penrith	17.9	21.9	17.7	21.6	15.8	17.7
Horsley Park	17.0	21.4	16.8	21.1	14.8	17.0
Camden	18.2	21.6	17.9	21.4	15.8	17.2
Olympic Park	15.4	21.2	15.1	20.9	12.8	16.1
Campbelltown	16.7	21.0	16.4	20.7	14.3	16.2

Table 2. Sensible and total cooling load saving for a typical new high-rise office building with roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 0.2-0.3 kWh/m² which is equivalent to 0.9-1.7 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 3.7-7.3 kWh/m² which is equivalent to 19.9-39.2% of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	0.2	1.6	0.2	1.1	3.8	30.6	7.3	39.2
Terry Hill	0.3	2.2	0.3	1.6	1.9	13.9	3.7	19.9
Bankstown	0.3	1.9	0.3	1.4	3.1	19.5	6.3	29.3
Canterbury	0.2	1.5	0.2	1.0	2.9	22.0	5.9	30.6
Observatory	0.2	1.7	0.3	1.7	2.7	22.5	5.5	30.4
Richmond	0.3	1.5	0.3	1.3	2.3	11.6	4.2	17.7
Penrith	0.2	1.1	0.3	1.4	2.1	11.7	4.2	19.2
Horsley Park	0.2	1.2	0.3	1.4	2.2	12.9	4.4	20.6
Camden	0.3	1.6	0.2	0.9	2.4	13.2	4.4	20.4
Olympic Park	0.3	1.9	0.3	1.4	2.6	16.9	5.1	24.1
Campbelltown	0.3	1.8	0.3	1.4	2.4	14.4	4.8	22.9

In the eleven weather stations in Sydney, the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the new high-rise office building with roof insulation during the summer season.

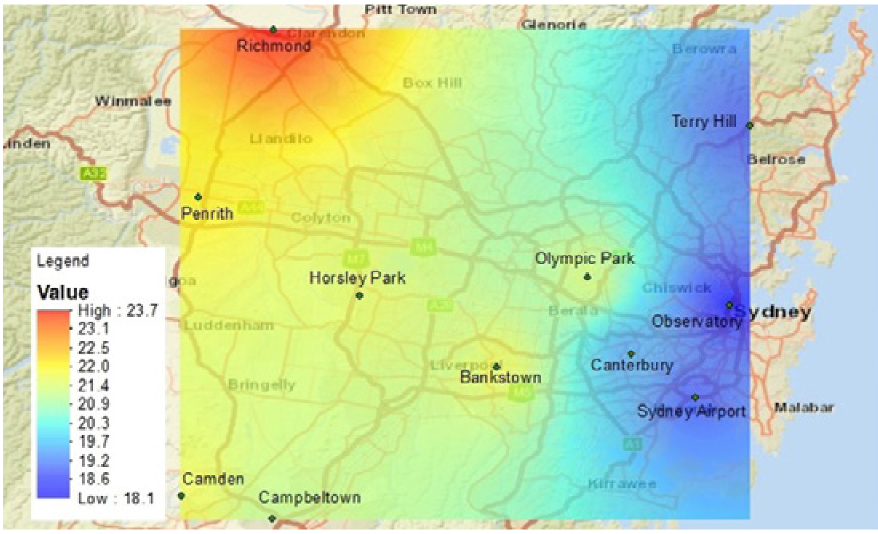


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

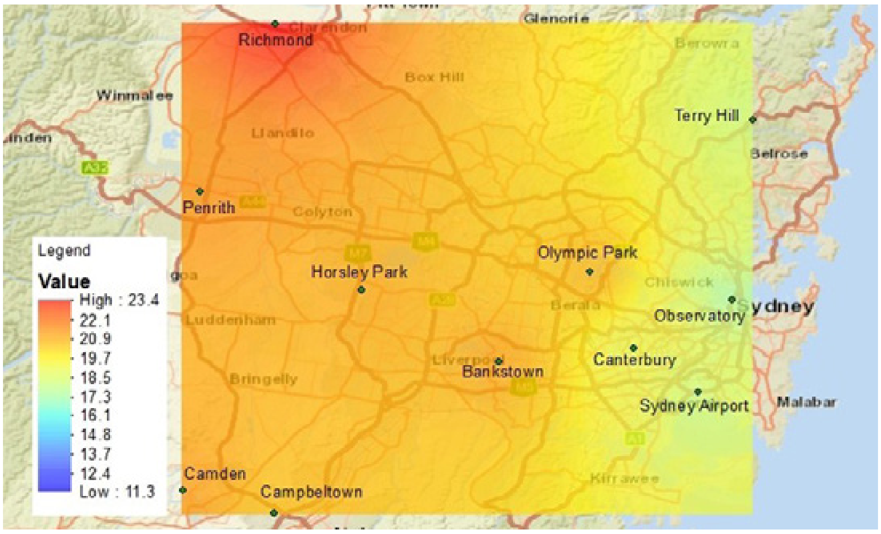


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

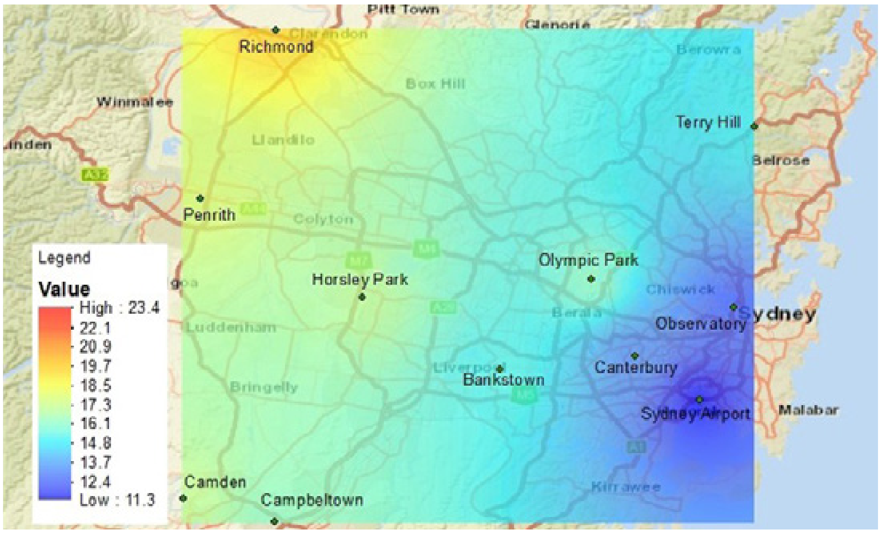


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a new high-rise office building with roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.1 kWh/m²) is significantly lower than the annual cooling load reduction (0.3-0.7 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	26.2	34.7	0.2	0.7	26.0	34.4	0.2	0.7
Terry Hill	17.1	24.1	0.6	1.7	16.8	23.7	0.6	1.8
Bankstown	30.0	38.9	0.7	2.0	29.6	38.5	0.7	2.1
Canterbury	24.1	32.2	0.7	2.1	23.8	31.9	0.7	2.1
Observatory	26.3	34.4	0.2	0.8	26.0	34.0	0.2	0.8
Richmond	33.7	43.5	1.2	3.2	33.3	43.0	1.2	3.2
Penrith	34.8	44.7	0.7	2.1	34.3	44.0	0.8	2.2
Horsley Park	28.8	36.0	0.8	2.2	28.4	35.5	0.8	2.3
Camden	28.4	35.1	1.4	3.8	28.0	34.6	1.4	3.8
Olympic Park	29.2	39.6	0.6	1.8	28.8	39.1	0.6	1.8
Campbelltown	27.3	33.1	1.2	3.3	26.8	32.7	1.3	3.3

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise office building with roof insulation using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 0.9-1.7 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.3 and 0.6 kWh/m² (~0.7-1.3 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	0.2	0.8	0.3	0.9	0.0	0.0	0.2	0.8	0.3	0.8
Terry Hill	0.3	1.8	0.4	1.7	0.0	0.1	0.3	1.7	0.3	1.2
Bankstown	0.4	1.3	0.4	1.0	0.0	0.1	0.4	1.3	0.3	0.7
Canterbury	0.3	1.2	0.3	0.9	0.0	0.0	0.3	1.2	0.3	0.9
Observatory	0.3	1.1	0.4	1.2	0.0	0.0	0.3	1.1	0.4	1.1
Richmond	0.4	1.2	0.5	1.1	0.0	0.0	0.4	1.1	0.5	1.1
Penrith	0.5	1.4	0.7	1.6	0.1	0.1	0.4	1.1	0.6	1.3
Horsley Park	0.4	1.4	0.5	1.4	0.0	0.1	0.4	1.4	0.4	1.0
Camden	0.4	1.4	0.5	1.4	0.0	0.0	0.4	1.3	0.5	1.3
Olympic Park	0.4	1.4	0.5	1.3	0.0	0.0	0.4	1.3	0.5	1.2
Campbelltown	0.5	1.8	0.4	1.2	0.1	0.0	0.4	1.4	0.4	1.1

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 °C in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

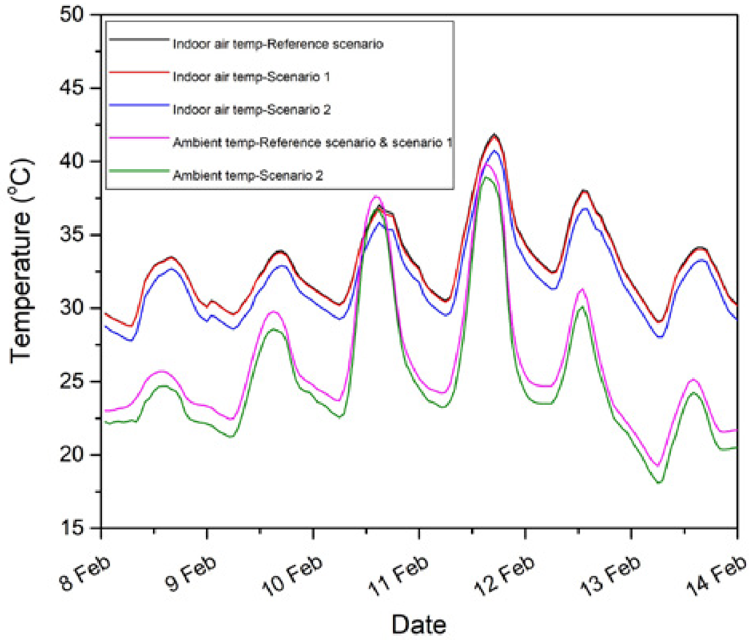


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

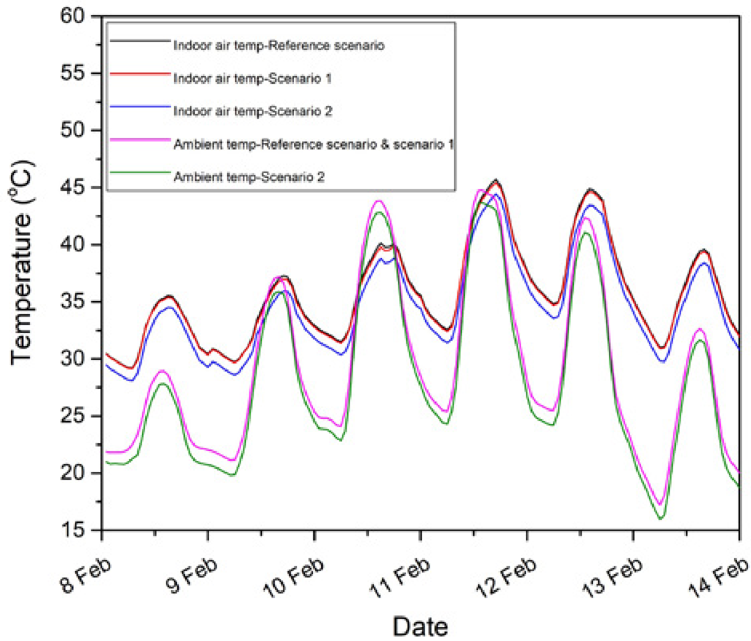


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 28.5-41.8 °C and 29.1-45.7 °C in Observatory and Richmond stations, respectively.

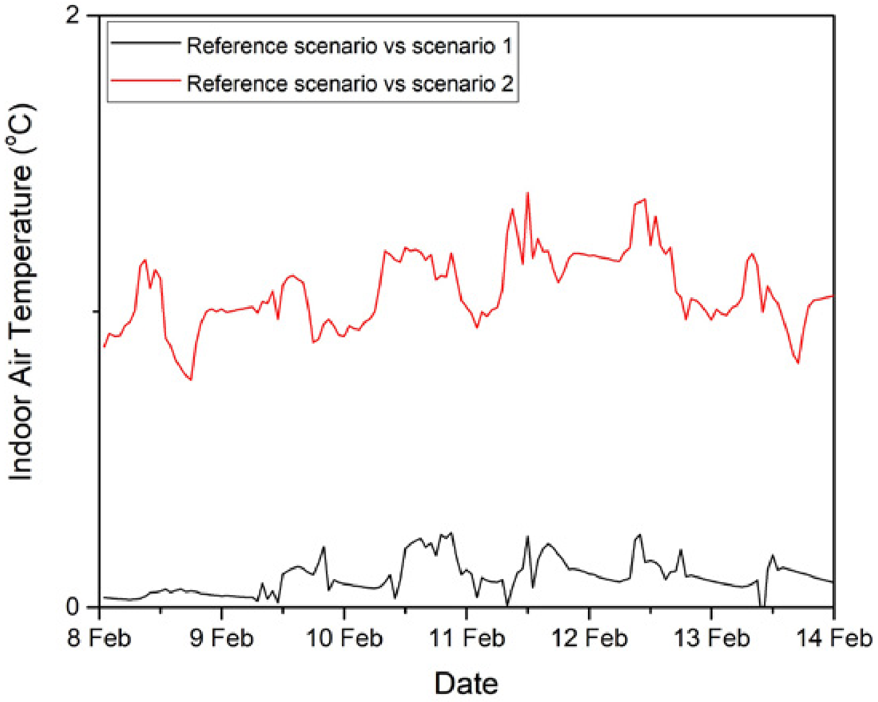


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.2 °C and 0.3 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.4 and 1.5 °C in Observatory and Richmond stations, respectively.

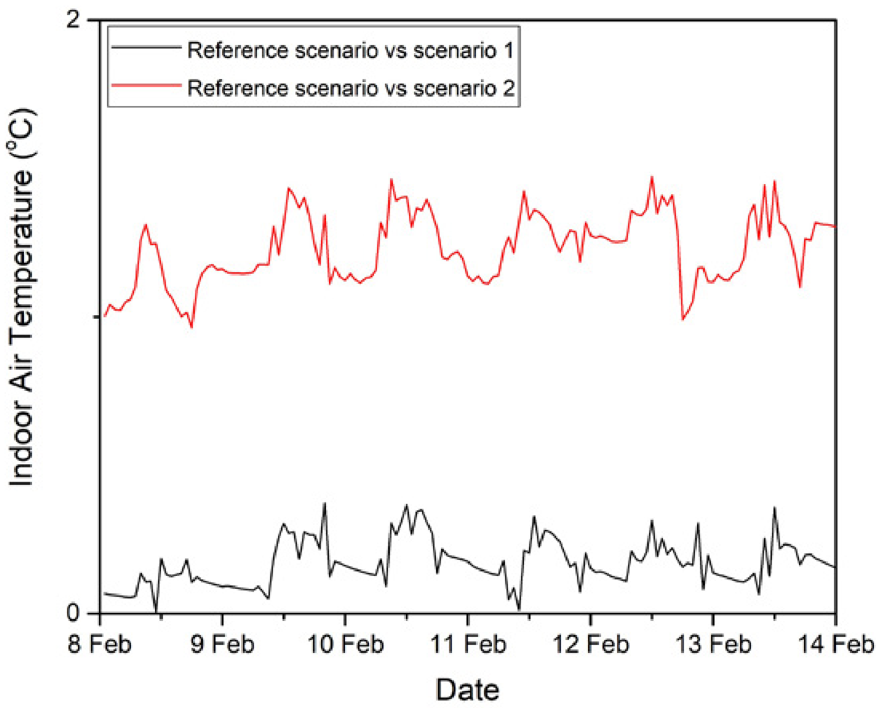


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise office building with insulation under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to remain almost the same in reference scenario and reference with cool roof scenario (scenario 1) in Observatory Hill and Richmond stations, respectively.

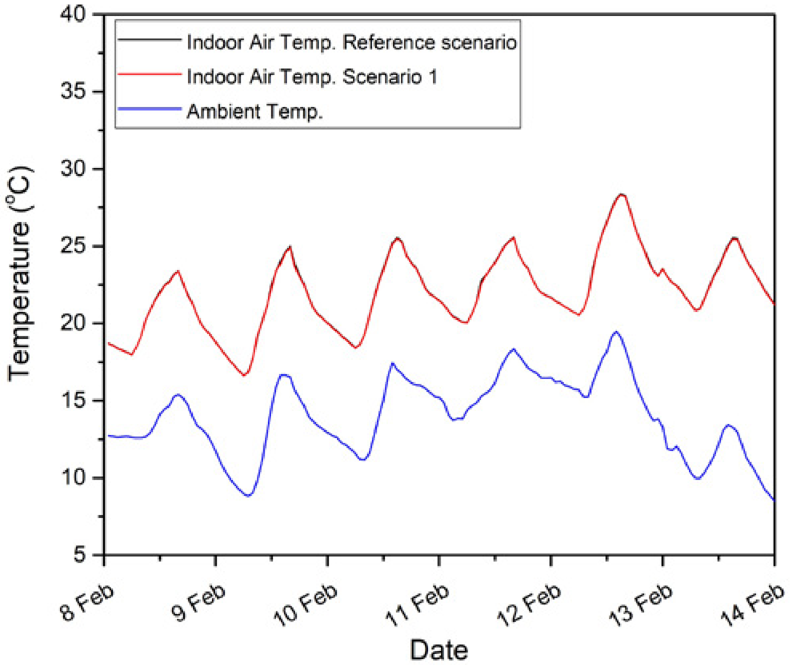


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise office building with insulation under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

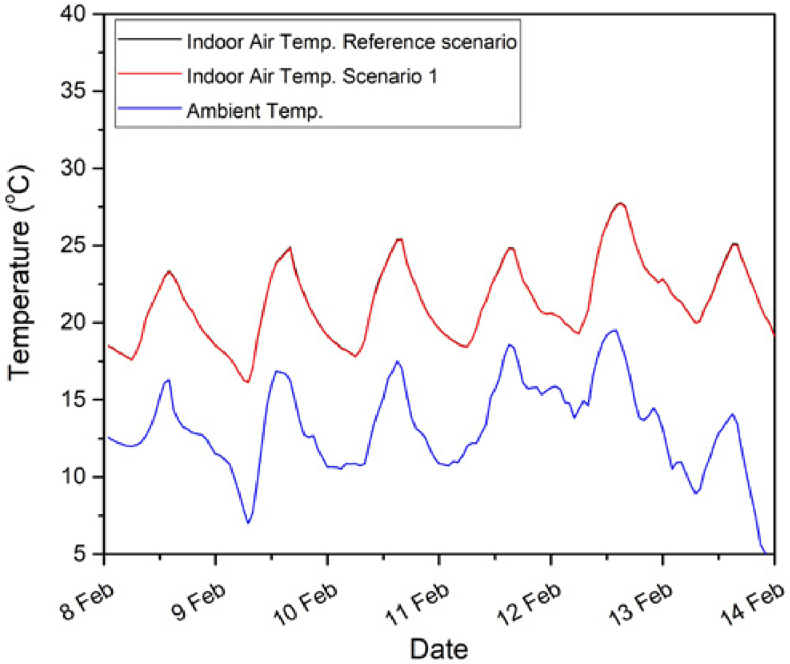


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise office building with insulation under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C and 0.1 °C in Observatory and Richmond stations, respectively.

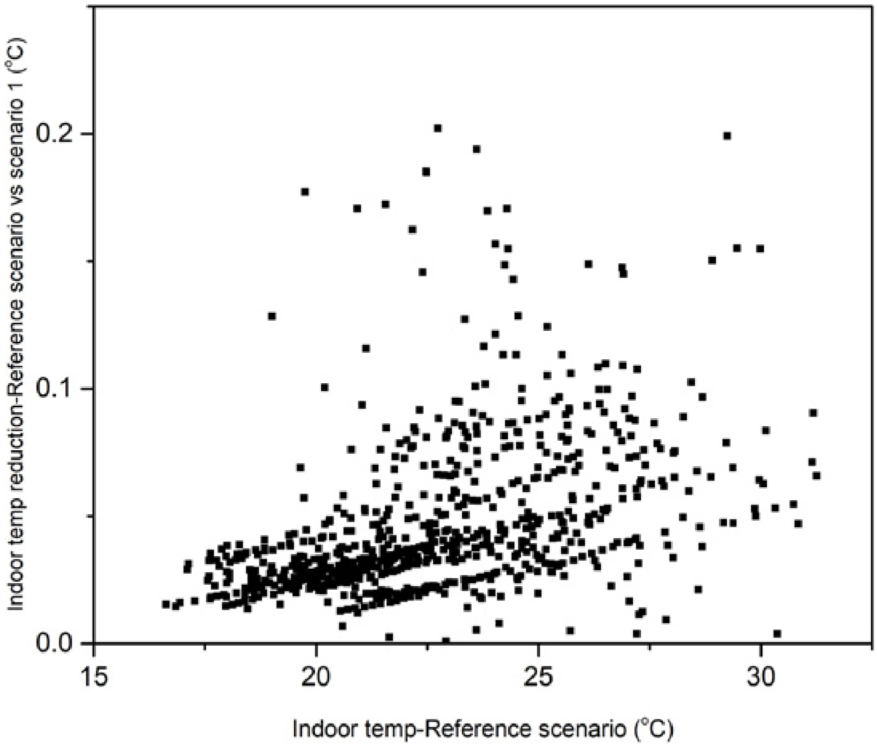


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

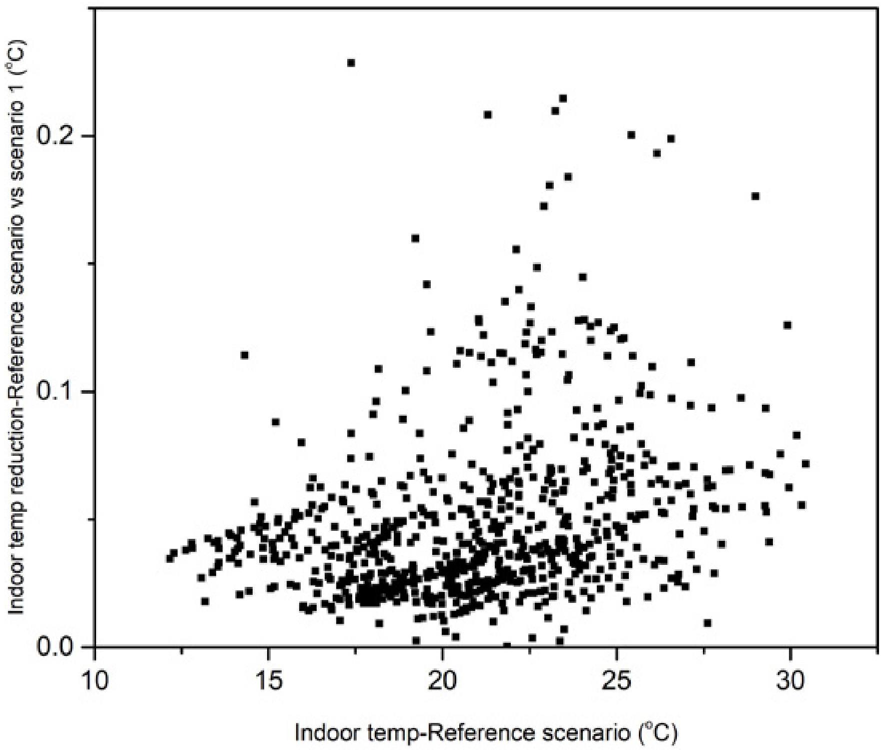


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a high-rise office building without insulation under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	21	67	22	70
Richmond	65	225	82	226

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 67 hours in reference scenario to 70 and hours and from 225 to 226 hours in scenario 1 in Observatory and Richmond stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 21 hours in reference scenario to 22 hours; and from 65 to 82 hours in scenario 1 in Observatory and Richmond stations, respectively.

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	672	672	657
Richmond	661	659	634

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 672 hours in reference scenario to 672 and 657 hours under scenario 1 and 2, in Observatory station; and from 661 hours in reference scenario to 656 and 634 hours under scenario 1 and 2 in Richmond station, respectively.

6

CONCLUSIONS

• In the eleven weather stations in Sydney, the building-scale application of cool roofs is predicted to reduce the cooling load of new high-rise office building with roof insulation by 0.2-0.3 kWh/m^2 (~ 0.9-1.7%) (See Table 1 and 2 and Figures 1 and 2). The combined building-scale and urban-scale application of cool roofs is foreseen to have a significant contribution to cooling load reduction. It is estimated that the cooling load of cool roof with modified urban temperature scenario (scenario 2) is around 3.7-7.3 kWh/m^2 (~19.9-39.2%) lower than the reference scenario (See Table 1 and 2 and Figures 2 and 3) . Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0-0.1 kWh/m^2) is lower than the annual cooling load reduction (0.3-0.7 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 0.9-1.7%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.3 and 0.6 kWh/m^2 (~0.7-1.3%) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 28.5-41.8 ^{o}C and 29.1-45.7 ^{o}C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.2 and 0.3 ^{o}C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.4 and 1.5 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 ^{o}C in reference scenario to a range between 18.1 and 38.9 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 ^{o}C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 ^{o}C in reference scenario to 15.9-43.6 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 ^{o}C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to remain almost the same in reference scenario and reference with cool roof scenario (scenario 1) in Observatory Hill and Richmond stations (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 ^{o}C and 0.1 ^{o}C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase slightly from 67 hours in reference scenario to 70 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slight increase in total number of hours below 19 °C from 225 hours in reference scenario to 226 hours in reference with cool roof scenario (scenario 1). Also, the number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to increase from 21 hours in reference scenario to 22 hours in reference with cool roof scenario (scenario 1) in Observatory station. Similarly, the calculation in Richmond station shows a slight increase of number of hours below 19 °C from 65 hours to 82 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, the number of hours above 26 °C in reference with cool scenario (scenario 1) is predicted to remain the same as the reference scenario in Observatory station. The combined building-scale and urban-scale application of cool roofs is predicted to reduce the total number of hours above 26 °C from 672 hours to 657 hours. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 oC from 661 hours in reference scenario to 659 in reference with cool roof scenario (scenario 1) and 634 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B04

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

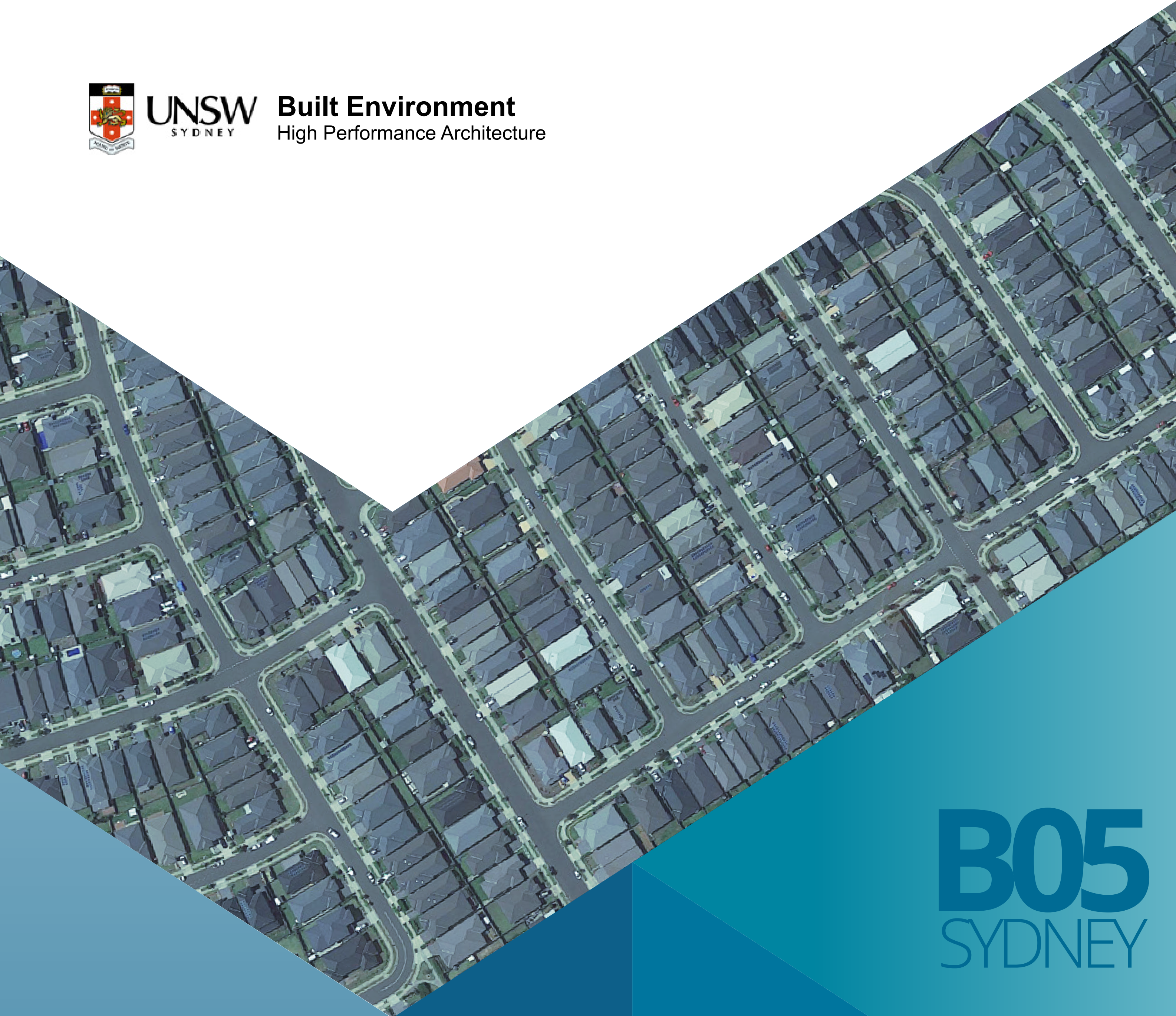
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY
Built Environment
High Performance Architecture



B05
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

New low-rise shopping mall centre
2021

BUILDING 05

NEW LOW-RISE SHOPPING MALL CENTRE

Floor area : $1100m^2$
Number of stories : 2

Image source: Westfield Tea Tree Plaza, Tea Tree Plaza 976 North East Rd, Modbury, Tea Tree Gully, South Australia 5092, Australia

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the new low-rise office building from 76.6-83.0 kWh/m² to 74.8-80.6 kWh/m².

Table 1. Sensible and total cooling load for a new low-rise shopping mall centre without roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	52.7	80.0	51.2	78.4	47.0	61.8
Terry Hill	55.7	76.6	54.0	74.8	51.7	65.3
Bankstown	58.1	80.2	56.6	78.5	52.9	63.2
Canterbury	54.0	79.3	52.5	77.8	48.9	63.7
Observatory	52.3	79.1	50.8	77.5	48.1	65.3
Richmond	67.0	83.0	64.8	80.6	61.8	69.5
Penrith	62.9	79.1	61.0	77.1	58.1	65.9
Horsley Park	61.2	78.6	59.4	76.6	53.5	62.6
Camden	63.7	77.9	61.9	75.9	58.4	64.0
Olympic Park	57.2	80.4	55.5	78.6	52.9	66.6
Campbelltown	60.6	77.9	58.8	75.9	55.5	63.5

Table 2. Sensible and total cooling load saving for a new low-rise shopping mall centre without roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 1.5-2.4 kWh/m² which is equivalent to 1.9-2.9 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 11.3-18.2 kWh/m² which is equivalent to 14.8-22.8 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	1.5	2.8	1.6	2.0	5.7	10.8	18.2	22.8
Terry Hill	1.7	3.1	1.8	2.3	4.0	7.2	11.3	14.8
Bankstown	1.5	2.6	1.7	2.1	5.2	9.0	17.0	21.2
Canterbury	1.5	2.8	1.5	1.9	5.1	9.4	15.6	19.7
Observatory	1.5	2.9	1.6	2.0	4.2	8.0	13.8	17.4
Richmond	2.2	3.3	2.4	2.9	5.2	7.8	13.5	16.3
Penrith	1.9	3.0	2.0	2.5	4.8	7.6	13.2	16.7
Horsley Park	1.8	2.9	2.0	2.5	7.7	12.6	16.0	20.4
Camden	1.8	2.8	2.0	2.6	5.3	8.3	13.9	17.8
Olympic Park	1.7	3.0	1.8	2.2	4.3	7.5	13.8	17.2
Campbelltown	1.8	3.0	2.0	2.6	5.1	8.4	14.4	18.5

In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs can reduce the cooling load of the new low-rise shopping mall centre with insulation during the summer season.

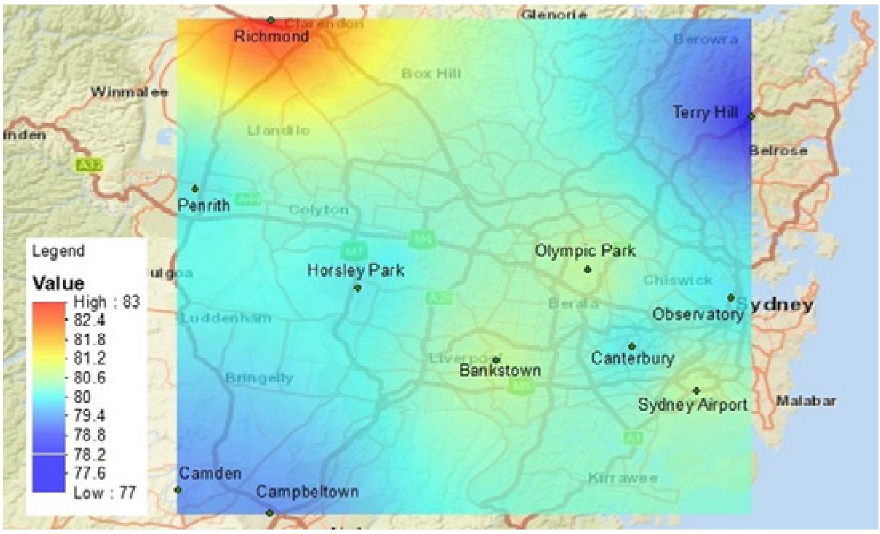


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

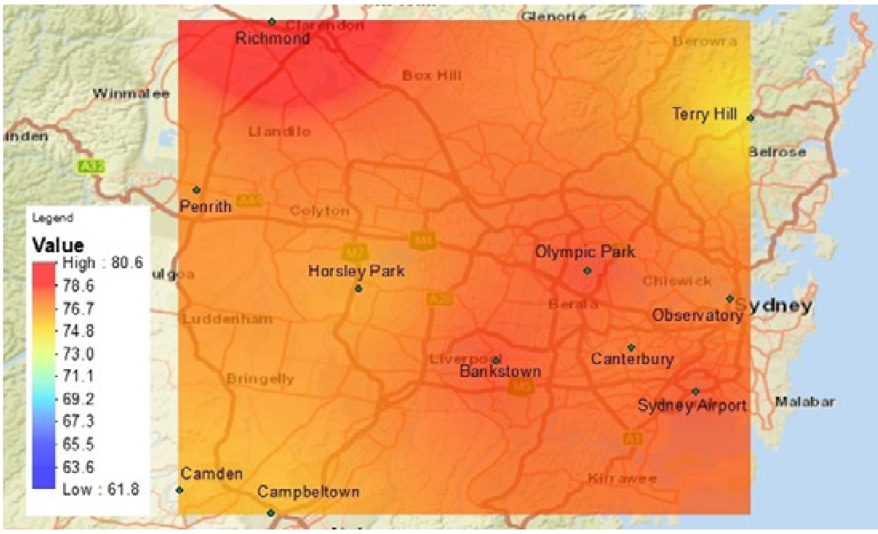


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

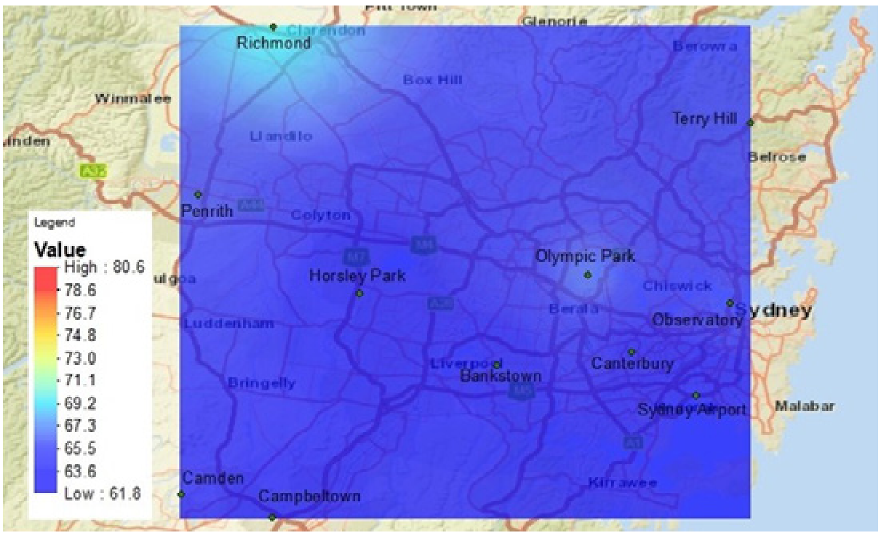


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.1 kWh/m²) is significantly lower than the annual cooling load reduction (4.6-7.6 kWh/m²).

Table 3. Annual cooling and heating loads for a new low-rise shopping mall centre for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	182.2	233.4	0.7	1.5	177.8	228.8	0.7	1.6
Terry Hill	154.3	212.7	1.2	3.2	148.5	206.3	1.2	3.3
Bankstown	182.9	228.0	1.6	4.3	177.6	222.4	1.6	4.4
Canterbury	168.2	213.4	1.4	4.2	163.2	208.1	1.5	4.3
Observatory	182.5	224.7	0.7	1.5	177.2	219.1	0.7	1.6
Richmond	186.0	235.0	2.5	6.9	179.9	228.5	2.5	6.9
Penrith	195.5	245.9	1.7	4.5	188.3	238.3	1.7	4.6
Horsley Park	180.5	219.4	1.8	4.7	173.6	212.1	1.8	4.8
Camden	172.6	207.1	2.9	8.2	166.4	200.5	2.9	8.3
Olympic Park	186.5	242.5	1.4	3.7	179.9	235.5	1.4	3.7
Campbelltown	170.5	202.8	2.6	6.9	164.0	196.0	2.6	7.0

The annual cooling load saving by building-scale application of cool roofs is around 2.0-3.4 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.5 and 7.5 kWh/m² (~1.9-3.2 %).

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for new low-rise shopping mall centre using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	4.4	2.4	4.6	2.0	0.0	0.1	4.4	2.4	4.5	1.9
Terry Hill	5.8	3.8	6.4	3.0	0.0	0.1	5.8	3.7	6.3	2.9
Bankstown	5.3	2.9	5.6	2.5	0.0	0.1	5.3	2.9	5.5	2.4
Canterbury	5.0	3.0	5.3	2.5	0.1	0.1	4.9	2.9	5.2	2.4
Observatory	5.3	2.9	5.6	2.5	0.0	0.1	5.3	2.9	5.5	2.4
Richmond	6.1	3.3	6.5	2.8	0.0	0.0	6.1	3.2	6.5	2.7
Penrith	7.2	3.7	7.6	3.1	0.0	0.1	7.2	3.7	7.5	3.0
Horsley Park	6.9	3.8	7.3	3.3	0.0	0.1	6.9	3.8	7.2	3.2
Camden	6.2	3.6	6.6	3.2	0.0	0.1	6.2	3.5	6.5	3.0
Olympic Park	6.6	3.5	7.0	2.9	0.0	0.0	6.6	3.5	7.0	2.8
Campbelltown	6.5	3.8	6.8	3.4	0.0	0.1	6.5	3.8	6.7	3.2

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

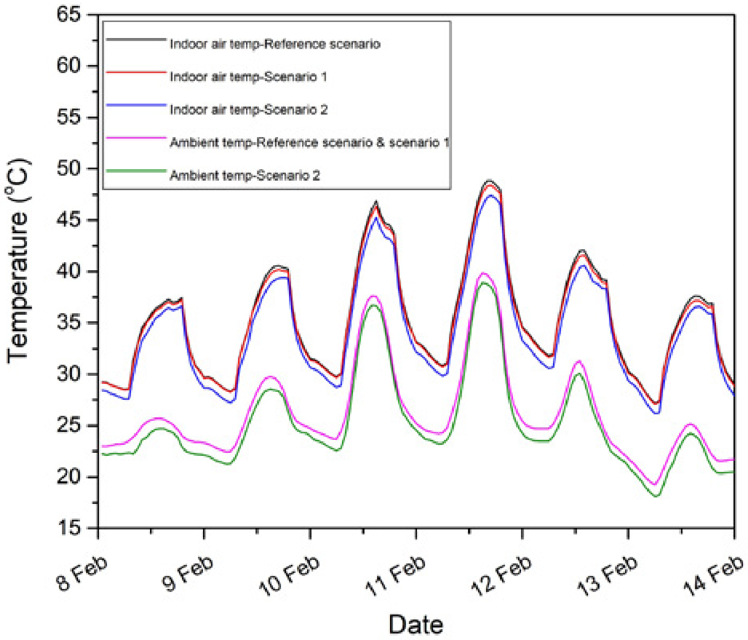


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for new low-rise shopping mall centre under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

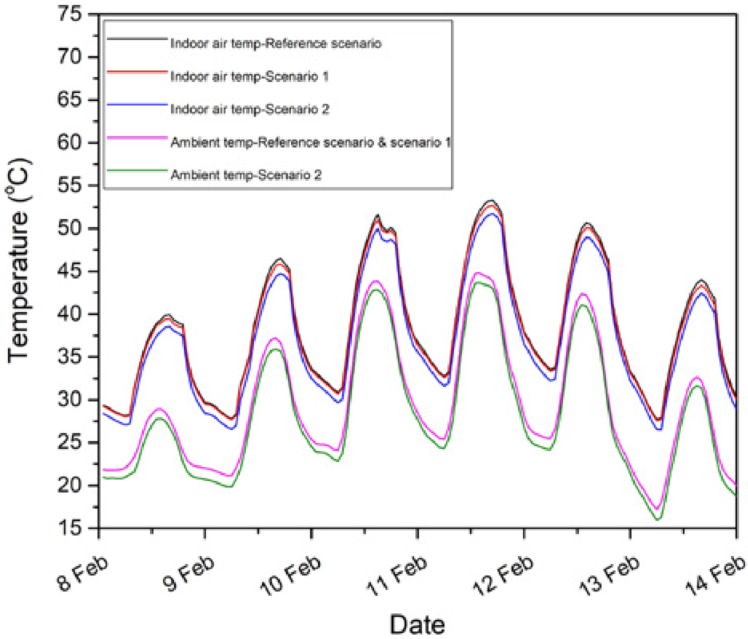


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 27.1-48.8 °C and 27.2-53.2 °C in Observatory and Richmond stations, respectively.

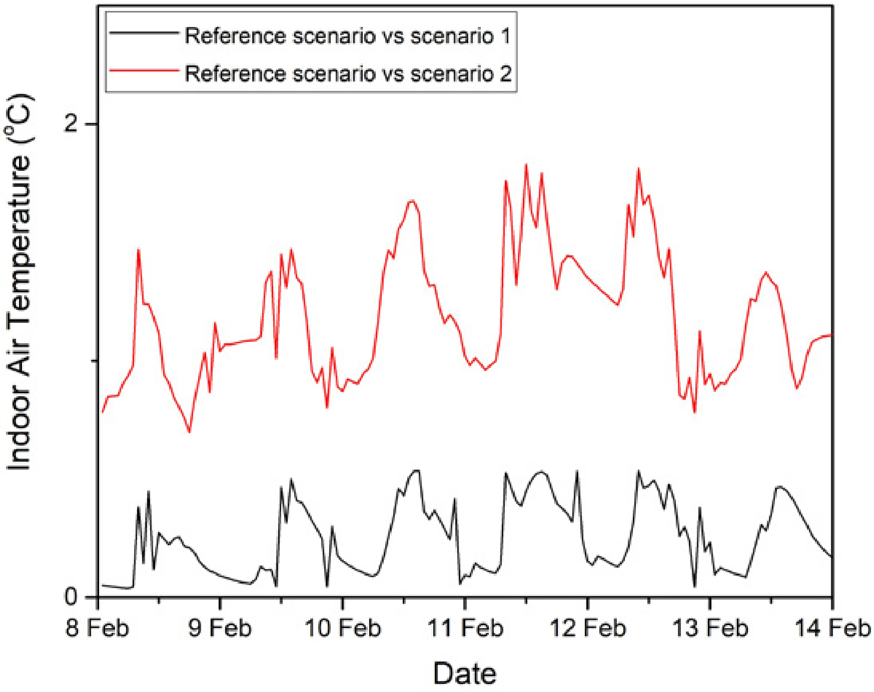


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.5 °C and 0.8 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.8°C and 2.1°C in Observatory and Richmond stations, respectively.

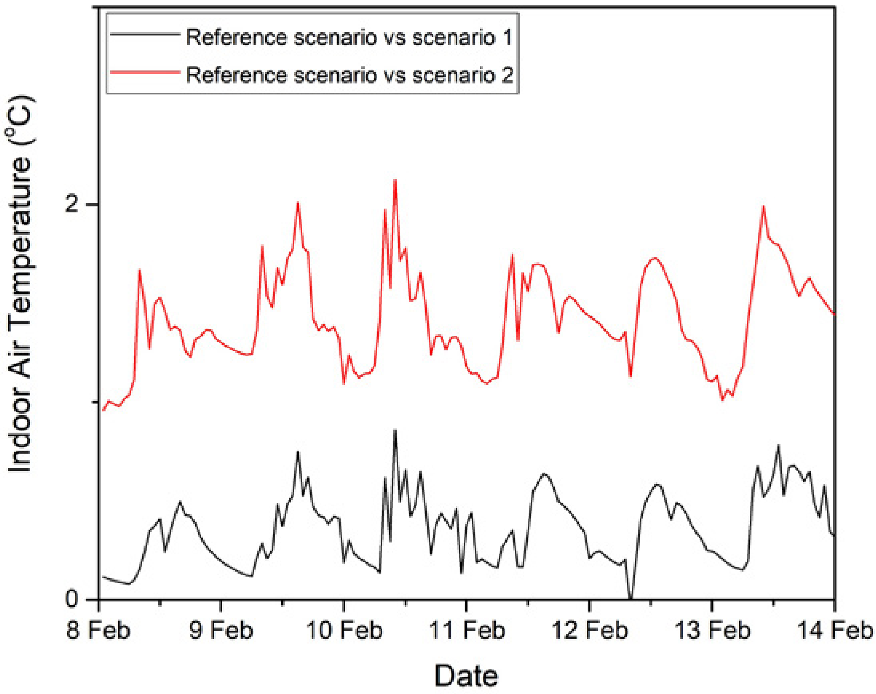


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise shopping mall centre under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 14.7-32.8 °C in reference scenario to a range 14.6-32.5 °C in scenario 1 in Observatory Hill station.

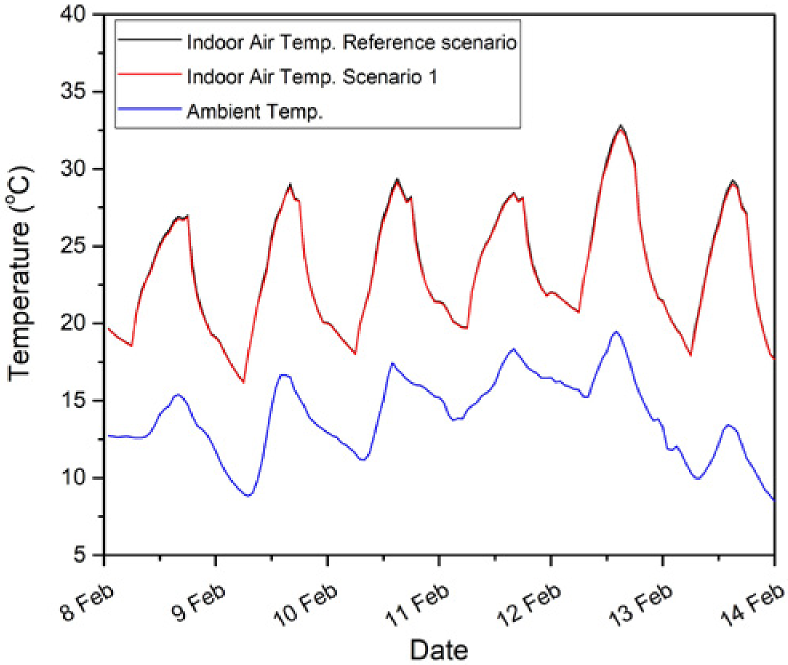


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 9.4-32.1 °C in reference scenario to a range 9.4-31.9 °C in scenario 1 in Richmond station.

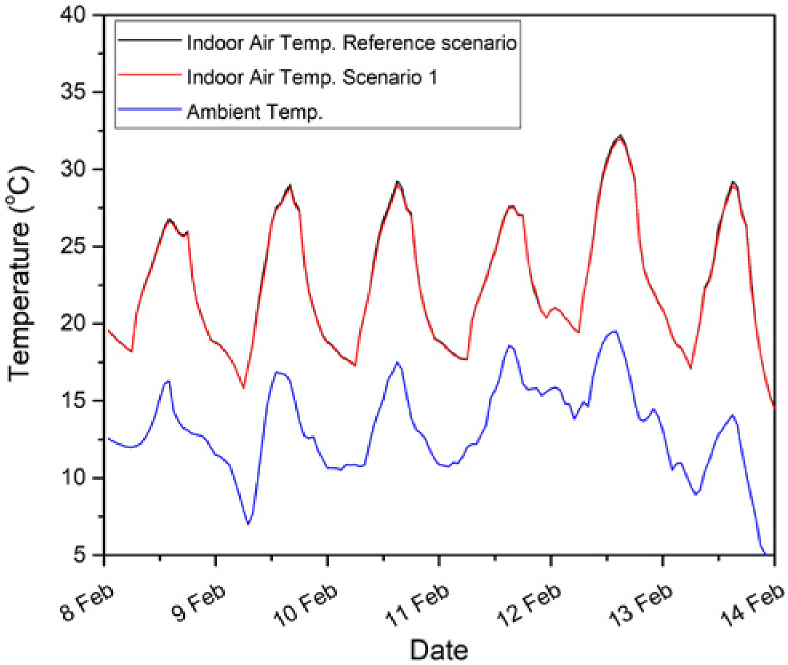


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C and 0.4°C in Observatory and Richmond stations, respectively.

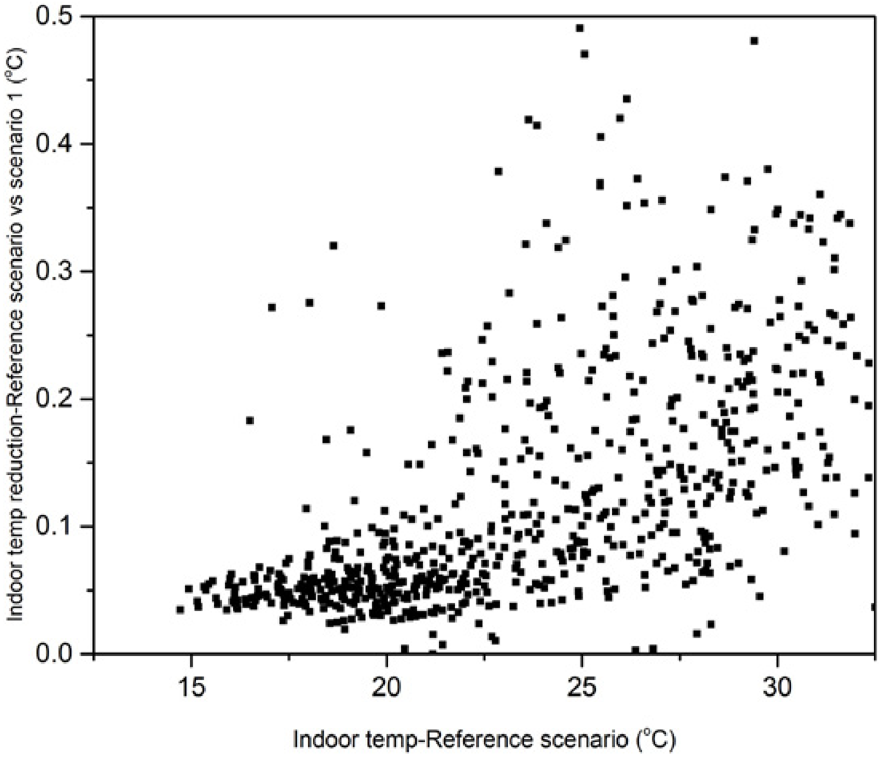


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

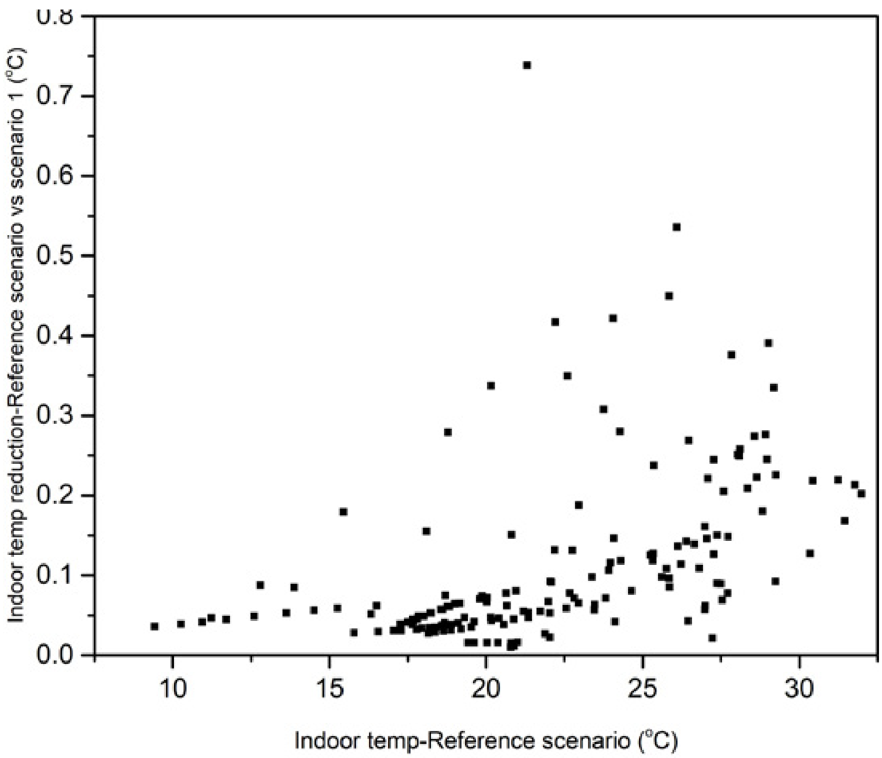


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise shopping mall centre under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 131 hours in reference scenario to 134 hours, and from 253 to 257 hours in scenario 1 in Observatory and Richmond stations, respectively.

The number operational hours with air temperature <19 °C during nearly remain the same in reference scenario compared to scenario 1 in Observatory; and slightly increased from 51 to 53 hours in Richmond station.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	18	131	18	134
Richmond	51	253	53	257

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decreased from 669 hours in reference scenario to 668 and 611 hours under scenario 1 and 2 in Observatory station; and from 641 hours in reference scenario to 639 and 619 hours under scenario 1 and 2 in Richmond station, respectively.

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	669	668	611
Richmond	641	639	619

6

CONCLUSIONS

• In the eleven weather stations in Sydney, the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the new low-rise shopping mall centre during the summer season. Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

• In the eleven weather stations in Sydney, the total cooling load of a typical low-rise shopping mall centre under the reference scenario is approximately 76.6 and 83 kWh/m^2, which reduces to a range between 74.8 and 80.6 kWh/m^2 under Reference with cool roof scenario (scenario 1). As computed, the total cooling load saving by building-scale application of cool roofs is around 1.5-2.4 kWh/m^2 (~ 1.9-2.9%) (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the total cooling load of low-rise shopping mall centre is estimated to be around 11.3-18.2 kWh/m^2 lower under cool roof with modified urban temperature scenario (scenario 2) compared to the reference scenario. This is equivalent to 14.8-22.8% total cooling load saving by combined building-scale and urban-scale application of cool roof.

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0-0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (4.6-7.6 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 2-3.4%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.5 and 7.5 kWh/m^2 (~1.9-3.2%) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 27.1-48.8 ^{o}C and 27.2-53.2 ^{o}C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.5 and 0.8 ^{o}C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.8 and 2.1 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 ^{o}C in reference scenario to a range between 18.1 and 38.9 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 ^{o}C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 ^{o}C in reference scenario to 15.9-43.6 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 ^{o}C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 14.7 and 32.8 ^{o}C in reference scenario to a range between 14.6 and 32.5 ^{o}C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 9.4 and 32.1 °C in reference scenario to a range between 9.4 and 31.9 °C in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C and 0.4 °C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 131 hours in reference scenario to 134 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slight increase in total number of hours below 19 °C from 253 hours in reference scenario to 257 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. 7 am-6 pm) remain the same in reference scenario compared to reference with cool roof scenario (scenario 1) in Observatory station. The calculation in Richmond station shows a slight increase of number of hours below 19 °C from 51 hours to 53 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 669 hours under the reference scenario in Observatory station, which decreases to 668 and 611 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 °C from 641 hours in reference scenario to 639 in reference with cool roof scenario (scenario 1) and 619 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B05

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

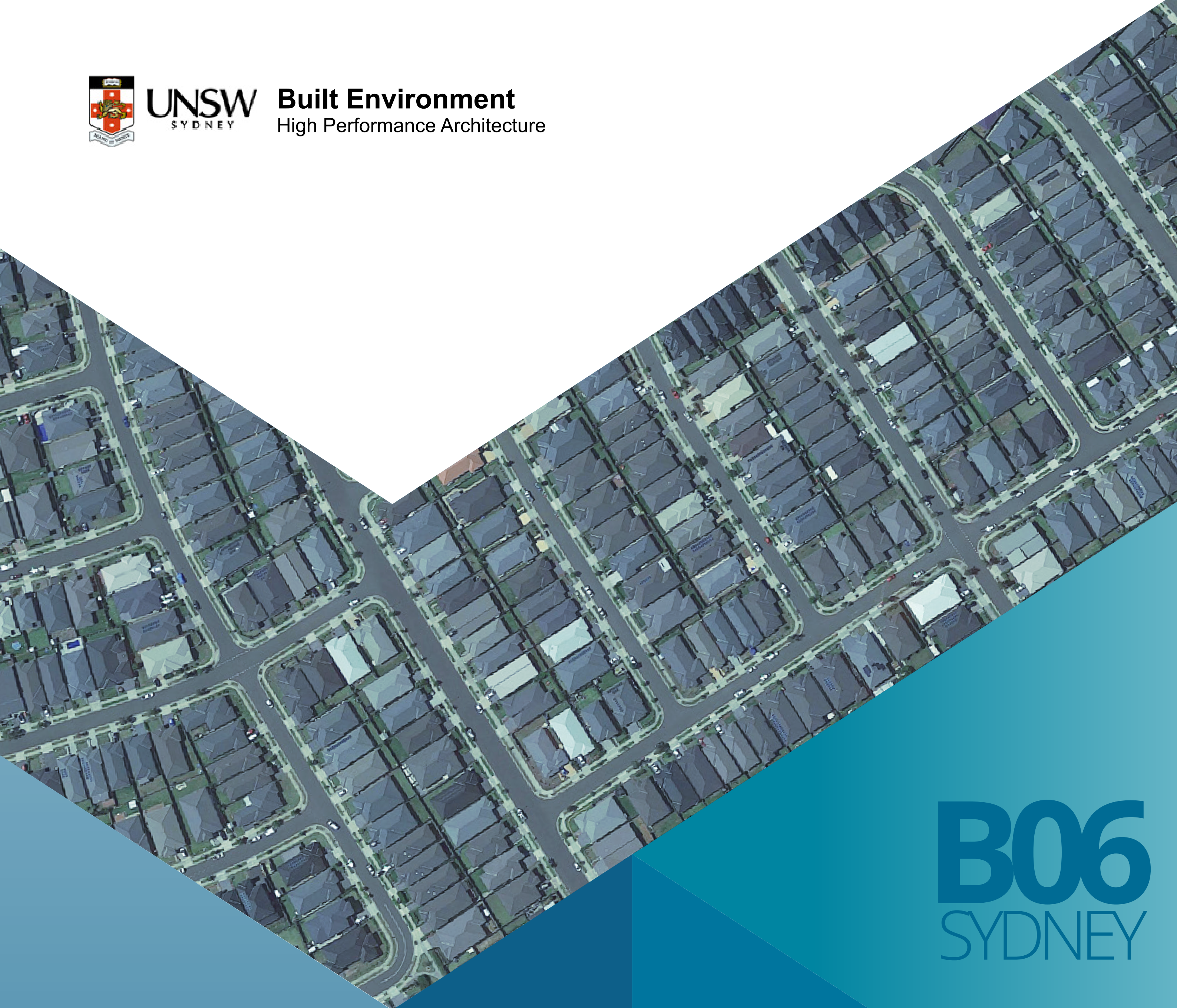
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY
Built Environment
High Performance Architecture



B06
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

New mid-rise shopping mall centre
2021

BUILDING 06

NEW MID-RISE SHOPPING MALL CENTRE

Floor area : 1100m^2
Number of stories : 4

Image source: Yamanto Central, Brisbane

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a new mid-rise shopping mall centre without roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new mid-rise shopping mall centre from 75.4-81.7 kWh/m² to 74.5-80.6 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	51.7	79.0	51.0	78.3	46.9	61.7
Terry Hill	54.5	75.4	53.7	74.5	51.6	65.2
Bankstown	57.0	79.1	56.3	78.3	52.7	63.0
Canterbury	53.0	78.2	52.3	77.5	48.7	63.5
Observatory	51.3	78.1	50.6	77.3	47.9	65.2
Richmond	65.8	81.7	64.7	80.6	61.7	69.5
Penrith	61.6	77.8	60.7	76.8	57.9	65.7
Horsley Park	60.0	77.3	59.1	76.3	53.3	62.3
Camden	62.5	76.6	61.6	75.6	58.1	63.8
Olympic Park	56.1	79.3	55.3	78.4	52.8	66.5
Campbelltown	59.4	76.6	58.5	75.7	55.4	63.4

Table 2. Sensible and total cooling load saving for a new mid-rise shopping mall centre without roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 0.7-1.1 kWh/m² which is equivalent to 0.9-1.3 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 10.2-17.3 kWh/m² which is equivalent to 13.5-21.9 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	0.7	1.4	0.7	0.9	4.8	9.3	17.3	21.9
Terry Hill	0.8	1.5	0.9	1.2	2.9	5.3	10.2	13.5
Bankstown	0.7	1.2	0.8	1.0	4.3	7.5	16.1	20.4
Canterbury	0.7	1.3	0.7	0.9	4.3	8.1	14.7	18.8
Observatory	0.7	1.4	0.8	1.0	3.4	6.6	12.9	16.5
Richmond	1.1	1.7	1.1	1.3	4.1	6.2	12.2	14.9
Penrith	0.9	1.5	1.0	1.3	3.7	6.0	12.1	15.6
Horsley Park	0.9	1.5	1.0	1.3	6.7	11.2	15.0	19.4
Camden	0.9	1.4	1.0	1.3	4.4	7.0	12.8	16.7
Olympic Park	0.8	1.4	0.9	1.1	3.3	5.9	12.8	16.1
Campbelltown	0.9	1.5	0.9	1.2	4.0	6.7	13.2	17.2

In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs can significantly reduce the cooling load of a new mid-rise shopping mall centre during the summer season.

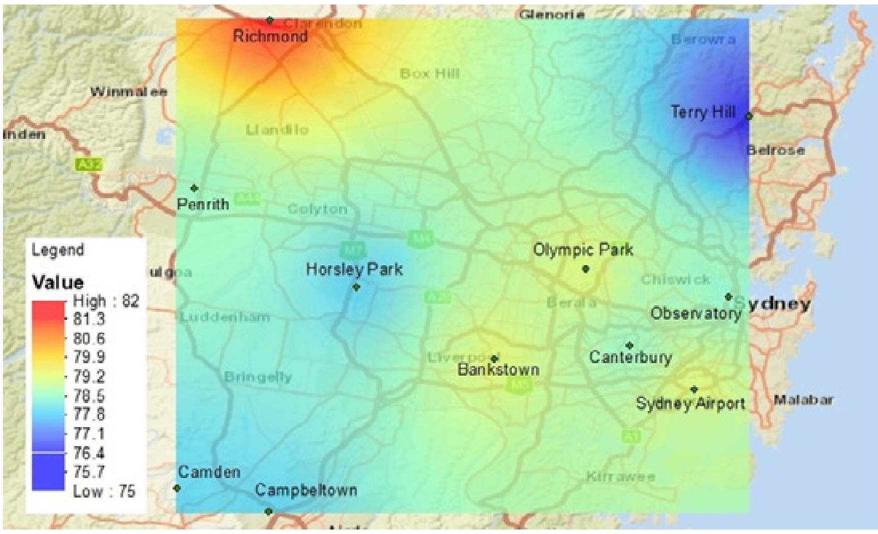


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

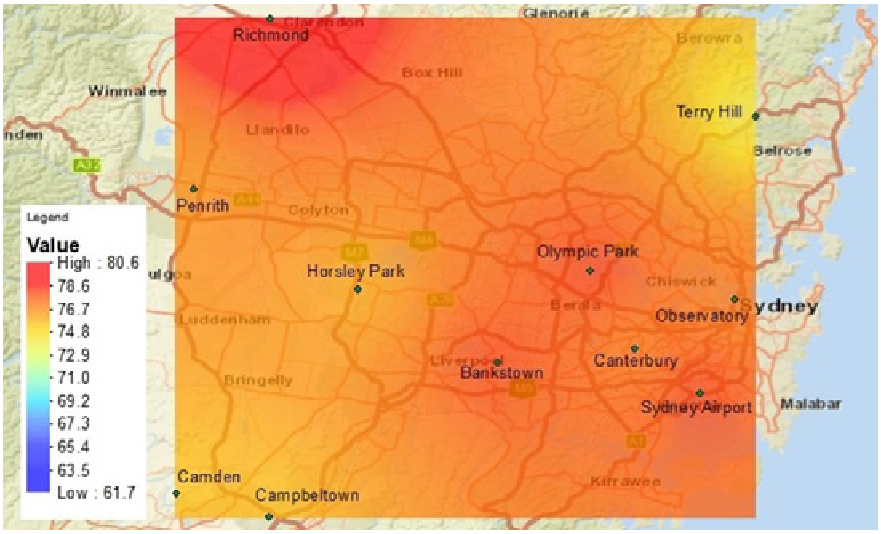


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

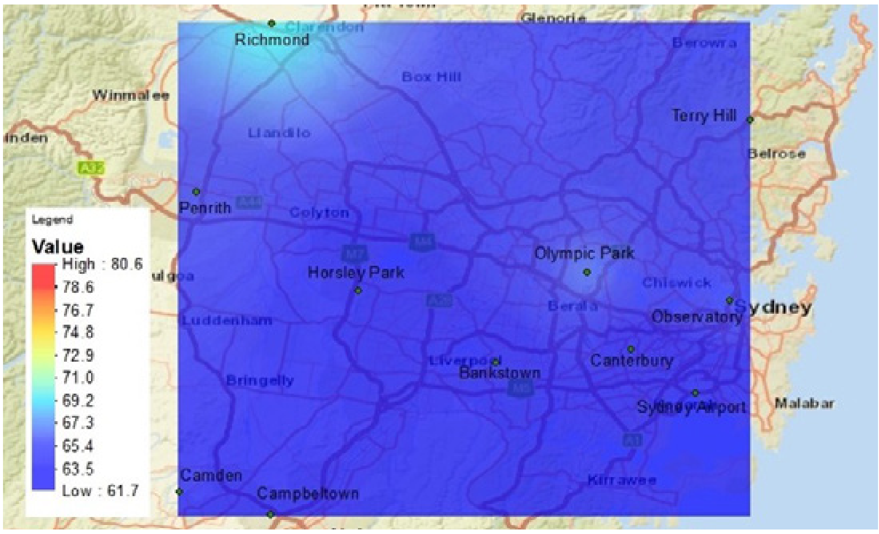


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new mid-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.1 kWh/m²) is significantly lower than the annual cooling load reduction (2.2-3.6 kWh/m²).

Table 3. Annual cooling and heating loads for a new mid-rise shopping mall centre for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	176.3	227.4	0.5	1.2	174.3	225.2	0.5	1.2
Terry Hill	147.1	205.1	0.9	2.7	144.3	202.1	0.9	2.7
Bankstown	175.8	220.7	1.2	3.6	173.3	218.1	1.2	3.6
Canterbury	161.7	206.7	1.0	3.5	159.3	204.2	1	3.5
Observatory	176.6	218.7	0.4	1.1	174.1	216.0	0.4	1.1
Richmond	178.4	227.1	2.1	6.3	175.5	224.0	2.1	6.3
Penrith	187.7	237.7	1.3	3.9	184.2	234.1	1.3	4
Horsley Park	172.8	211.5	1.4	4.1	169.5	208.0	1.4	4.1
Camden	164.9	199.3	2.3	7.3	161.9	196.2	2.4	7.4
Olympic Park	179.0	234.7	1.1	3.1	175.9	231.4	1.1	3.2
Campbelltown	162.4	194.6	2.1	6.1	159.4	191.4	2.1	6.2

The annual cooling load saving by building-scale application of cool roofs is around 1.0-1.6 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.2 and 3.5 kWh/m² (~1.0-1.6%).

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for new mid-rise shopping mall centre using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	2.0	1.1	2.2	1.0	0.0	0.0	2.0	1.1	2.2	1.0
Terry Hill	2.8	1.9	3.0	1.5	0.0	0.0	2.8	1.9	3.0	1.4
Bankstown	2.5	1.4	2.6	1.2	0.0	0.0	2.5	1.4	2.6	1.2
Canterbury	2.4	1.5	2.5	1.2	0.0	0.0	2.4	1.5	2.5	1.2
Observatory	2.5	1.4	2.7	1.2	0.0	0.0	2.5	1.4	2.7	1.2
Richmond	2.9	1.6	3.1	1.4	0.0	0.0	2.9	1.6	3.1	1.3
Penrith	3.5	1.9	3.6	1.5	0.0	0.1	3.5	1.9	3.5	1.4
Horsley Park	3.3	1.9	3.5	1.7	0.0	0.0	3.3	1.9	3.5	1.6
Camden	3.0	1.8	3.1	1.6	0.1	0.1	2.9	1.7	3.0	1.5
Olympic Park	3.1	1.7	3.3	1.4	0.0	0.1	3.1	1.7	3.2	1.3
Campbelltown	3.0	1.8	3.2	1.6	0.0	0.1	3.0	1.8	3.1	1.5

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

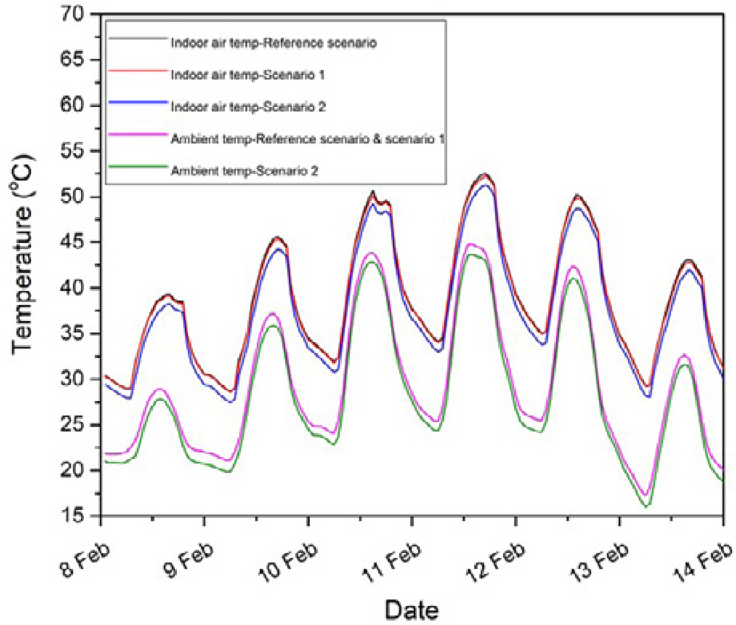


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for new mid-rise shopping mall centre under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

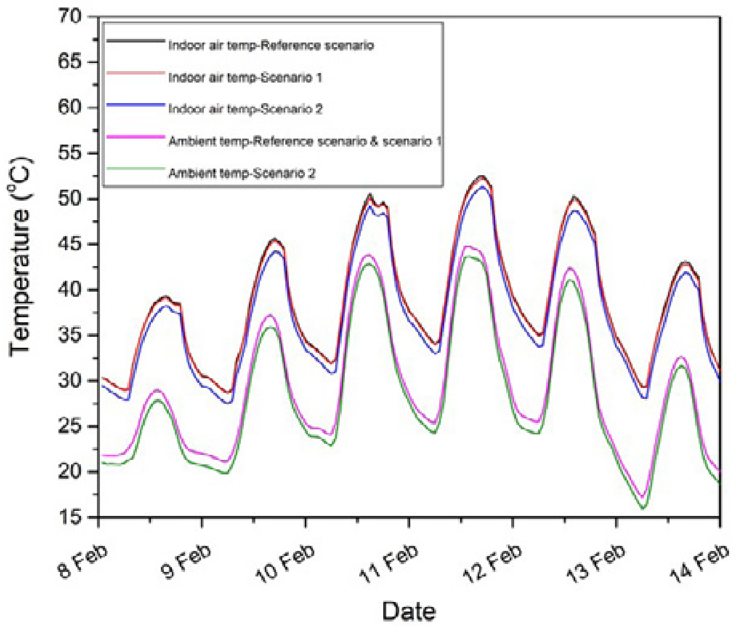


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 28.2 -48.1 °C and 28.4-52.6 °C in Observatory and Richmond stations, respectively.

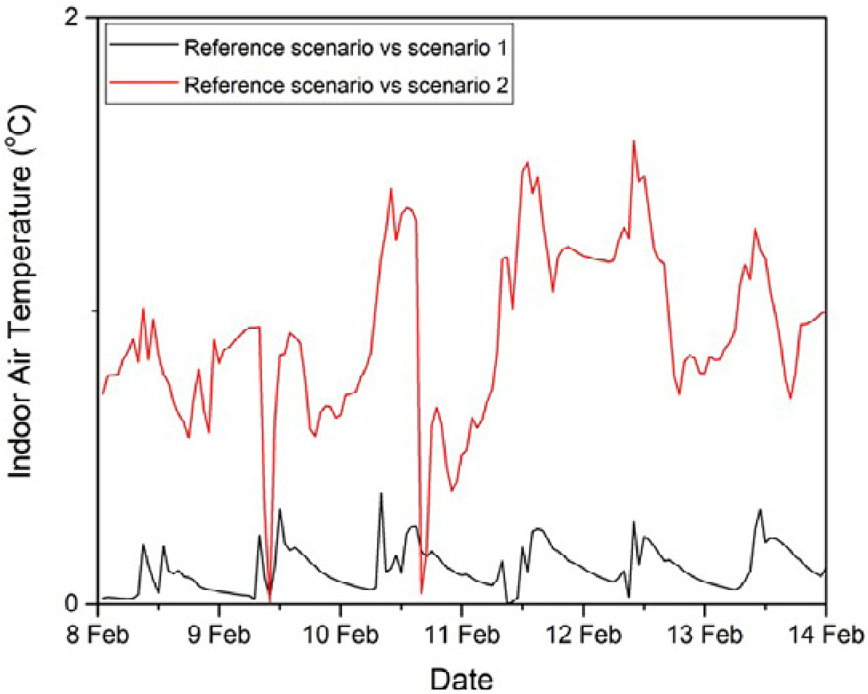


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.4 °C and 0.7 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.6 °C and 1.8 °C in Observatory and Richmond stations, respectively.

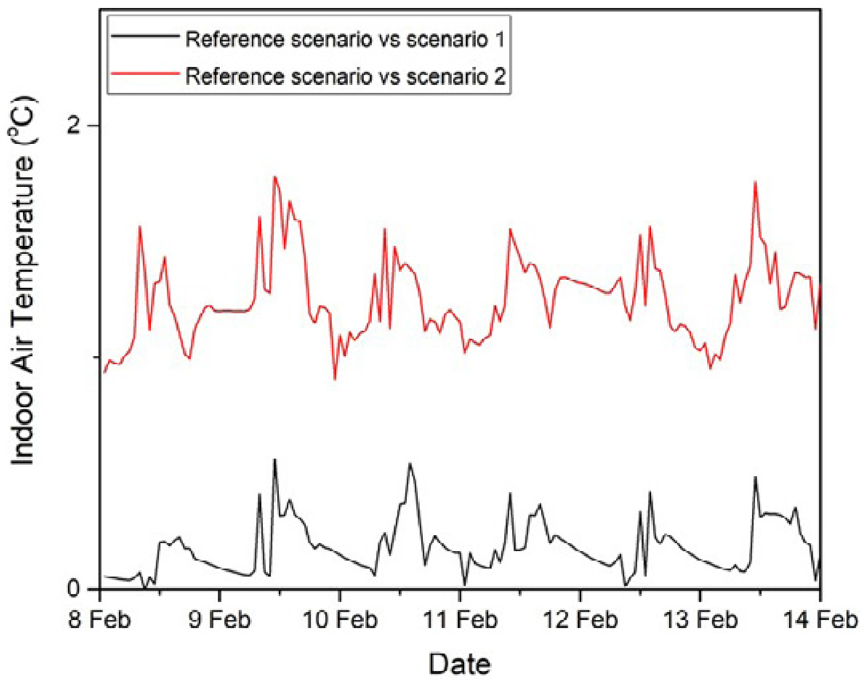


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise shopping mall centre under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly reduce from a range 15.7-32.1 °C in reference scenario to a range 15.6-32.0 °C in scenario 1 in Observatory Hill station.

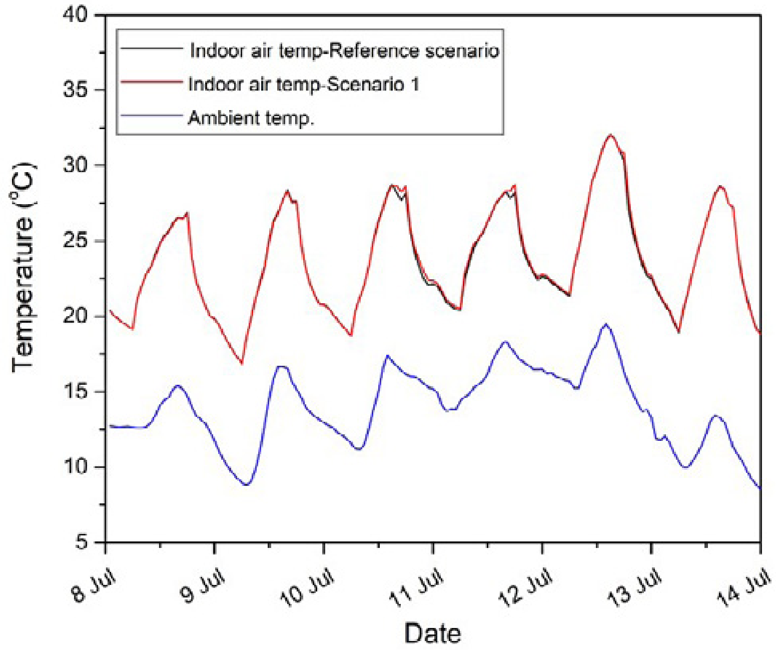


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to slightly reduce from a range 10.7-31.4 °C in reference scenario to a range 10.7-31.3 °C in scenario 1 in Richmond station.

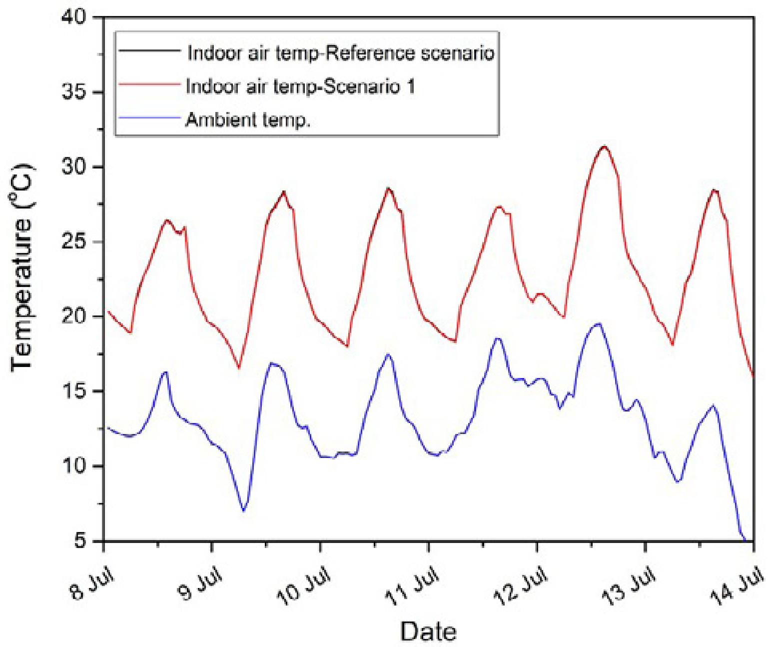


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 °C and 0.2 °C in Observatory and Richmond stations, respectively.

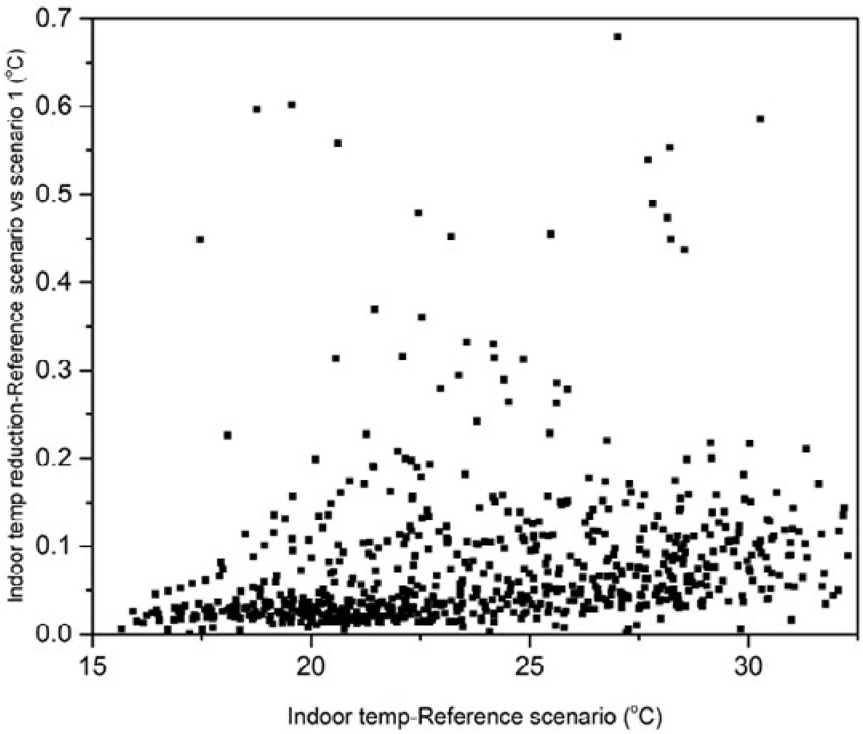


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

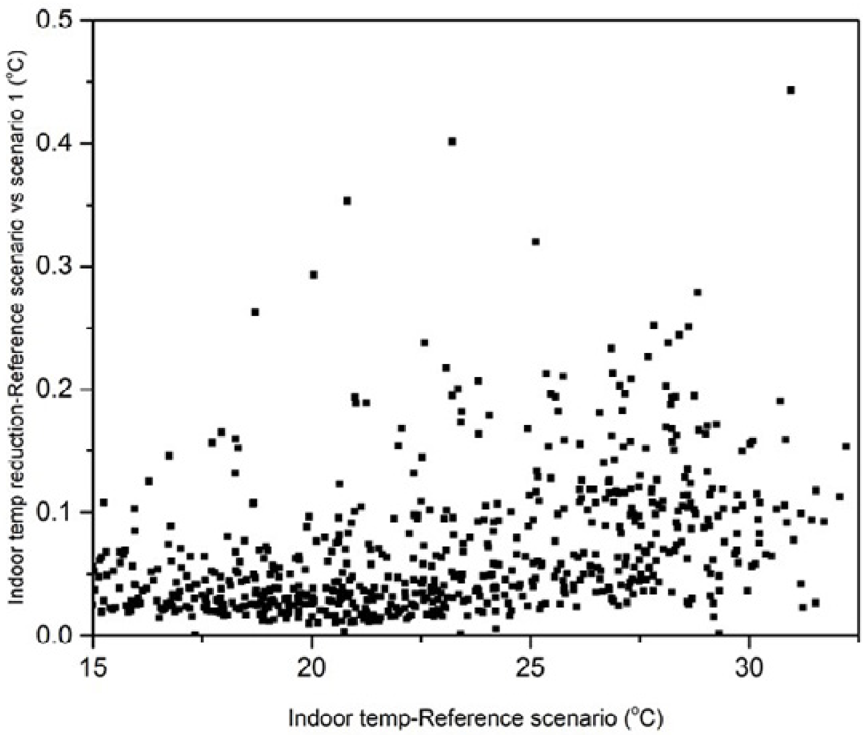


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise shopping mall centre under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	14	89	14	89
Richmond	50	219	50	219

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to remain the same with 89 and 219 hours for both scenarios in Observatory and Richmond stations, respectively.

The number operational hours with air temperature <19 °C during remain the same in reference scenario compared to scenario 1 in Observatory and Richmond stations.

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	670	670	668
Richmond	662	661	638

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decreased from 670 hours in reference scenario to 668 hours under scenario 2 in Observatory station; and from 662 hours in reference scenario to 661 and 638 hours under scenario 1 and 2 in Richmond station, respectively.

6

CONCLUSIONS

• It is estimated that the combined building-scale and urban-scale application of cool roofs can significantly reduce the cooling load of a new mid-rise shopping mall centre during the summer season.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of the mid-rise shopping mall centre from 75.4-81.7 kWh/m^2 to 74.5-80.6 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.7-1.1 kWh/m^2. This is equivalent to approximately 0.9-1.3 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 10.2-17.3 kWh/m^2. This is equivalent to 13.5-21.9 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.0-0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (2.2-3.6 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 1.0-1.6 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 2.2 and 3.5 kWh/m^2 (~1.0-1.6%) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 28.2 -48.1 ^{o}C and 28.4-5 2.6 ^{o}C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.4 and 0.7 ^{o}C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.6 and 1 .8 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 ^{o}C in reference scenario to a range between 18.1 and 38.9 oC in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 ^{o}C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 oC in reference scenario to 15.9-43.6 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 ^{o}C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to reduce slightly from a range between 15.7 and 32.1 ^{o}C in reference scenario to a range between 15.6 and 32.0 ^{o}C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce between 10.7 and 31.4 °C in reference scenario to a range between 10.6 and 31.3 °C in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 °C and 0.2 °C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to remain the same with 89 hours for both scenarios in Observatory station. The estimations for Richmond stations also show the same number of hours below 19 oC with 219 for both scenarios. The results show no increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) also remain the same between reference scenario and cool roof scenario (scenario 1) with 14 hours in Observatory station and 50 hours in Richmond station (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 670 hours under the reference scenario in Observatory station, which remains the same for the cool roof scenario (scenario 1) and slightly decreases to 668 hours for the cool roof and modified urban temperature scenario (scenario 2). The simulations in Richmond station also illustrate a similar reduction in number of hours above 26 °C from 662 hours in reference scenario to 661 in reference with cool roof scenario (scenario 1) and 638 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B06

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

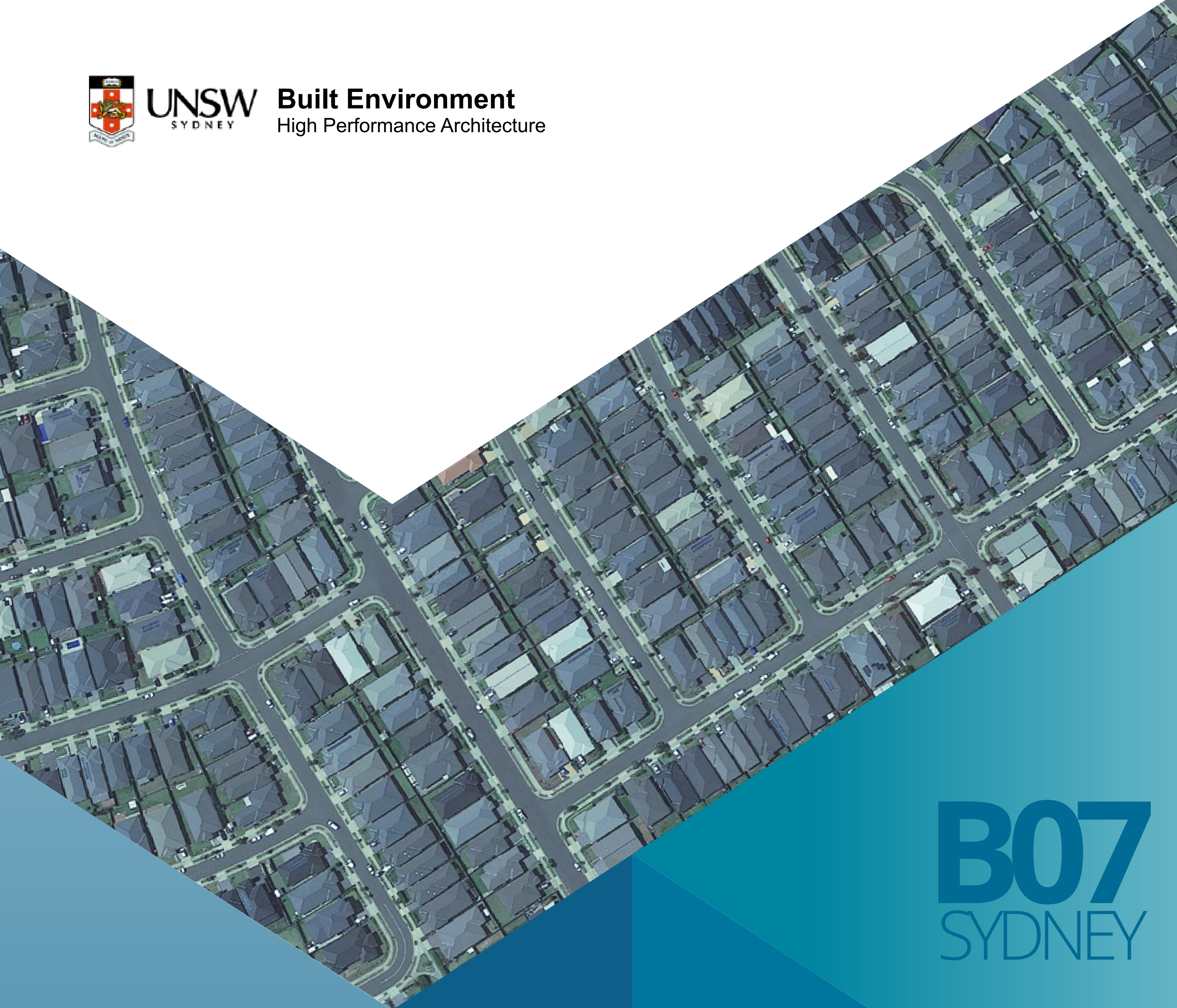
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY
Built Environment
High Performance Architecture



B07
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

New high-rise shopping mall centre
2021

BUILDING 07

NEW HIGH-RISE SHOPPING MALL CENTRE

Floor area : 1100m^2
Number of stories : 6

Image source: Mall of America, Minneapolis

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a new high-rise shopping mall centre for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise shopping mall centre from 74.9-81.3 kWh/m² to 74.3-80.5 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	51.4	78.6	50.9	78.1	46.7	61.5
Terry Hill	54.1	74.9	53.5	74.3	51.4	65.0
Bankstown	56.6	78.6	56.2	78.1	52.5	62.9
Canterbury	52.6	77.8	52.1	77.3	48.6	63.4
Observatory	50.9	77.7	50.5	77.2	47.7	65.0
Richmond	65.4	81.3	64.7	80.5	61.7	69.5
Penrith	61.2	77.3	60.6	76.6	57.8	65.6
Horsley Park	59.6	76.8	59.0	76.2	53.1	62.1
Camden	62.0	76.1	61.4	75.5	58.0	63.7
Olympic Park	55.7	78.8	55.2	78.2	52.7	66.4
Campbelltown	58.9	76.2	58.4	75.5	55.3	63.3

Table 2. Sensible and total cooling load saving for a new high-rise shopping mall centre for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 0.5-0.8 kWh/m² which is equivalent to 0.6-1.0 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 9.9-17.1 kWh/m² which is equivalent to 13.2-21.8 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	0.5	1.0	0.5	0.6	4.7	9.1	17.1	21.8
Terry Hill	0.6	1.1	0.6	0.8	2.7	5.0	9.9	13.2
Bankstown	0.4	0.7	0.5	0.6	4.1	7.2	15.7	20.0
Canterbury	0.5	1.0	0.5	0.6	4.0	7.6	14.4	18.5
Observatory	0.4	0.8	0.5	0.6	3.2	6.3	12.7	16.3
Richmond	0.7	1.1	0.8	1.0	3.7	5.7	11.8	14.5
Penrith	0.6	1.0	0.7	0.9	3.4	5.6	11.7	15.1
Horsley Park	0.6	1.0	0.6	0.8	6.5	10.9	14.7	19.1
Camden	0.6	1.0	0.6	0.8	4.0	6.5	12.4	16.3
Olympic Park	0.5	0.9	0.6	0.8	3.0	5.4	12.4	15.7
Campbelltown	0.5	0.8	0.7	0.9	3.6	6.1	12.9	16.9

> *In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs can significantly reduce the cooling load of a new high-rise shopping mall centre during the summer season.*

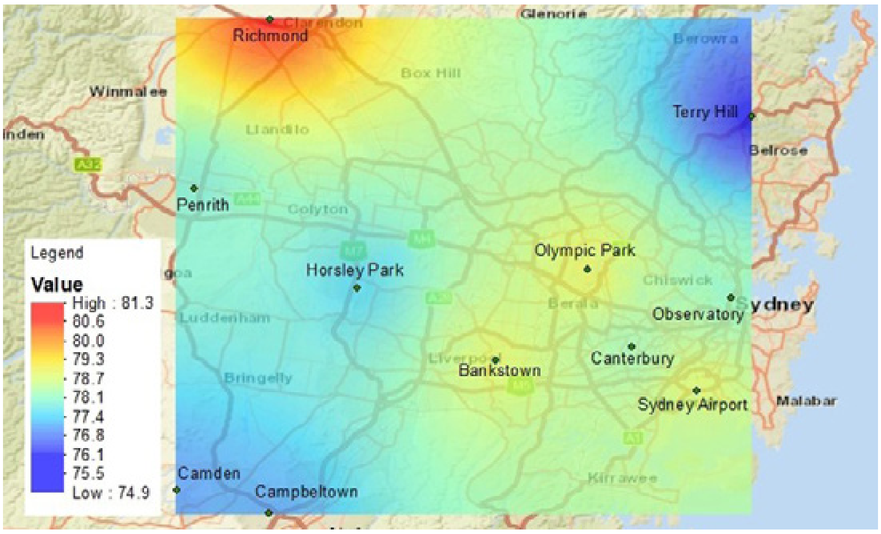


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

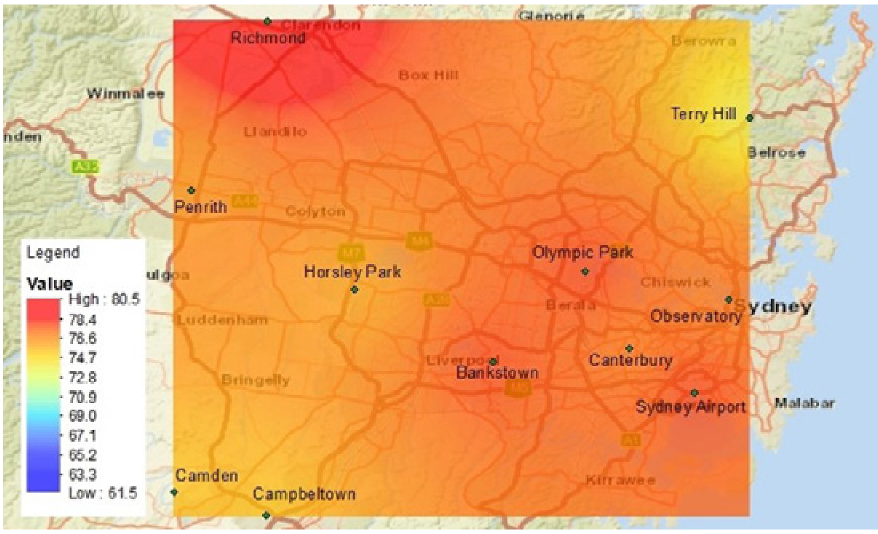


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

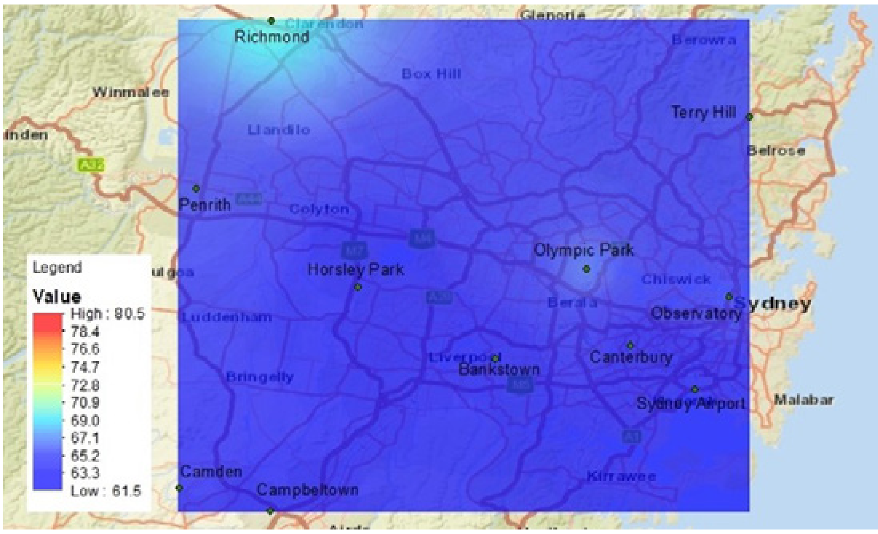


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a new high-rise shopping mall centre for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.1 kWh/m²) is significantly lower than the annual cooling load reduction (1.4-2.4 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	174.0	225.0	0.4	1.1	172.7	223.6	0.4	1.1
Terry Hill	144.3	202.2	0.8	2.6	142.6	200.2	0.8	2.6
Bankstown	173.1	217.9	1.1	3.4	171.5	216.3	1.1	3.5
Canterbury	159.2	204.1	0.9	3.3	157.7	202.5	1.0	3.3
Observatory	174.3	216.2	0.4	1.0	172.7	214.6	0.4	1.0
Richmond	175.7	224.2	2.0	6.1	173.8	222.2	2.0	6.1
Penrith	184.9	234.8	1.2	3.8	182.6	232.4	1.2	3.8
Horsley Park	170.0	208.6	1.3	3.9	167.9	206.4	1.3	3.9
Camden	162.1	196.4	2.2	7.1	160.2	194.4	2.2	7.2
Olympic Park	176.3	231.8	1.0	3.0	174.3	229.7	1.0	3.0
Campbelltown	159.5	191.6	1.9	6.0	157.5	189.5	1.9	6.0

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 0.6-1.1 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.4 and 2.4 kWh/m² (~0.6-1.1 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	1.3	0.7	1.4	0.6	0.0	0.0	1.3	0.7	1.4	0.6
Terry Hill	1.7	1.2	2.0	1.0	0.0	0.0	1.7	1.2	2.0	1.0
Bankstown	1.6	0.9	1.6	0.7	0.0	0.1	1.6	0.9	1.5	0.7
Canterbury	1.5	0.9	1.6	0.8	0.1	0.0	1.4	0.9	1.6	0.8
Observatory	1.6	0.9	1.6	0.7	0.0	0.0	1.6	0.9	1.6	0.7
Richmond	1.9	1.1	2.0	0.9	0.0	0.0	1.9	1.1	2.0	0.9
Penrith	2.3	1.2	2.4	1.0	0.0	0.0	2.3	1.2	2.4	1.0
Horsley Park	2.1	1.2	2.2	1.1	0.0	0.0	2.1	1.2	2.2	1.0
Camden	1.9	1.2	2.0	1.0	0.0	0.1	1.9	1.2	1.9	0.9
Olympic Park	2.0	1.1	2.1	0.9	0.0	0.0	2.0	1.1	2.1	0.9
Campbelltown	2.0	1.3	2.1	1.1	0.0	0.0	2.0	1.2	2.1	1.1

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

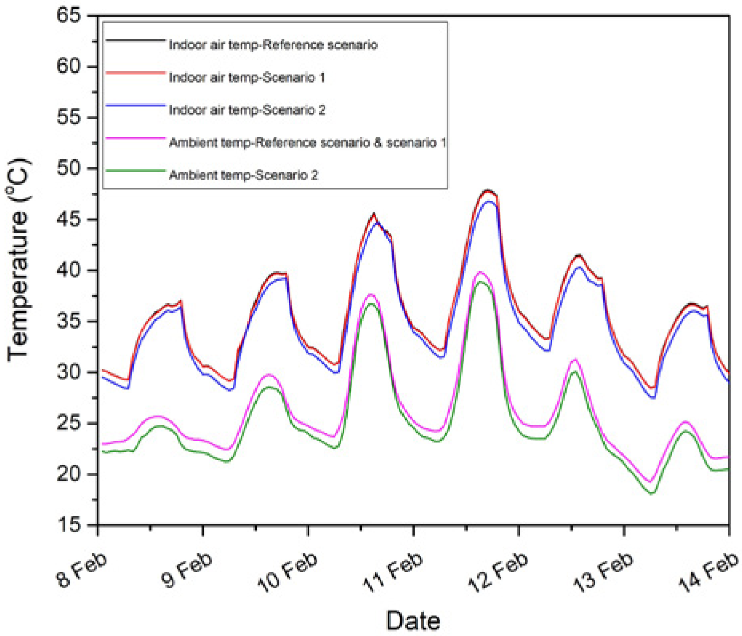


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

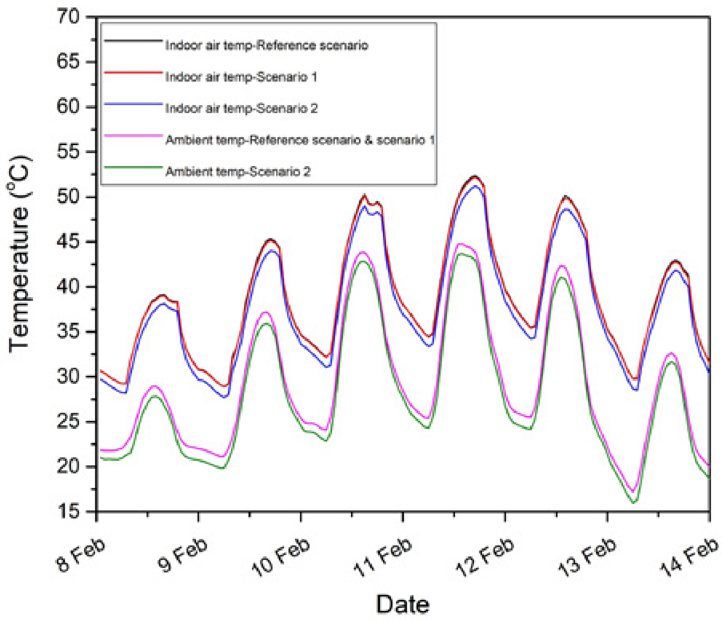


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 28.4-47.9 °C and 28.7-52.4 °C in Observatory and Richmond stations, respectively.

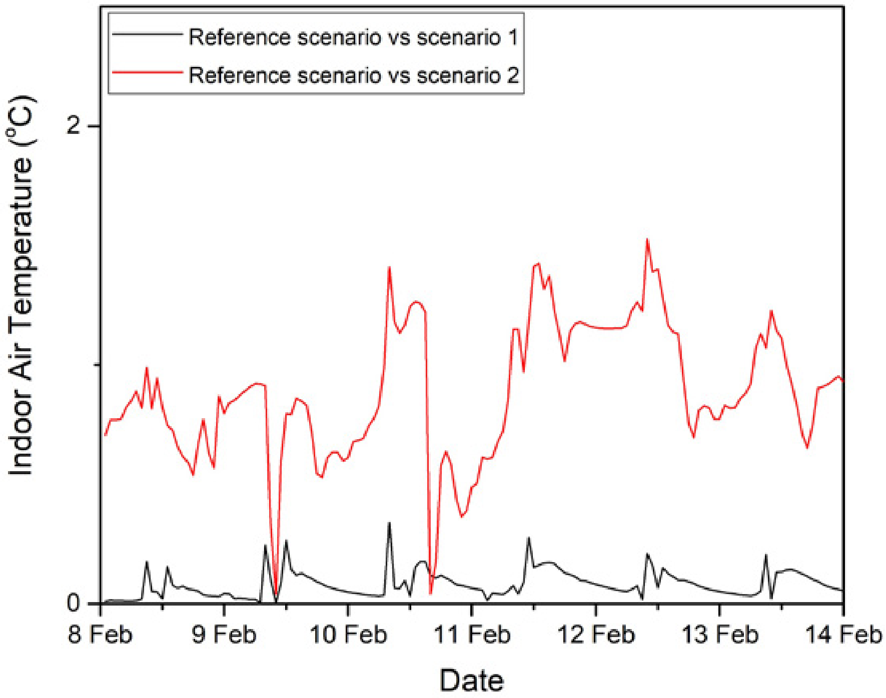


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise shopping mall centre under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.3 °C and 0.5 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.5 °C and 1.7 °C in Observatory and Richmond stations, respectively.

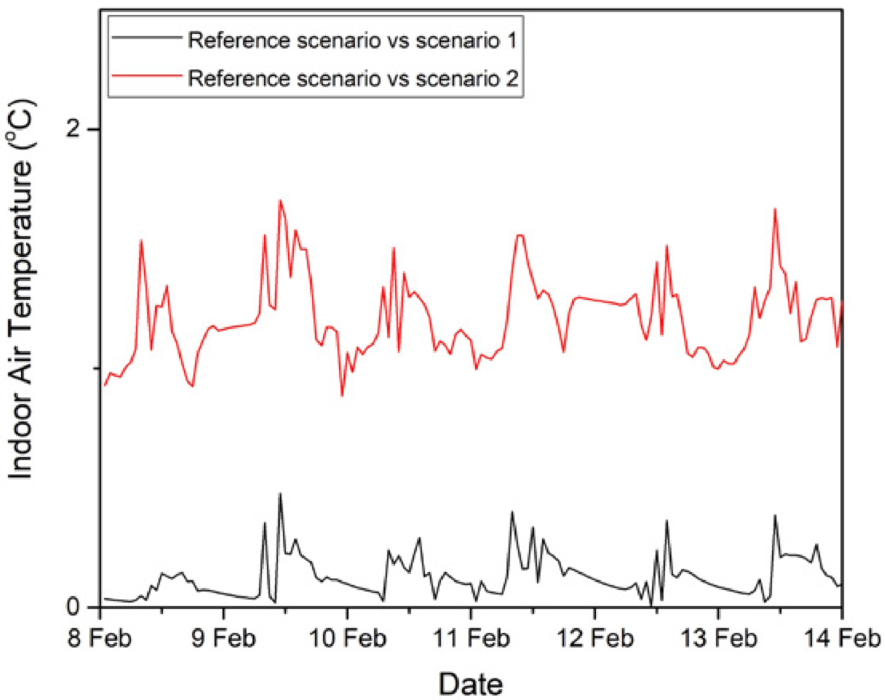


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new highrise shopping mall centre under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 15.7-32.1 °C in reference scenario to a range 15.7-32.0 °C in scenario 1 in Observatory Hill station.

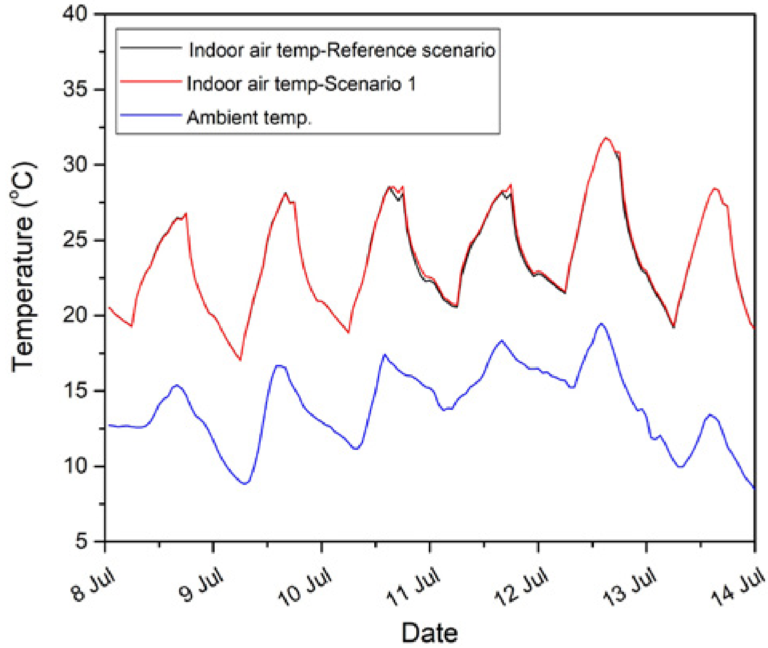


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 11.0-31.2 °C in reference scenario to a range 10.9-31.1 °C in scenario 1 in Richmond station.

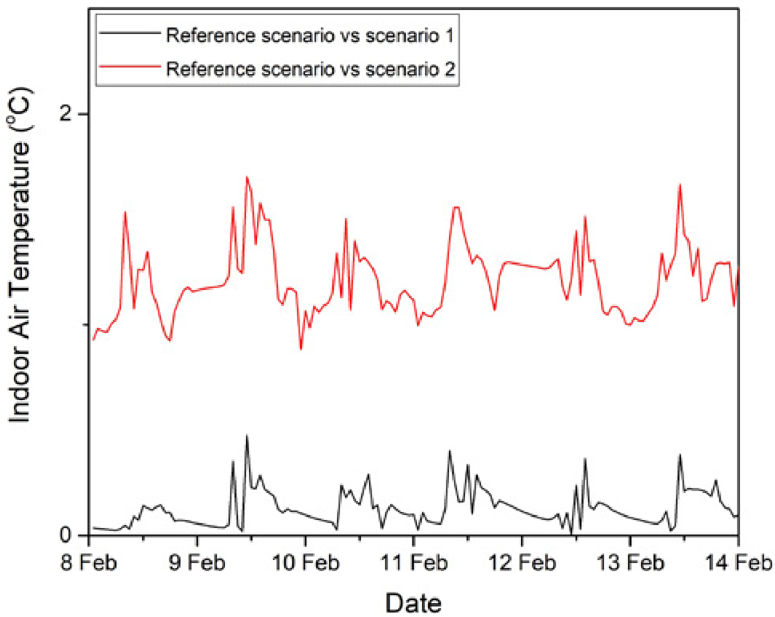


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 °C and 0.1 °C in Observatory and Richmond stations, respectively.

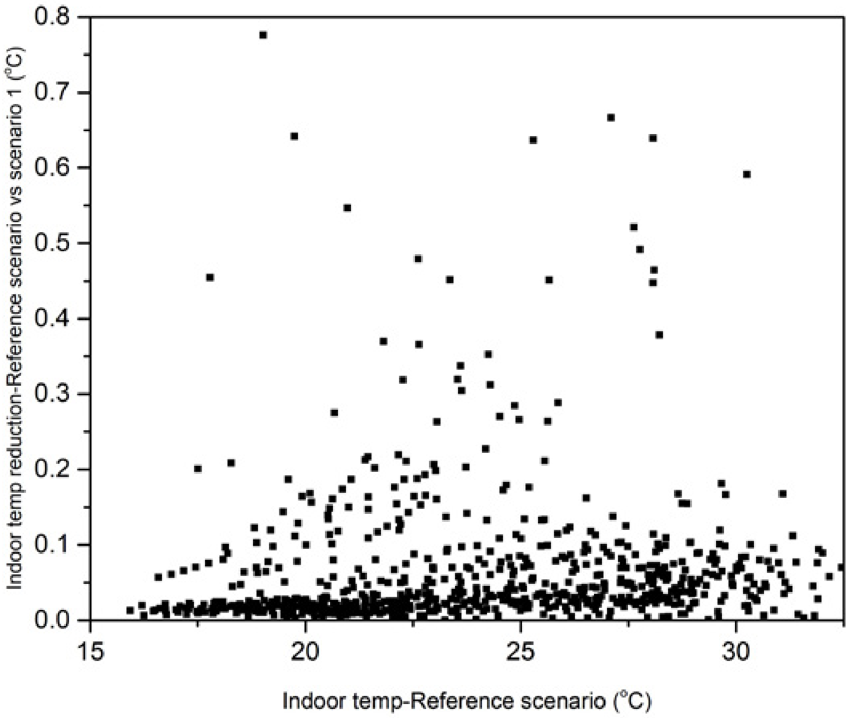


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

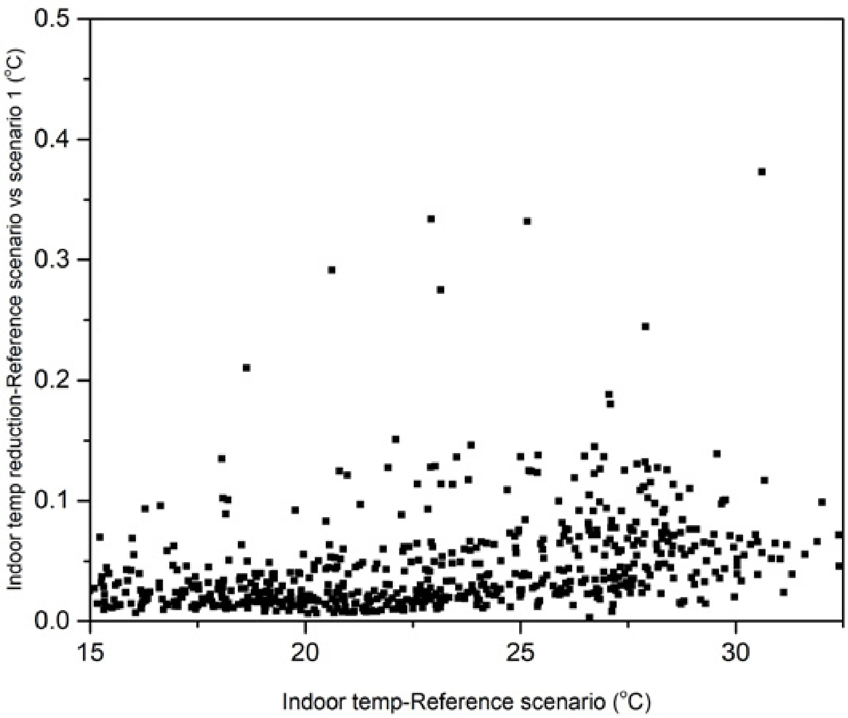


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to remain the same with 79 and 208 hours for both scenarios in Observatory and Richmond stations, respectively.

The number operational hours with air temperature <19 °C during remain the same in reference scenario compared to scenario 1 in Observatory and Richmond stations.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	13	79	13	79
Richmond	50	208	50	208

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decreased from 672 hours in reference scenario to 669 hours under scenario 2 in Observatory station; and from 665 hours in reference scenario to 642 hours under scenario 2 in Richmond station, respectively.

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	672	672	669
Richmond	665	665	642

6

CONCLUSIONS

• It is estimated that the combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of the new high-rise shopping mall centre during the summer season.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of the new high-rise shopping mall centre from 74.9-81.3 kWh/m^2 to 74.3-80.5 kWh/m^2 . As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.5-0.8 kWh/m^2. This is equivalent to approximately 0.6-1.0 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 9.9-17.1 kWh/m^2. This is equivalent to 13.2-21.8 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.0-0.1 kWh/m^2) is significantly lower than the annual cooling load reduction (1.4-2.4 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 0.6-1.1 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.4 and 2.4 kWh/m2 (~0.6-1.1 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 28.4-47 .9 °C and 28.7-5 2.4 °C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.3 and 0.5 °C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.5 and 1 .7 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 °C in reference scenario to a range between 18.1 and 38.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 °C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 °C in reference scenario to 15.9-43.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 °C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 15.7 and 32.1 °C in reference scenario to a range between 15.7 and 32.0 °C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 11. 0 and 31.2 °C in reference scenario to a range between 10.9 and 31.1 °C in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 °C and 0.1 °C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to remain the same with 79 hours for both scenarios in Observatory station. The estimations for Richmond stations also show the same number of hours below 19 °C with 208 for both scenarios. The results show no increase in total number hours below 19 oC between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) also remain the same between reference scenario and cool roof scenario (scenario 1) with 13 hours in Observatory station and 50 hours in Richmond station (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 672 hours under the reference scenario in Observatory station, which remains the same for the cool roof scenario (scenario 1) and slightly decreases to 669 hours for the cool roof and modified urban temperature scenario (scenario 2). The simulations in Richmond station also illustrate a similar reduction in number of hours above 26 °C from 665 hours in reference scenario to 665 in reference with cool roof scenario (scenario 1) and 642 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B07

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

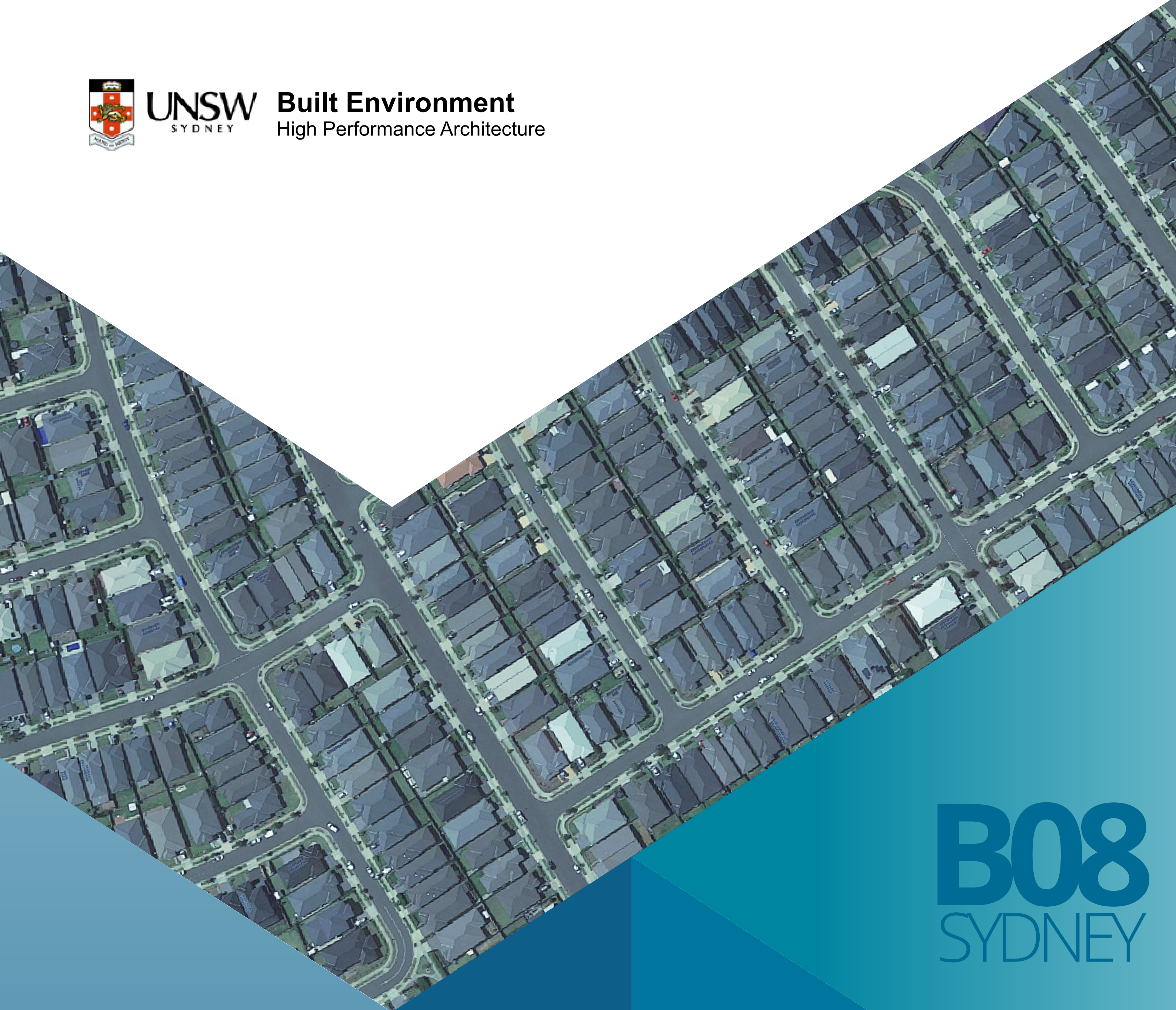
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

Built Environment
High Performance Architecture



B08 SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

New low-rise apartment
2021

BUILDING 08

NEW LOW-RISE APARTMENT

Floor area : 624m^2
Number of stories : 3

Image source: KTGY Architecture and Planning - Multi Family 3-Story Walk Up - Boulder View Apartments.

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new low-rise apartment building from 13.9-19.4 kWh/m² to 12.4-16.6 kWh/m².

Table 1. Sensible and total cooling load for a new low-rise apartment building for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	7.9	15.0	7.0	13.6	4.6	7.2
Terry Hill	8.6	13.9	7.6	12.4	6.4	9.1
Bankstown	10.0	16.4	9.0	15.1	6.8	9.1
Canterbury	8.3	14.9	7.4	13.6	5.3	8.1
Observatory	7.6	14.3	6.7	13.0	5.1	8.2
Richmond	13.9	19.4	12.4	17.6	10.7	12.9
Penrith	11.6	16.7	10.4	15.1	8.8	10.8
Horsley Park	11.0	16.1	9.8	14.6	7.4	9.6
Camden	11.9	16.3	10.7	14.8	8.9	10.4
Olympic Park	9.8	16.4	8.7	14.9	7.0	10.0
Campbelltown	10.7	15.7	9.5	14.2	7.8	9.7

For Scenario 1, the total cooling load saving is around 1.3-1.8 kWh/m² which is equivalent to 1.9-10.8 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 4.8-7.8 kWh/m² which is equivalent to 33.5-52.0 % total cooling load reduction.

Table 2. Sensible and total cooling load saving for a new low-rise apartment building for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	0.9	11.4	1.4	9.3	3.3	41.8	7.8	52.0
Terry Hill	1.0	11.6	1.5	10.8	2.2	25.6	4.8	34.5
Bankstown	1.0	10.0	1.3	7.9	3.2	32.0	7.3	44.5
Canterbury	0.9	10.8	1.3	8.7	3.0	36.1	6.8	45.6
Observatory	0.9	11.8	1.3	9.1	2.5	32.9	6.1	42.7
Richmond	1.5	10.8	1.8	9.3	3.2	23.0	6.5	33.5
Penrith	1.2	10.3	1.6	9.6	2.8	24.1	5.9	35.3
Horsley Park	1.2	10.9	1.5	9.3	3.6	32.7	6.5	40.4
Camden	1.2	10.1	1.5	9.2	3.0	25.2	5.9	36.2
Olympic Park	1.1	11.2	1.5	9.1	2.8	28.6	6.4	39.0
Campbelltown	1.2	11.2	1.5	9.6	2.9	27.1	6.0	38.2

In the eleven weather stations in Sydney, both building-scale and the combined building-scale and urban scale application of cool roofs can reduce the cooling load of a new low-rise apartment buiding with insulation during the summer season.

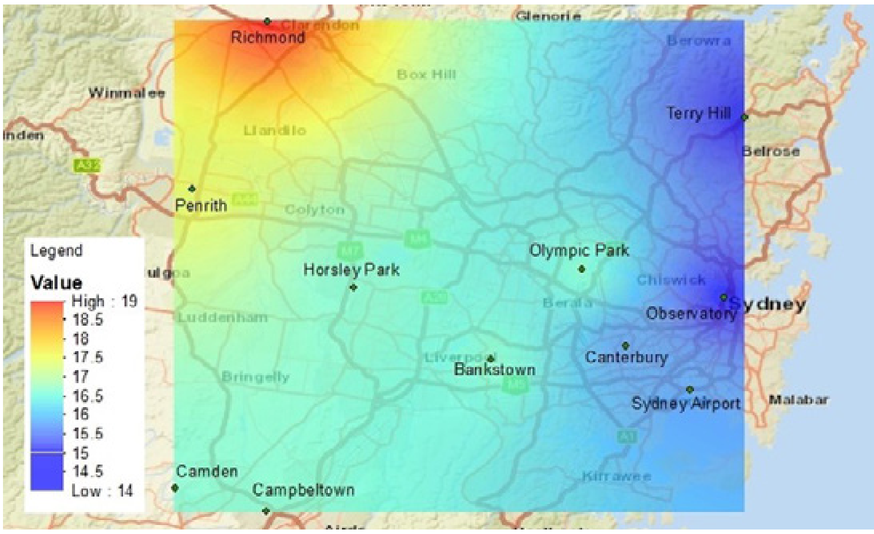


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new low-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

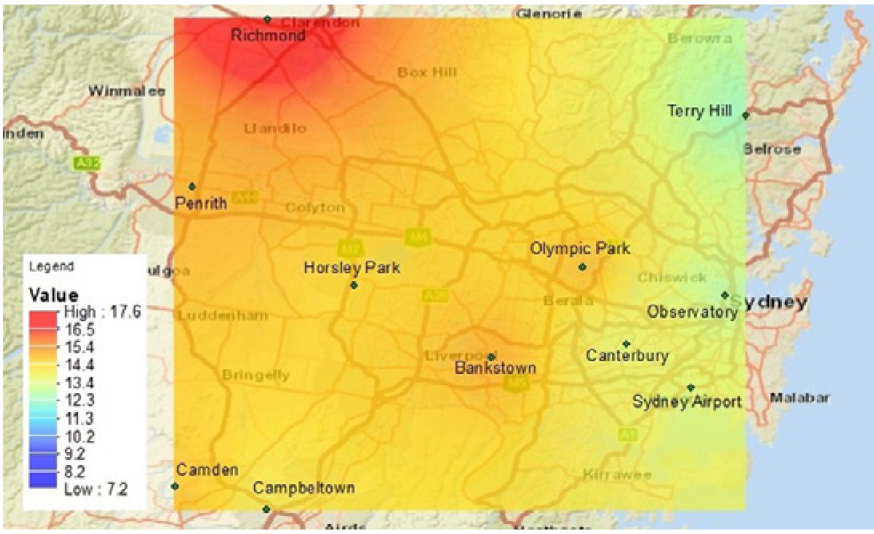


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new low-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

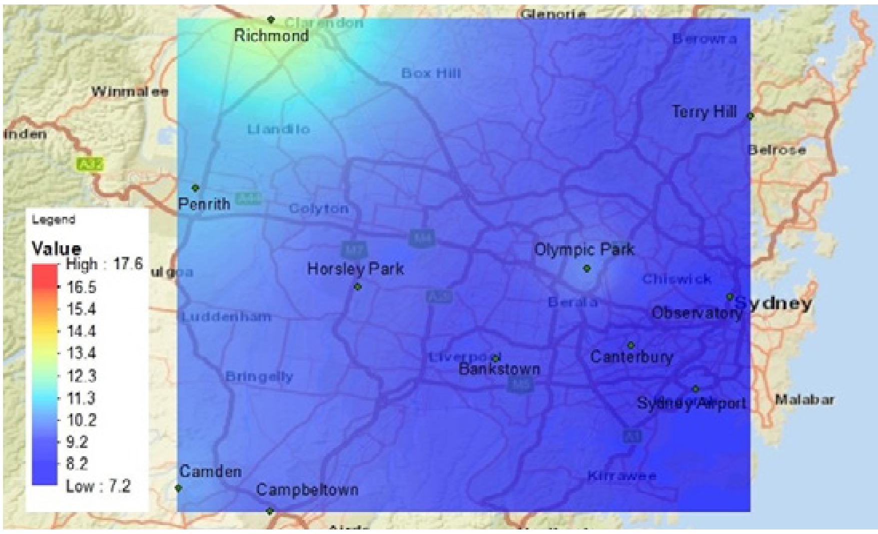


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new low-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

2

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-1.0 kWh/m²) is lower than the annual cooling load reduction (1.7-3.3 kWh/m²).

Table 3. Annual cooling and heating loads for a new low-rise apartment building for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	13.7	21.8	7.4	11.5	12.5	20.1	7.3	11.5
Terry Hill	9.8	16.2	11.8	18.4	8.5	14.2	11.8	18.5
Bankstown	15.9	24.2	11.3	17.9	14.3	22.0	11.8	18.6
Canterbury	12.9	20.1	11.0	17.6	11.5	18.2	11.5	18.3
Observatory	13.5	20.4	7.0	11.1	12.0	18.3	7.4	11.7
Richmond	18.4	27.7	14.1	22.2	16.3	25.0	14.7	23.0
Penrith	20.8	31.4	11.2	17.9	18.2	28.1	11.9	18.8
Horsley Park	16.0	22.6	12.6	19.8	13.9	19.9	13.3	20.7
Camden	14.7	20.3	16.1	25.3	12.8	17.9	16.9	26.3
Olympic Park	16.4	27.0	10.4	16.6	14.3	24.1	10.9	17.3
Campbelltown	13.6	18.2	16.2	25.4	11.7	15.9	17.0	26.4

The annual cooling load saving by building-scale application of cool roofs is around 7.8-12.6 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.2 and 2.4 kWh/m² (~3.0-5.5 %).

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	1.2	8.8	1.7	7.8	-0.1	0.0	1.3	6.2	1.7	5.1
Terry Hill	1.3	13.3	2.0	12.3	0.0	0.1	1.3	6.0	1.9	5.5
Bankstown	1.6	10.1	2.2	9.1	0.5	0.7	1.1	4.0	1.5	3.6
Canterbury	1.4	10.9	1.9	9.5	0.5	0.7	0.9	3.8	1.2	3.2
Observatory	1.5	11.1	2.1	10.3	0.4	0.6	1.1	5.4	1.5	4.8
Richmond	2.1	11.4	2.7	9.7	0.6	0.8	1.5	4.6	1.9	3.8
Penrith	2.6	12.5	3.3	10.5	0.7	0.9	1.9	5.9	2.4	4.9
Horsley Park	2.1	13.1	2.7	11.9	0.7	0.9	1.4	4.9	1.8	4.2
Camden	1.9	12.9	2.4	11.8	0.8	1.0	1.1	3.6	1.4	3.1
Olympic Park	2.1	12.8	2.9	10.7	0.5	0.7	1.6	6.0	2.2	5.0
Campbelltown	1.9	14.0	2.3	12.6	0.8	1.0	1.1	3.7	1.3	3.0

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

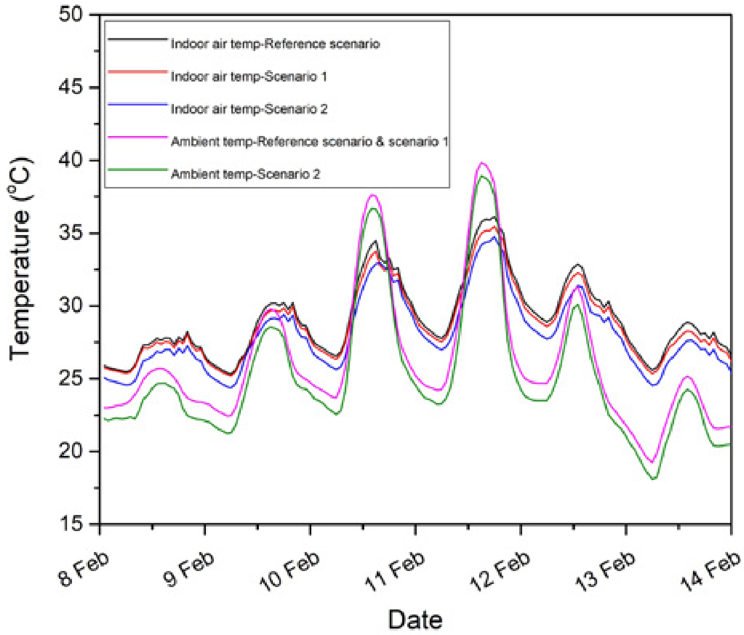


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

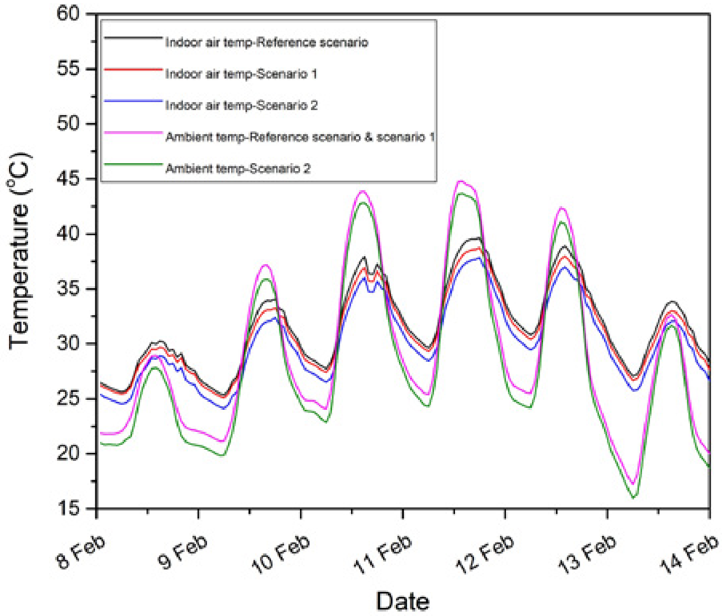


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 25.2-36.1 °C and 25.4-39.6 °C in Observatory and Richmond stations, respectively.

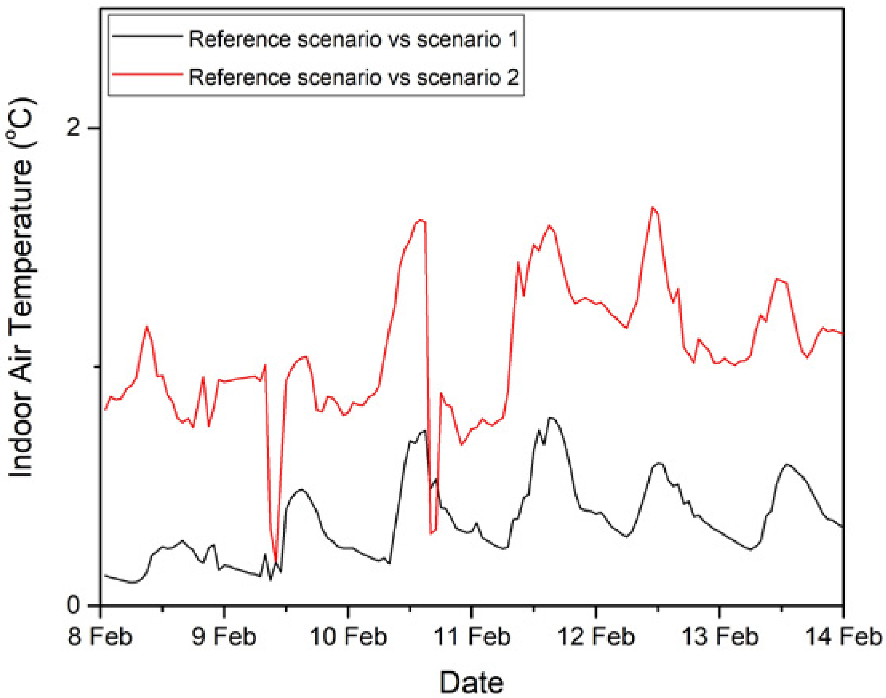


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.8 °C and 1.0 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.7 °C and 2.0 °C in Observatory and Richmond stations, respectively.

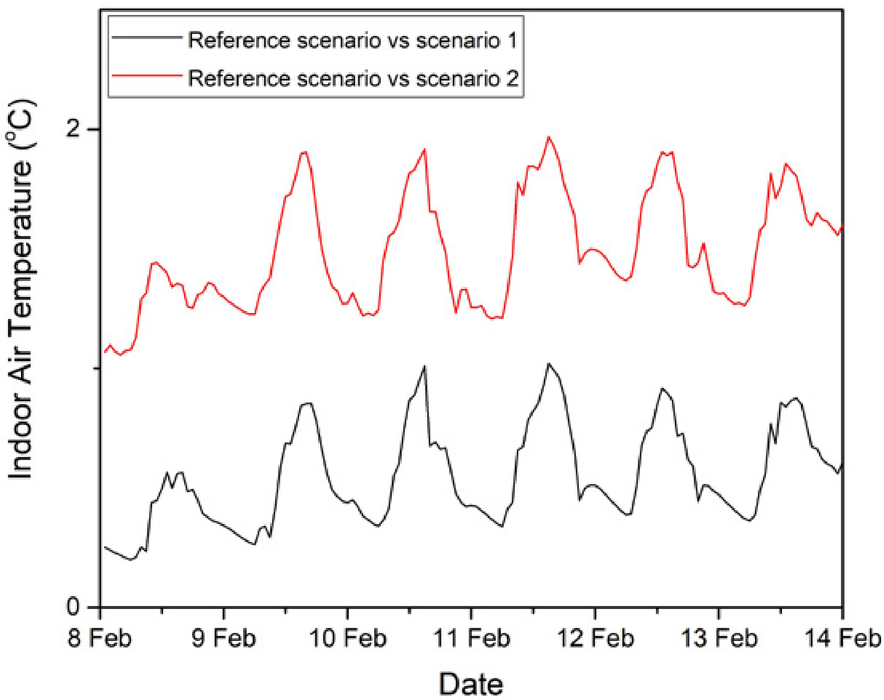


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new low-rise apartment building under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 14.0-22.5 °C in reference scenario to a range 14.0-22.3 °C in scenario 1 in Observatory Hill station.

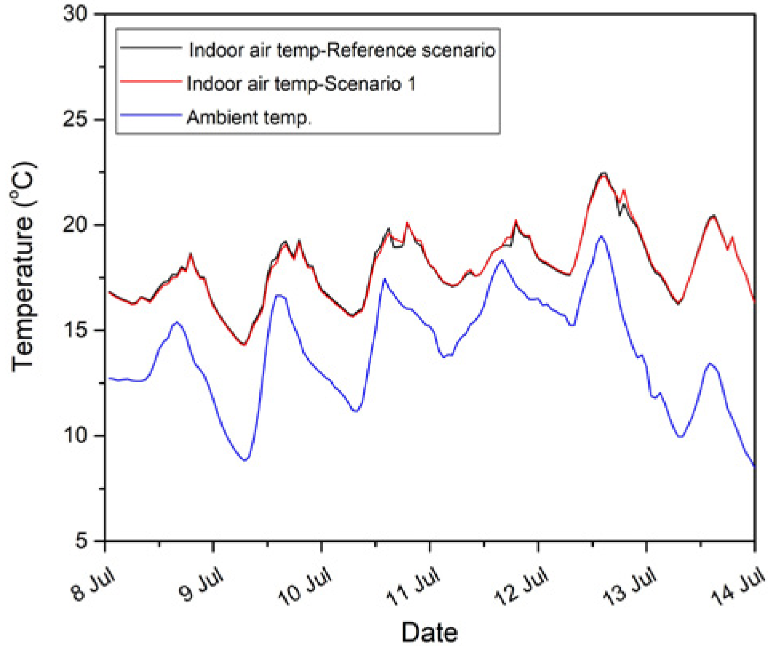


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 10.2-21.8 °C in reference scenario to a range 10.1-21.6 °C in scenario 1 in Richmond station.

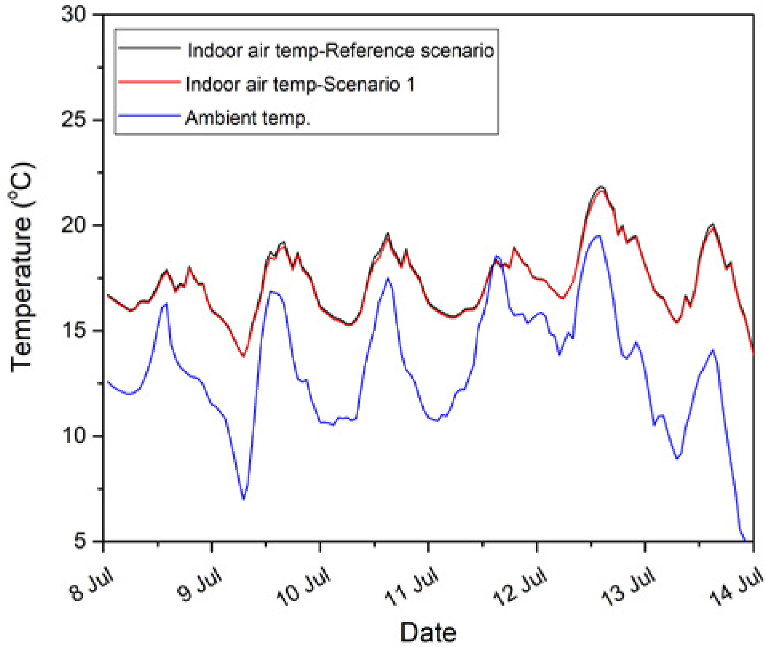


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C for both Observatory and Richmond stations.

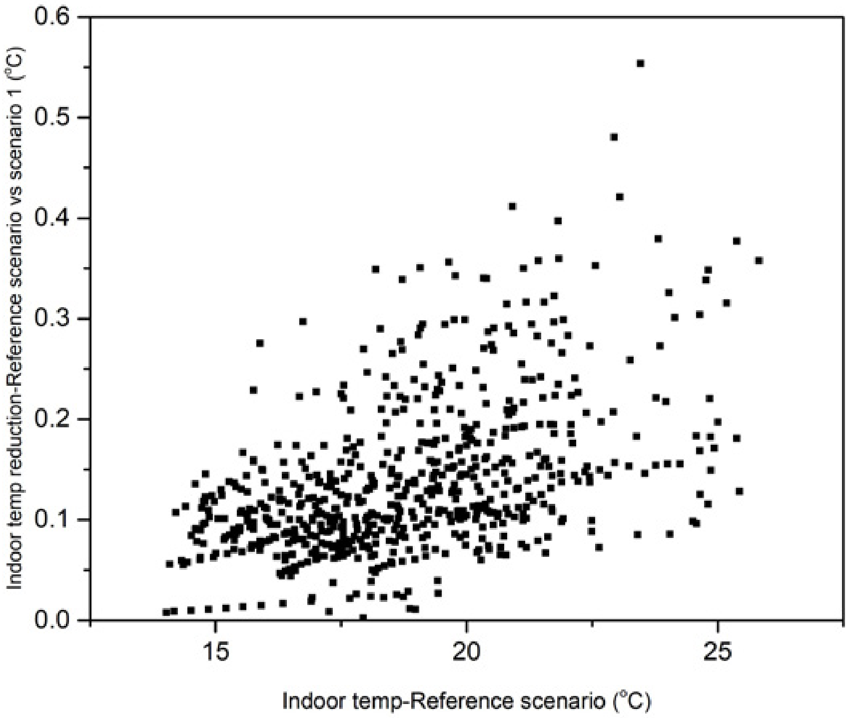


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

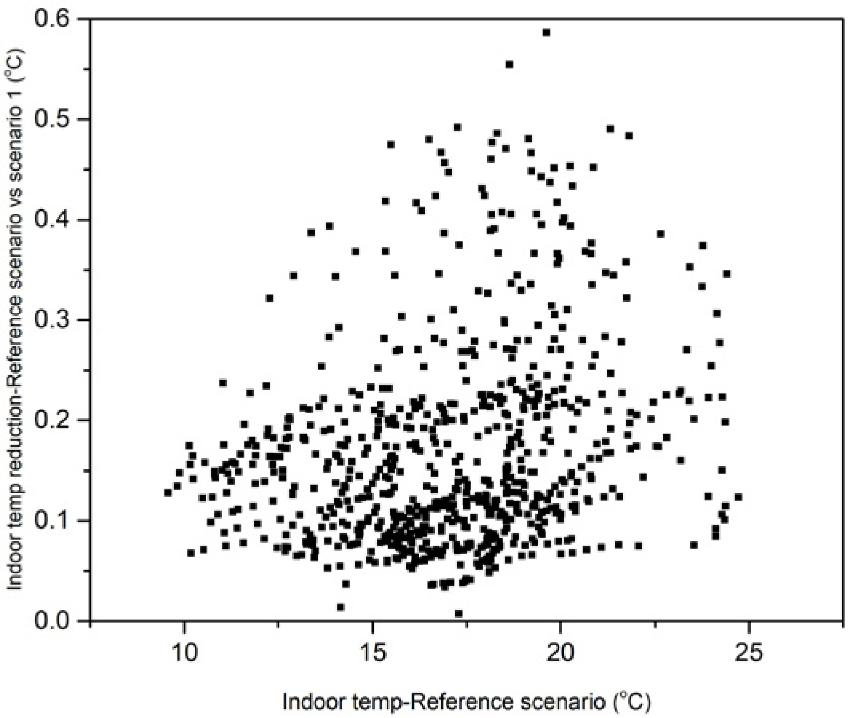


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new low-rise apartment building under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Observatory	428	438
Richmond	549	566

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 428 hours in reference scenario to 438 and hours and from 549 to 566 hours in scenario 1 in Observatory and Richmond stations, respectively.

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	440	411	341
Richmond	529	507	421

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decreased from 440 hours in reference scenario to 411 and 341 hours under scenario 1 and 2 in Observatory station; and from 529 hours in reference scenario to 507 and 421 hours under scenario 1 and 2 in Richmond station, respectively.

6

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of a new low-rise apartment building during the summer season.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new low-rise apartment from 13.9-19.4 kWh/m^2 to 12.4-16.6 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 1.3-1.8 kWh/m^2. This is equivalent to approximately 8.7-10.8 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 4.8-7.8 kWh/m^2. This is equivalent to 33.5-52.0 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.0-1.0 kWh/m^2) is lower than the annual cooling load reduction (1.7-3.3 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 7.8-12.6 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.2 and 2.4 kWh/m^2 (~3.0-5.5 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 25.2-36.1 ^{o}C and 25.4-39.6 ^{o}C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.8 and 1.0 ^{o}C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.7 and 2.0 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 ^{o}C in reference scenario to a range between 18.1 and 38.9 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 ^{o}C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 ^{o}C in reference scenario to 15.9-43.6 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 ^{o}C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 14. 0 and 22.5 ^{o}C in reference scenario to a range between 14.0 and 22.3 ^{o}C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 10.2 and 21.8 ^{o}C in reference scenario to a range between 10.1 and 21.6 ^{o}C in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 ^{o}C for both Observatory and Richmond stations. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase slightly from 428 hours in reference scenario to 438 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slightly increase in total number of hours below 19 ^{o}C from 549 hours in reference scenario to 566 hours in reference with cool roof scenario (scenario 1) (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 oC is 4 40 hours under the reference scenario in Observatory station, which decreases to 411 and 341 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 ^{o}C from 529 hours in reference scenario to 507 in reference with cool roof scenario (scenario 1) and 421 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B08

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

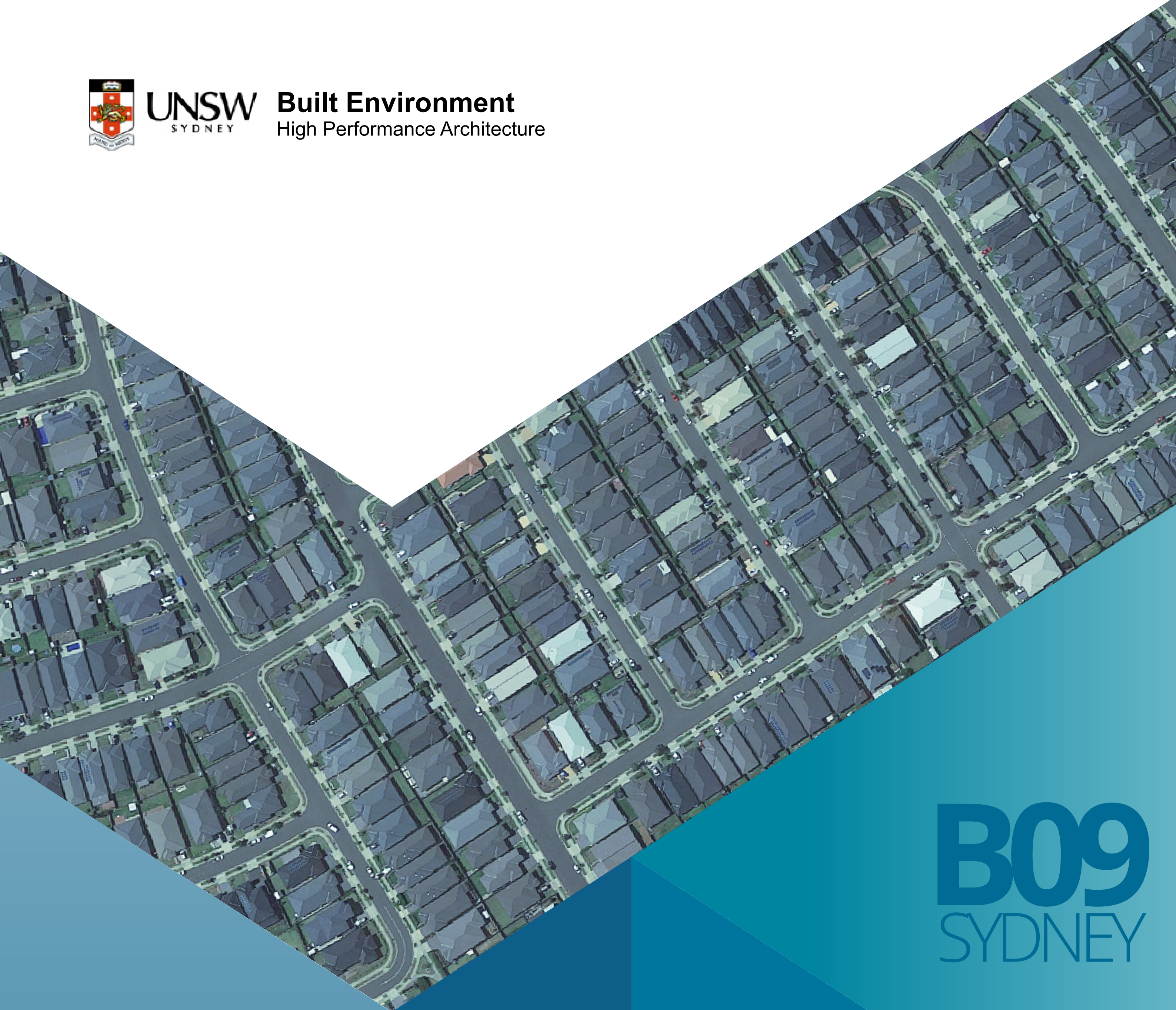
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY
Built Environment
High Performance Architecture



B09
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

New mid-rise apartment
2021

BUILDING 09

NEW MID-RISE APARTMENT

Floor area : 624m^2
Number of stories : 5

Image source: 282 Eldert Street, Bushwick.

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new mid-rise apartment building from 13.7-19.3 kWh/m² to 12.8-18.2 kWh/m².

Table 1. Sensible and total cooling load for a new mid-rise apartment building for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	7.8	14.8	7.2	14.1	4.8	7.5
Terry Hill	8.4	13.7	7.7	12.8	6.5	9.4
Bankstown	9.8	16.2	9.2	15.5	7.0	9.4
Canterbury	8.1	14.7	7.6	14.0	5.5	8.4
Observatory	7.5	14.2	6.9	13.4	5.2	8.5
Richmond	13.6	19.3	12.7	18.2	10.9	13.3
Penrith	11.4	16.4	10.6	15.5	9.0	11.1
Horsley Park	10.7	15.9	10.0	15.0	7.5	9.7
Camden	11.6	16.1	10.9	15.2	9.0	10.6
Olympic Park	9.5	16.2	8.9	15.3	7.2	10.3
Campbelltown	10.4	15.5	9.7	14.6	8.0	10.0

For Scenario 1, the total cooling load saving is around 0.7-1.1 kWh/m² which is equivalent to 4.3-5.8 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 4.3-7.3 kWh/m² which is equivalent to 33.1-49.3 % total cooling load reduction.

Table 2. Sensible and total cooling load saving for a new mid-rise apartment building for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	0.6	7.7	0.7	4.7	3.0	38.5	7.3	49.3
Terry Hill	0.7	8.3	0.9	6.6	1.9	22.6	4.3	31.4
Bankstown	0.6	6.1	0.7	4.3	2.8	28.6	6.8	42.0
Canterbury	0.5	6.2	0.7	4.8	2.6	32.1	6.3	42.9
Observatory	0.6	8.0	0.8	5.6	2.3	30.7	5.7	40.1
Richmond	0.9	6.6	1.1	5.7	2.7	19.9	6.0	31.1
Penrith	0.8	7.0	0.9	5.5	2.4	21.1	5.3	32.3
Horsley Park	0.7	6.5	0.9	5.7	3.2	29.9	6.2	39.0
Camden	0.7	6.0	0.9	5.6	2.6	22.4	5.5	34.2
Olympic Park	0.6	6.3	0.9	5.6	2.3	24.2	5.9	36.4
Campbelltown	0.7	6.7	0.9	5.8	2.4	23.1	5.5	35.5

In the eleven weather stations in Sydney, both building-scale and combined building-scale and urban-scale application of cool roof can significantly reduce the cooling load of a new mid-rise apartment during the summer season.

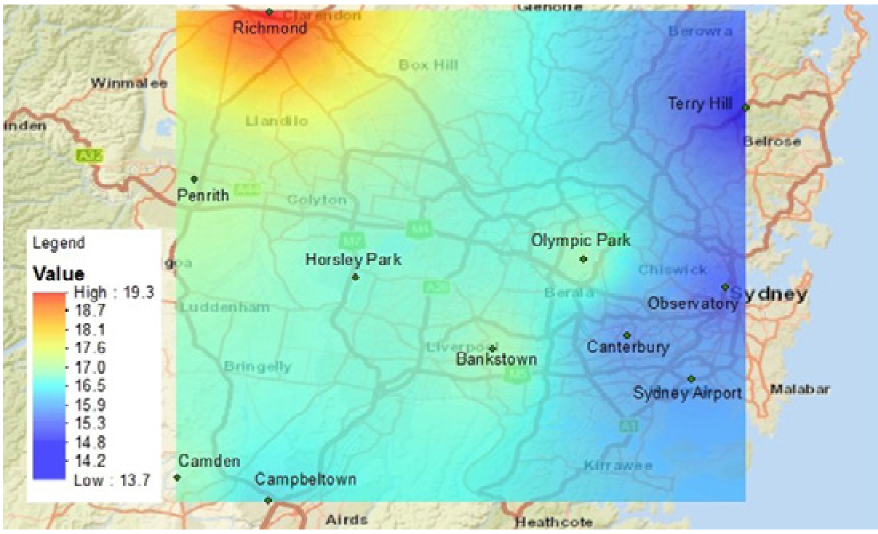


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

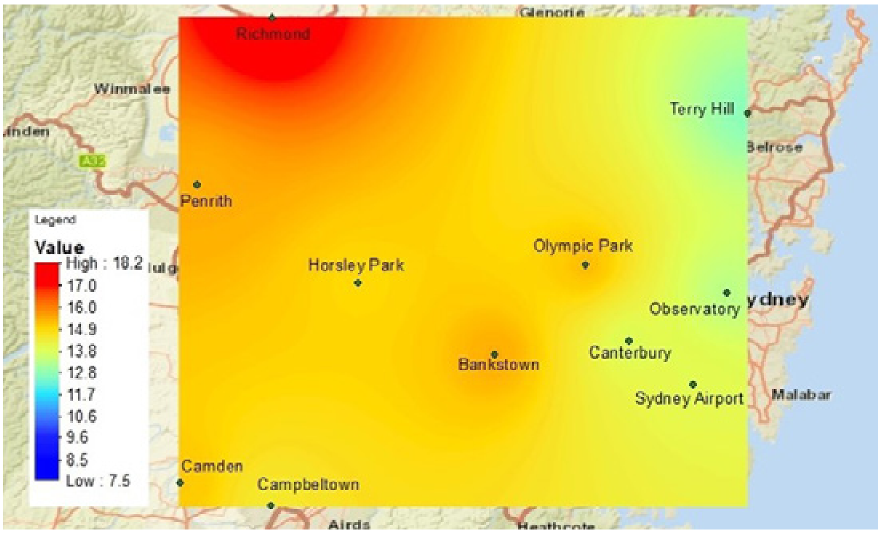


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

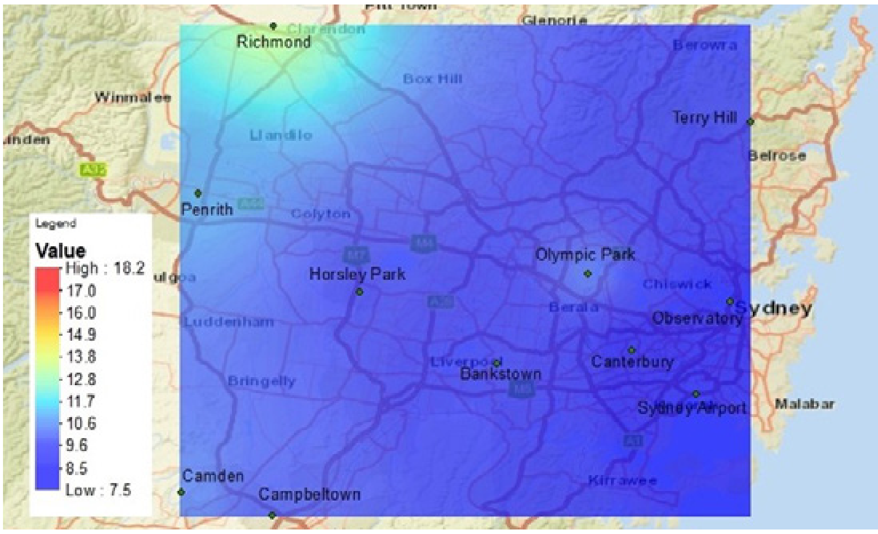


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new mid-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.2-0.6 kWh/m²) is significantly lower than the annual cooling load reduction (0.9-1.9 kWh/m²).

Table 3. Annual cooling and heating loads for a new mid-rise apartment building for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	13.4	21.5	6.8	10.8	12.7	20.6	6.7	10.6
Terry Hill	9.3	15.6	11.0	17.4	8.5	14.4	10.9	17.2
Bankstown	15.4	23.6	10.5	16.9	14.4	22.4	10.7	17.2
Canterbury	12.4	19.7	10.2	16.6	11.6	18.6	10.5	17.0
Observatory	13.1	20.0	6.4	10.3	12.2	18.8	6.6	10.6
Richmond	17.6	26.9	13.2	21.1	16.4	25.4	13.5	21.5
Penrith	19.9	30.5	10.3	16.8	18.4	28.6	10.7	17.3
Horsley Park	15.3	21.8	11.6	18.6	14.0	20.2	12.0	19.1
Camden	14.0	19.6	15.1	24.1	12.9	18.2	15.5	24.7
Olympic Park	15.7	26.3	9.5	15.5	14.5	24.6	9.8	15.9
Campbelltown	12.9	17.4	15.2	24.2	11.8	16.1	15.6	24.8

The annual cooling load saving by building-scale application of cool roofs is around 4.2-7.7 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.7 and 1.4 kWh/m² (~1.7-3.1 %).

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	0.7	5.2	0.9	4.2	0.1	0.2	0.6	3.0	0.7	2.2
Terry Hill	0.8	8.6	1.2	7.7	0.1	0.2	0.7	3.5	1.0	3.0
Bankstown	1.0	6.5	1.2	5.1	0.2	0.3	0.8	3.1	0.9	2.2
Canterbury	0.8	6.5	1.1	5.6	0.3	0.4	0.5	2.2	0.7	1.9
Observatory	0.9	6.9	1.2	6.0	0.2	0.3	0.7	3.6	0.9	3.0
Richmond	1.2	6.8	1.5	5.6	0.3	0.4	0.9	2.9	1.1	2.3
Penrith	1.5	7.5	1.9	6.2	0.4	0.5	1.1	3.6	1.4	3.0
Horsley Park	1.3	8.5	1.6	7.3	0.4	0.5	0.9	3.3	1.1	2.7
Camden	1.1	7.9	1.4	7.1	0.4	0.6	0.7	2.4	0.8	1.8
Olympic Park	1.2	7.6	1.7	6.5	0.3	0.4	0.9	3.6	1.3	3.1
Campbelltown	1.1	8.5	1.3	7.5	0.4	0.6	0.7	2.5	0.7	1.7

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

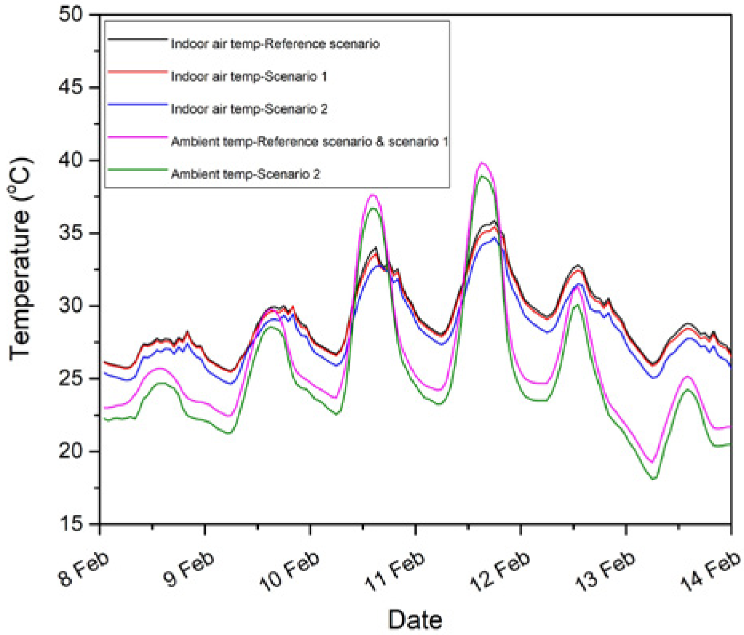


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

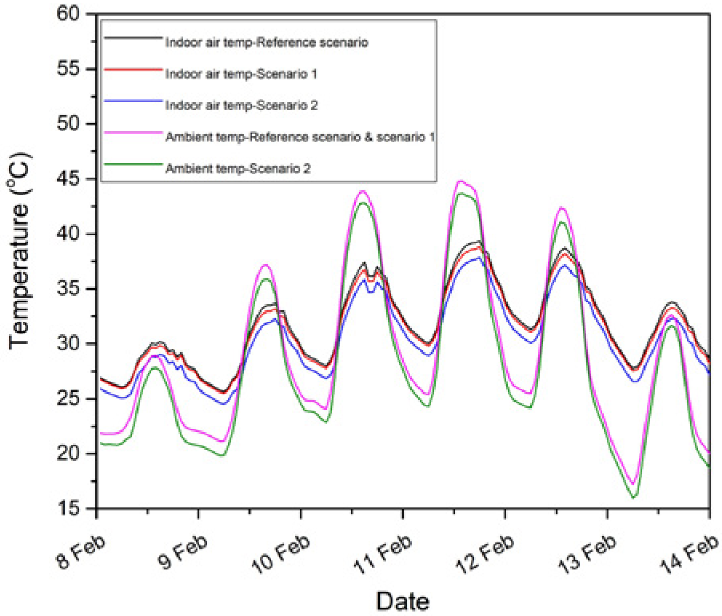


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 25.4-35.9 °C and 25.7-39.4 °C in Observatory and Richmond stations, respectively.

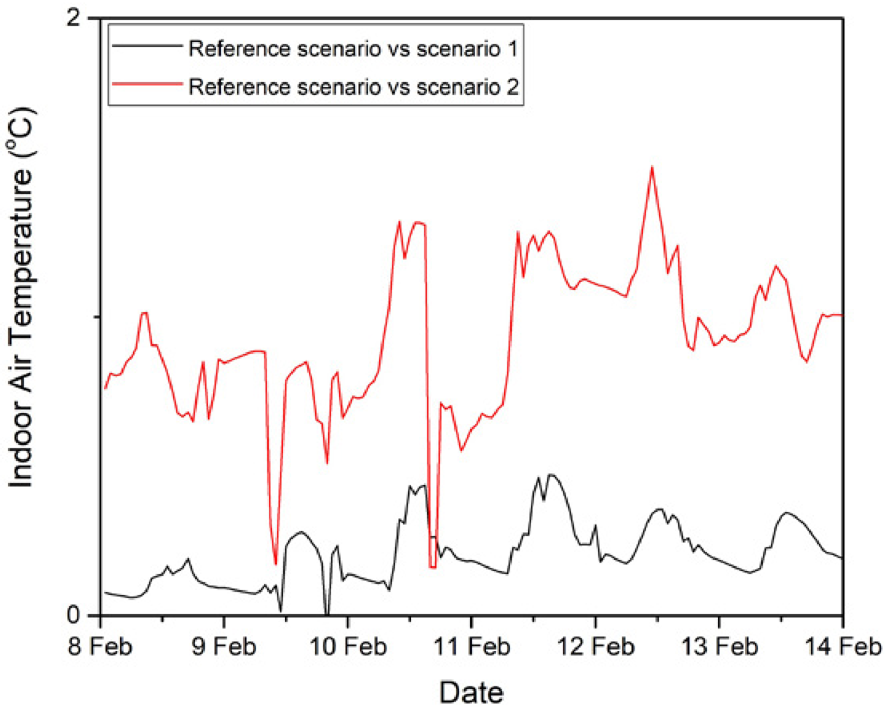


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.5 °C and 0.7 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.5 °C and 1.6 °C in Observatory and Richmond stations, respectively.

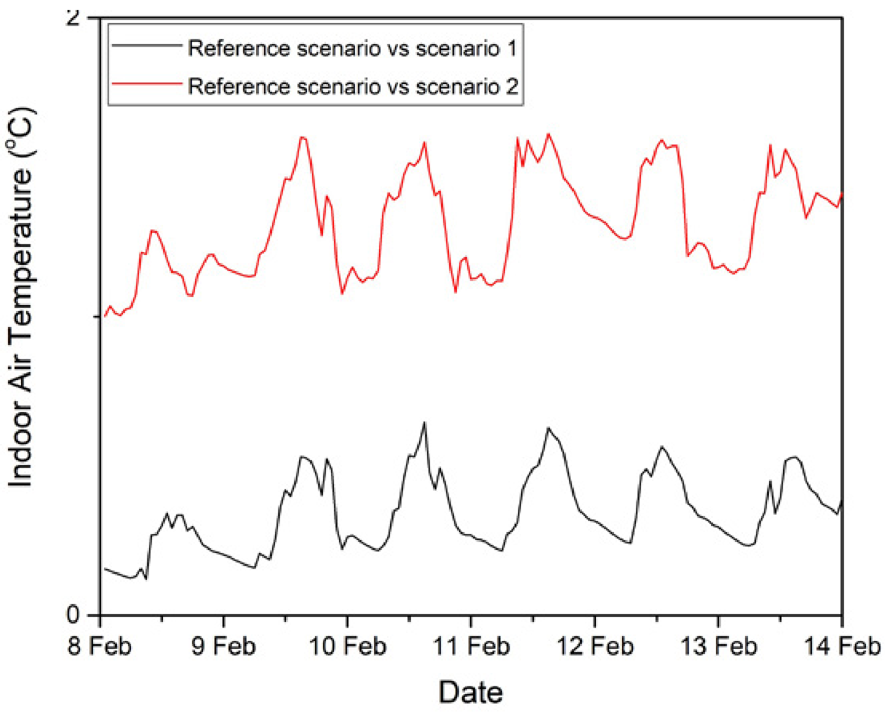


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new mid-rise apartment building under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 14.4-22.2 °C in reference scenario to a range 14.4-22.1 °C in scenario 1 in Observatory Hill station.

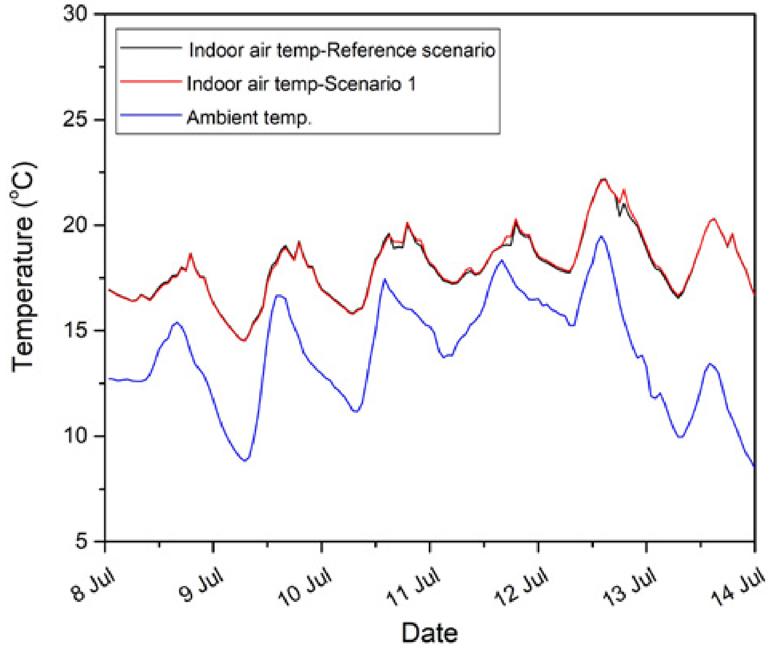


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 10.7-21.5 °C in reference scenario to a range 10.7-21.4 °C in scenario 1 in Richmond station.

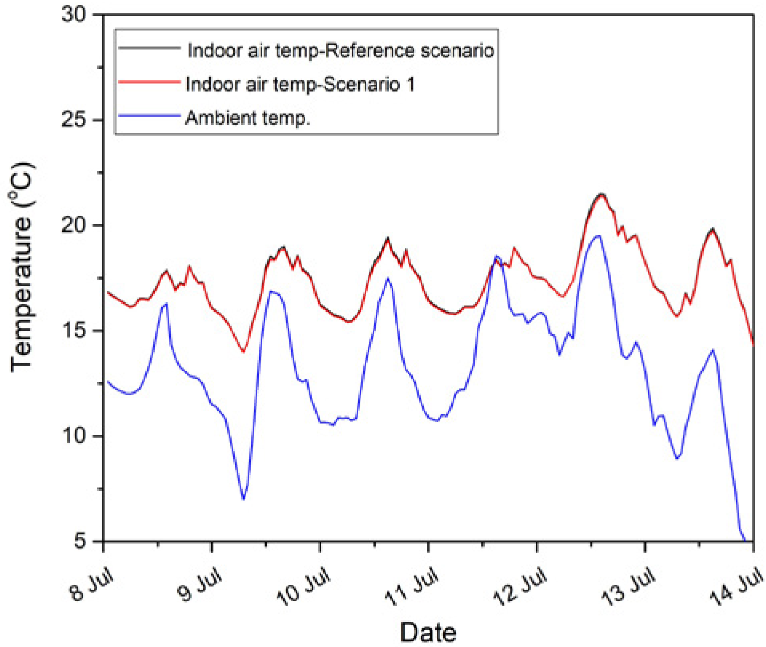


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C and 0.2 °C in Observatory and Richmond stations, respectively.

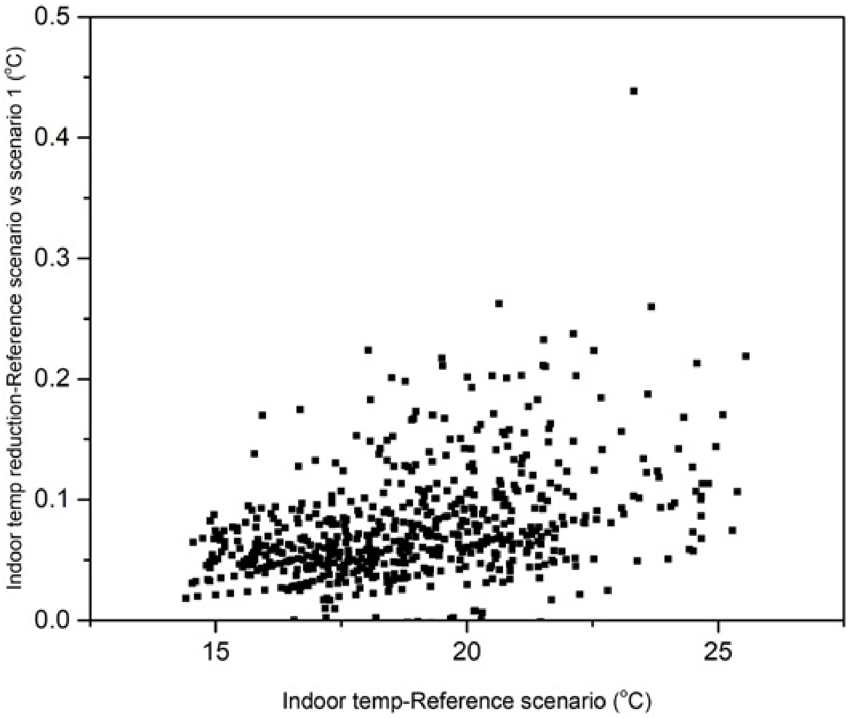


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

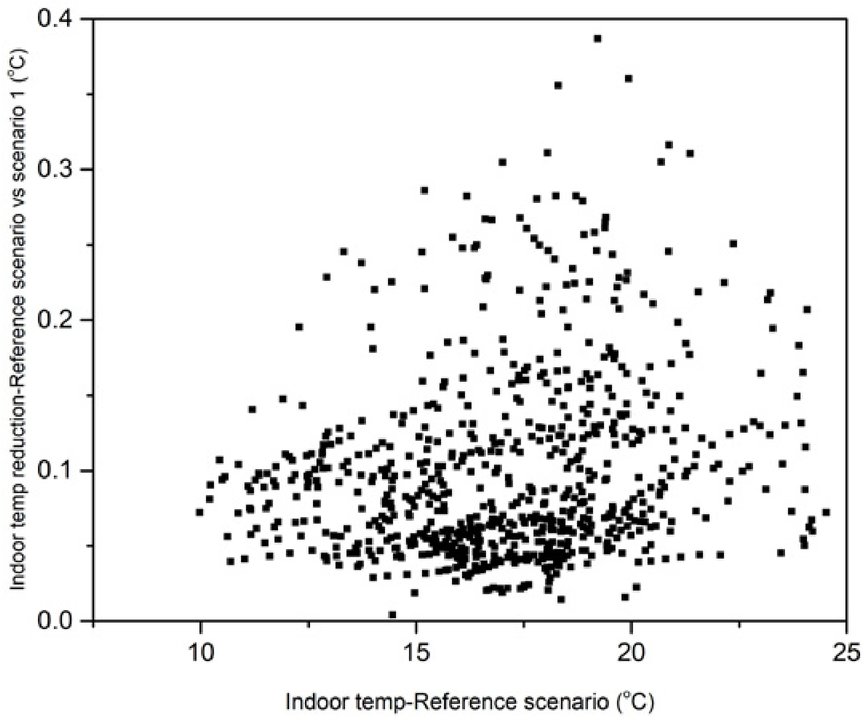


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new mid-rise apartment building under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to remain the same for the reference scenario and scenario 1 in Observatory station with 431; and to slightly increase from 558 hours to 572 hours in Richmond station.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Observatory	431	431
Richmond	558	572

Table 6. 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.

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decreased from 450 hours in reference scenario to 433 and 371 hours under scenario 1 and 2 in Observatory station; and from 556 hours in reference scenario to 540 and 444 hours under scenario 1 and 2 in Richmond station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	450	433	371
Richmond	556	540	444

6

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban-scale application of cool roof can significantly reduce the cooling load of a new mid-rise apartment building during the summer season .

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new mid-rise apartment from 13.7-19.3 kWh/m^2 to 12.8-18.2 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.7-1.1 kWh/m^2. This is equivalent to approximately 4.3-5.8 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 4.3-7.3 kWh/m^2 . This is equivalent to 33.1-49.3 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.2-0.6 kWh/m^2) is lower than the annual cooling load reduction (0.9-1.9 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 4.2-7.7 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.7 and 1.4 kWh/m^2 (~1.7-3.1 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 25.4-3 5.9 ^{o}C and 25.7-39.4 ^{o}C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.5 and 0.7 ^{o}C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.5 and 1.6 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 ^{o}C in reference scenario to a range between 18.1 and 38.9 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 ^{o}C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 ^{o}C in reference scenario to 15.9-43.6 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 ^{o}C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to slightly decrease from a range between 14. 4 and 22.2 ^{o}C in reference scenario to a range between 14.4 and 22.1 ^{o}C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 10. 7 and 21.5 °C in reference scenario to a range between 10.7 and 21.4 oC in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 and 0.2 °C for Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted remain the same for both the reference scenario and reference with cool roof scenario (scenario 1) with 431 in Observatory station. The estimations for Richmond stations also show a slightly increase in total number of hours below 19 °C from 558 hours in reference scenario to 572 hours in reference with cool roof scenario (scenario 1) (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 450 hours under the reference scenario in Observatory station, which decreases to 433 and 371 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 oC from 556 hours in reference scenario to 540 in reference with cool roof scenario (scenario 1) and 444 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B09

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

Sydney, NSW 2052
Australia

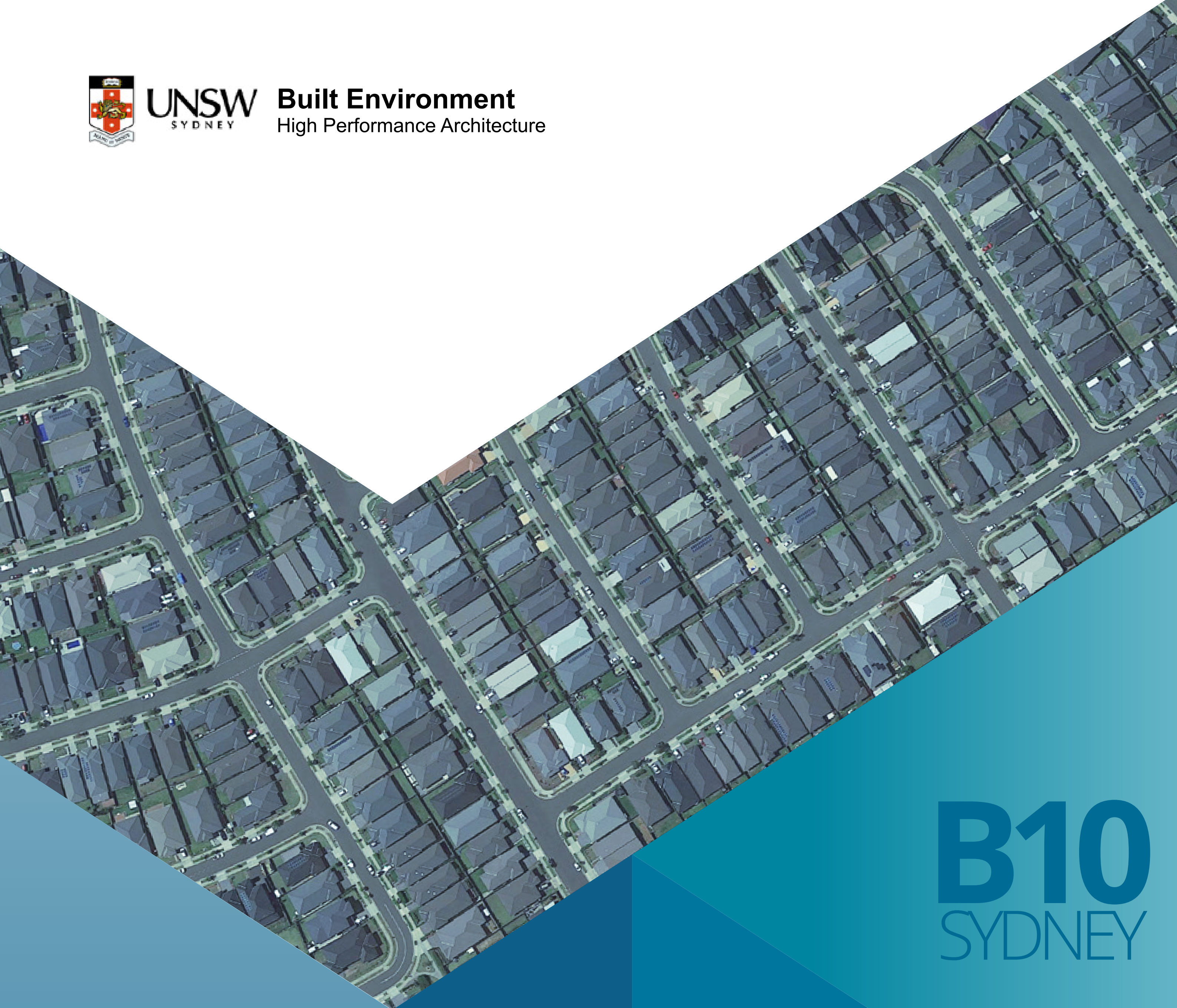
Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY

Built Environment
High Performance Architecture



B10 SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

New high-rise apartment
2021

BUILDING 10

NEW HIGH-RISE APARTMENT

Floor area : 624m^2
Number of stories : 8

Image source: Sunshine Gardens, City of Fredericton.

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a new high-rise apartment building for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment building from 13.5-19.1 kWh/m² to 12.9-18.4 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	7.6	14.7	7.3	14.2	4.8	7.6
Terry Hill	8.2	13.5	7.8	12.9	6.6	9.5
Bankstown	9.6	16.1	9.3	15.6	7.0	9.5
Canterbury	8.0	14.6	7.7	14.1	5.5	8.5
Observatory	7.3	14.0	7.0	13.5	5.2	8.6
Richmond	13.4	19.1	12.9	18.4	11.0	13.5
Penrith	11.2	16.3	10.7	15.7	9.1	11.2
Horsley Park	10.5	15.7	10.1	15.2	7.5	9.7
Camden	11.4	15.9	10.9	15.4	9.1	10.7
Olympic Park	9.4	16.0	9.0	15.5	7.2	10.5
Campbelltown	10.2	15.3	9.8	14.8	8.1	10.1

Table 2. Sensible and total cooling load saving for a new high-rise apartment building for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 0.5-0.7 kWh/m² which is equivalent to 3.1-4.4 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 5.1-7.1 kWh/m² which is equivalent to 31.3-48.3 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	0.3	3.9	0.5	3.4	2.8	36.8	7.1	48.3
Terry Hill	0.4	4.9	0.6	4.4	1.6	19.5	4.0	29.6
Bankstown	0.3	3.1	0.5	3.1	2.6	27.1	6.6	41.0
Canterbury	0.3	3.8	0.5	3.4	2.5	31.3	6.1	41.8
Observatory	0.3	4.1	0.5	3.6	2.1	28.8	5.4	38.6
Richmond	0.5	3.7	0.7	3.7	2.4	17.9	5.6	29.3
Penrith	0.5	4.5	0.6	3.7	2.1	18.8	5.1	31.3
Horsley Park	0.4	3.8	0.5	3.2	3.0	28.6	6.0	38.2
Camden	0.5	4.4	0.5	3.1	2.3	20.2	5.2	32.7
Olympic Park	0.4	4.3	0.5	3.1	2.2	23.4	5.5	34.4
Campbelltown	0.4	3.9	0.5	3.3	2.1	20.6	5.2	34.0

In the eleven weather stations in Sydney, both building-scale and the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the new high-rise apartment building during the summer season.

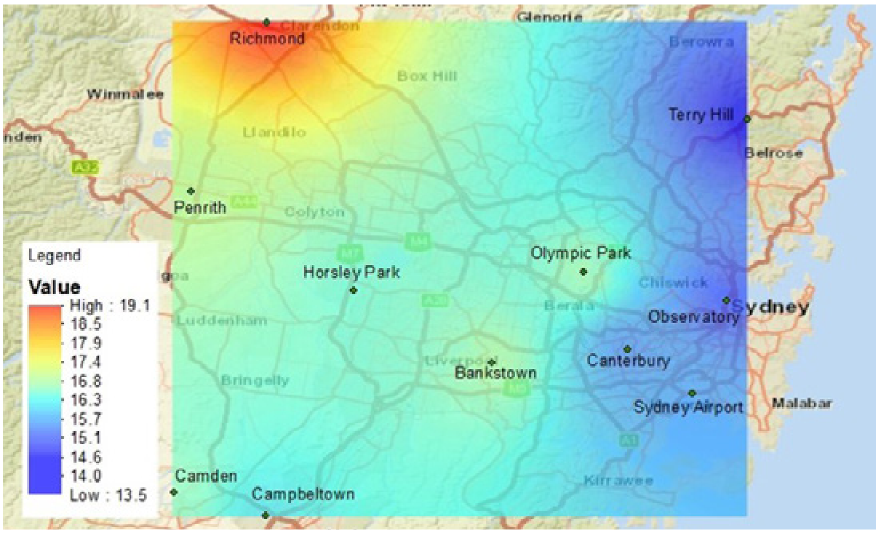


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

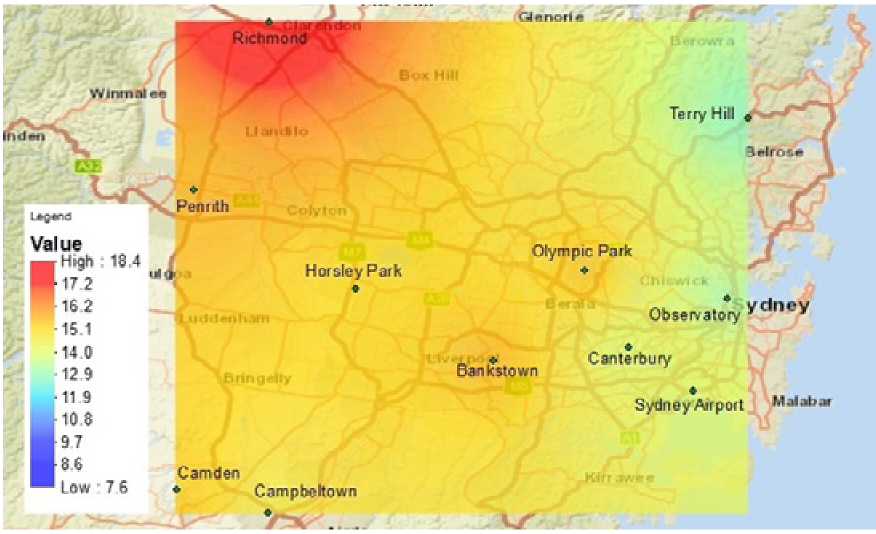


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

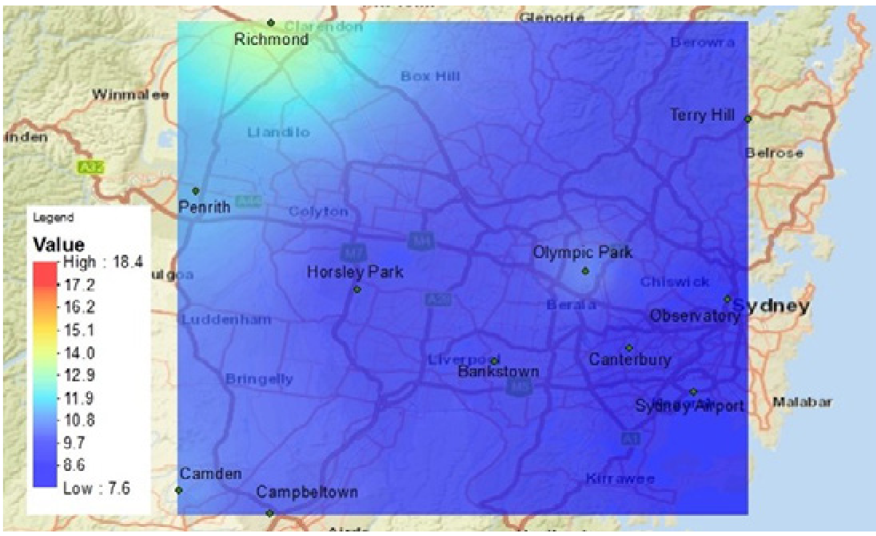


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new high-rise apartment building with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for a new high-rise apartment building for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.2-0.5 kWh/m²) is significantly lower than the annual cooling load reduction (0.5-1.4 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	13.1	21.2	6.3	10.1	12.7	20.7	6.4	10.3
Terry Hill	8.9	15.1	10.3	16.4	8.5	14.4	10.5	16.7
Bankstown	15.0	23.2	10.1	16.4	14.4	22.5	10.3	16.7
Canterbury	12.6	20.0	9.8	16.2	11.6	18.6	10.0	16.4
Observatory	12.8	19.6	6.1	10.0	12.3	18.9	6.2	10.2
Richmond	17.1	26.4	12.8	20.6	16.4	25.5	13.0	20.9
Penrith	19.3	29.9	9.7	16.0	18.4	28.7	9.9	16.3
Horsley Park	14.8	21.2	10.9	17.6	14.0	20.3	11.2	18.0
Camden	13.6	19.1	14.7	23.6	12.9	18.2	14.9	24.0
Olympic Park	15.3	25.7	8.9	14.7	14.5	24.7	9.2	15.0
Campbelltown	12.4	16.9	14.3	23.1	11.7	16.1	14.7	23.6

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 2.4-7.0 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.3 and 1.2 kWh/m² (~0.7-3.3 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	0.4	3.1	0.5	2.4	0.1	0.2	0.3	1.5	0.3	1.0
Terry Hill	0.4	4.5	0.7	4.6	0.2	0.3	0.2	1.0	0.4	1.3
Bankstown	0.6	4.0	0.7	3.0	0.2	0.3	0.4	1.6	0.4	1.0
Canterbury	1.0	7.9	1.4	7.0	0.2	0.2	0.8	3.6	1.2	3.3
Observatory	0.5	3.9	0.7	3.6	0.1	0.2	0.4	2.1	0.5	1.7
Richmond	0.7	4.1	0.9	3.4	0.2	0.3	0.5	1.7	0.6	1.3
Penrith	0.9	4.7	1.2	4.0	0.2	0.3	0.7	2.4	0.9	2.0
Horsley Park	0.8	5.4	0.9	4.2	0.3	0.4	0.5	1.9	0.5	1.3
Camden	0.7	5.1	0.9	4.7	0.2	0.4	0.5	1.8	0.5	1.2
Olympic Park	0.8	5.2	1.0	3.9	0.3	0.3	0.5	2.1	0.7	1.7
Campbelltown	0.7	5.6	0.8	4.7	0.4	0.5	0.3	1.1	0.3	0.7

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

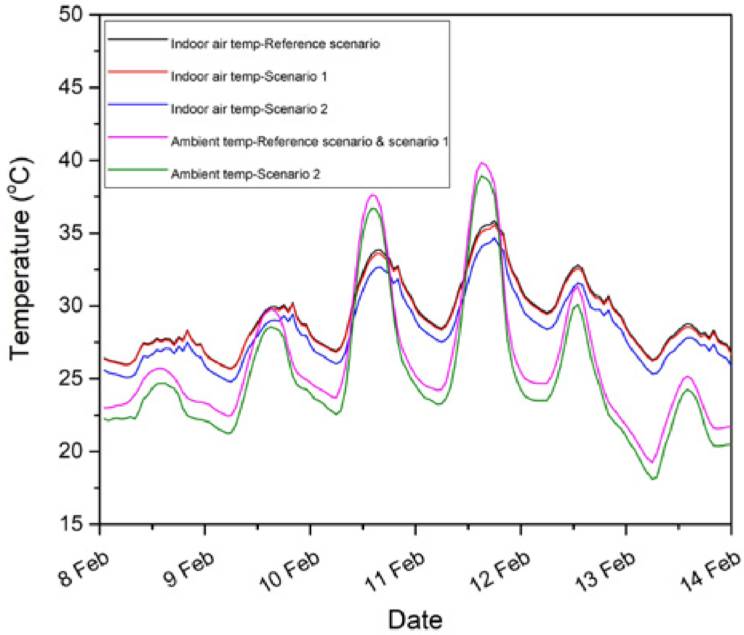


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

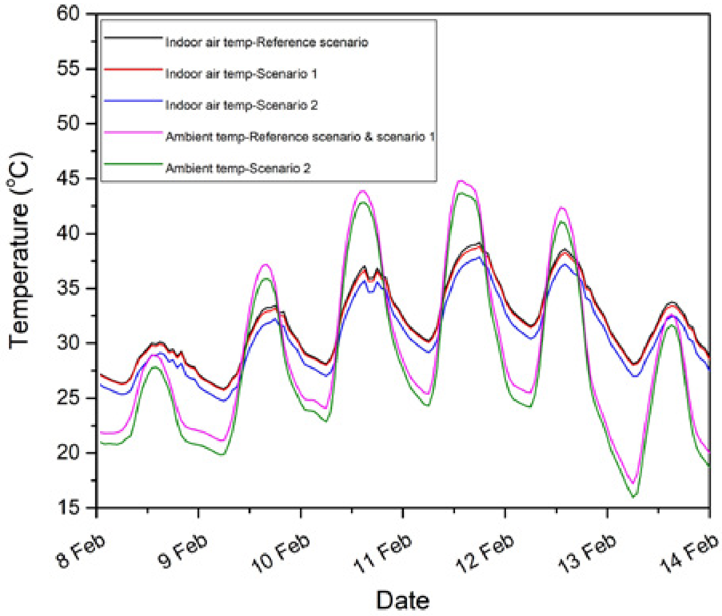


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 25.6-3 5.9 °C and 25.8- 39.2 °C in Observatory and Richmond stations, respectively.

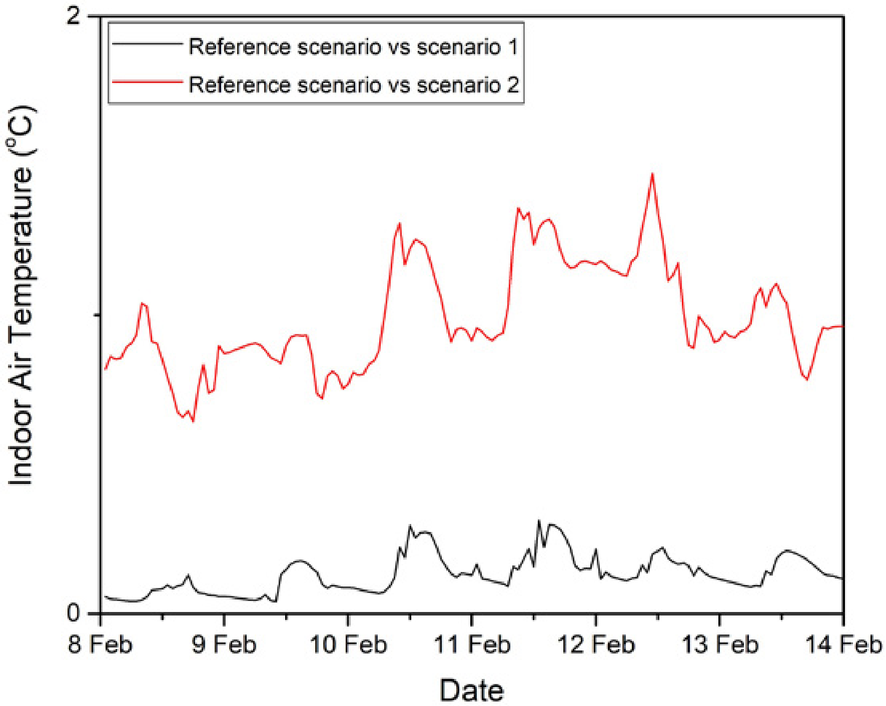


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.3 °C and 0.4 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.5 °C and 1.5 °C in Observatory and Richmond stations, respectively.

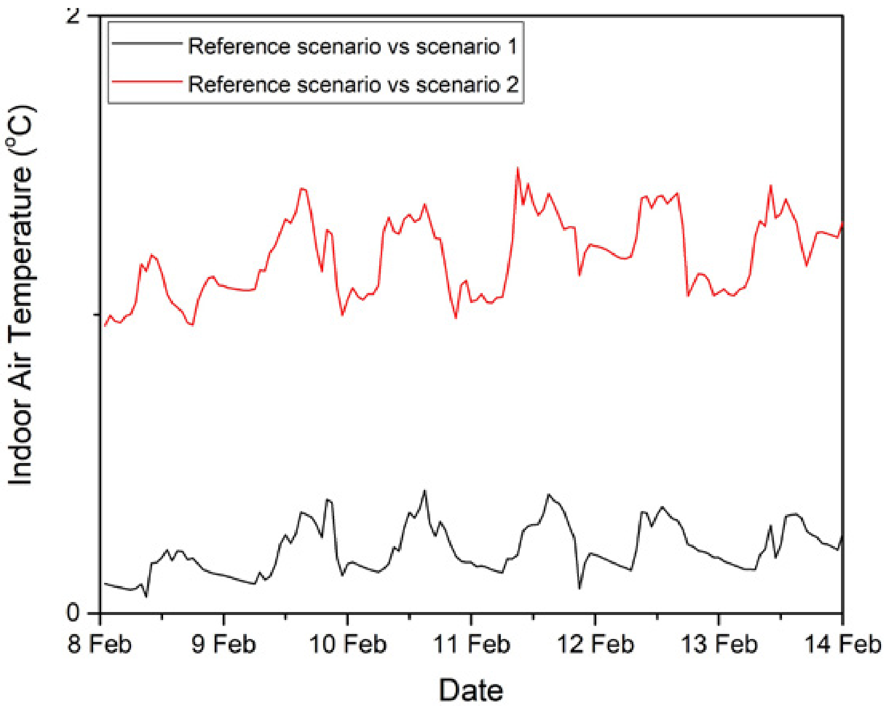


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new high-rise apartment building under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 14.6-22.1 °C in reference scenario to a range 14.6-22.0 °C in scenario 1 in Observatory Hill station.

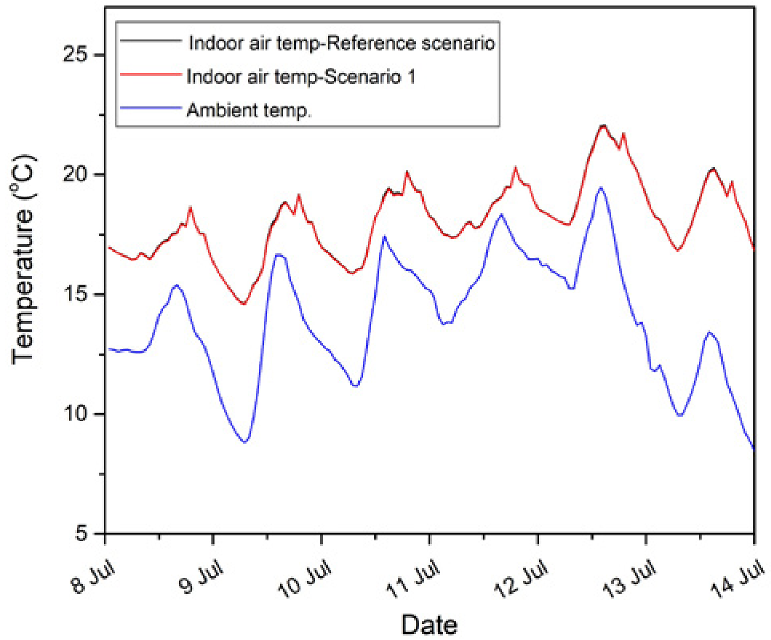


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 10.9-21.3 °C in reference scenario to a range 10.9-21.2 °C in scenario 1 in Richmond station.

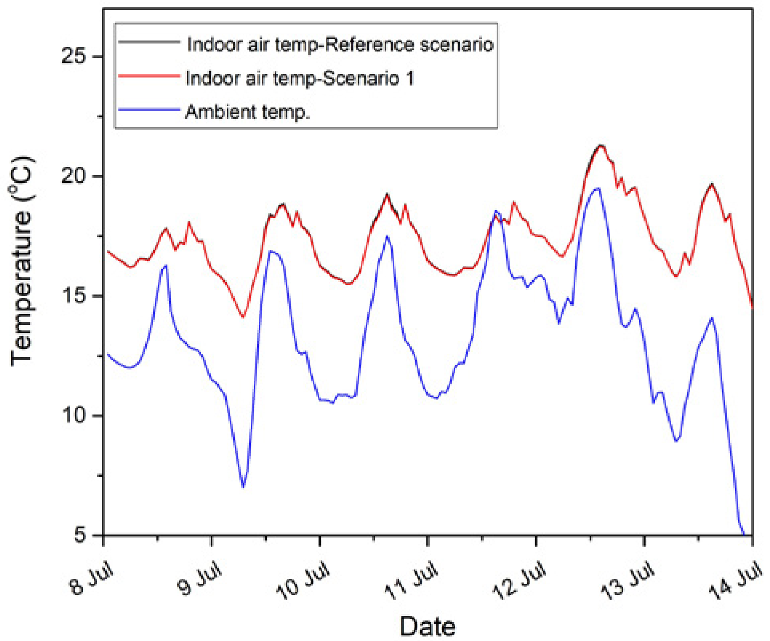


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 °C and 0.1 °C in Observatory and Richmond stations, respectively.

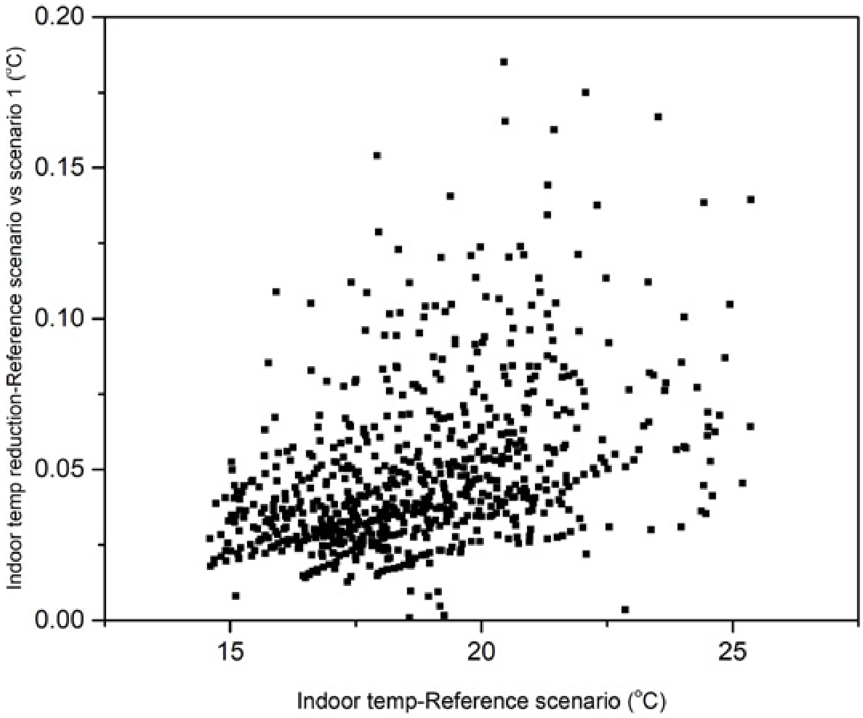


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

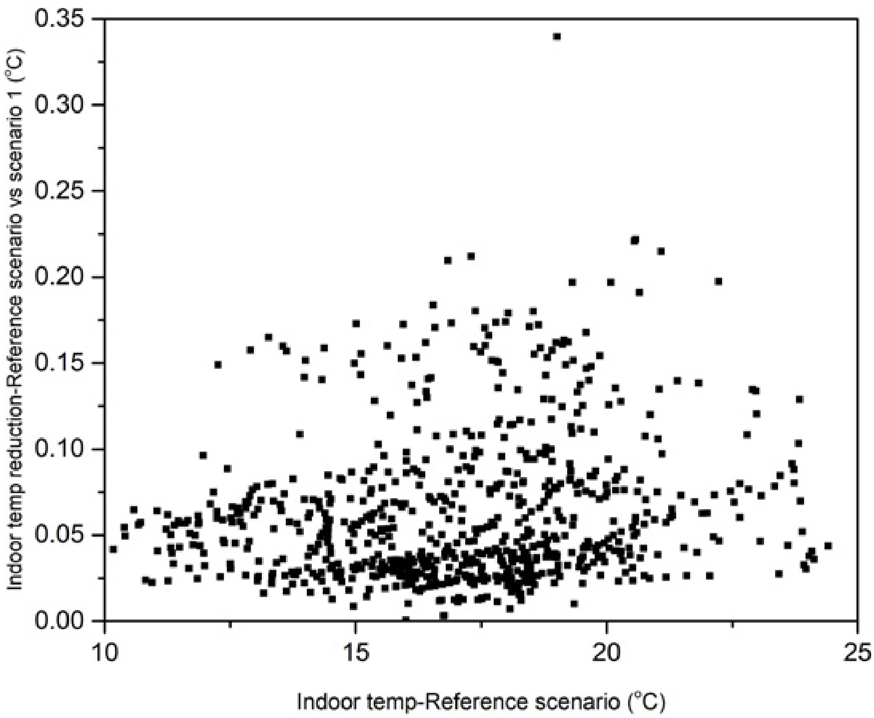


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise apartment building under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 429 hours in reference scenario to 436 hours, and from 566 to 576 hours in scenario 1 in Observatory and Richmond stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Observatory	429	436
Richmond	566	576

Table 6. 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.

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decreased from 480 hours in reference scenario to 464 and 377 hours under scenario 1 and 2 in Observatory station; and from 568 hours in reference scenario to 556 and 464 hours under scenario 1 and 2 in Richmond station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	480	464	377
Richmond	568	556	464

6

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban-scale application of cool roof can significantly reduce the cooling load of a new high-rise apartment building during the summer season . Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 13.5-19.1 kWh/m^2 to 12.9-18.4 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 0.5-0.7 kWh/m^2. This is equivalent to approximately 3.1-4.4 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 5.2-7.1 kWh/m^2. This is equivalent to 31.3-48.3 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.2-0.5 kWh/m^2) is lower than the annual cooling load reduction (0.5-1.4 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 2.4-7.0 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 0.3 and 1.2 kWh/m^2 (~0.7-3.3 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 25.6-3 5.9 ^{o}C and 25.8-39.2 ^{o}C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.3 and 0.4 ^{o}C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.5 and 1.5 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 ^{o}C in reference scenario to a range between 18.1 and 38.9 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 ^{o}C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 ^{o}C in reference scenario to 15.9-43.6 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 ^{o}C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to slightly decrease from a range between 14. 6 and 22.1 ^{o}C in reference scenario to a range between 14.6 and 22.0 ^{o}C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8). Similarly, the indoor air temperature is predicted to slightly reduce from a range between 10. 9 and 21.3 °C in reference scenario to a range between 10.9 and 21.2 °C in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.1 and 0.1 °C for Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 429 hours in reference scenario to 436 hours in reference with cool roof scenario (scenario 1) in Observatory station.. The estimations for Richmond stations also show a slightly increase in total number of hours below 19 °C from 566 hours in reference scenario to 576 hours in reference with cool roof scenario (scenario 1) (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 480 hours under the reference scenario in Observatory station, which significantly decreases to 464 and 377 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 °C from 568 hours in reference scenario to 556 in reference with cool roof scenario (scenario 1) and 464 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B10

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

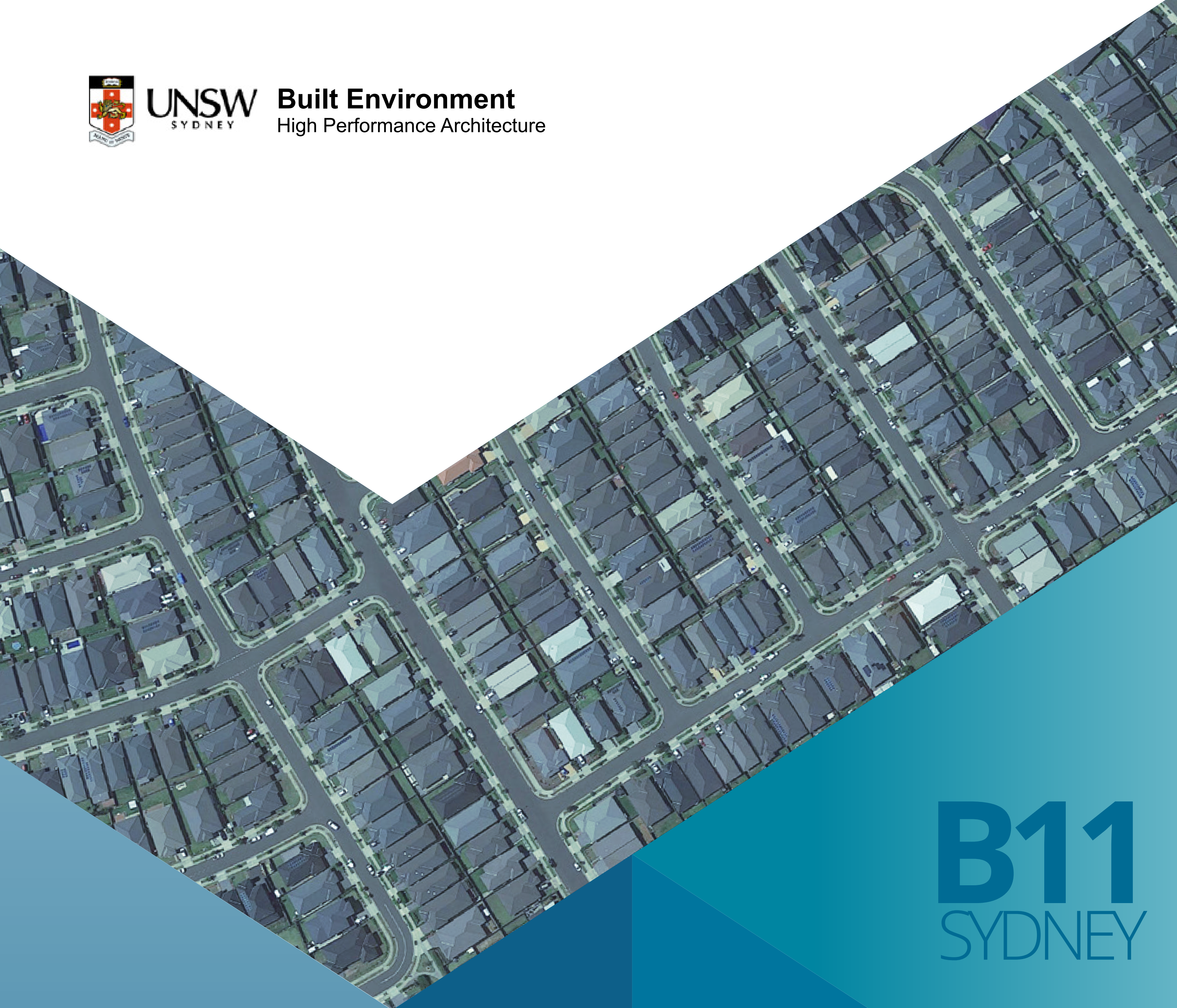
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY
Built Environment
High Performance Architecture



B11
SYDNEY

COOL ROOFS COST BENEFIT **ANALYSIS STUDY**

Existing standalone house
2021

BUILDING 11

EXISTING STANDALONE HOUSE

Floor area : 242m^2
Number of stories : 1

Image source: https://www.newhomesguide.com.au/builders/long-island-homes/homes/new-homes/moonbi-240

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

Table 1. Sensible and total cooling load for an existing stand-alone house for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of an existing standalone house from 15.3-19.3 kWh/m² to 8.2-11.7 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	9.4	15.3	4.5	8.6	3.1	4.6
Terry Hill	10.7	15.3	5.2	8.3	4.5	6.1
Bankstown	11.5	16.6	6.2	10.1	4.9	6.2
Canterbury	9.8	15.4	4.9	8.8	3.7	5.4
Observatory	9.2	14.9	4.4	8.2	3.4	5.3
Richmond	15.1	19.3	8.6	11.7	7.6	8.9
Penrith	13.1	17.0	7.4	10.4	6.5	7.7
Horsley Park	12.6	16.7	7.0	10.0	6.0	7.5
Camden	13.3	16.8	7.7	10.3	6.6	7.5
Olympic Park	11.1	16.5	6.0	9.9	4.9	6.8
Campbelltown	12.2	16.3	6.7	9.7	5.7	6.8

Table 2. Sensible and total cooling load saving for an existing stand-alone house for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 6.5-7.6 kWh/m² which is equivalent to 38.7-45.8 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 9.2-10.7 kWh/m² which is equivalent to 53.9-69.9 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	4.9	52.1	6.7	43.8	6.3	67.0	10.7	69.9
Terry Hill	5.5	51.4	7.0	45.8	6.2	57.9	9.2	60.1
Bankstown	5.3	46.1	6.5	39.2	6.6	57.4	10.4	62.7
Canterbury	4.9	50.0	6.6	42.9	6.1	62.2	10.0	64.9
Observatory	4.8	52.2	6.7	45.0	5.8	63.0	9.6	64.4
Richmond	6.5	43.0	7.6	39.4	7.5	49.7	10.4	53.9
Penrith	5.7	43.5	6.6	38.8	6.6	50.4	9.3	54.7
Horsley Park	5.6	44.4	6.7	40.1	6.6	52.4	9.2	55.1
Camden	5.6	42.1	6.5	38.7	6.7	50.4	9.3	55.4
Olympic Park	5.1	45.9	6.6	40.0	6.2	55.9	9.7	58.8
Campbelltown	5.5	45.1	6.6	40.5	6.5	53.3	9.5	58.3

In the eleven weather stations in Sydney, both building-scale and the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the existing standalone house during the summer season.

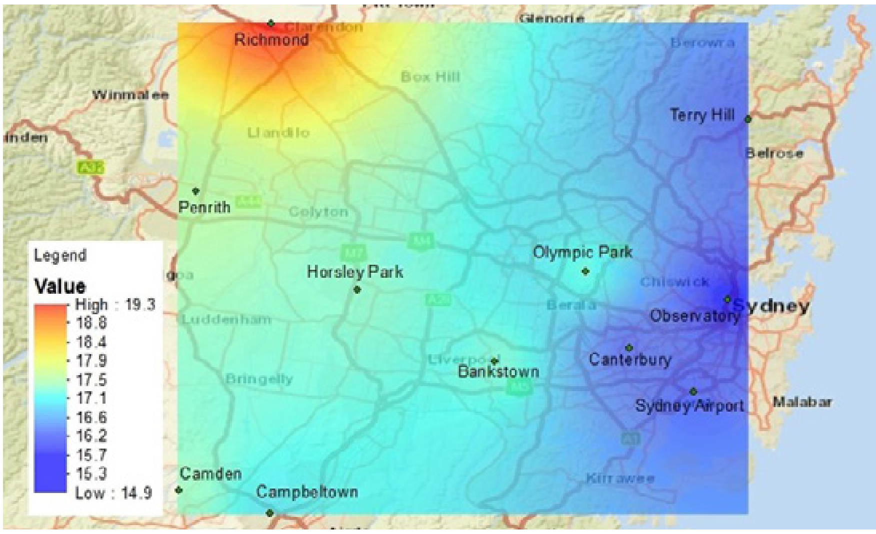


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

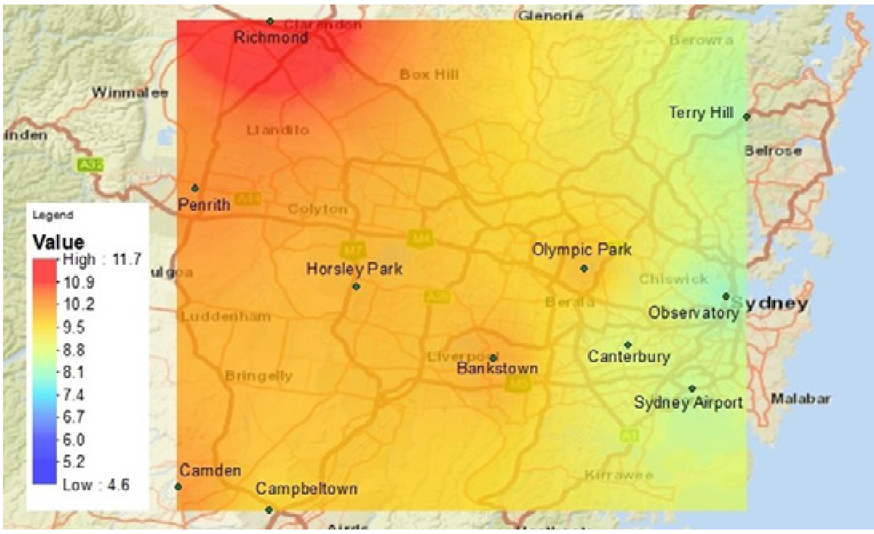


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

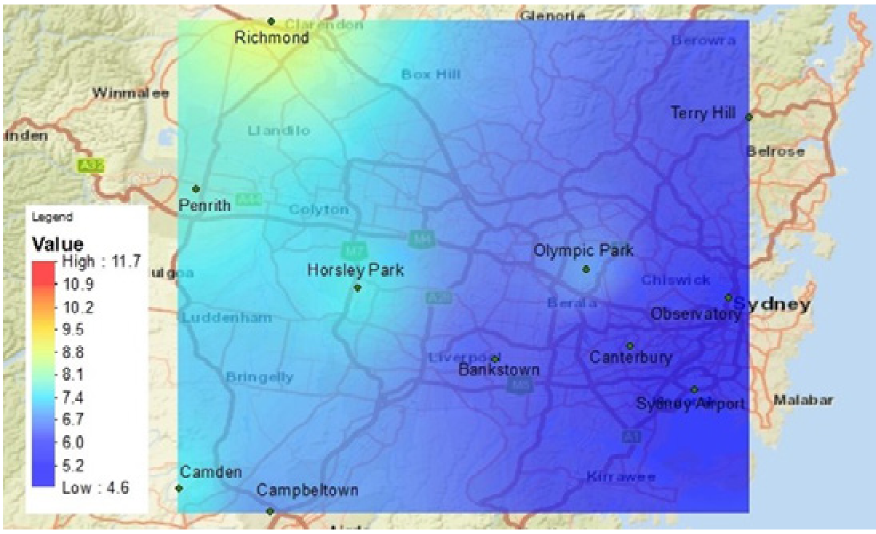


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a typical existing stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for an existing stand-alone house for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (2.8-4.9 kWh/m^2) is significantly lower than the annual cooling load reduction (10.2-16.1 kWh/m^2).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m^2)		Annual heating load (kWh/m^2)		Annual cooling load (kWh/m^2)		Annual heating load (kWh/m^2)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	16.6	23.6	13.8	16.4	8.6	13.4	16.4	19.2
Terry Hill	15.6	22.4	19.5	23.2	6.2	9.9	24.0	28.1
Bankstown	20.6	27.8	19.2	22.9	10.4	15.5	23.1	27.0
Canterbury	18.1	24.9	18.6	22.2	8.1	12.4	22.7	26.7
Observatory	17.7	23.8	15.3	17.9	7.9	11.9	18.6	21.6
Richmond	23.4	31.6	20.8	25.0	12.3	18.2	25.0	29.4
Penrith	27.1	36.1	18.9	22.7	13.5	20.0	22.6	26.7
Horsley Park	22.0	28.1	20.9	24.8	10.3	14.3	25.0	29.2
Camden	20.2	25.3	23.2	27.8	9.9	13.2	28.1	33.0
Olympic Park	22.1	31.4	18.0	21.6	10.2	16.6	21.4	25.2
Campbelltown	19.8	24.3	23.5	28.1	9.1	11.9	28.0	33.0

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for an existing stand-alone house using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 42.4-55.8 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 6.9 and 12.1 kWh/m^2 (~13.0-21.1 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2		kWh/m^2	%	kWh/m^2	%
Sydney Airport	8.0	48.2	10.2	43.2	2.6	2.8	5.4	17.8	7.4	18.5
Terry Hill	9.4	60.3	12.5	55.8	4.5	4.9	4.9	14.0	7.6	16.7
Bankstown	10.2	49.5	12.3	44.2	3.9	4.1	6.3	15.8	8.2	16.2
Canterbury	10.0	55.2	12.5	50.2	4.1	4.5	5.9	16.1	8.0	17.0
Observatory	9.8	55.4	11.9	50.0	3.3	3.7	6.5	19.7	8.2	19.7
Richmond	11.1	47.4	13.4	42.4	4.2	4.4	6.9	15.6	9.0	15.9
Penrith	13.6	50.2	16.1	44.6	3.7	4.0	9.9	21.5	12.1	20.6
Horsley Park	11.7	53.2	13.8	49.1	4.1	4.4	7.6	17.7	9.4	17.8
Camden	10.3	51.0	12.1	47.8	4.9	5.2	5.4	12.4	6.9	13.0
Olympic Park	11.9	53.8	14.8	47.1	3.4	3.6	8.5	21.2	11.2	21.1
Campbelltown	10.7	54.0	12.4	51.0	4.5	4.9	6.2	14.3	7.5	14.3

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

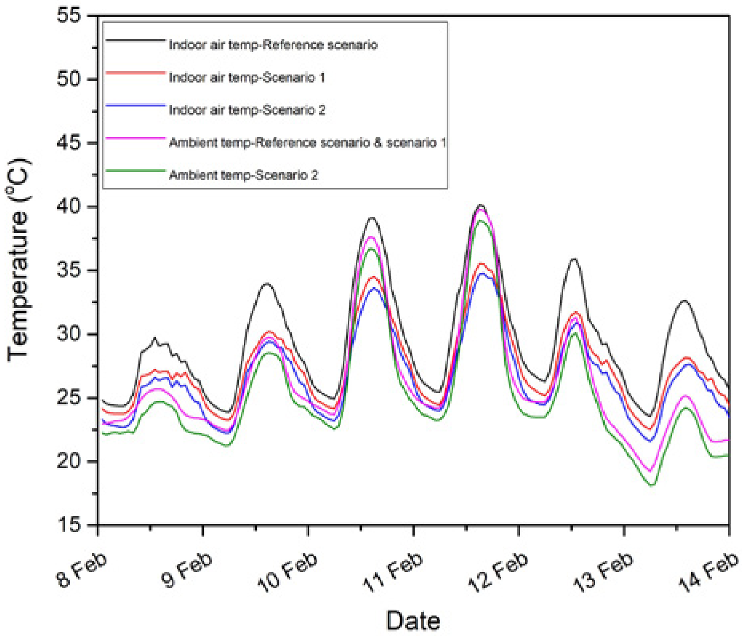


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing stand-alone house under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

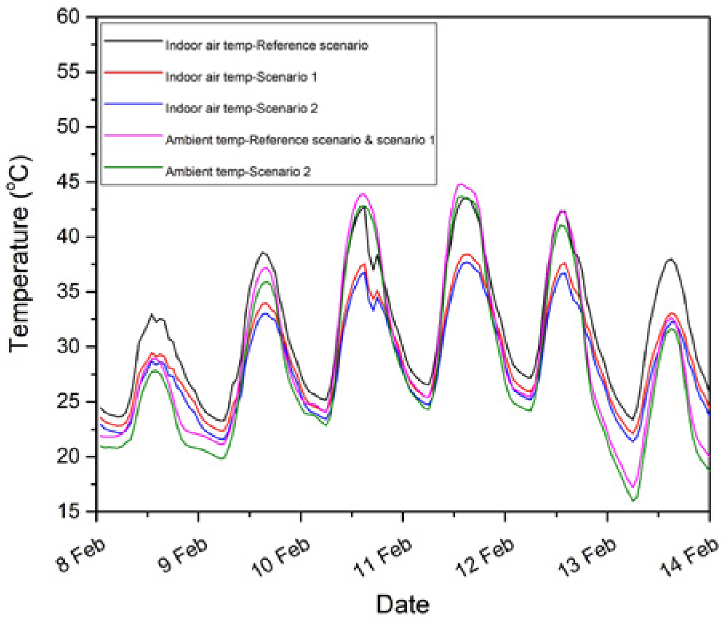


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing stand-alone house under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 23.6-40.2 °C and 23.3- 43.6 °C in Observatory and Richmond stations, respectively.

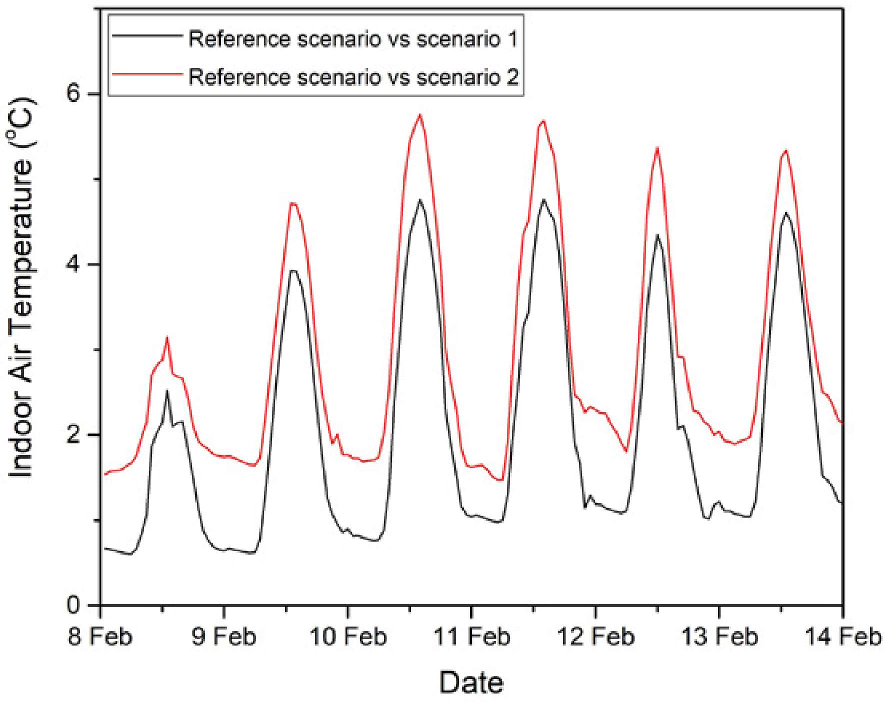


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a existing stand-alone house under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 4.8 °C and 5.2 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 5.8 °C and 6.1 °C in Observatory and Richmond stations, respectively.

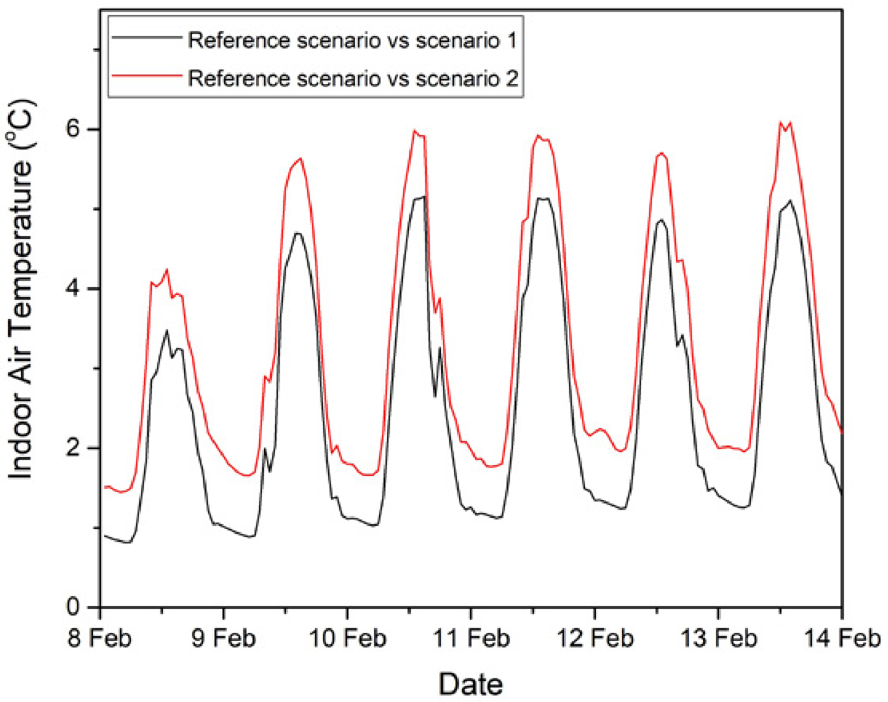


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a existing stand-alone house under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease from a range 11.3-23.7 ºC in reference scenario to a range 11.1-22.1 ºC in scenario 1 in Observatory Hill station.

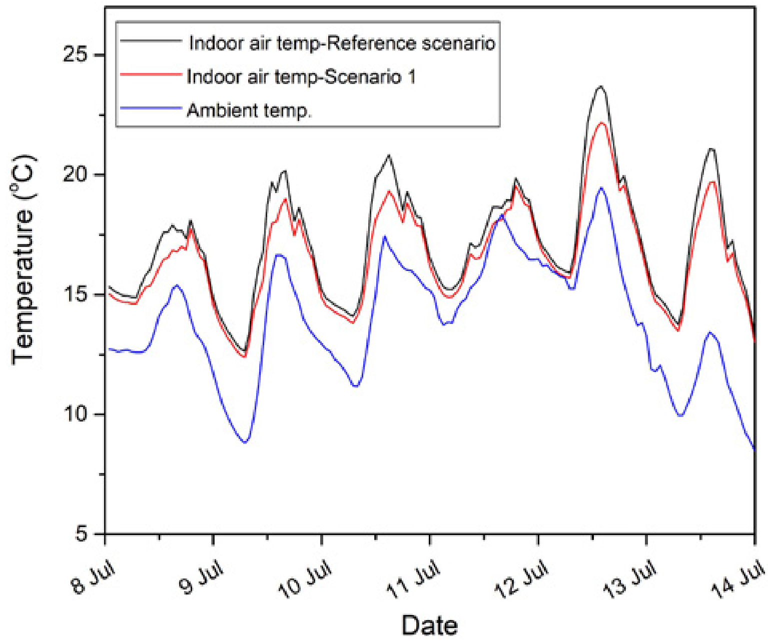


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a typical existing stand-alone house under free-floating condition during a winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 7.4-23.2 ºC in reference scenario to a range 7.1-21.9 ºC in scenario 1 in Richmond station.

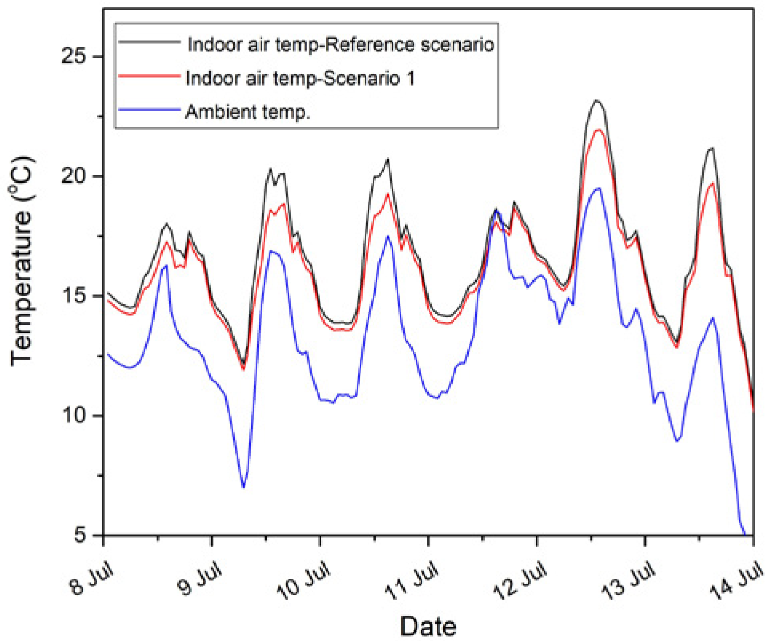


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a typical existing stand-alone house under free-floating condition during a winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.9 °C and 1.9 °C in Observatory and Richmond stations, respectively.

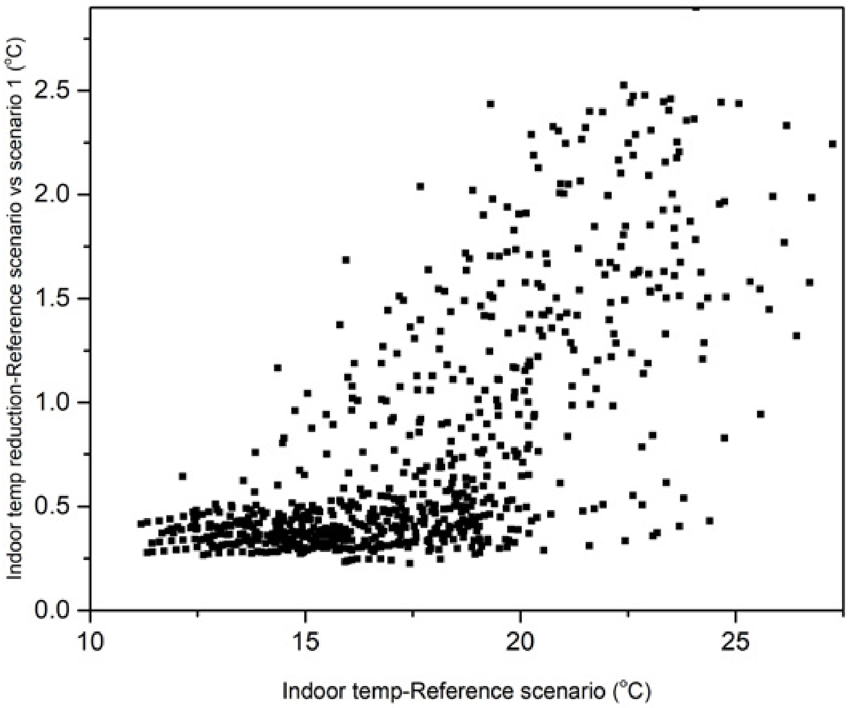


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a existing stand-alone house under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

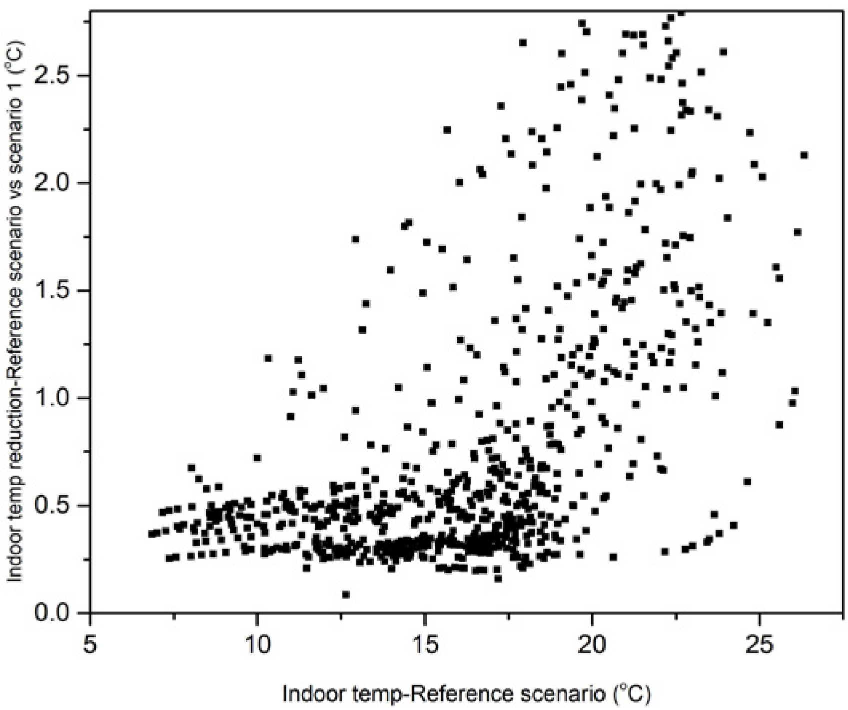


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a existing stand-alone house under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to considerably increase from 504 hours in reference scenario to 578 hours; and from 563 to 621 hours in scenario 1 in Observatory and Richmond stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Observatory	504	578
Richmond	563	621

Table 6. 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.

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decrease from 397 hours in reference scenario to 273 and 213 hours under scenario 1 and 2 in Observatory station; and from 431 hours in reference scenario to 342 and 287 hours under scenario 1 and 2 in Richmond station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	397	273	213
Richmond	431	342	287

6

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban-scale application of cool roof can significantly reduce the cooling load of an existing standalone house during the summer season.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 15.3-19.3 kWh/m^2 to 8.2-11.7 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 6.5-7.6 kWh/m^2. This is equivalent to approximately 38.7-45.8 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 9.2-10.7 kWh/m^2. This is equivalent to 53.9-69.9 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (2.8-4.9 kWh/m^2) is lower than the annual cooling load reduction (10.2-16.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 42.4-55.8 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 6.9 and 12.1 kWh/m^2 (~13.0-21.1%) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 23.6-40.2 °C and 23.3-43.6 °C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 4.8 and 5.2 °C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 5.8 and 6.1 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 °C in reference scenario to a range between 18.1 and 38.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 °C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 °C in reference scenario to 15.9-43.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 °C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease from a range between 11. 3 and 23.7 °C in reference scenario to a range between 11.1 and 22.1 °C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 7.4 and 23.2 ^{o}C in reference scenario to a range between 7.1 and 21.9 ^{o}C in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.9 and 1.9 ^{o}C for Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to considerably increase from 504 hours in reference scenario to 578 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slightly increase in total number of hours below 19 ^{o}C from 563 hours in reference scenario to 621 hours in reference with cool roof scenario (scenario 1) (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 ^{o}C is 397 hours under the reference scenario in Observatory station, which significantly decreases to 276 and 213 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 ^{o}C from 431 hours in reference scenario to 342 in reference with cool roof scenario (scenario 1) and 287 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B11

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

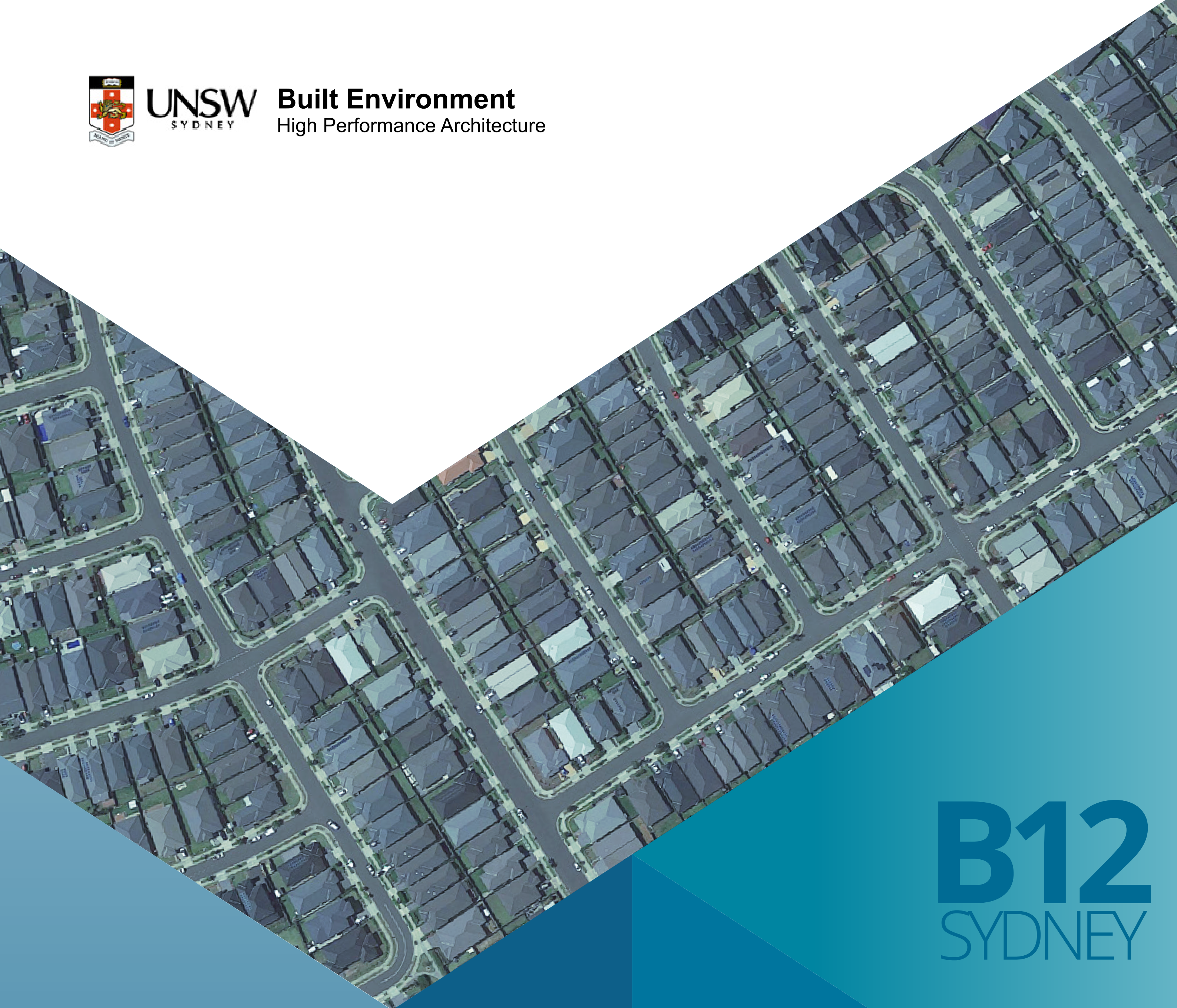
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY
Built Environment
High Performance Architecture



B12
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

Existing school
2021

BUILDING 12

EXISTING SCHOOL

Floor area : 1100m^2
Number of stories : 3

Image source: Pavia National High School, Evangelista St., Pavia, Iloilo

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

Table 1. Sensible and total cooling load for an existing school for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of an existing school from 26.8-33.5 kWh/m² to 25.5-32.1 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	14.7	28.1	14.2	26.8	13.0	15.9
Terry Hill	17.9	26.8	17.2	25.5	17.0	20.1
Bankstown	19.4	29.9	18.8	28.7	18.2	20.1
Canterbury	16.0	28.0	15.5	26.8	14.7	17.9
Observatory	14.5	27.4	14.0	26.1	13.7	17.8
Richmond	26.4	33.5	25.4	32.1	24.9	26.9
Penrith	24.0	31.0	23.2	29.7	22.7	24.5
Horsley Park	22.6	30.1	21.8	28.8	21.0	23.0
Camden	25.1	31.0	24.3	29.8	23.2	24.3
Olympic Park	18.6	29.7	17.9	28.4	17.9	21.3
Campbelltown	22.1	29.6	21.3	28.4	20.6	22.2

Table 2. Sensible and total cooling load saving for an existing school for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 1.2-1.4 kWh/m² which is equivalent to 3.9-4.9 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 6.5-12.2 kWh/m² which is equivalent to 19.7-43.4 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	0.5	3.4	1.3	4.6	1.7	11.6	12.2	43.4
Terry Hill	0.7	3.9	1.3	4.9	0.9	5.0	6.7	25.0
Bankstown	0.6	3.1	1.2	4.0	1.2	6.2	9.8	32.8
Canterbury	0.5	3.1	1.2	4.3	1.3	8.1	10.1	36.1
Observatory	0.5	3.4	1.3	4.7	0.8	5.5	9.6	35.0
Richmond	1.0	3.8	1.4	4.2	1.5	5.7	6.6	19.7
Penrith	0.8	3.3	1.3	4.2	1.3	5.4	6.5	21.0
Horsley Park	0.8	3.5	1.3	4.3	1.6	7.1	7.1	23.6
Camden	0.8	3.2	1.2	3.9	1.9	7.6	6.7	21.6
Olympic Park	0.7	3.8	1.3	4.4	0.7	3.8	8.4	28.3
Campbelltown	0.8	3.6	1.2	4.1	1.5	6.8	7.4	25.0

In the eleven weather stations in Sydney, both building-scale and the combined building-scale and urban scale application of cool roofs can reduce the cooling load of an existing school during the summer season.

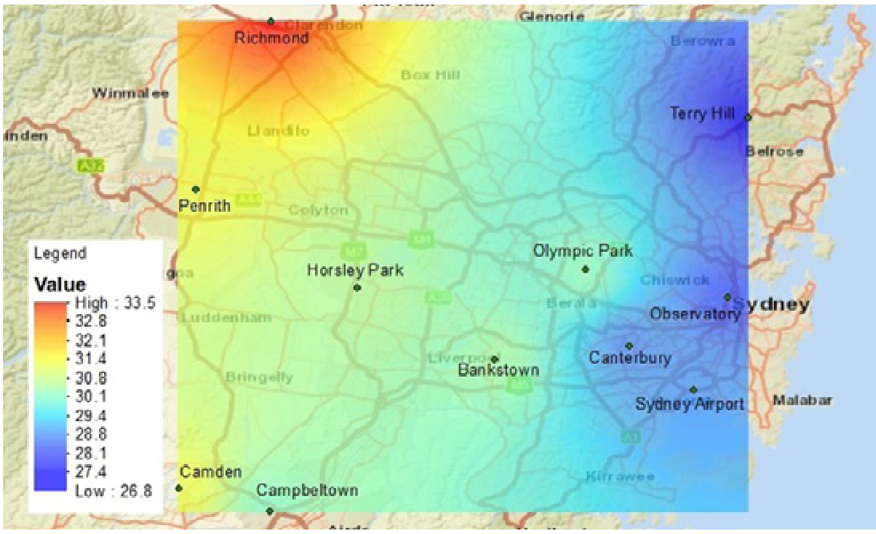


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for aan existing school with weather data simulated by WRF for COP=1 for heating and cooling.

Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

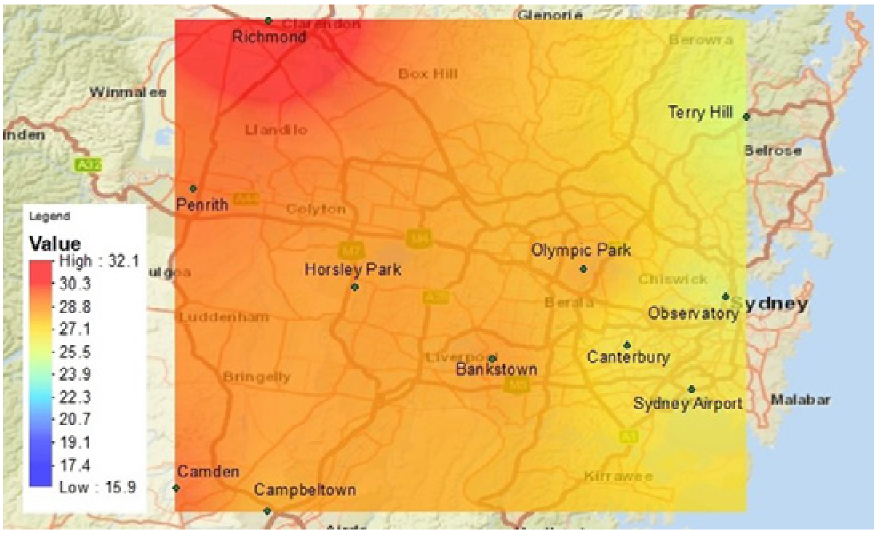


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing school with weather data simulated by WRF for COP=1 for heating and cooling.

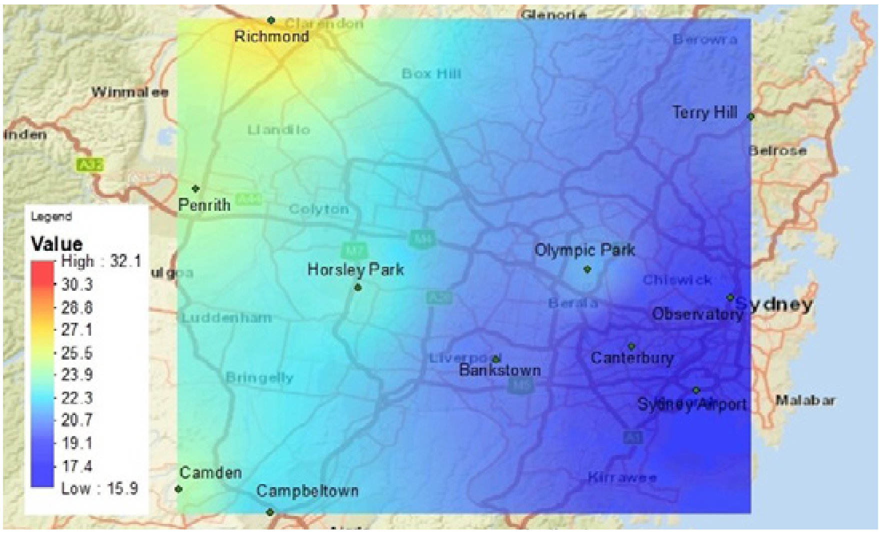


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing school with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for an existing school for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.1-0.4 kWh/m²) is significantly lower than the annual cooling load reduction (1.9-3.3 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	37.7	53.2	1.6	9.0	36.5	51.3	1.7	9.1
Terry Hill	27.0	44.1	2.6	15.2	25.7	41.6	2.7	15.5
Bankstown	42.9	57.5	3.0	15.7	41.4	55.2	3.1	16.0
Canterbury	35.0	48.4	2.9	18.1	33.3	45.6	2.9	18.4
Observatory	38.0	49.0	1.7	10.1	36.6	46.7	1.8	10.3
Richmond	46.5	64.8	3.8	20.2	44.8	62.0	3.9	20.5
Penrith	48.2	67.9	3.0	16.6	46.2	64.6	3.0	17.0
Horsley Park	42.7	54.6	3.2	16.8	40.9	51.7	3.3	17.2
Camden	42.2	51.5	4.3	23.0	40.4	49.1	4.4	23.4
Olympic Park	40.2	61.2	2.8	14.2	38.4	58.1	2.8	14.5
Campbelltown	41.4	49.2	4.1	20.9	39.6	46.7	4.2	21.4

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for an existing school using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 3.6-5.8 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.8 and 2.9 kWh/m² (~2.7-3.8 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	1.2	3.2	1.9	3.6	0.1	0.1	1.1	2.8	1.8	2.9
Terry Hill	1.3	4.8	2.5	5.7	0.1	0.3	1.2	4.1	2.2	3.7
Bankstown	1.5	3.5	2.3	4.0	0.1	0.3	1.4	3.1	2.0	2.7
Canterbury	1.7	4.9	2.8	5.8	0.0	0.3	1.7	4.5	2.5	3.8
Observatory	1.4	3.7	2.3	4.7	0.1	0.2	1.3	3.3	2.1	3.6
Richmond	1.7	3.7	2.8	4.3	0.1	0.3	1.6	3.2	2.5	2.9
Penrith	2.0	4.1	3.3	4.9	0.0	0.4	2.0	3.9	2.9	3.4
Horsley Park	1.8	4.2	2.9	5.3	0.1	0.4	1.7	3.7	2.5	3.5
Camden	1.8	4.3	2.4	4.7	0.1	0.4	1.7	3.7	2.0	2.7
Olympic Park	1.8	4.5	3.1	5.1	0.0	0.3	1.8	4.2	2.8	3.7
Campbelltown	1.8	4.3	2.5	5.1	0.1	0.5	1.7	3.7	2.0	2.9

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

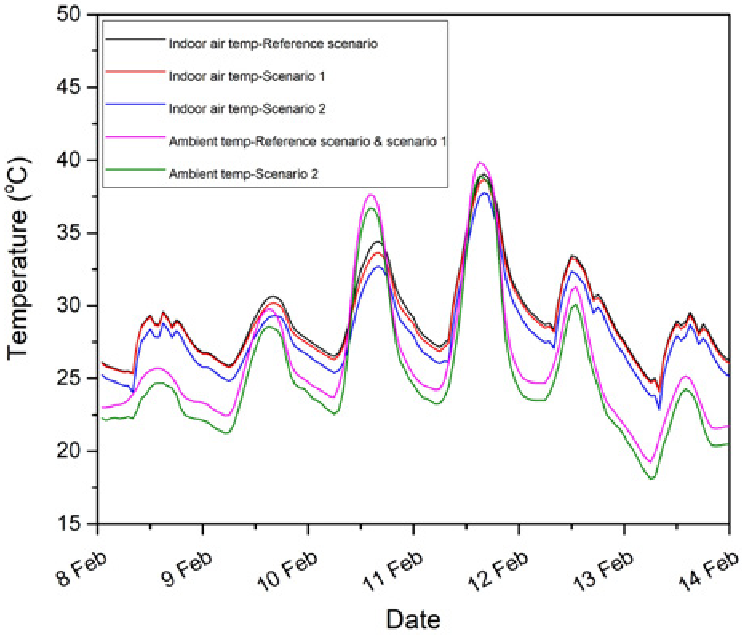


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing school under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

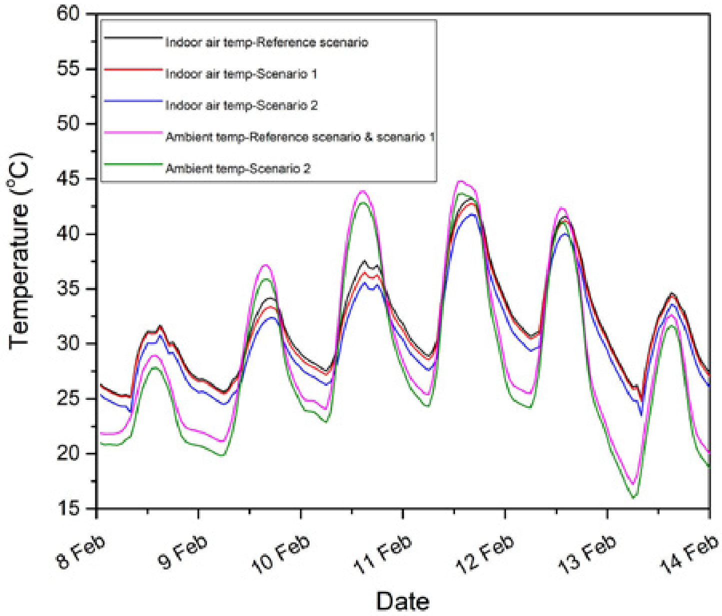


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing school under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 24.2-39.1 °C and 24.6-43.2 °C in Observatory and Richmond stations, respectively.

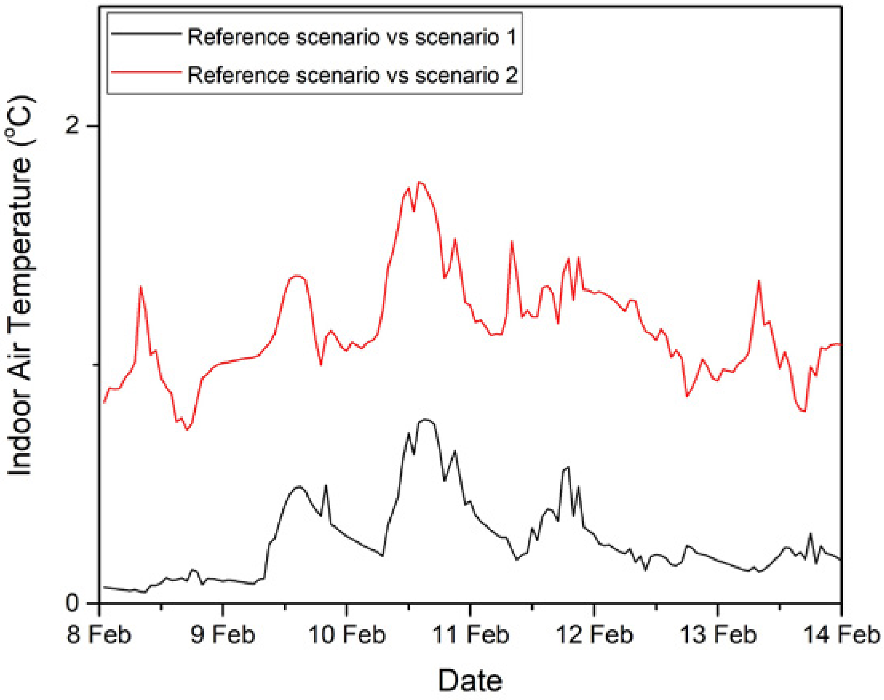


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing school under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 0.8 °C and 1.0 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 1.8 °C and 2.0 °C in Observatory and Richmond stations, respectively.

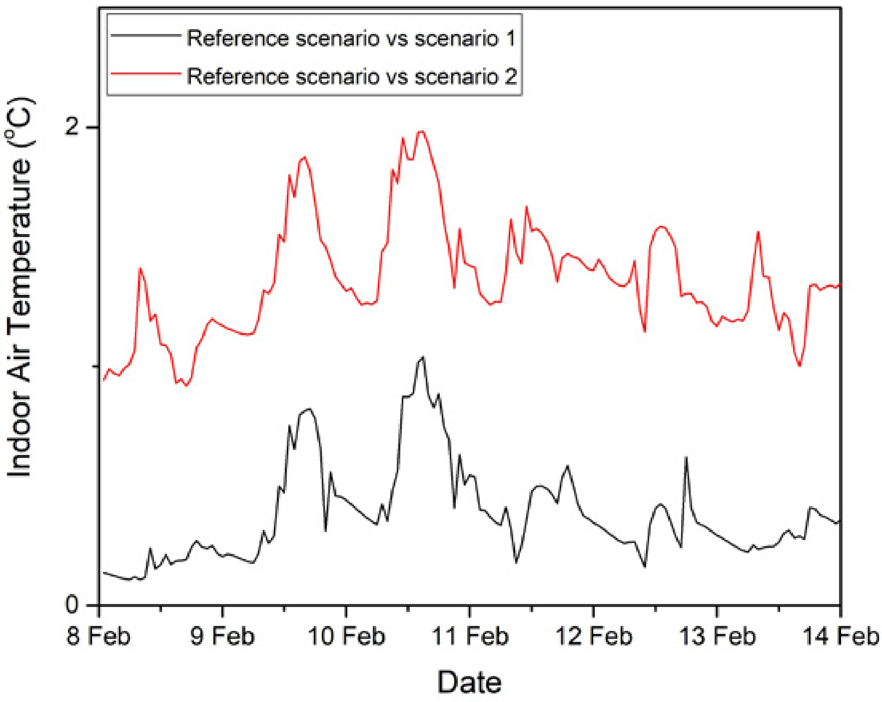


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing school under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease from a range 12.5-24.9 °C in reference scenario to a range 12.5-24.8 °C in scenario 1 in Observatory Hill station.

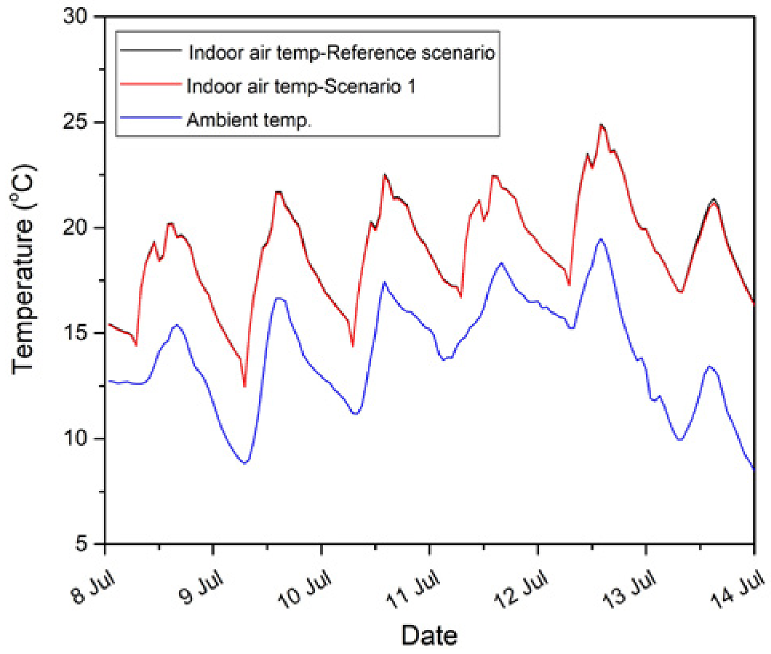


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing school under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 10.0-24.8 °C in reference scenario to a range 9.9-24.7 °C in scenario 1 in Richmond station.

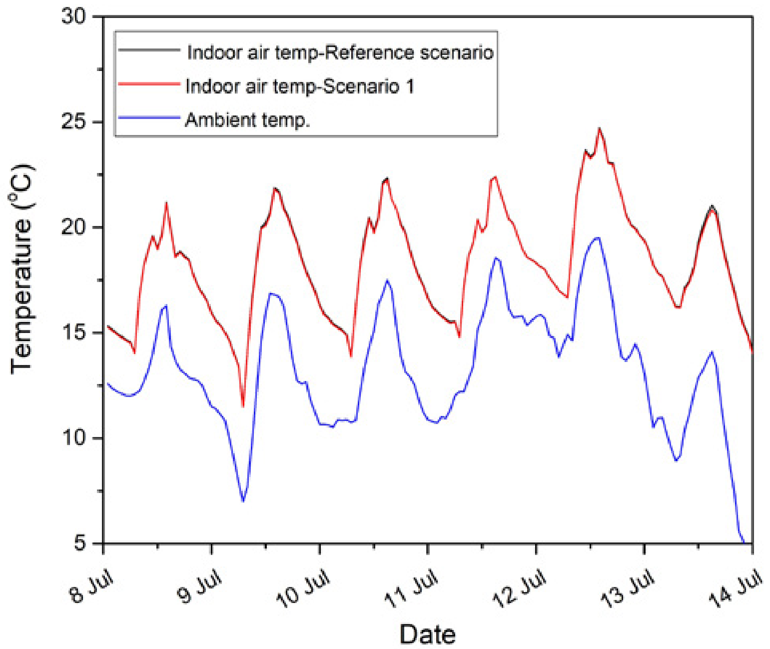


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing school under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 °C and 0.2 °C in Observatory and Richmond stations, respectively.

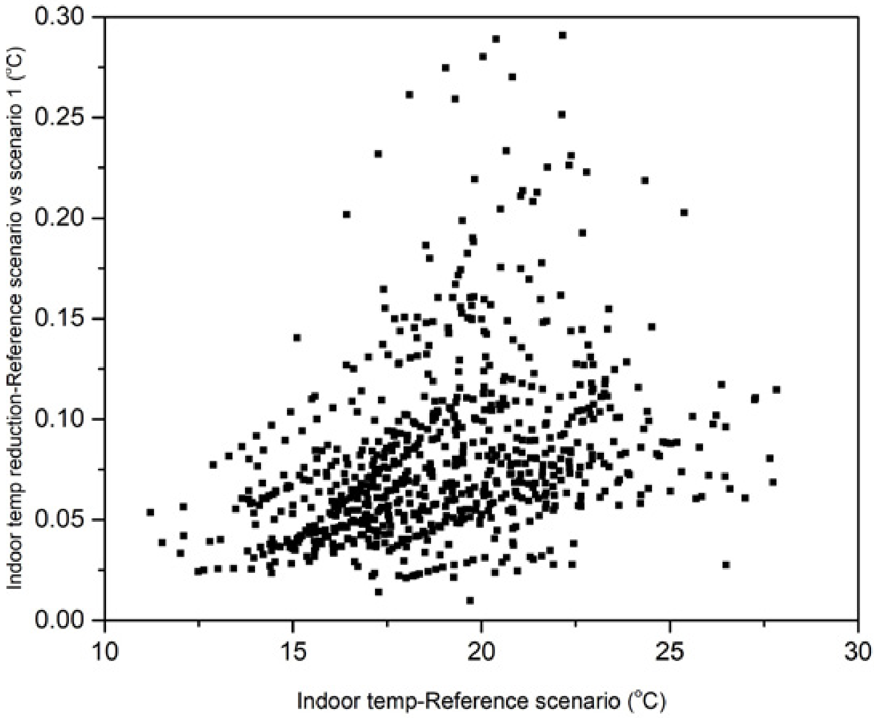


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing school under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

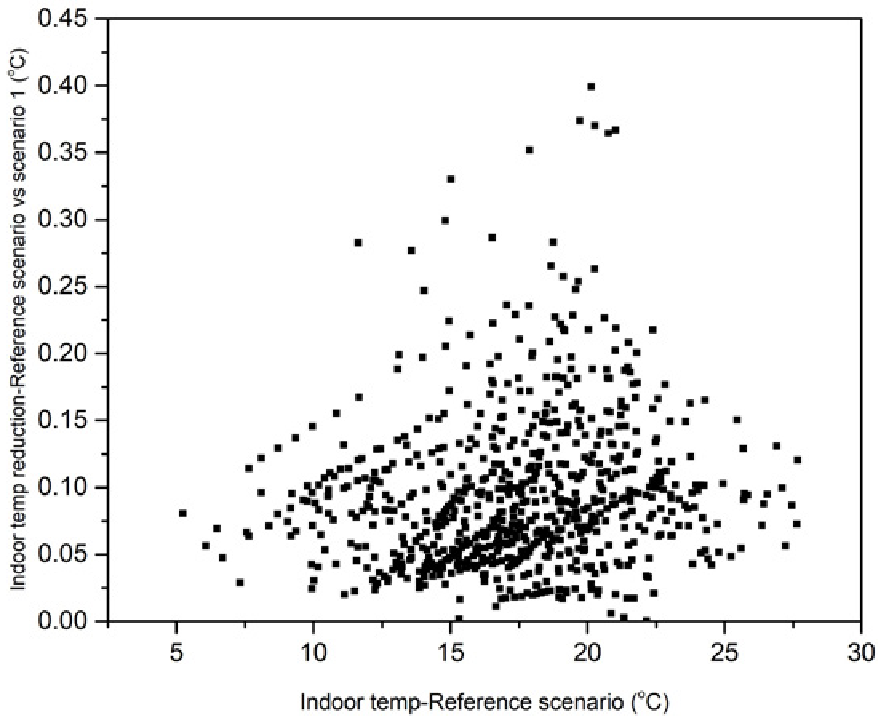


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing school under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	84	383	86	389
Richmond	106	481	111	495

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 383 hours in reference scenario to 389 hours; and from 481 to 495 hours in scenario 1 in Observatory and Richmond stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 84 hours in reference scenario to 86 hours; and from 106 to 111 hours in scenario 1 in Observatory and Richmond stations, respectively.

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	486	471	368
Richmond	533	508	446

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 486hours in reference scenario to 471 and 368 hours under scenario 1 and 2, in Observatory station; and from 533 hours in reference scenario to 508 and 446 hours under scenario 1 and 2 in Richmond station, respectively.

6

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of the typical existing school during the summer season. Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing school from 26.8-33.5 kWh/m2 to 25.5-32.1 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 1.2-1.4 kWh/m^2. This is equivalent to approximately 3.9-4.9 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 6.5-12.2 kWh/m^2. This is equivalent to 19.7-43.4 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.1-0.4 kWh/m^2) is significantly lower than the annual cooling load reduction (1.9-3.3 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 3.6-5.8 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.8 and 2.9 kWh/m^2 (~2.7-3.8 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 24.2-39.1 °C and 24.6-43.2 °C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 0.8 and 1.0 °C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 1.8 and 2.0 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 °C in reference scenario to a range between 18.1 and 38.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 °C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 °C in reference scenario to 15.9-43.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 °C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 12. 5 and 24.9 °C in reference scenario to a range between 12.5 and 24.8 °C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 10. 0 and 24.8 °C in reference scenario to a range between 9.9 and 24.7 °C in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.2 °C and 0.2 °C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 383 hours in reference scenario to 389 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slight increase in total number of hours below 19 °C from 481 hours in reference scenario to 495 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building.

The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to increase from 84 hours in reference scenario to 86 hours in reference with cool roof scenario (scenario 1) in Observatory station. Similarly, the calculation in Richmond station shows a slight increase of number of hours below 19 °C from 106 hours to 111 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 486 hours under the reference scenario in Observatory station, which decreases to 471 and 368 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 °C from 533 hours in reference scenario to 508 in reference with cool roof scenario (scenario 1) and 446 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B12

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

Sydney, NSW 2052
Australia

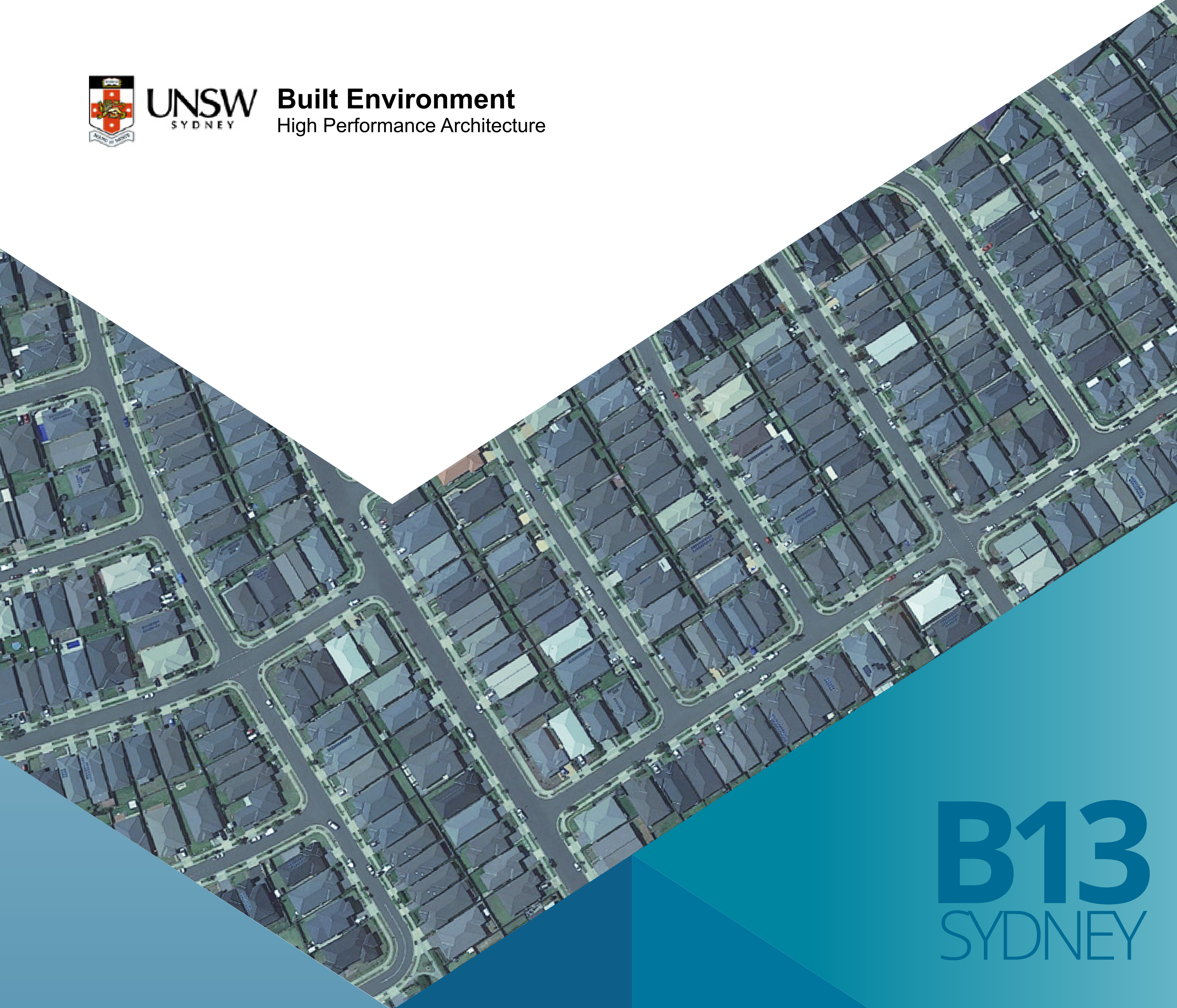
Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY

Built Environment
High Performance Architecture



B13
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

Existing low-rise office building with roof insulation
2021

BUILDING 13

EXISTING LOW-RISE OFFICE BUILDING WITH ROOF INSULATION

Floor area : 1200m^2
Number of stories : 2

Image source: Ecipark Office Building. https://jhmrad.com/21-delightful-two-story-building/ecipark-office-building-two-story/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the existing low-rise office building with roof insulation from 21.6-28.6 kWh/m² to 16.5-21.6 kWh/m².

Table 1. Sensible and total cooling load for an existing low-rise office building with roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	15.5	22.2	10.7	16.9	7.6	10.1
Terry Hill	17.6	22.9	12.2	16.9	10.6	13.5
Bankstown	19.4	25.4	14.2	19.7	11.4	13.7
Canterbury	16.6	23.0	11.6	17.6	9.1	12.1
Observatory	15.2	21.6	10.5	16.5	8.3	11.5
Richmond	24.4	28.6	17.6	21.5	15.9	17.8
Penrith	21.8	26.2	16.1	20.0	14.4	16.2
Horsley Park	20.9	25.7	15.3	19.6	13.8	15.9
Camden	22.1	25.9	16.4	19.8	14.5	15.8
Olympic Park	18.8	25.1	13.7	19.4	11.5	14.5
Campbelltown	20.6	25.2	15.0	19.2	12.9	14.7

For Scenario 1, the total cooling load saving is around 5.1-7.1 kWh/m² which is equivalent to 22.4-26.2 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 9.4-12.1 kWh/m² which is equivalent to 37.8-54.5% of total cooling load reduction.

Table 2. Sensible and total cooling load saving for an existing low-rise office building with roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	4.8	31.0	5.3	23.9	7.9	51.0	12.1	54.5
Terry Hill	5.4	30.7	6.0	26.2	7.0	39.8	9.4	41.0
Bankstown	5.2	26.8	5.7	22.4	8.0	41.2	11.7	46.1
Canterbury	5.0	30.1	5.4	23.5	7.5	45.2	10.9	47.4
Observatory	4.7	30.9	5.1	23.6	6.9	45.4	10.1	46.8
Richmond	6.8	27.9	7.1	24.8	8.5	34.8	10.8	37.8
Penrith	5.7	26.1	6.2	23.7	7.4	33.9	10.0	38.2
Horsley Park	5.6	26.8	6.1	23.7	7.1	34.0	9.8	38.1
Camden	5.7	25.8	6.1	23.6	7.6	34.4	10.1	39.0
Olympic Park	5.1	27.1	5.7	22.7	7.3	38.8	10.6	42.2
Campbelltown	5.6	27.2	6.0	23.8	7.7	37.4	10.5	41.7

In the eleven weather stations in Sydney, both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of the existing low-rise office building with roof insulation during the summer season.

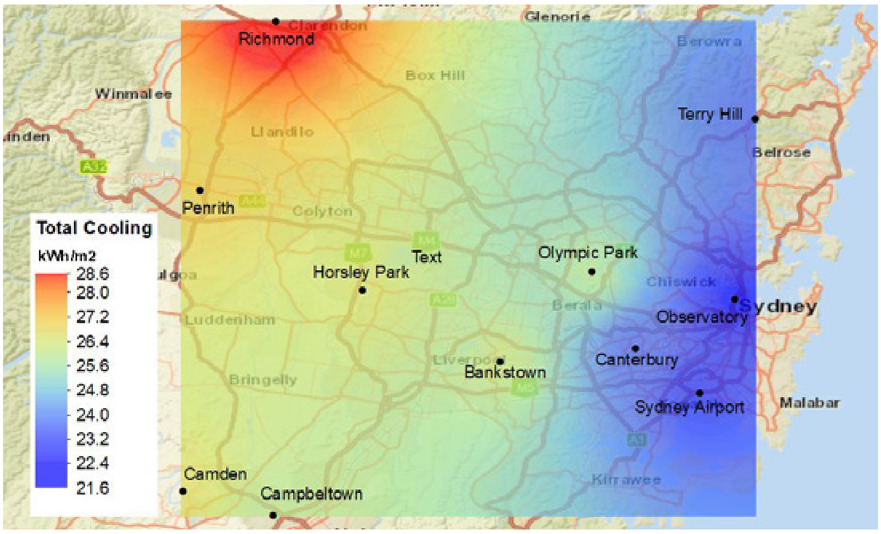


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

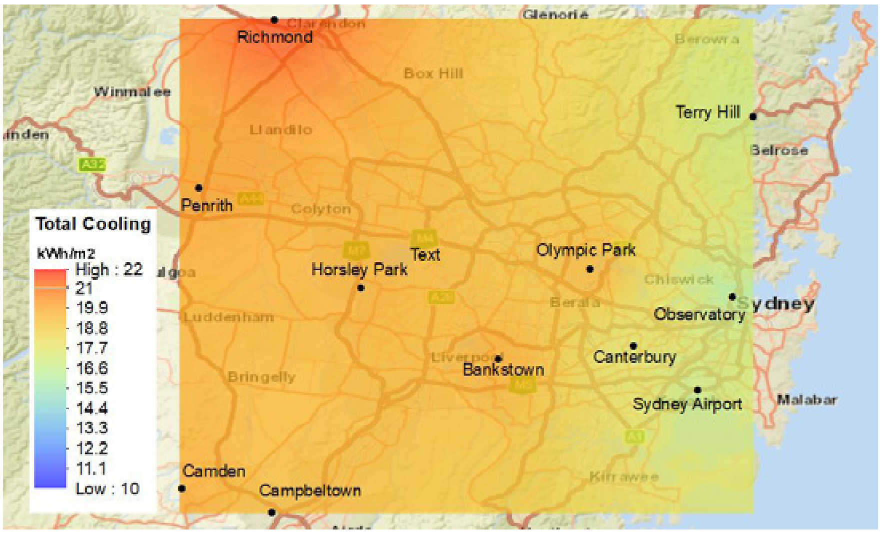


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

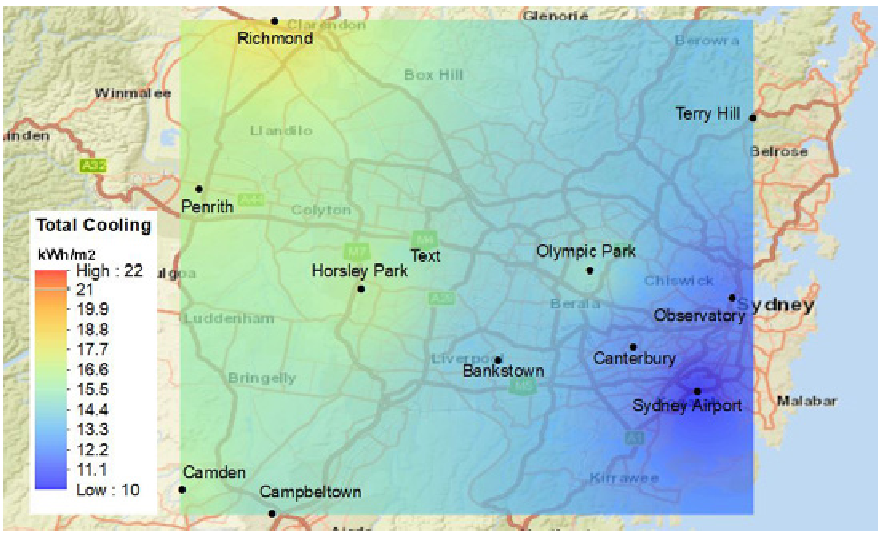


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing low-rise office building with roof insulation with weather data simulated by WRF for COP=1 for heating and cooling.

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.4-1.1 kWh/m²) is significantly lower than the annual cooling load reduction (8.2-14.0 kWh/m²).

Table 3. Annual cooling and heating loads for an existing low-rise office building with roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	30.8	39.8	1.0	2.2	23.5	31.6	1.3	2.6
Terry Hill	23.2	30.9	1.6	3.6	15.7	22.1	2.1	4.4
Bankstown	36.8	46.7	1.8	4.0	27.2	35.9	2.2	4.7
Canterbury	29.9	38.7	1.8	4.2	21.7	29.4	2.3	5.1
Observatory	32.0	40.6	1.2	2.5	23.1	30.8	1.5	3.0
Richmond	41.7	52.5	2.1	4.8	31.2	40.4	2.6	5.7
Penrith	44.6	55.5	1.7	3.9	32.3	41.5	2.1	4.7
Horsley Park	37.2	45.1	1.9	4.2	26.4	33.2	2.4	5.1
Camden	36.0	43.1	2.5	5.7	26.0	32.3	3.1	6.8
Olympic Park	37.3	48.9	1.6	3.5	26.7	36.7	1.9	4.1
Campbelltown	35.3	41.7	2.4	5.3	25.0	30.7	2.9	6.3

The annual cooling load saving by building-scale application of cool roofs is around 20.6-28.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 7.8 and 13.2 kWh/m² (~18.6-23.2 %).

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	7.3	23.7	8.2	20.6	0.3	0.4	7.0	22.0	7.8	18.6
Terry Hill	7.5	32.3	8.8	28.5	0.5	0.8	7.0	28.2	8.0	23.2
Bankstown	9.6	26.1	10.8	23.1	0.4	0.7	9.2	23.8	10.1	19.9
Canterbury	8.2	27.4	9.3	24.0	0.5	0.9	7.7	24.3	8.4	19.6
Observatory	8.9	27.8	9.8	24.1	0.3	0.5	8.6	25.9	9.3	21.6
Richmond	10.5	25.2	12.1	23.0	0.5	0.9	10.0	22.8	11.2	19.5
Penrith	12.3	27.6	14.0	25.2	0.4	0.8	11.9	25.7	13.2	22.2
Horsley Park	10.8	29.0	11.9	26.4	0.5	0.9	10.3	26.3	11.0	22.3
Camden	10.0	27.8	10.8	25.1	0.6	1.1	9.4	24.4	9.7	19.9
Olympic Park	10.6	28.4	12.2	24.9	0.3	0.6	10.3	26.5	11.6	22.1
Campbelltown	10.3	29.2	11.0	26.4	0.5	1.0	9.8	26.0	10.0	21.3

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 °C in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

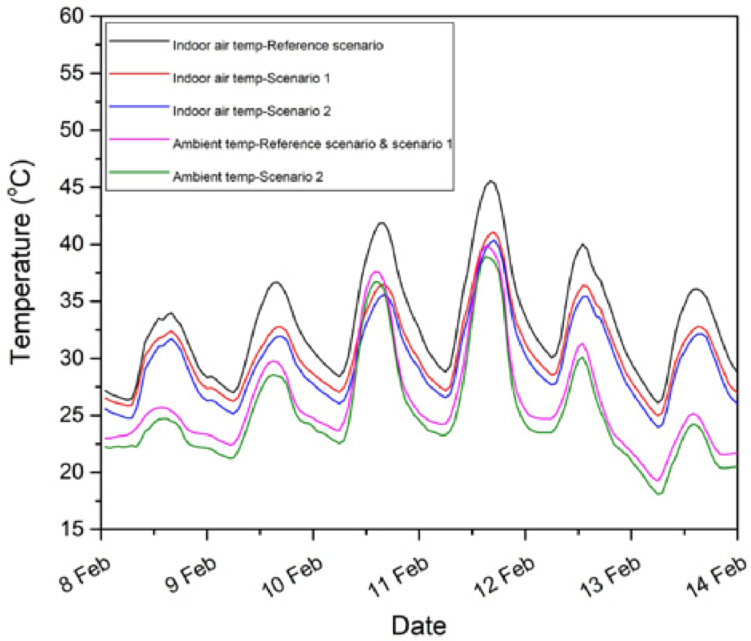


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

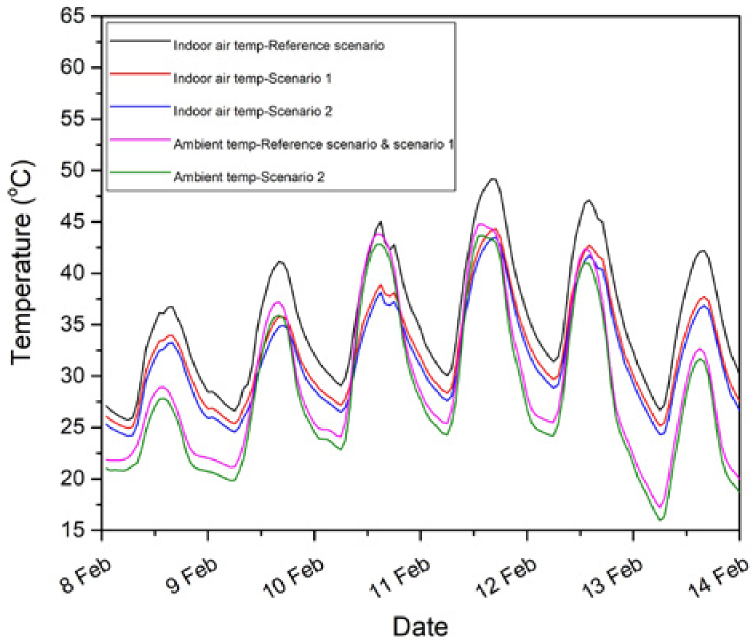


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 26.1-45.5 °C and 25.7-49.2 °C in Observatory and Richmond stations, respectively.

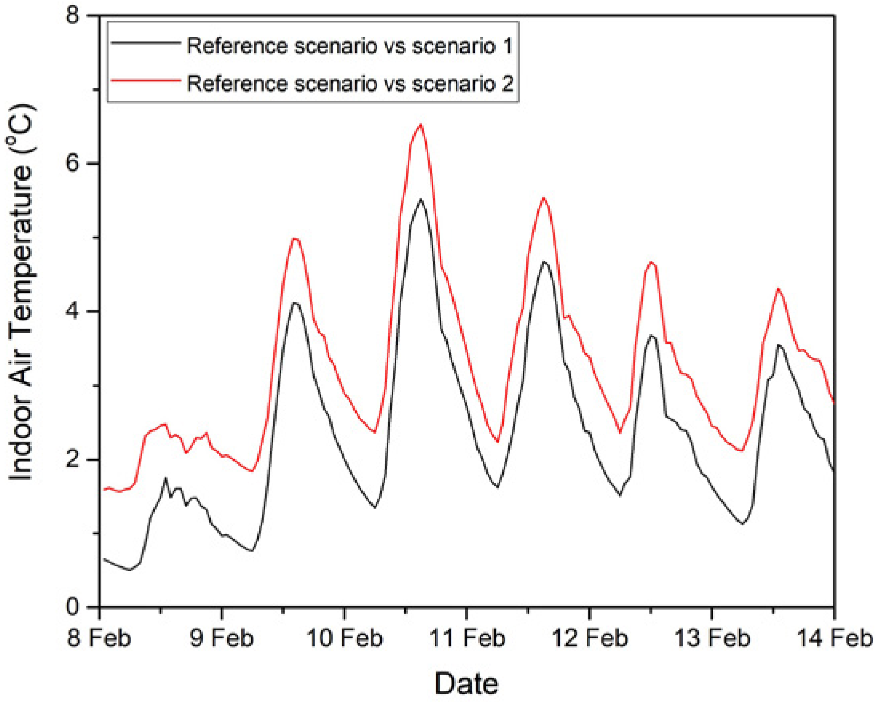


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 5.5 °C and 6.1 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 6.5 and 6.9 °C in Observatory and Richmond stations, respectively.

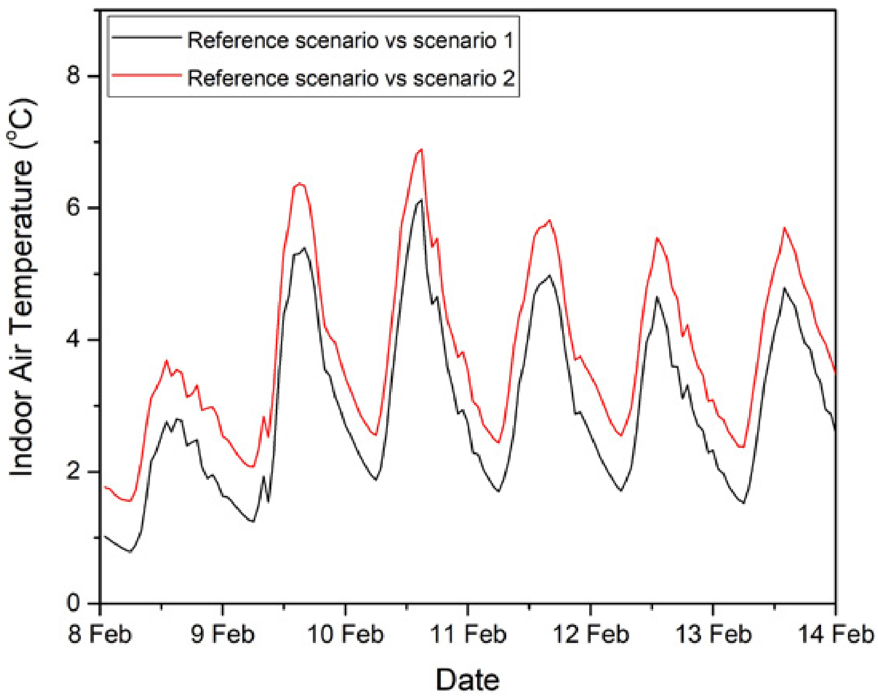


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise office building with roof insulation under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range between 13.8 and 28.5 °C in reference scenario to a range between 13.5 and 27.5 °C in scenario 1 in Observatory Hill station.

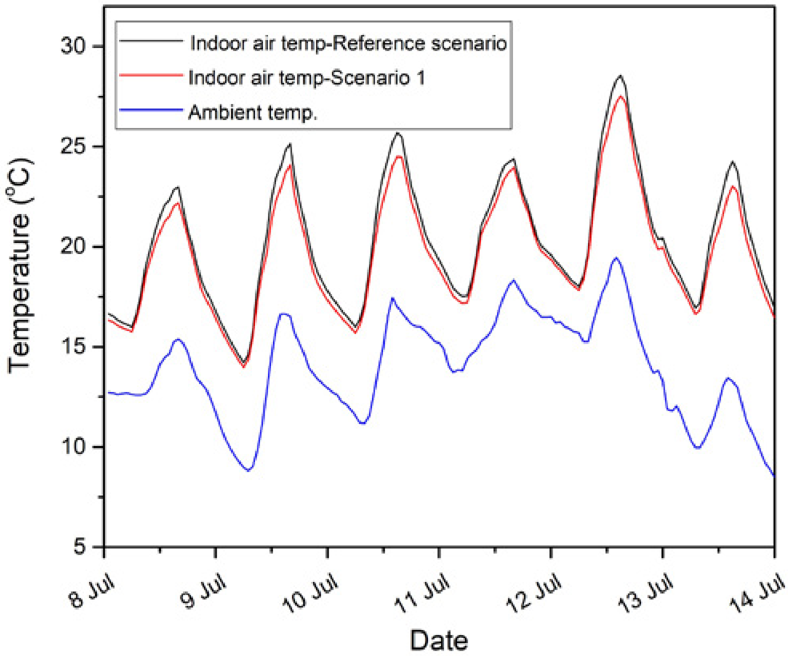


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range between 10.1 and 28.0 °C in reference scenario to a range between 9.8 and 27.2 °C in scenario 1 in Richmond station.

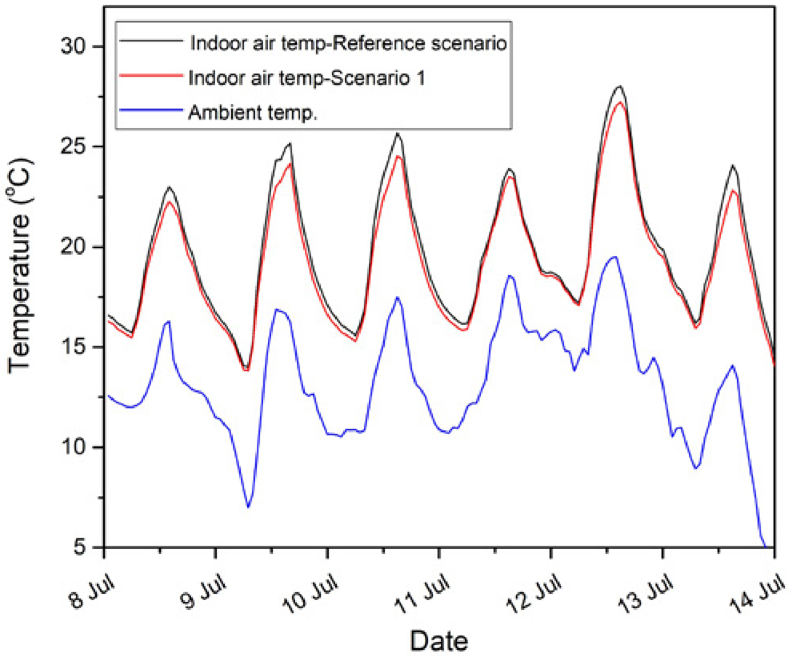


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.4 °C and 1.5 °C in Observatory and Richmond stations, respectively.

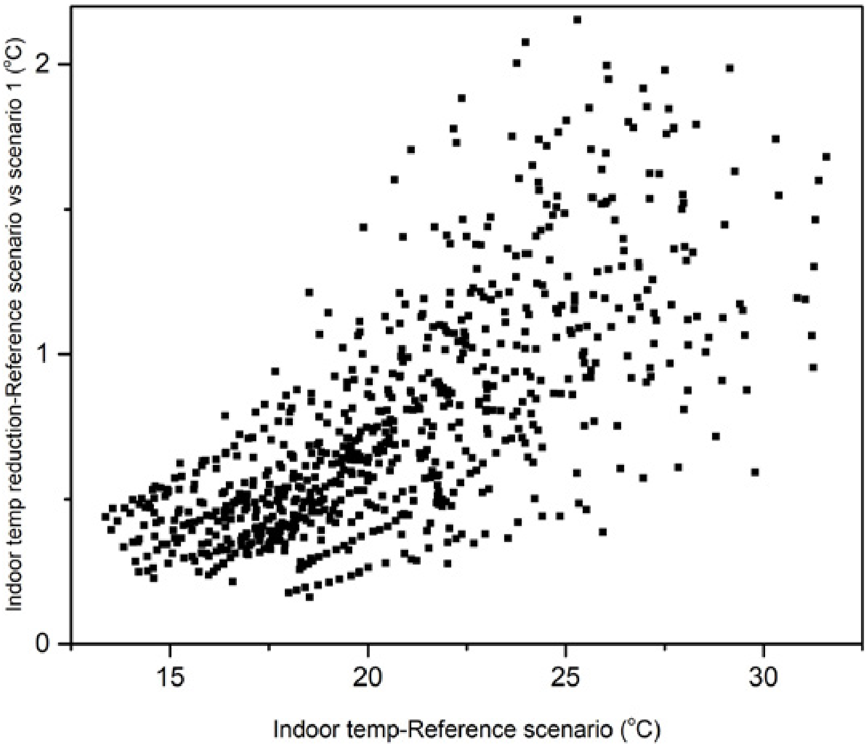


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

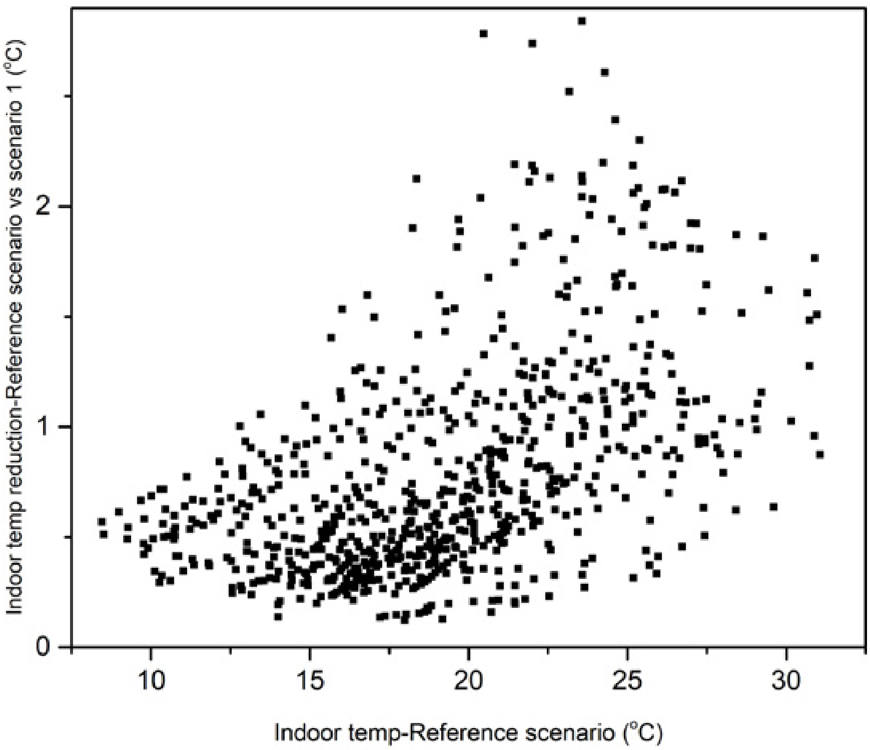


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise office building with roof insulation under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to increase from 284 hours in reference scenario to 329 and hours and from 363 to 407 hours in scenario 1 in Observatory and Richmond stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 74 hours in reference scenario to 89 hours; and from 95 to 114 hours in scenario 1 in Observatory and Richmond stations, respectively.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	74	284	89	329
Richmond	95	363	114	407

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 606 hours in reference scenario to 544 and 473 hours under scenario 1 and 2, in Observatory station; and from 604 hours in reference scenario to 519 and 472 hours under scenario 1 and 2 in Richmond station, respectively.

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	606	544	473
Richmond	604	519	472

6

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale ap-plication of cool roof can significantly reduce the cooling load of the existing low-rise office building with roof insulation during the summer season.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing low-rise office building with roof insulation from 21.6-28.6 kWh/m² to 16.5-21.6 kWh/m² . As computed, the two sum-mer months total cooling load saving by building-scale application of cool roofs is around 5.1-7.1 kWh/m². This is equivalent to approximately 22.4-26.2 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 9.4-12.1 kWh/m². This is equivalent to 37.8-54.5 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the ref-erence scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illus-trate that the annual heating penalty (0.4-1.1 kWh/m²) is significantly lower than the annual cooling load reduction (8.2-14.0 kWh/m²). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 20.6-28.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 7.8 and 13.2 kWh/m² (~18.6-23.2%) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 26.1-45.5 °C and 25.7-49.2 °C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 5.5 and 6.1 °C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 6.5 and 6.9 °C by com-bined building-scale and urban-scale application of cool roofs (scenario 2) in Observato-ry and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 °C in reference scenario to a range be-tween 18.1 and 38.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approx-imately 0.6-1.6 °C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 °C in reference scenario to 15.9-43.6 °C in cool roof and modified urban tem-perature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 °C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 13.8 and 28.5 °C in reference scenario to a range between 13.5 and 27.5 °C in reference with cool roof scenario (scenario 1) in

Observatory Hill station (See Figure 8). Similarly, the indoor air temperature is predicted to reduce from a range between 10.1 and 28.0 ^{o}C in reference scenario to a range between 9.8 and 27.2 ^{o}C in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.4 ^{o}C and 1.5 ^{o}C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when in-door temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase from 284 hours in reference scenario to 329 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slight in-crease in total number of hours below 19 oC from 363 hours in reference scenario to 407 hours in reference with cool roof scenario (scenario 1). The results show less in-crease in total number hours below 19 ^{o}C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 ^{o}C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to increase from 74 hours in reference scenario to 89 hours in reference with cool roof scenario (scenario 1) in Observatory station. Similarly, the calculation in Richmond station shows a slight increase of number of hours below 19 ^{o}C from 95 hours to 114 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 ^{o}C is 606 hours under the reference scenario in Observa-tory station, which decreases to 544 and 473 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduc-tion in number of hours above 26 ^{o}C from 604 hours in reference scenario to 519 in ref-erence with cool roof scenario (scenario 1) and 472 hours in cool roof and modified ur-ban temperature scenario (scenario 2), respectively (See Table 6).

B13

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

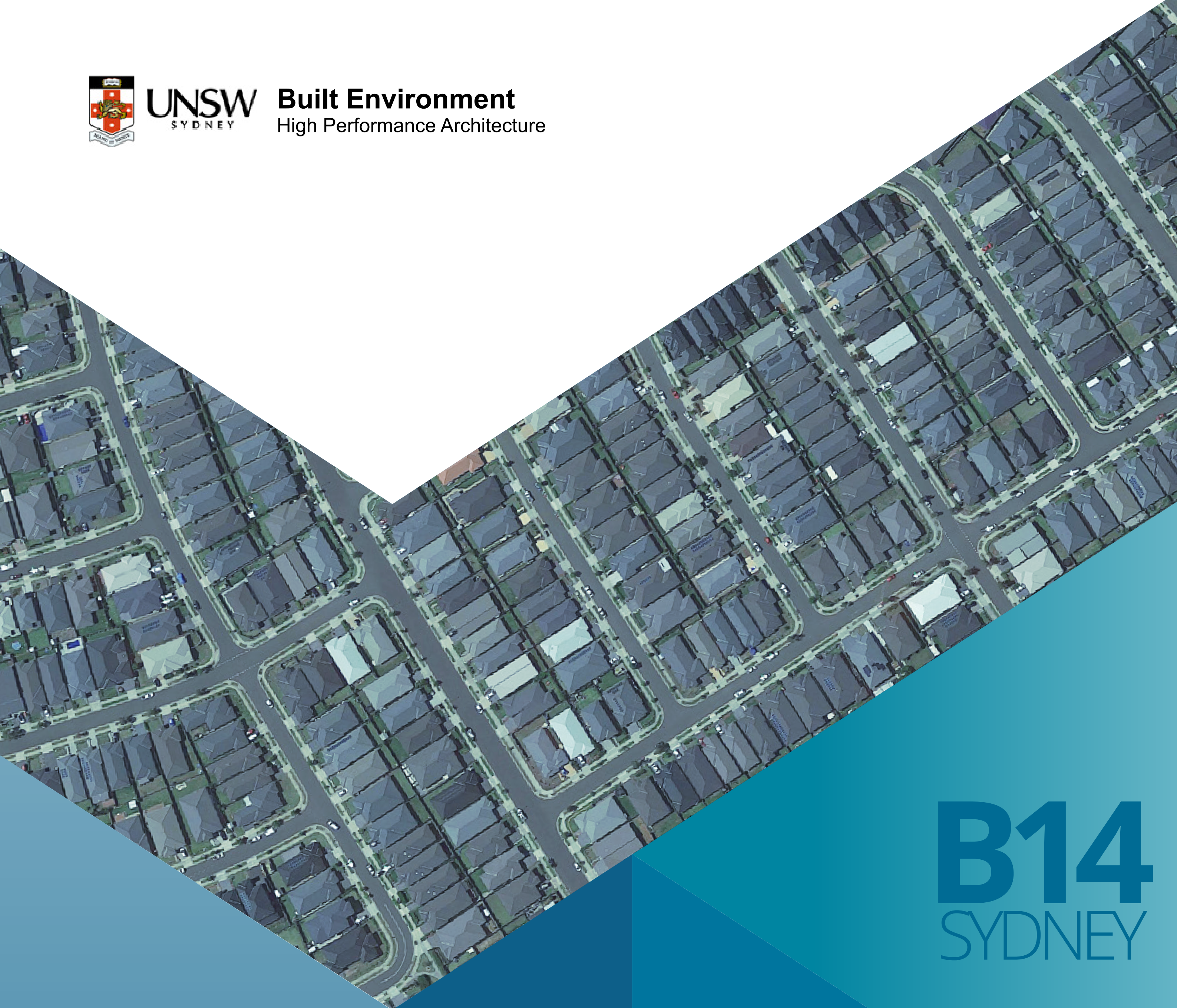
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY
Built Environment
High Performance Architecture



B14
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

Existing high-rise office building with roof insulation
2021

BUILDING 14

EXISTING HIGH-RISE OFFICE BUILDING WITH ROOF INSULATION

Floor area : 1200m^2
Number of stories : 10

Image source: Ecipark Office Building. https://jerseydigs.com/bayonne-city-council-approves-10-story-building-975-broadway/

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the existing high-rise office building with roof insulation from 18.6-24.4 kWh/m² to 17.6-23.0 kWh/m².

Table 1. Sensible and total cooling load for an existing high-rise office building with roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	12.9	19.2	12.0	18.1	8.4	11.1
Terry Hill	14.3	19.2	13.2	18.1	11.6	14.6
Bankstown	16.4	22.0	15.5	20.9	12.5	15.0
Canterbury	13.8	19.8	12.8	18.8	10.1	13.1
Observatory	12.5	18.6	11.7	17.6	9.1	12.4
Richmond	20.6	24.4	19.3	23.0	17.2	19.2
Penrith	18.5	22.5	17.4	21.3	15.5	17.4
Horsley Park	17.7	22.0	16.6	20.8	14.6	16.8
Camden	18.8	22.2	17.7	21.0	15.6	17.0
Olympic Park	15.9	21.7	14.9	20.6	12.6	15.8
Campbelltown	17.3	21.6	16.2	20.4	14.1	16.0

Table 2. Sensible and total cooling load saving for an existing high-rise office building with roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 1.0-1.4 kWh/m² which is equivalent to 5.1-5.7 % total cooling load reduction.

For Scenario 2, the total cooling load saving is around 4.6-8.1 kWh/m² which is equivalent to 121.3-42.2 % of total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	0.9	7.0	1.1	5.7	4.5	34.9	8.1	42.2
Terry Hill	1.1	7.7	1.1	5.7	2.7	18.9	4.6	24.0
Bankstown	0.9	5.5	1.1	5.0	3.9	23.8	7.0	31.8
Canterbury	1.0	7.2	1.0	5.1	3.7	26.8	6.7	33.8
Observatory	0.8	6.4	1.0	5.4	3.4	27.2	6.2	33.3
Richmond	1.3	6.3	1.4	5.7	3.4	16.5	5.2	21.3
Penrith	1.1	5.9	1.2	5.3	3.0	16.2	5.1	22.7
Horsley Park	1.1	6.2	1.2	5.5	3.1	17.5	5.2	23.6
Camden	1.1	5.9	1.2	5.4	3.2	17.0	5.2	23.4
Olympic Park	1.0	6.3	1.1	5.1	3.3	20.8	5.9	27.2
Campbelltown	1.1	6.4	1.2	5.6	3.2	18.5	5.6	25.9

In the eleven weather stations in Sydney, the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the existing high-rise office building with roof insulation during the summer season.

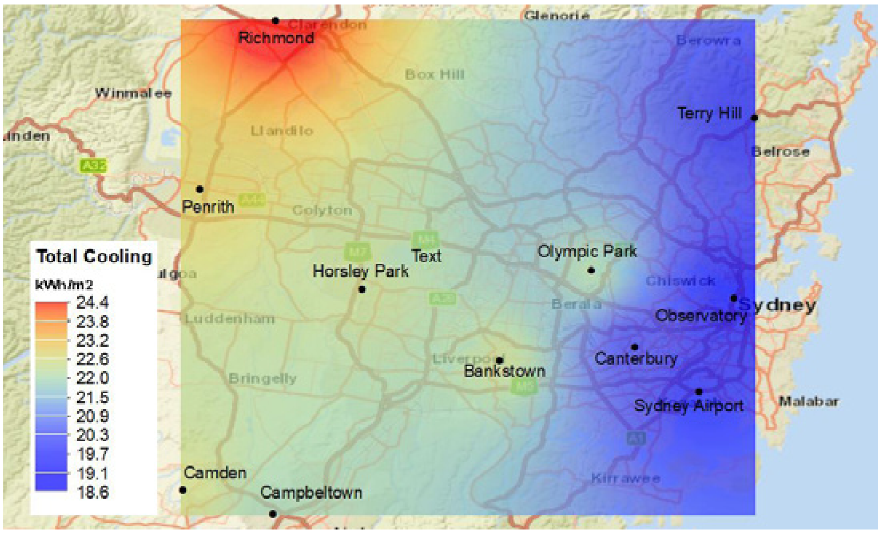


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban scale.

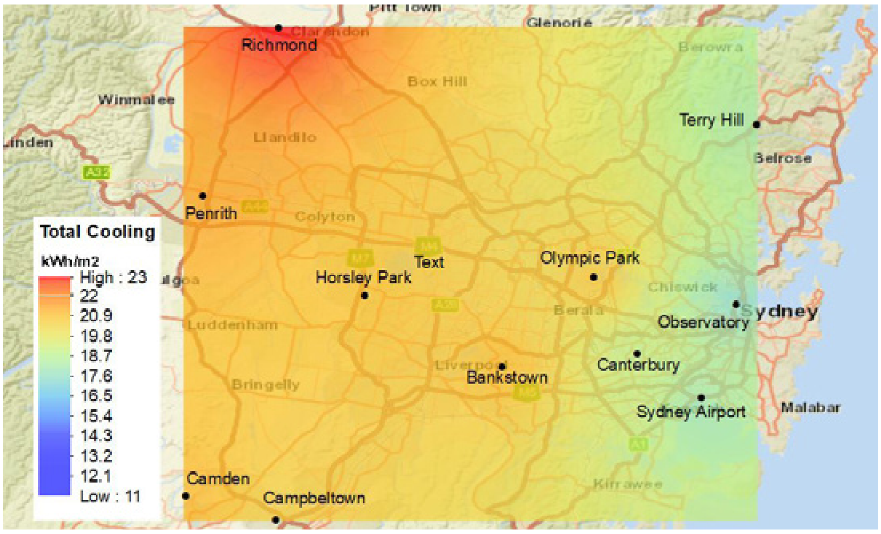


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. Januray and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

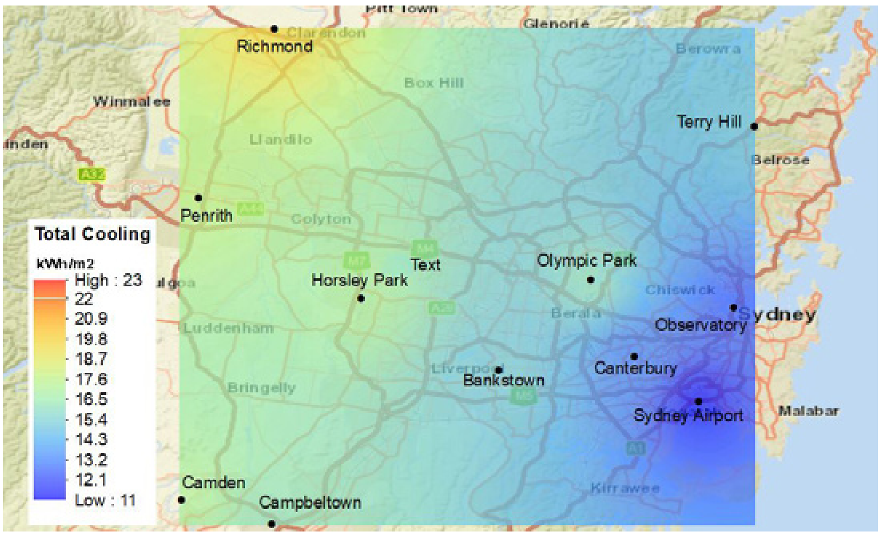


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing high-rise office building with insulation with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

Table 3. Annual cooling and heating loads for an existing high-rise office building with roof insulation for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.1-0.2 kWh/m²) is significantly lower than the annual cooling load reduction (1.3-2.6 kWh/m²).

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	26.7	35.2	0.3	0.9	25.5	33.9	0.4	1.0
Terry Hill	17.9	24.9	0.7	2.0	16.6	23.4	0.8	2.1
Bankstown	30.8	39.8	0.8	2.3	29.2	37.9	0.9	2.4
Canterbury	24.8	33.0	0.8	2.4	23.4	31.4	0.8	2.5
Observatory	27.0	35.1	0.4	1.0	25.5	33.4	0.4	1.1
Richmond	34.7	44.5	1.3	3.4	32.9	42.4	1.4	3.6
Penrith	36.2	46.0	0.9	2.4	34.0	43.4	0.9	2.5
Horsley Park	29.9	37.1	0.9	2.5	28.0	35.0	1.0	2.7
Camden	29.3	36.0	1.5	4.0	27.6	34.1	1.6	4.2
Olympic Park	30.3	40.8	0.7	2.0	28.3	38.6	0.8	2.1
Campbelltown	28.2	34.2	1.4	3.6	26.4	32.2	1.5	3.7

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building with roof insulation using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 3.7-6.0 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.2 and 2.5 kWh/m² (~3.3-5.2 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	1.2	4.5	1.3	3.7	0.1	0.1	1.1	4.1	1.2	3.3
Terry Hill	1.3	7.3	1.5	6.0	0.1	0.1	1.2	6.5	1.4	5.2
Bankstown	1.6	5.2	1.9	4.8	0.1	0.1	1.5	4.7	1.8	4.3
Canterbury	1.4	5.6	1.6	4.8	0.0	0.1	1.4	5.5	1.5	4.2
Observatory	1.5	5.6	1.7	4.8	0.0	0.1	1.5	5.5	1.6	4.4
Richmond	1.8	5.2	2.1	4.7	0.1	0.2	1.7	4.7	1.9	4.0
Penrith	2.2	6.1	2.6	5.7	0.0	0.1	2.2	5.9	2.5	5.2
Horsley Park	1.9	6.4	2.1	5.7	0.1	0.2	1.8	5.8	1.9	4.8
Camden	1.7	5.8	1.9	5.3	0.1	0.2	1.6	5.2	1.7	4.2
Olympic Park	2.0	6.6	2.2	5.4	0.1	0.1	1.9	6.1	2.1	4.9
Campbelltown	1.8	6.4	2.0	5.8	0.1	0.1	1.7	5.7	1.9	5.0

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 °C in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

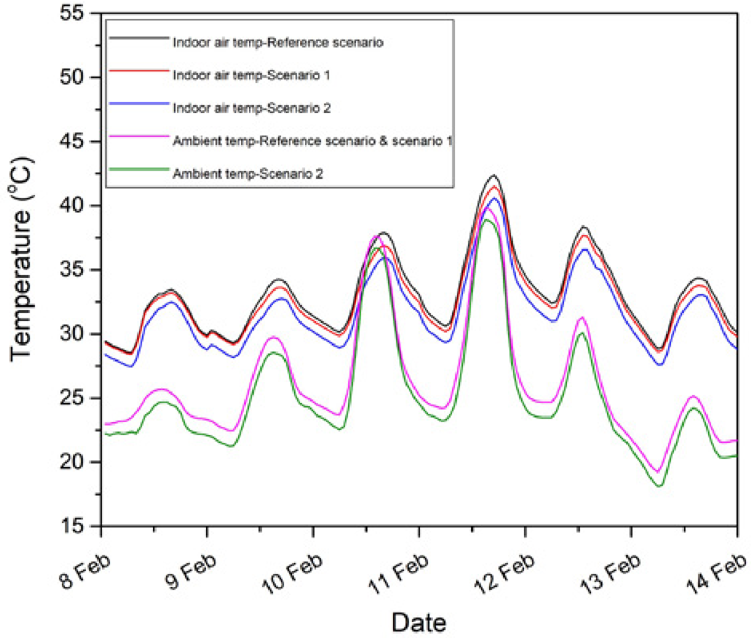


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

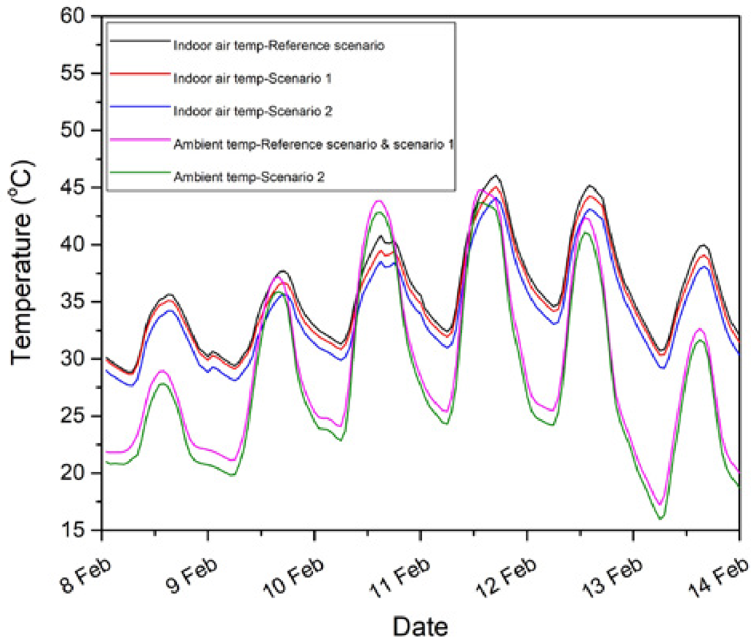


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 28.4-42.4 °C and 28.9-46.1 °C in Observatory and Richmond stations, respectively.

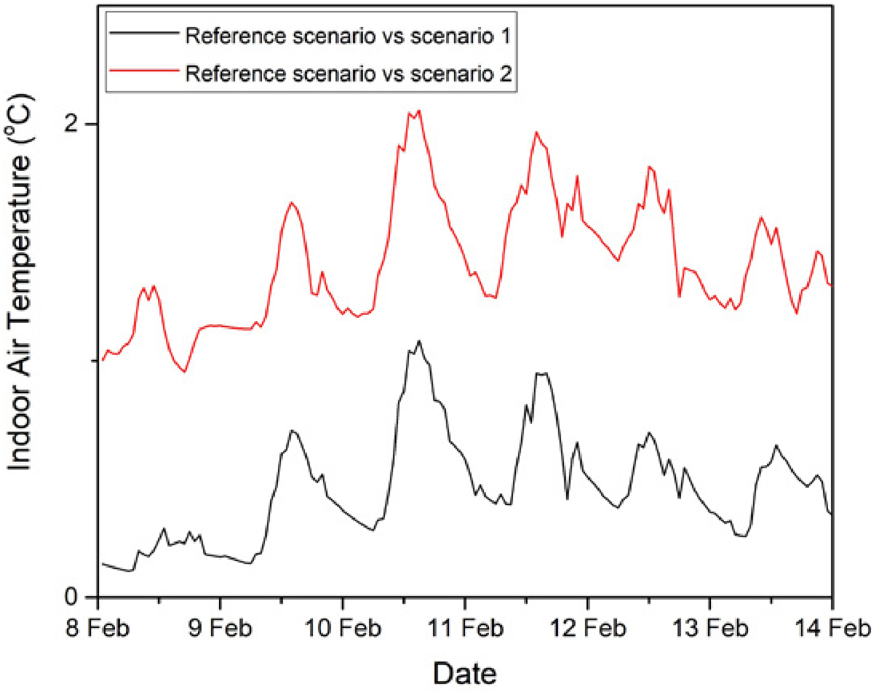


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 1.1 °C and 1.3 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.1 and 2.3 °C in Observatory and Richmond stations, respectively.

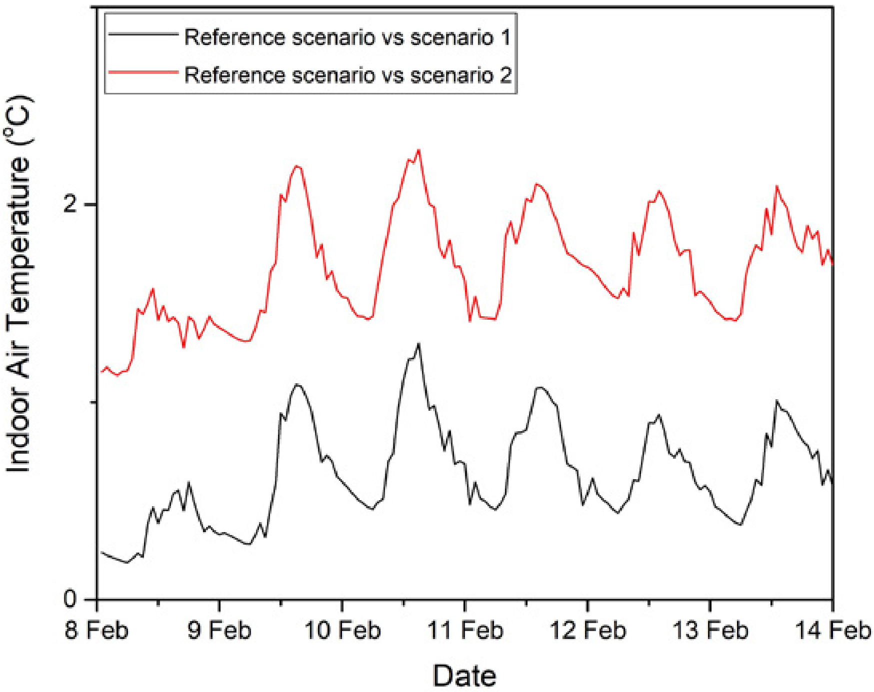


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise office building with insulation under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to remain almost the same in reference scenario and reference with cool roof scenario (scenario 1) in Observatory Hill and Richmond stations, respectively.

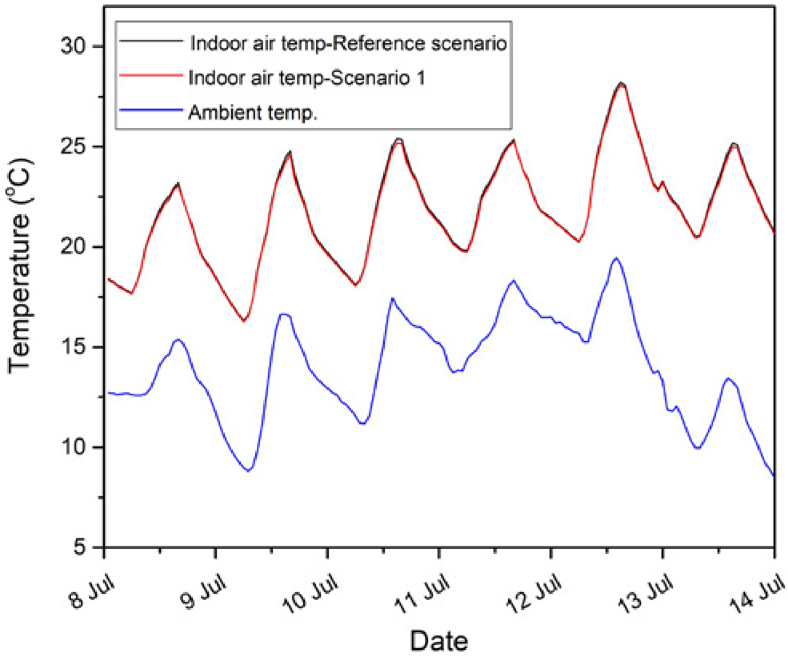


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise office building with insulation under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

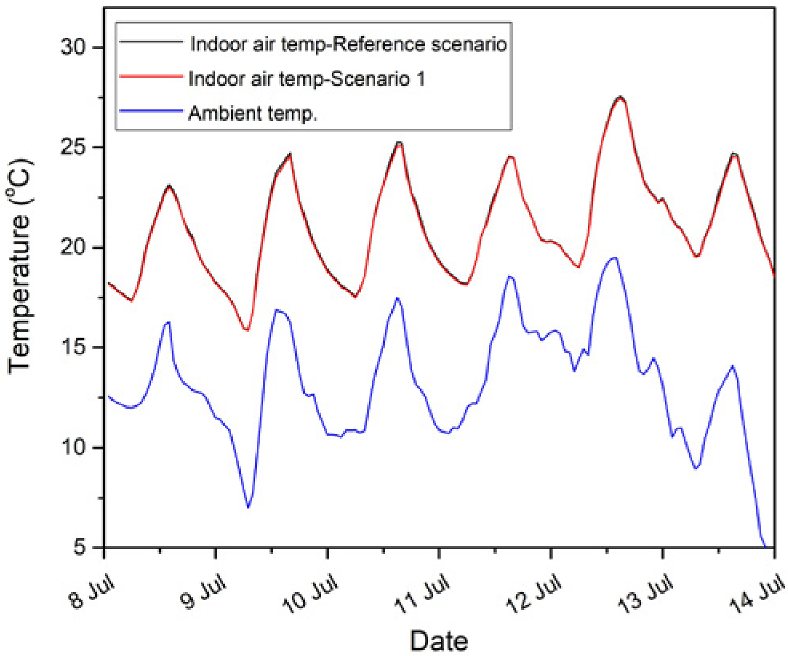


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise office building with insulation under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C and 0.3 °C in Observatory and Richmond stations, respectively.

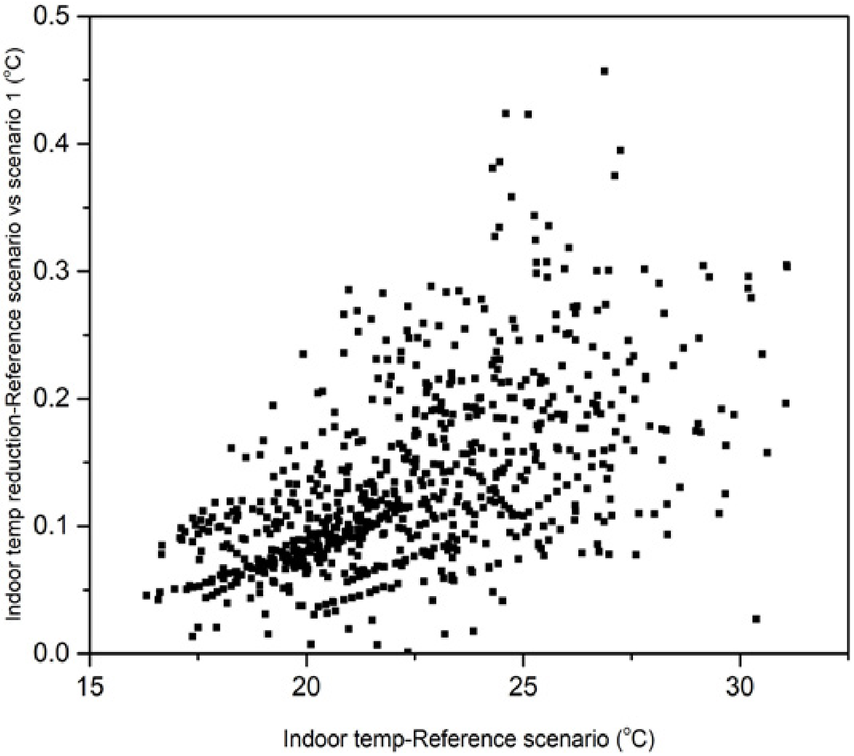


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building without insulation under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

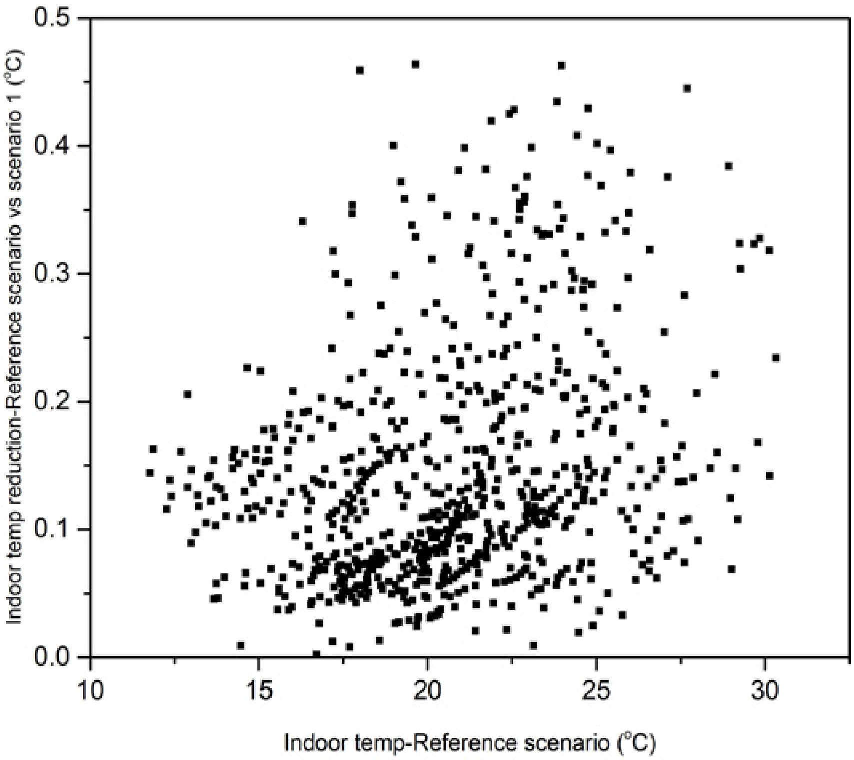


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise office building without insulation under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	26	88	27	93
Richmond	69	241	75	249

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 26 hours in reference scenario to 27 and hours and from 69 to 75 hours in scenario 1 in Observatory and Richmond stations, respectively.

The number operational hours with air temperature <19 °C during is expected to slightly increase from 88 hours in reference scenario to 93 hours; and from 241 to 249 hours in scenario 1 in Observatory and Richmond stations, respectively.

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	670	670	650
Richmond	657	653	625

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decrease from 670 hours in reference scenario to 670 and 650 hours under scenario 1 and 2, in Observatory station; and from 657 hours in reference scenario to 653 and 625 hours under scenario 1 and 2 in Richmond station, respectively.

6

CONCLUSIONS

• It is estimated that the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the existing high-rise office building with insulation during the summer season. Overall, the simulation results indicate that the cooling load reductions by cool roofs can be significant if they are implemented at an urban-scale.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing high-rise office building from 18.6-24.4 kWh/m^2 to 17.6-23.0 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 1.0-1.4 kWh/m^2. This is equivalent to approximately 5.1-5.7 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 4.6-8.1 kWh/m^2. This is equivalent to 1.3-2.6 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.1-0.2 kWh/m^2) is significantly lower than the annual cooling load reduction (24.6-43.1 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 3.7-6.0 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 1.2 and 2.5 kWh/m^2 (~3.3-5.2 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 28.4- 42.4 °C and 28.9-46.1 °C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 1.1 and 1.3 °C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.1 and 2.3 °C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 °C in reference scenario to a range between 18.1 and 38.9 °C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 °C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 °C in reference scenario to 15.9-43.6 °C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 °C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to remain almost the same in reference scenario and reference with cool roof scenario (scenario 1) in Observatory Hill and

Richmond stations, respectively (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C and 0.3 °C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to increase slightly from 88 hours in reference scenario to 93 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slight increase in total number of hours below 19 °C from 241 hours in reference scenario to 249 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 °C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 °C during operational hours of the building (i.e. Monday to Friday, 7 am-6 pm) is expected to increase from 26 hours in reference scenario to 27 hours in reference with cool roof scenario (scenario 1) in Observatory station. Similarly, the calculation in Richmond station shows a slight increase of number of hours below 19 °C from 69 hours to 75 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 670 hours under the reference scenario in Observatory station, which decreases to 670 and 650 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 °C from 657 hours in reference scenario to 653 in reference with cool roof scenario (scenario 1) and 625 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B14

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

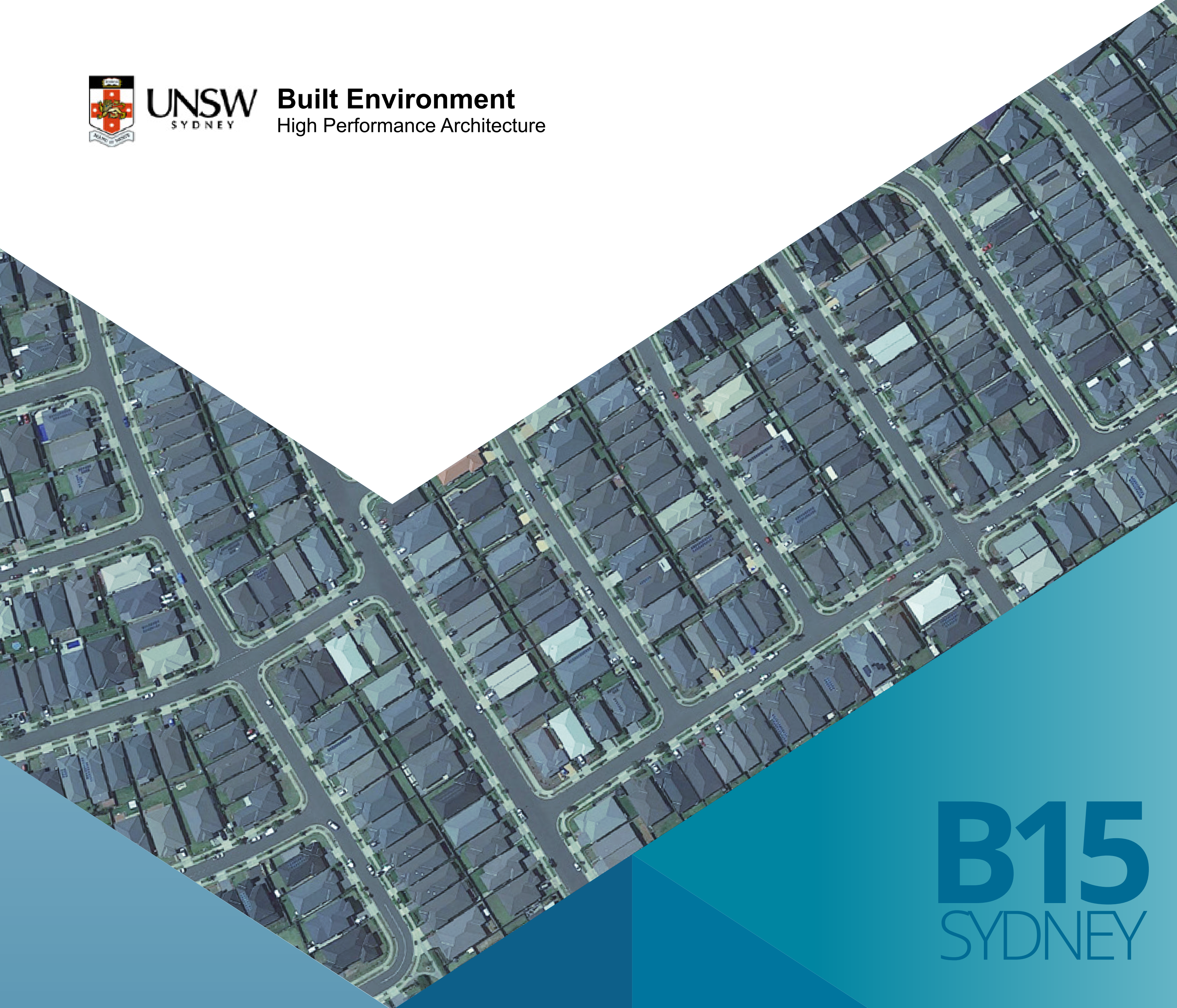
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY
Built Environment
High Performance Architecture



B15 SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

Existing low-rise shopping mall centre
2021

BUILDING 15

EXISTING LOW-RISE SHOPPING MALL CENTRE

Floor area : 1100m²
Number of stories : 2

Image source: Westfield Tea Tree Plaza, Tea Tree Plaza 976 North East Rd, Modbury, Tea Tree Gully, South Australia 5092, Australia

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of the existing low-rise shopping mall centre from 80.3-87. kWh/m² to 71.4-77.4 kWh/m².

Table 1. Sensible and total cooling load for an existing low-rise shopping mall centre without roof insulation for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	55.3	82.7	48.4	75.0	44.0	58.2
Terry Hill	59.4	80.3	51.2	71.4	48.7	61.8
Bankstown	61.2	83.2	53.9	75.3	49.9	59.9
Canterbury	56.7	82.0	49.8	74.4	45.9	60.2
Observatory	54.9	81.7	48.0	74.1	45.1	61.8
Richmond	71.6	87.5	62.0	77.4	59.1	66.5
Penrith	66.4	82.6	58.3	73.9	55.3	62.8
Horsley Park	64.8	82.1	56.7	73.4	51.3	60.0
Camden	67.3	81.5	59.2	72.9	55.7	61.1
Olympic Park	60.2	83.4	53.0	75.5	50.2	63.4
Campbelltown	64.0	81.3	56.1	72.8	52.7	60.4

For Scenario 1, the total cooling load saving is around 7.7-10.1 kWh/m² which is equivalent to 9.3-11.5 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 18.5-24.5 kWh/m² which is equivalent to 23.0-29.6 % total cooling load reduction.

Table 2. Sensible and total cooling load saving for an existing low-rise shopping mall centre without roof insulation for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	6.9	12.5	7.7	9.3	11.3	20.4	24.5	29.6
Terry Hill	8.2	13.8	8.9	11.1	10.7	18.0	18.5	23.0
Bankstown	7.3	11.9	7.9	9.5	11.3	18.5	23.3	28.0
Canterbury	6.9	12.2	7.6	9.3	10.8	19.0	21.8	26.6
Observatory	6.9	12.6	7.6	9.3	9.8	17.9	19.9	24.4
Richmond	9.6	13.4	10.1	11.5	12.5	17.5	21.0	24.0
Penrith	8.1	12.2	8.7	10.5	11.1	16.7	19.8	24.0
Horsley Park	8.1	12.5	8.7	10.6	13.5	20.8	22.1	26.9
Camden	8.1	12.0	8.6	10.6	11.6	17.2	20.4	25.0
Olympic Park	7.2	12.0	7.9	9.5	10.0	16.6	20.0	24.0
Campbelltown	7.9	12.3	8.5	10.5	11.3	17.7	20.9	25.7

In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs can reduce the cooling load of the existing low-rise shopping mall centre with insulation during the summer season.

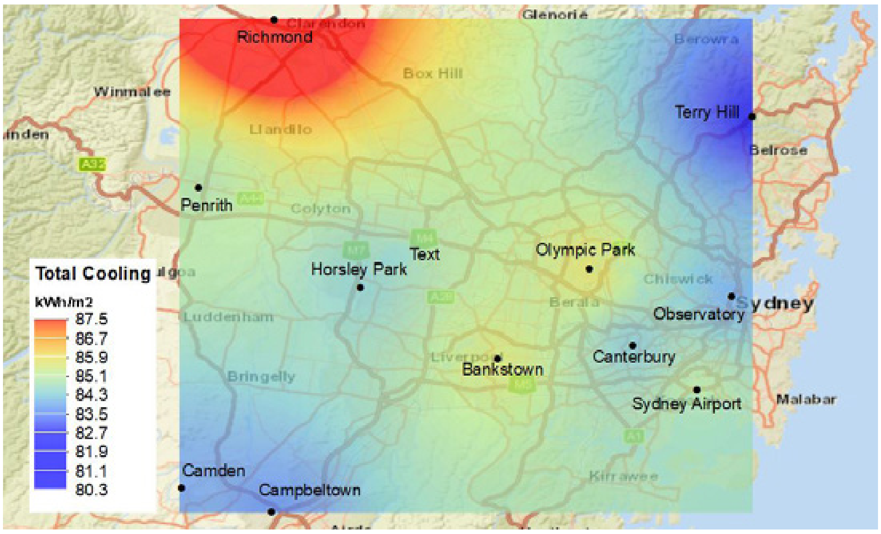


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

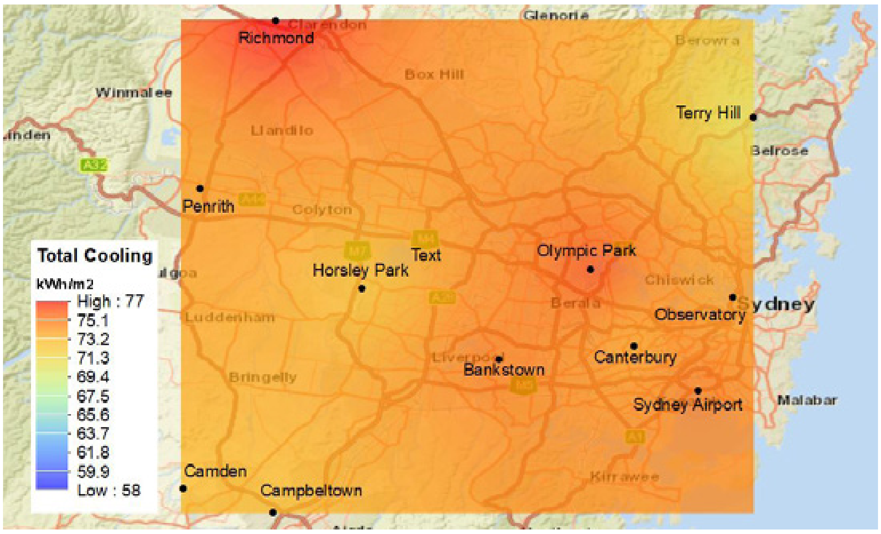


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

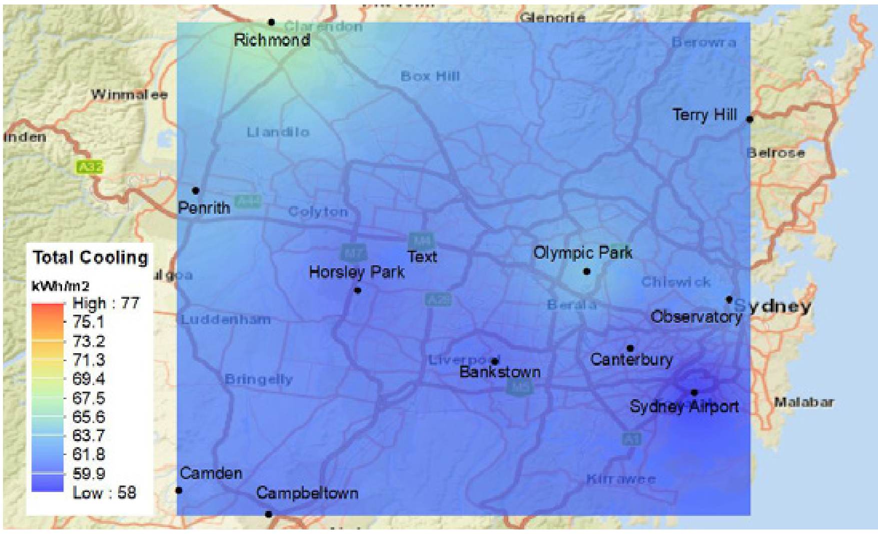


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing low-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.1-0.7 kWh/m²) is significantly lower than the annual cooling load reduction (20.1-31.5 kWh/m²).

Table 3. Annual cooling and heating loads for an existing low-rise shopping mall centre for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	177.6	227.8	0.8	2.2	158.7	207.7	0.9	2.3
Terry Hill	157.2	214.7	1.4	4.3	130.7	185.7	1.5	4.6
Bankstown	183.6	228.1	1.8	5.3	160.1	203.1	1.9	5.6
Canterbury	167.8	212.3	1.6	5.4	145.4	188.4	1.8	5.9
Observatory	180.6	222.2	0.9	2.4	157.3	197.6	0.9	2.6
Richmond	188.8	237.4	2.4	7.5	164.2	211.1	2.5	7.9
Penrith	202.1	252.3	1.7	5.4	172.5	220.8	1.9	5.8
Horsley Park	185.1	223.5	1.9	5.7	156.7	193.7	2.1	6.1
Camden	175.7	209.7	2.8	9.0	150.3	183.0	3.0	9.7
Olympic Park	189.9	245.4	1.6	4.6	163.0	216.6	1.6	4.9
Campbelltown	174.4	206.3	2.6	7.9	148.0	178.6	2.8	8.4

The annual cooling load saving by building-scale application of cool roofs is around 8.8-13.5 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 20.0 and 31.1 kWh/m² (~8.7-12.8 %).

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	18.9	10.6	20.1	8.8	0.1	0.1	18.8	10.5	20.0	8.7
Terry Hill	26.5	16.9	29.0	13.5	0.1	0.3	26.4	16.6	28.7	13.1
Bankstown	23.5	12.8	25.0	11.0	0.1	0.3	23.4	12.6	24.7	10.6
Canterbury	22.4	13.3	23.9	11.3	0.2	0.5	22.2	13.1	23.4	10.7
Observatory	23.3	12.9	24.6	11.1	0.0	0.2	23.3	12.8	24.4	10.9
Richmond	24.6	13.0	26.3	11.1	0.1	0.4	24.5	12.8	25.9	10.6
Penrith	29.6	14.6	31.5	12.5	0.2	0.4	29.4	14.4	31.1	12.1
Horsley Park	28.4	15.3	29.8	13.3	0.2	0.4	28.2	15.1	29.4	12.8
Camden	25.4	14.5	26.7	12.7	0.2	0.7	25.2	14.1	26.0	11.9
Olympic Park	26.9	14.2	28.8	11.7	0.0	0.3	26.9	14.0	28.5	11.4
Campbelltown	26.4	15.1	27.7	13.4	0.2	0.5	26.2	14.8	27.2	12.7

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

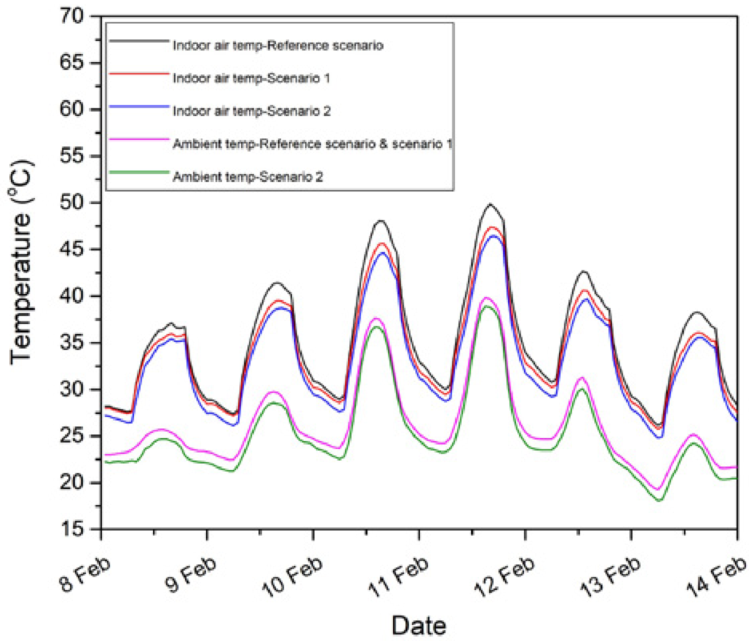


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

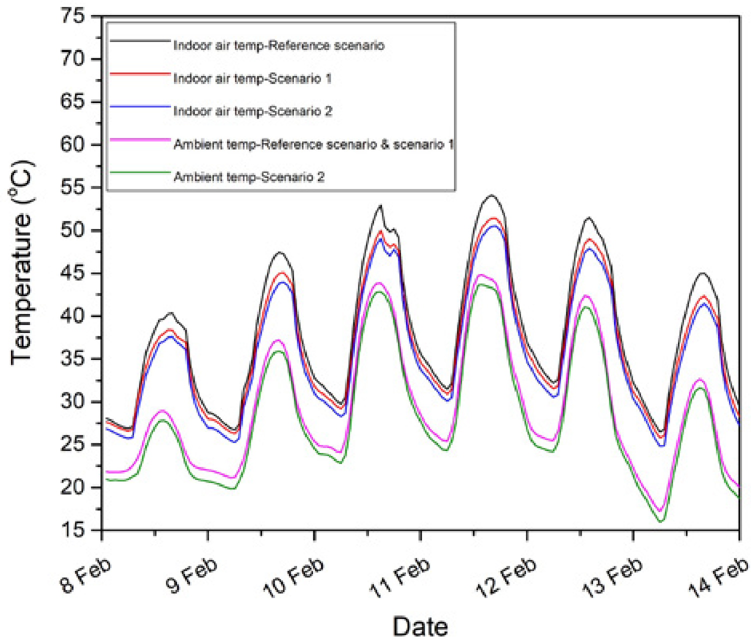


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

During a typical summer week, the indoor air temperature of the reference scenario ranges between 26.1-49.9 °C and 26.4-54.1 °C in Observatory and Richmond stations, respectively.

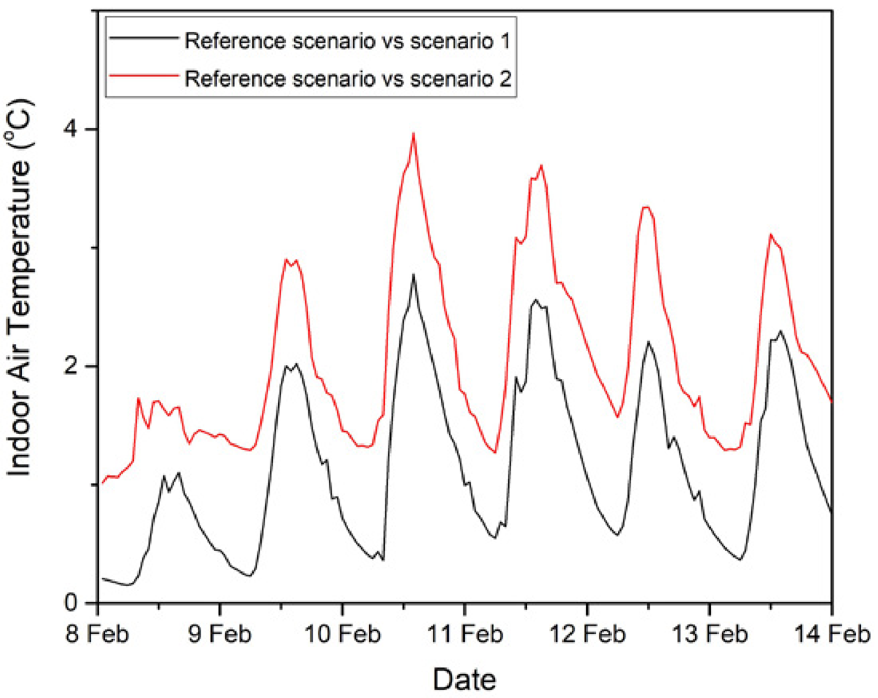


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing low-rise shopping mall centre under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.8 °C and 3.0 °C in Observatory and Richmond stations, respectively.

For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 4.0 °C and 4.0 °C in Observatory and Richmond stations, respectively.

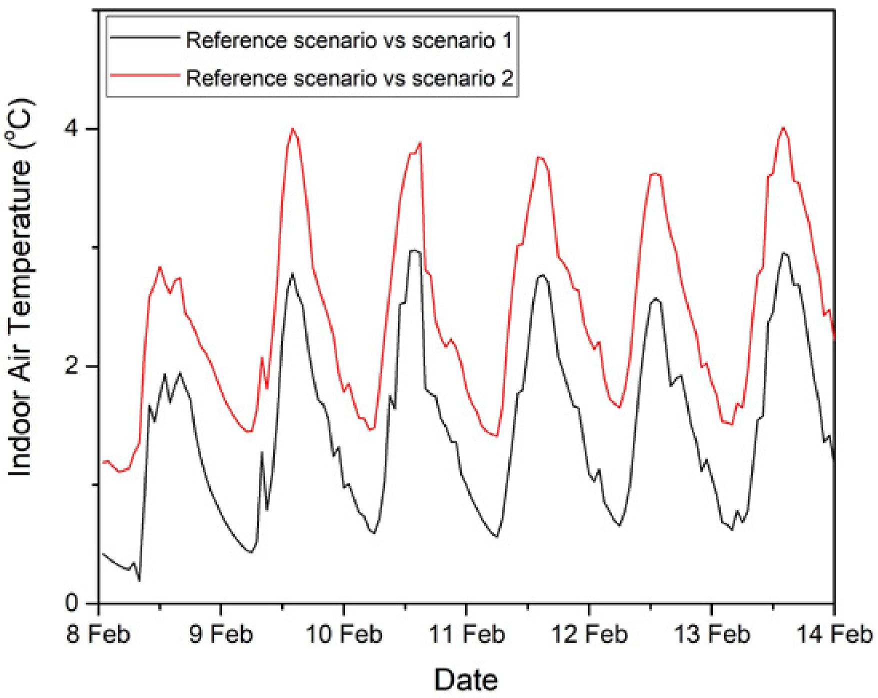


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) an existing new low-rise shopping mall centre under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease slightly from a range 13.4-31.9 °C in reference scenario to a range 13.3-31.3 °C in scenario 1 in Observatory Hill station.

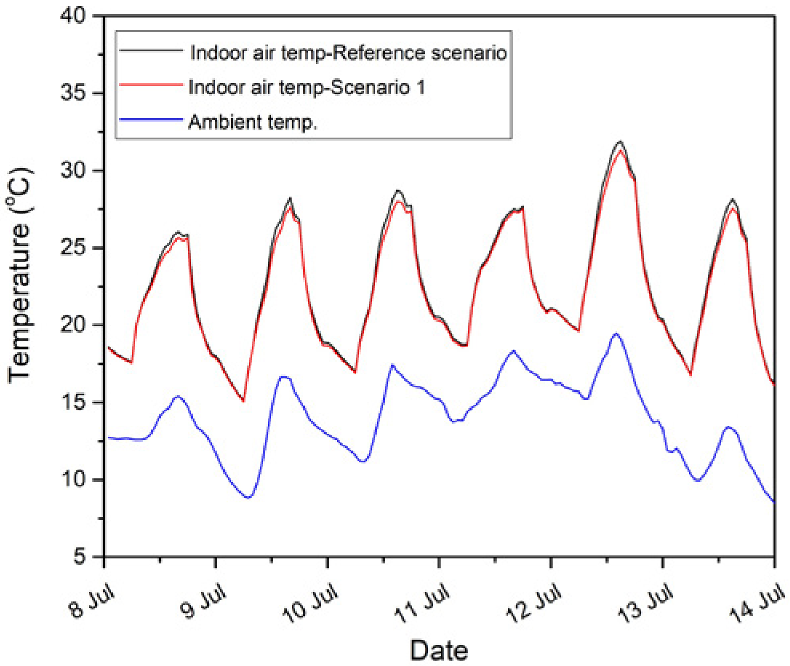


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 8.2-31.3 °C in reference scenario to a range 8.1-30.8 °C in scenario 1 in Richmond station.

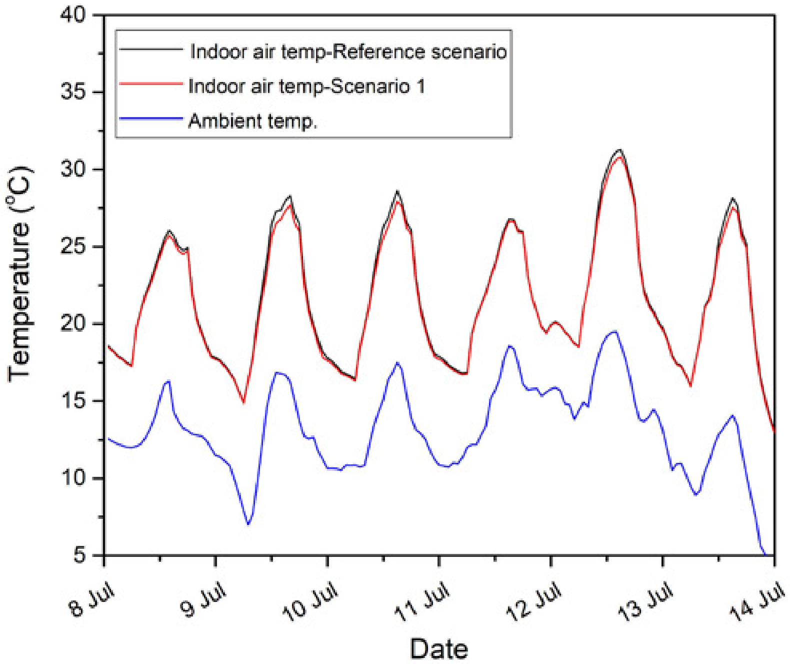


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.9 °C and 0.9 °C in Observatory and Richmond stations, respectively.

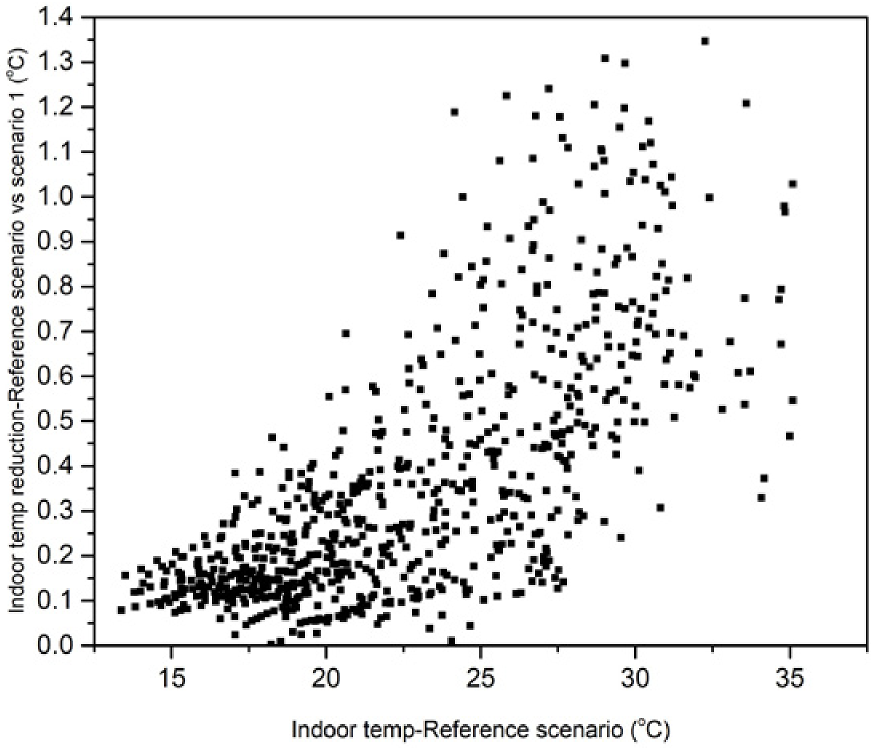


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

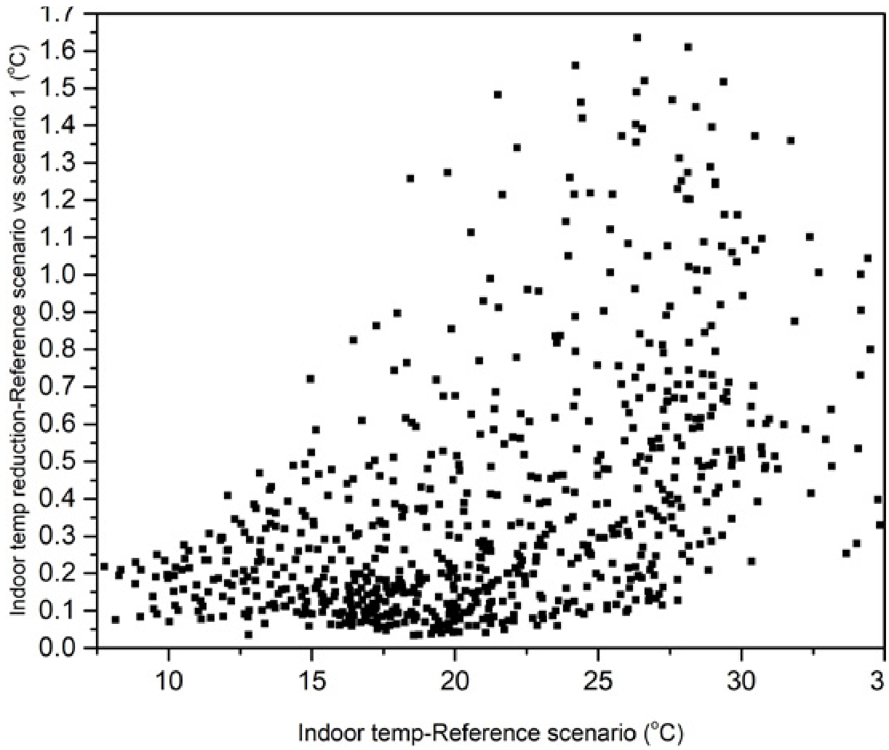


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing low-rise shopping mall centre under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	32	208	34	217
Richmond	60	293	62	302

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to slightly increase from 208 hours in reference scenario to 217 hours, and from 293 to 302 hours in scenario 1 in Observatory and Richmond stations, respectively.

The number operational hours with air temperature <19 °C during slightly increase from 32 hours in reference scenario compared to 34 hours in scenario 1 in Observatory; and from 60 to 62 hours in Richmond station.

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	658	650	595
Richmond	624	604	570

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decreased from 658 hours in reference scenario to 650 and 595 hours under scenario 1 and 2 in Observatory station; and from 624 hours in reference scenario to 604 and 570 hours under scenario 1 and 2 in Richmond station, respectively.

6

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of the existing low-rise shopping mall centre during the summer season.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of the existing low-rise shopping mall centre from 80.3-87.5 kWh/m^2 to 71.4-77.4 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 7.7-10.1 kWh/m^2. This is equivalent to approximately 9.3-11.5 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 18.5-24.5 kWh/m^2. This is equivalent to 23-29.6 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.1-0.7 kWh/m^2) is significantly lower than the annual cooling load reduction (20.1-31.5 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 8.8-13.5 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 20.0 and 31.1 kWh/m^2 (~8.7-12.8%) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 26.1-49.9 ^oC and 26.4-54.1 ^oC in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 2.8 and 3.0 ^oC in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 4.0 and 4.0 ^oC by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 ^oC in reference scenario to a range between 18.1 and 38.9 ^oC in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 ^oC. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 ^oC in reference scenario to 15.9-43.6 ^oC in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 ^oC in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 13.4 and 31.9 ^oC in reference scenario to a range between 13.3 and 31.3 ^oC in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 8.2 and 31.3 ^{o}C in reference scenario to a range between 8.1 and 30.8 ^{o}C in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.9 ^{o}C and 0.9 ^{o}C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase slightly from 208 hours in reference scenario to 217 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slight increase in total number of hours below 19 ^{o}C from 293 hours in reference scenario to 302 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 oC between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building.

The number of hours below 19 ^{o}C during operational hours of the building (i.e. 7 am-6 pm) is expected to increase from 32 hours in reference scenario to 34 hours in reference with cool roof scenario (scenario 1) in Observatory station. Similarly, the calculation in Richmond station shows a slight increase of number of hours below 19 oC from 60 hours to 62 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 ^{o}C is 658 hours under the reference scenario in Observatory station, which decreases to 650 and 595 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 ^{o}C from 624 hours in reference scenario to 604 in reference with cool roof scenario (scenario 1) and 570 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B15

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

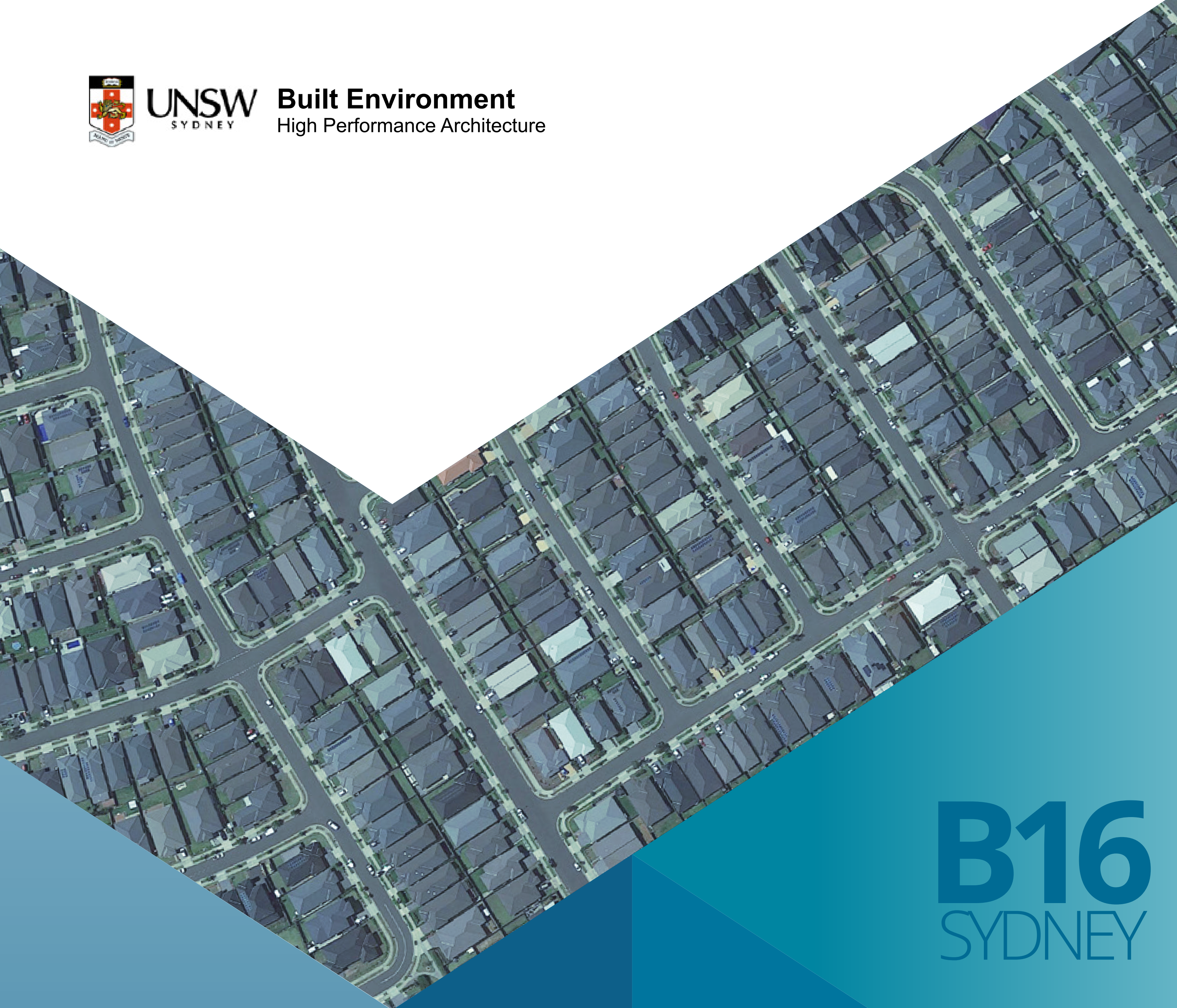
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

Built Environment
High Performance Architecture



B16
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

Existing high-rise shopping mall centre
2021

BUILDING 16

EXISTING HIGH-RISE SHOPPING MALL CENTRE

Floor area : 1100m^2
Number of stories : 6

Image source: Mall of America, Minneapolis

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1: Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 : Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

The building-scale application of cool roofs can decrease the two summer months total cooling load of an existing high-rise shopping mall centre from 75.9-82.6 kWh/m² to 73.1-79.3 kWh/m².

Table 1. Sensible and total cooling load for an existing high-rise shopping mall centre for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)	Sensible cooling (kWh/m^2)	Total cooling (kWh/m^2)
Sydney Airport	52.0	79.2	49.9	76.9	45.6	60.2
Terry Hill	55.1	75.9	52.5	73.1	50.4	63.7
Bankstown	57.5	79.4	55.2	76.9	51.5	61.7
Canterbury	53.2	78.4	51.1	76.1	47.5	62.1
Observatory	51.5	78.2	49.4	75.9	46.7	63.8
Richmond	66.8	82.6	63.7	79.3	60.7	68.4
Penrith	62.2	78.2	59.6	75.5	56.8	64.5
Horsley Park	60.5	77.8	58.0	75.1	52.3	61.2
Camden	63.0	77.1	60.5	74.4	57.0	62.6
Olympic Park	56.5	79.5	54.2	77.1	51.7	65.2
Campbelltown	59.9	77.0	57.4	74.4	54.2	62.2

Table 2. Sensible and total cooling load saving for an existing high-rise shopping mall centre for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 2.3-3.3 kWh/m² which is equivalent to 2.9-4.0 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 12.2-19.0 kWh/m² which is equivalent to 16.1-24.0 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%	kWh/m^2	%
Sydney Airport	2.1	4.0	2.3	2.9	6.4	12.3	19.0	24.0
Terry Hill	2.6	4.7	2.8	3.7	4.7	8.5	12.2	16.1
Bankstown	2.3	4.0	2.5	3.1	6.0	10.4	17.7	22.3
Canterbury	2.1	3.9	2.3	2.9	5.7	10.7	16.3	20.8
Observatory	2.1	4.1	2.3	2.9	4.8	9.3	14.4	18.4
Richmond	3.1	4.6	3.3	4.0	6.1	9.1	14.2	17.2
Penrith	2.6	4.2	2.7	3.5	5.4	8.7	13.7	17.5
Horsley Park	2.5	4.1	2.7	3.5	8.2	13.6	16.6	21.3
Camden	2.5	4.0	2.7	3.5	6.0	9.5	14.5	18.8
Olympic Park	2.3	4.1	2.4	3.0	4.8	8.5	14.3	18.0
Campbelltown	2.5	4.2	2.6	3.4	5.7	9.5	14.8	19.2

In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs can significantly reduce the cooling load of an existing high-rise shopping mall centre during the summer season.

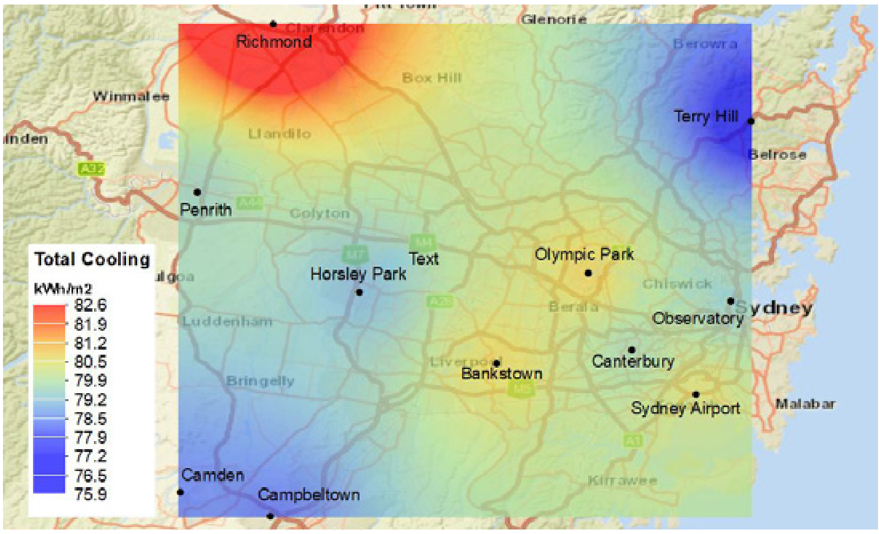


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

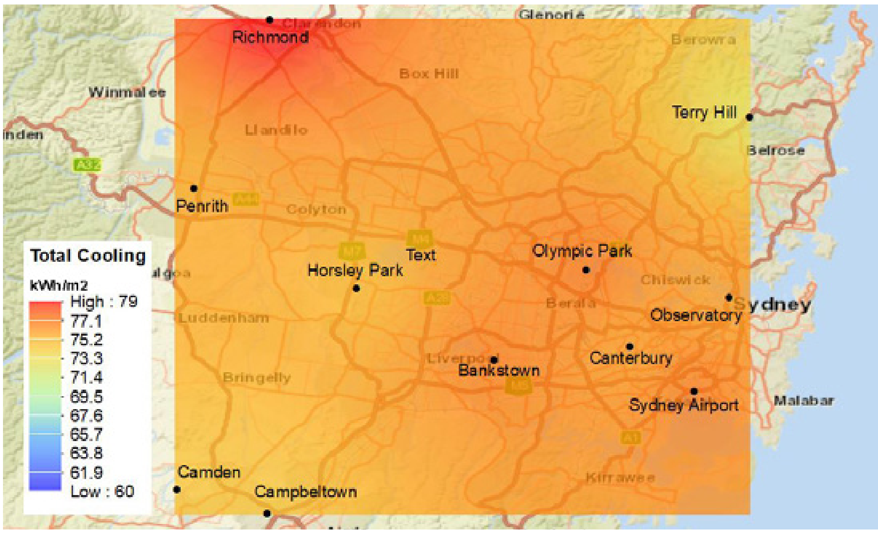


Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

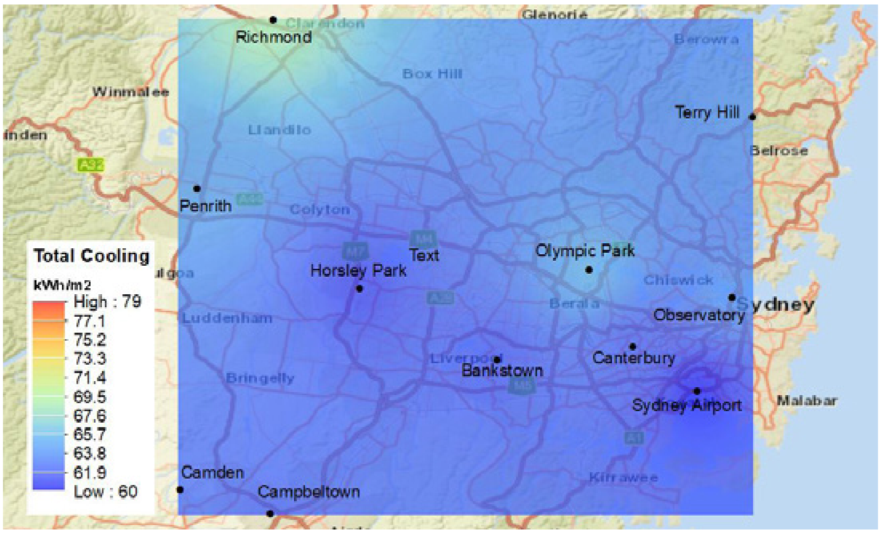


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for an existing high-rise shopping mall centre with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.0-0.2 kWh/m²) is significantly lower than the annual cooling load reduction (5.6-9.6 kWh/m²).

Table 3. Annual cooling and heating loads for an existing high-rise shopping mall centre for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m^2)		Annual heating load (kWh/m^2)		Annual cooling load (kWh/m^2)		Annual heating load (kWh/m^2)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	171.3	221.8	0.5	1.3	166.0	216.2	0.5	1.3
Terry Hill	144.1	201.5	0.9	2.9	136.3	192.9	0.9	3.0
Bankstown	172.2	216.6	1.1	3.8	165.3	209.4	1.2	3.9
Canterbury	157.9	202.5	1.0	3.7	151.4	195.5	1.0	3.9
Observatory	172.4	214.1	0.5	1.3	165.6	206.9	0.5	1.4
Richmond	175.6	223.9	1.9	6.3	168.2	216.0	1.9	6.4
Penrith	186.0	235.7	1.2	4.0	176.9	226.1	1.2	4.2
Horsley Park	170.4	208.8	1.3	4.2	161.9	199.8	1.3	4.3
Camden	162.0	196.1	2.1	7.4	154.5	188.2	2.2	7.6
Olympic Park	176.2	231.5	1.0	3.2	168.3	223.0	1.0	3.3
Campbelltown	159.6	191.5	1.9	6.2	151.9	183.4	1.9	6.4

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new high-rise shopping mall centre using annual measured weather data for COP=1 for heating and cooling.

The annual cooling load saving by building-scale application of cool roofs is around 2.5-4.3 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 5.6 and 9.4 kWh/m² (~2.5-4.2 %).

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m^2	%	kWh/m^2	%	kWh/m^2		kWh/m^2	%	kWh/m^2	%
Sydney Airport	5.3	3.1	5.6	2.5	0.0	0.0	5.3	3.1	5.6	2.5
Terry Hill	7.8	5.4	8.6	4.3	0.0	0.1	7.8	5.4	8.5	4.2
Bankstown	6.9	4.0	7.2	3.3	0.1	0.1	6.8	3.9	7.1	3.2
Canterbury	6.5	4.1	7.0	3.5	0.0	0.2	6.5	4.1	6.8	3.3
Observatory	6.8	3.9	7.2	3.4	0.0	0.1	6.8	3.9	7.1	3.3
Richmond	7.4	4.2	7.9	3.5	0.0	0.1	7.4	4.2	7.8	3.4
Penrith	9.1	4.9	9.6	4.1	0.0	0.2	9.1	4.9	9.4	3.9
Horsley Park	8.5	5.0	9.0	4.3	0.0	0.1	8.5	5.0	8.9	4.2
Camden	7.5	4.6	7.9	4.0	0.1	0.2	7.4	4.5	7.7	3.8
Olympic Park	7.9	4.5	8.5	3.7	0.0	0.1	7.9	4.5	8.4	3.6
Campbelltown	7.7	4.8	8.1	4.2	0.0	0.2	7.7	4.8	7.9	4.0

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

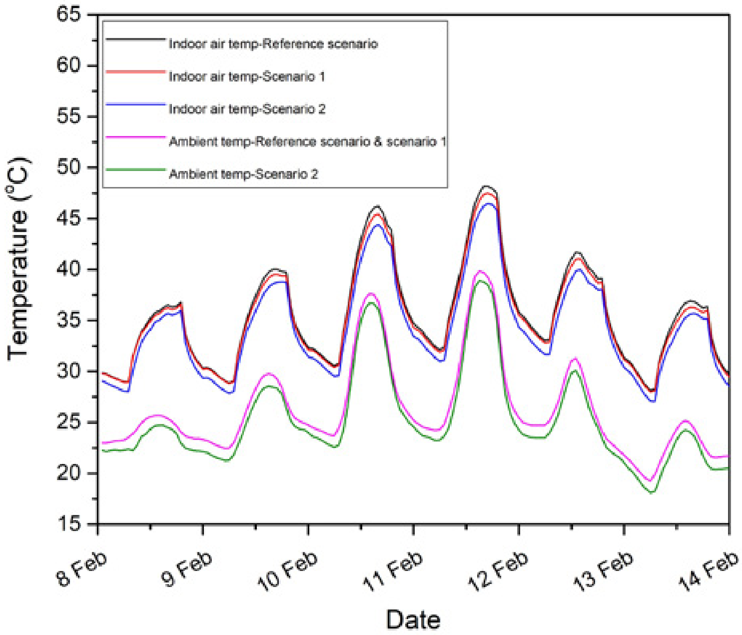


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

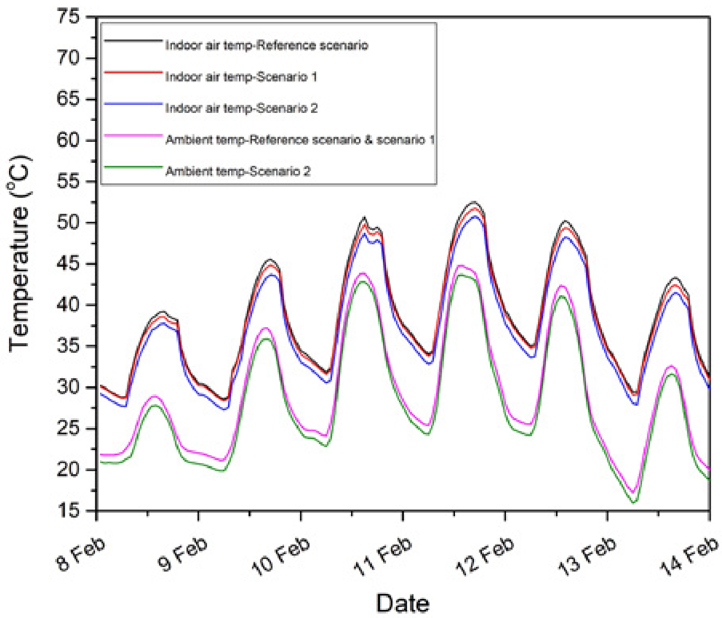


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

> *During a typical summer week, the indoor air temperature of the reference scenario ranges between 28.1-48.2 °C and 28.3-52.5 °C in Observatory and Richmond stations, respectively.*

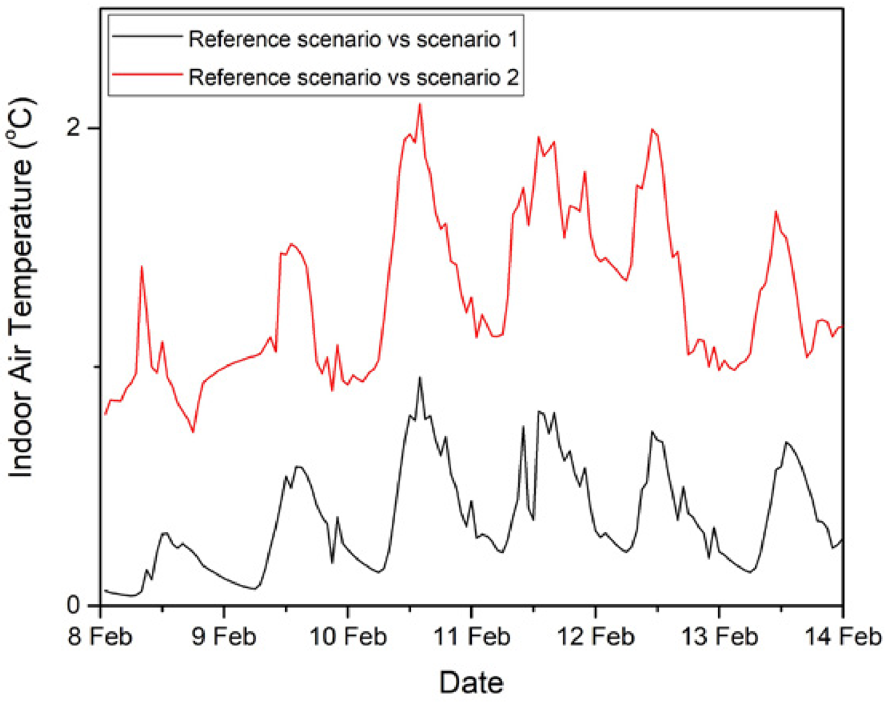


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing high-rise shopping mall centre under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

> *For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 1.0 °C and 1.1 °C in Observatory and Richmond stations, respectively.*

> *For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 2.1 °C and 2.2 °C in Observatory and Richmond stations, respectively.*

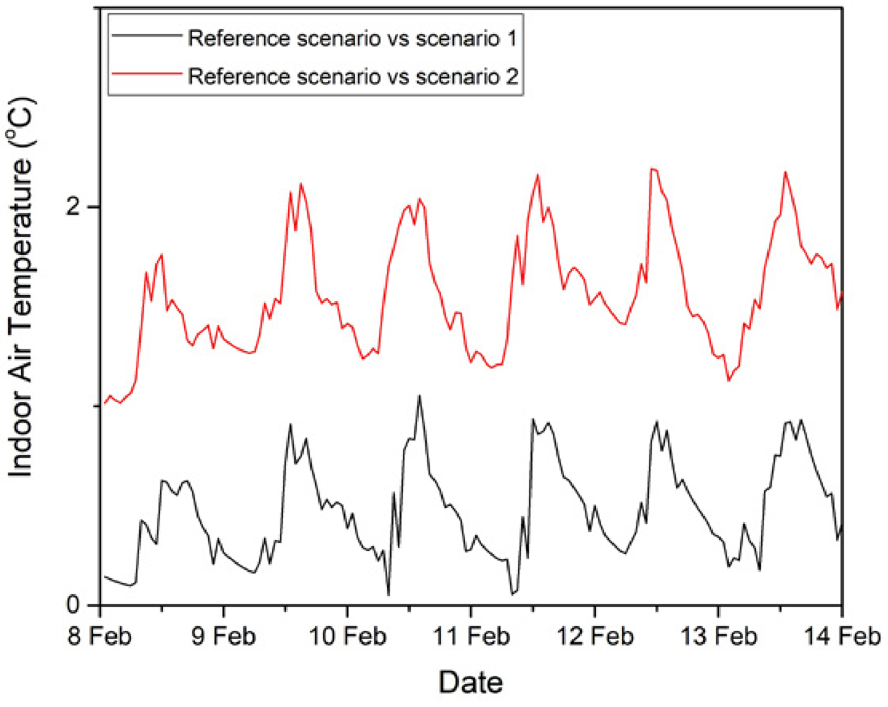


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for an existing highrise shopping mall centre under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to slightly decrease from a range 15.5-31.5 °C in reference scenario to a range 15.5-31.4 °C in scenario 1 in Observatory Hill station.

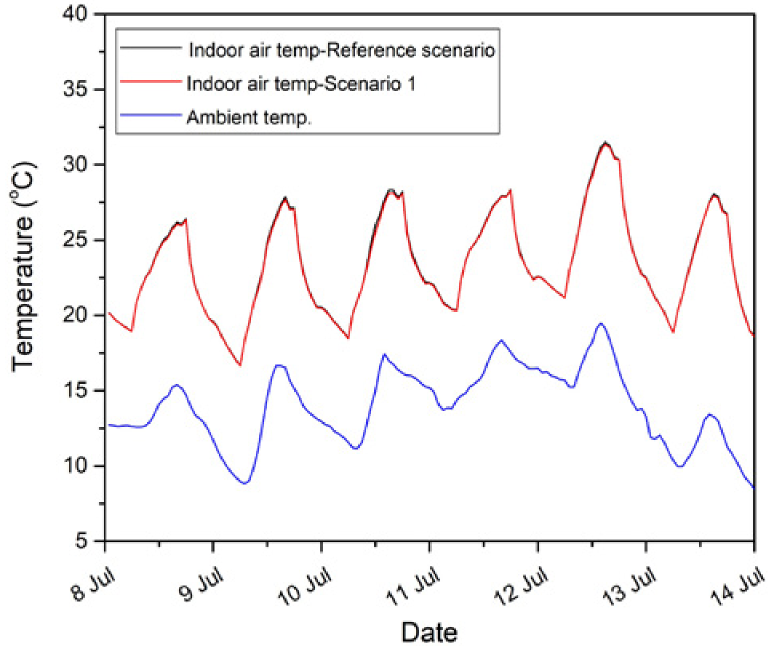


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating condition during a typical winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 10.5-30.8 °C in reference scenario to a range 10.5-30.7 °C in scenario 1 in Richmond station.

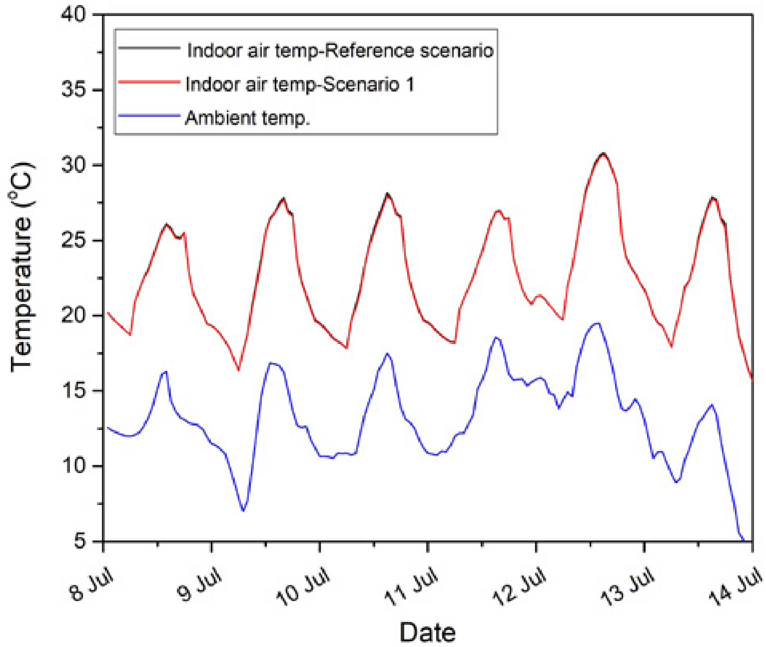


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating condition during a typical winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 °C and 0.3 °C in Observatory and Richmond stations, respectively.

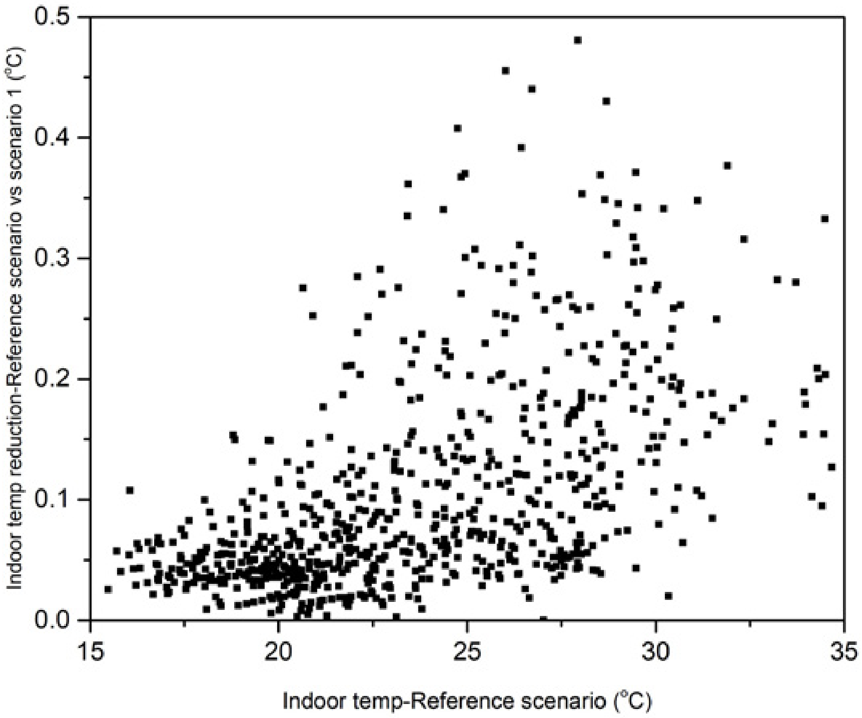


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

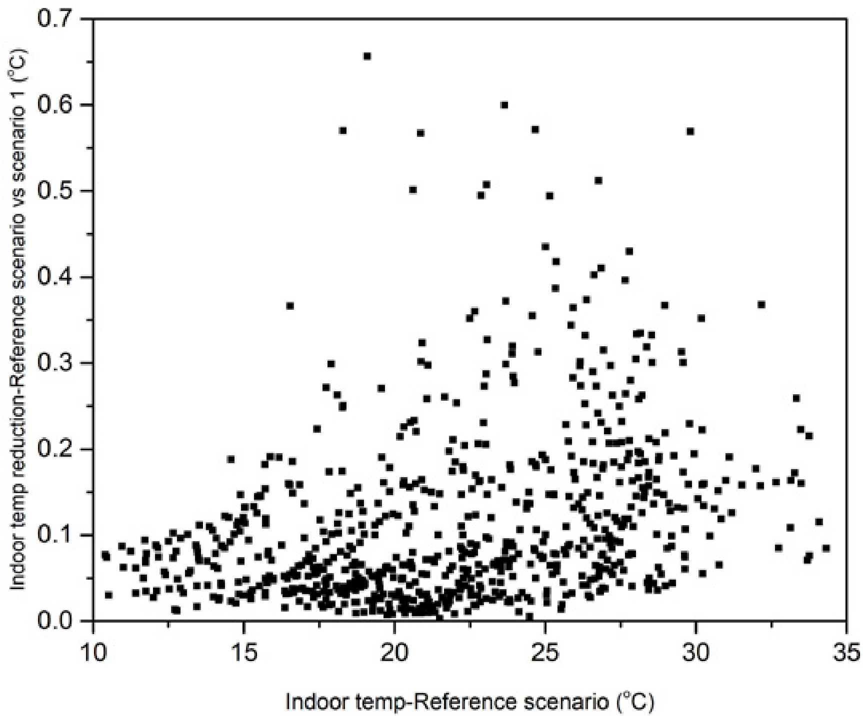


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for an existing high-rise shopping mall centre under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario	
	Operational hours*	Total	Operational hours*	Total
Observatory	16	97	16	99
Richmond	53	233	54	237

** Operational hours of the building: Monday to Friday, 7 am-6 pm.*

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to oC is predicted to increase slightly with 97 in the reference scenario and 99 hours in Scenario 1 in Observatory; and from 223 to 237 hours in Richmond stations, respectively.

The number operational hours with air temperature <19 °C during slightly increase from 16 hours in reference scenario compared to 16 hours in scenario 1 in Observatory; and from 53 to 54 hours in Richmond station.

Table 6. 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.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	670	670	666
Richmond	660	655	634

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to slightly decreased from 670 hours in reference scenario to 670 and 666 hours under scenario 1 and 2 in Observatory station; and from 660 hours in reference scenario to 655 and 634 hours under scenario 2 in Richmond station, respectively.

6

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban scale application of cool roof can significantly reduce the cooling load of an existing high-rise shopping mall centre during the summer season.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of the low-rise office building from 75.9-82.6 kWh/m^2 to 73.1-79.3 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 2.3-3.3 kWh/m^2. This is equivalent to approximately 2.9-4.0 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 12.2-19.0 kWh/m^2. This is equivalent to 16.1-24.0 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.0-0.2 kWh/m^2) is significantly lower than the annual cooling load reduction (5.6-9.6 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 2.5-4.3 %. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 5.6 and 9.4 kWh/m2 (~2.5-4.2 %) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 28.1-48.2 ^{o}C and 28.3-52.5 ^{o}C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 1.0 and 1.1 ^{o}C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 2.1 and 2.2 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 ^{o}C in reference scenario to a range between 18.1 and 38.9 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 ^{o}C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 ^{o}C in reference scenario to 15.9-43.6 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 ^{o}C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease slightly from a range between 15.5 and 31.5 ^{o}C in reference scenario to a range between 15.4 and 31.4 ^{o}C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8).

Similarly, the indoor air temperature is predicted to reduce from a range between 10.5 and 30.8 oC in reference scenario to a range between 10.5 and 30.7 oC in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 0.3 ^{o}C and 0.3 ^{o}C in Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 ^{o}C is predicted to increase slightly from 97 hours in reference scenario to 99 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slight increase in total number of hours below 19 ^{o}C from 233 hours in reference scenario to 237 hours in reference with cool roof scenario (scenario 1). The results show less increase in total number hours below 19 ^{o}C between the two scenarios (i.e. reference scenario and reference with cool roof scenario (scenario 1)) during operational hours of the building. The number of hours below 19 ^{o}C during operational hours of the building (i.e. 7 am-6 pm) is expected to increase from 16 hours in reference scenario to 16 hours in reference with cool roof scenario (scenario 1) in Observatory station. Similarly, the calculation in Richmond station shows a slight increase of number of hours below 19 ^{o}C from 53 hours to 54 hours during the operational hours (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 ^{o}C. As computed, the number of hours above 26 ^{o}C is 670 hours under the reference scenario in Observatory station, which slightly decreases to 670 and 666 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 ^{o}C from 660 hours in reference scenario to 655 in reference with cool roof scenario (scenario 1) and 634 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B16

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

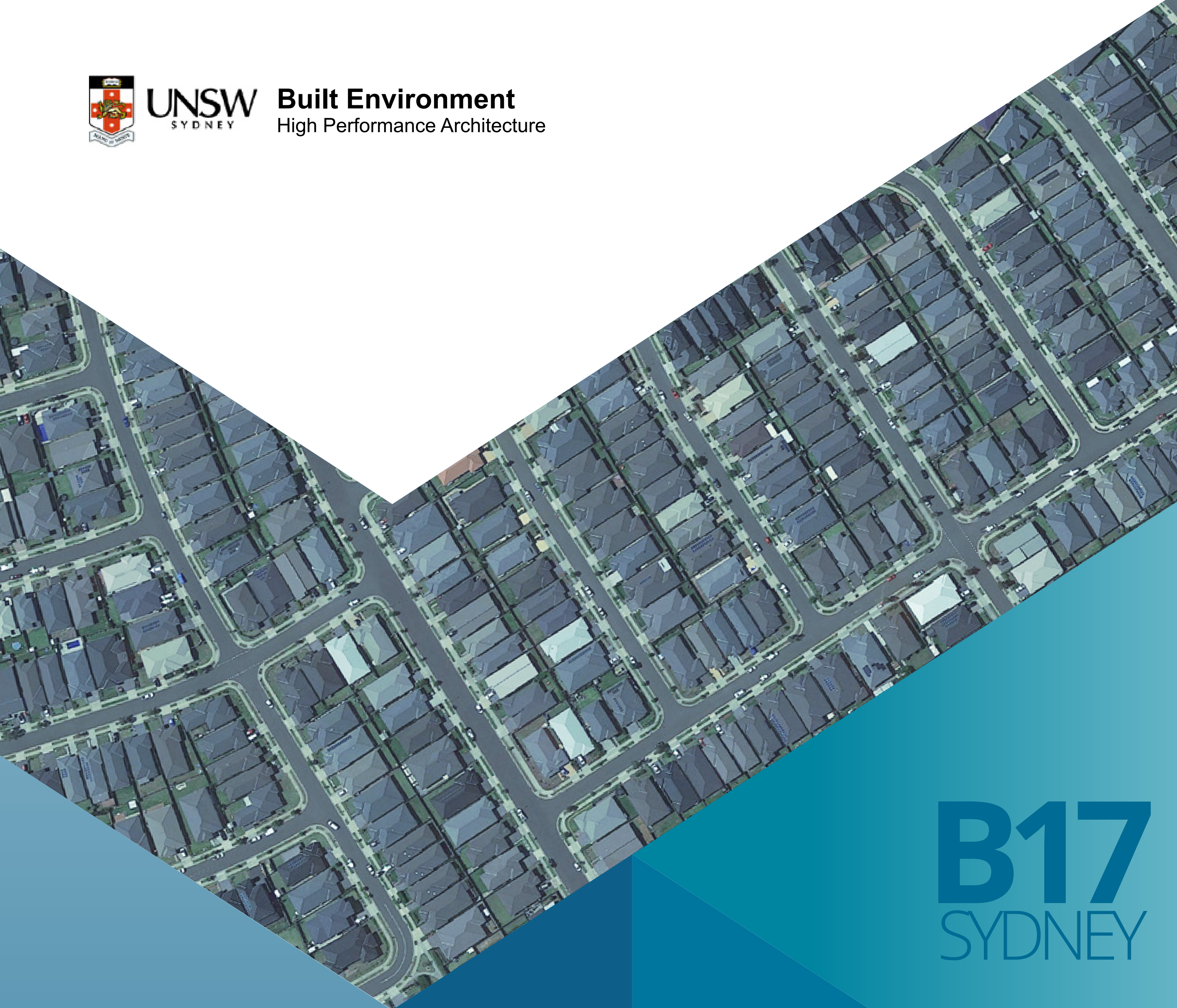
Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

UNSW SYDNEY
Built Environment
High Performance Architecture



B17
SYDNEY

COOL ROOFS
COST BENEFIT ANALYSIS

New standalone house
2021

BUILDING 17

NEW STANDALONE HOUSE

Floor area : $242m^2$
Number of stories : 1

Image source: https://www.newhomesguide.com.au/builders/long-island-homes/homes/new-homes/moonbi-240

Note: building characteristics change with climate zones

Reference scenario

Reference building as described in Appendix with a conventional roof. Use of two sets of climatic data including one climatic data simulated by Weather Research Forecast (WRF) for the current condition for two summer months and one measured annual weather data.

Scenario 1:
Reference with cool roof scenario

Same building as in the reference scenario with a cool roof. Use of two sets of climatic data including one climatic data simulated by WRF for the current condition for two summer months and one measured annual weather data.

Scenario 2 :
Cool roof with modified urban temperature scenario

Same building as in the reference scenario with a cool roof. Use of climatic data simulated by WRF considering an extensive use of cool roofs in the city.

Project name : Cool Roofs Cost Benefit Analysis Study
Project number : PRI-00004295
Date : 15 September 2021
Report contact : Prof Mattheos Santamouris

CONTENTS

FIGURES

1

SENSIBLE AND TOTAL COOLING LOAD FOR TWO SUMMER MONTHS UNDER THREE SCENARIOS[a]

[a] Reference scenario, scenario 1, and scenario 2; estimated for eleven weather stations in Sydney using weather data simulated by WRF.

Table 1. Sensible and total cooling load for a new stand-alone house for two summer months (i.e. January and February) under three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) with weather data simulated by WRF for COP=1 for heating and cooling.

The building-scale application of cool roofs can decrease the two summer months total cooling load of a new standalone house from 13.0-16.5 kWh/m² to 89.0-12.6 kWh/m².

Stations	Reference scenario		Scenario 1 Reference with cool roof scenario		Scenario 2 Cool roof with modified urban temperature scenario	
	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)	Sensible cooling (kWh/m²)	Total cooling (kWh/m²)
Sydney Airport	7.7	13.7	4.9	9.8	3.4	5.2
Terry Hill	8.5	13.0	5.4	9.0	4.7	6.5
Bankstown	9.4	14.7	6.5	11.0	5.1	6.7
Canterbury	8.0	13.6	5.3	9.9	4.0	5.9
Observatory	7.5	13.2	4.7	9.3	3.7	6.0
Richmond	12.2	16.5	8.9	12.6	8.0	9.5
Penrith	10.5	14.5	7.7	11.1	6.7	8.1
Horsley Park	10.0	14.1	7.2	10.7	6.3	8.0
Camden	10.7	14.2	7.9	10.9	6.8	7.8
Olympic Park	8.9	14.4	6.3	10.9	5.2	7.4
Campbelltown	9.7	13.8	7.0	10.4	5.9	7.3

Table 2. Sensible and total cooling load saving for a new stand-alone house for reference scenario versus reference with cool roof scenario (scenario 1), and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) with weather data simulated by WRF for COP=1 for heating and cooling.

For Scenario 1, the total cooling load saving is around 3.3-3.9 kWh/m² which is equivalent to 23.2-30.8 % of total cooling load reduction.

For Scenario 2, the total cooling load saving is around 6.1-8.5 kWh/m² which is equivalent to 42.4-62.0 % total cooling load reduction.

Stations	Reference scenario versus Reference with cool roof scenario (Scenario 1)				Reference scenario versus Cool roof with modified urban temperature scenario (Scenario 2)			
	Sensible cooling		Total cooling		Sensible cooling		Total cooling	
	kWh/m²	%	kWh/m²	%	kWh/m²	%	kWh/m²	%
Sydney Airport	2.8	36.4	3.9	28.5	4.3	55.8	8.5	62.0
Terry Hill	3.1	36.5	4.0	30.8	3.8	44.7	6.5	50.0
Bankstown	2.9	30.9	3.7	25.2	4.3	45.7	8.0	54.4
Canterbury	2.7	33.8	3.7	27.2	4.0	50.0	7.7	56.6
Observatory	2.8	37.3	3.9	29.5	3.8	50.7	7.2	54.5
Richmond	3.3	27.0	3.9	23.6	4.2	34.4	7.0	42.4
Penrith	2.8	26.7	3.4	23.4	3.8	36.2	6.4	44.1
Horsley Park	2.8	28.0	3.4	24.1	3.7	37.0	6.1	43.3
Camden	2.8	26.2	3.3	23.2	3.9	36.4	6.4	45.1
Olympic Park	2.6	29.2	3.5	24.3	3.7	41.6	7.0	48.6
Campbelltown	2.7	27.8	3.4	24.6	3.8	39.2	6.5	47.1

In the eleven weather stations in Sydney, both building-scale and the combined building-scale and urban scale application of cool roofs can reduce the cooling load of the new standalone house during the summer season.

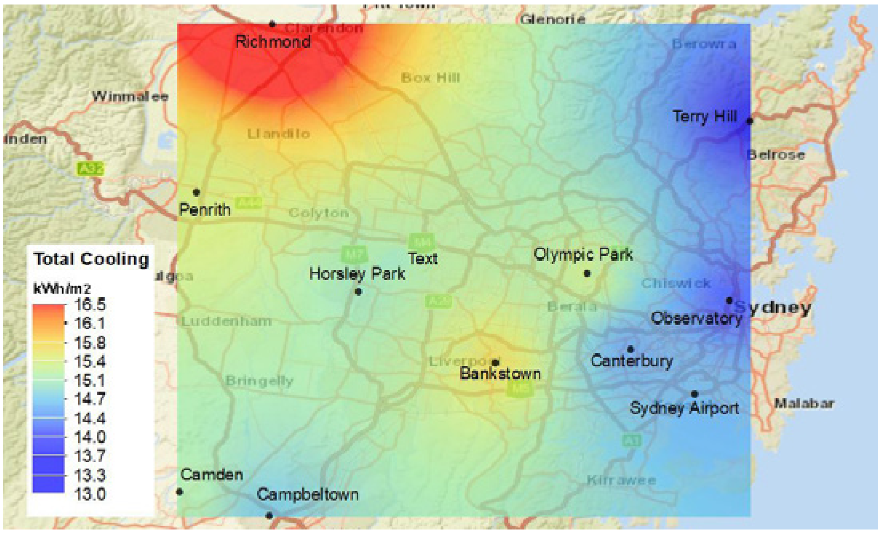


Figure 1. Spatial distribution of total cooling load for reference scenario for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

Figure 2. Spatial distribution of total cooling load for reference with cool roof scenario (scenario 1) for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

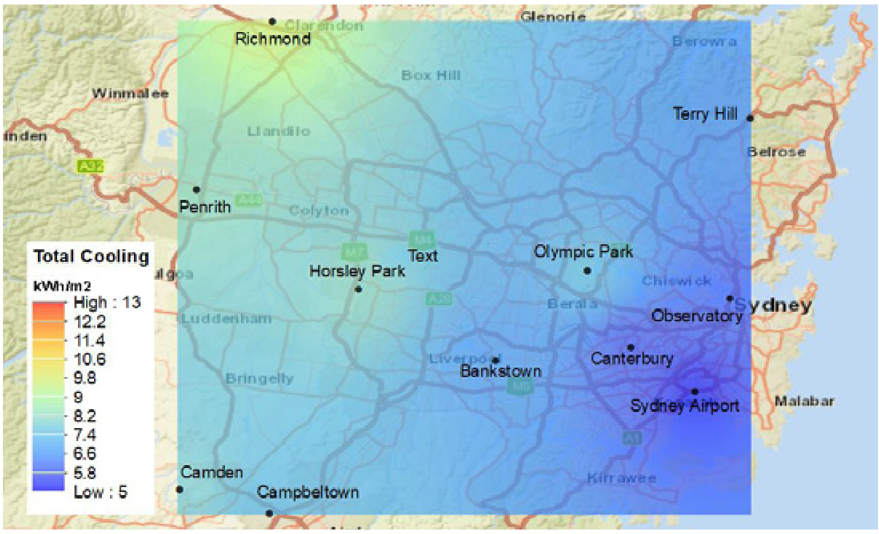


Figure 3. Spatial distribution of total cooling load for cool roof with modified urban temperature scenario (scenario 2) for two summer months (i.e. January and February) for a new stand-alone house with weather data simulated by WRF for COP=1 for heating and cooling.

2

[b] Reference scenario and scenario 1; estimated for eleven weather stations in Sydney using measured annual climate data.

ANNUAL COOLING AND HEATING LOAD UNDER TWO SCENARIOS[b]

The annual cooling and heating simulation using annual measured weather data illustrates that the annual heating penalty (0.7-1.6 kWh/m²) is significantly lower than the annual cooling load reduction (5.7-7.8 kWh/m²).

Table 3. Annual cooling and heating loads for a new stand-alone house for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) using annual measured weather data for COP=1 for heating and cooling.

Stations	Reference scenario				Scenario 1 Reference with cool roof scenario			
	Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)		Annual cooling load (kWh/m²)		Annual heating load (kWh/m²)	
	Sensible	Total	Sensible	Total	Sensible	Total	Sensible	Total
Sydney Airport	13.6	20.5	7.6	9.5	9.3	14.8	8.2	10.2
Terry Hill	10.7	16.8	12.1	14.9	6.1	10.3	13.4	16.4
Bankstown	15.9	23.0	13.1	16.1	10.6	16.2	14.2	17.3
Canterbury	13.1	19.4	12.7	15.6	8.4	13.3	13.9	16.9
Observatory	13.7	19.7	8.4	10.4	8.6	13.1	9.3	11.4
Richmond	17.5	25.3	15.3	18.8	12.3	18.8	16.4	20.0
Penrith	19.6	28.2	12.6	15.6	13.3	20.4	13.7	16.9
Horsley Park	15.6	21.2	13.8	16.9	10.3	14.7	15.0	18.3
Camden	14.6	19.3	17.8	21.8	9.9	13.5	19.2	23.4
Olympic Park	15.7	24.6	11.6	14.4	10.3	17.4	12.6	15.5
Campbelltown	13.9	17.9	17.3	21.3	9.0	12.1	18.7	22.9

The annual cooling load saving by building-scale application of cool roofs is around 25.7-38.7 %.

The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.2 and 6.5 kWh/m² (~10.2-18.6 %).

Table 4. Annual cooling load saving, heating load penalty, and total cooling and heating saving for reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house using annual measured weather data for COP=1 for heating and cooling.

Stations	Annual cooling load saving				Annual heating load penalty		Annual total cooling & heating load saving			
	Sensible		Total		Sens.	Total	Sensible		Total	
	kWh/m²	%	kWh/m²	%	kWh/m²		kWh/m²	%	kWh/m²	%
Sydney Airport	4.3	31.6	5.7	27.8	0.6	0.7	3.7	17.5	5.0	16.7
Terry Hill	4.6	43.0	6.5	38.7	1.3	1.5	3.3	14.5	5.0	15.8
Bankstown	5.3	33.3	6.8	29.6	1.1	1.2	4.2	14.5	5.6	14.3
Canterbury	4.7	35.9	6.1	31.4	1.2	1.3	3.5	13.6	4.8	13.7
Observatory	5.1	37.2	6.6	33.5	0.9	1.0	4.2	19.0	5.6	18.6
Richmond	5.2	29.7	6.5	25.7	1.1	1.2	4.1	12.5	5.3	12.0
Penrith	6.3	32.1	7.8	27.7	1.1	1.3	5.2	16.1	6.5	14.8
Horsley Park	5.3	34.0	6.5	30.7	1.2	1.4	4.1	13.9	5.1	13.4
Camden	4.7	32.2	5.8	30.1	1.4	1.6	3.3	10.2	4.2	10.2
Olympic Park	5.4	34.4	7.2	29.3	1.0	1.1	4.4	16.1	6.1	15.6
Campbelltown	4.9	35.3	5.8	32.4	1.4	1.6	3.5	11.2	4.2	10.7

3

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL WARM PERIOD UNDER THREE SCENARIOS[c]

[c] Reference scenario, scenario 1, and scenario 2; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using weather data simulated by WRF.

During a typical summer week, the ambient air temperature is predicted to decrease from a range 19.2-39.8 °C in reference scenario to a range 18.1-38.9 ° in scenario 2 in Observatory station.

For Scenario 2, the estimated ambient temperature reduction is 0.6-1.6 °C compared to the reference scenario in Observatory station.

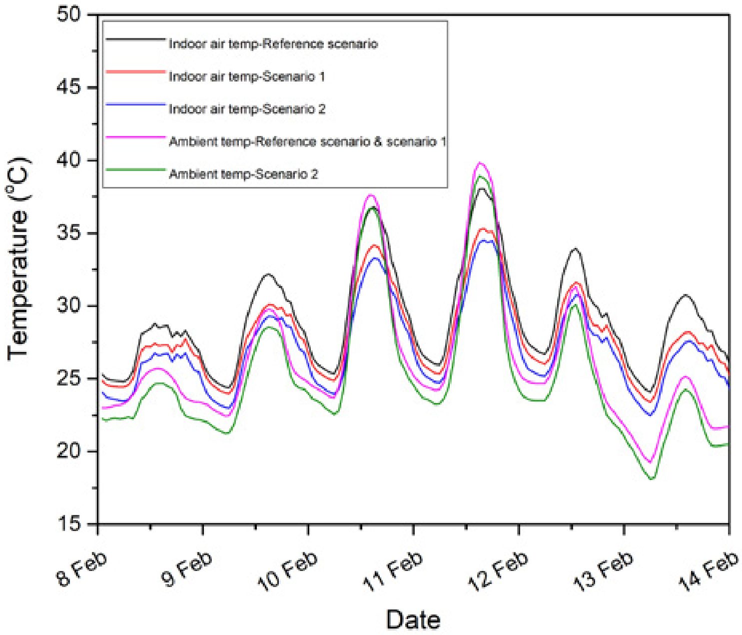


Figure 4. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

For scenario 2, the ambient temperature is predicted to decrease from 17.2-44.7°C in reference scenario to 15.9-43.6°C in Richmond station.

For Scenario 2, the estimated ambient temperature reduction is 0.7-1.7 °C compared to the reference scenario in Richmond station.

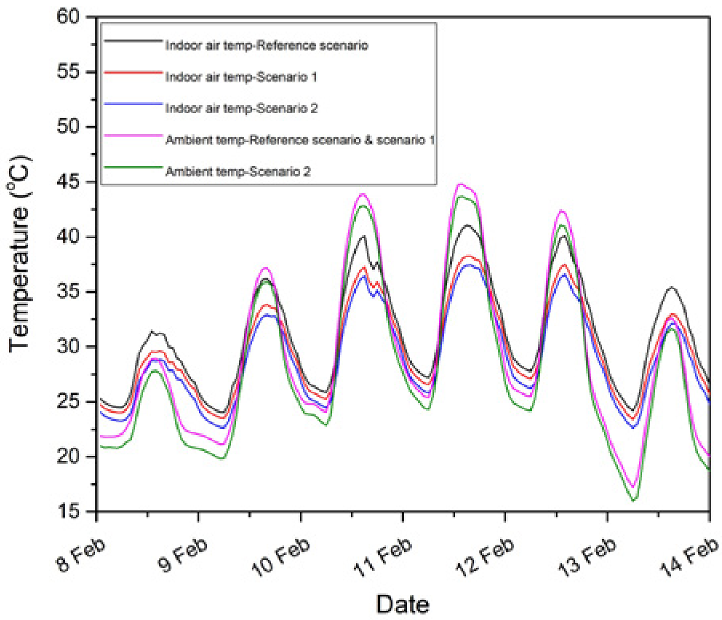


Figure 5. Indoor air temperature and ambient temperature for three scenarios including reference scenario, reference with cool roof scenario (scenario 1), and cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

> During a typical summer week, the indoor air temperature of the reference scenario ranges between 24.1-38.0 °C and 24.0- 41.1 °C in Observatory and Richmond stations, respectively.

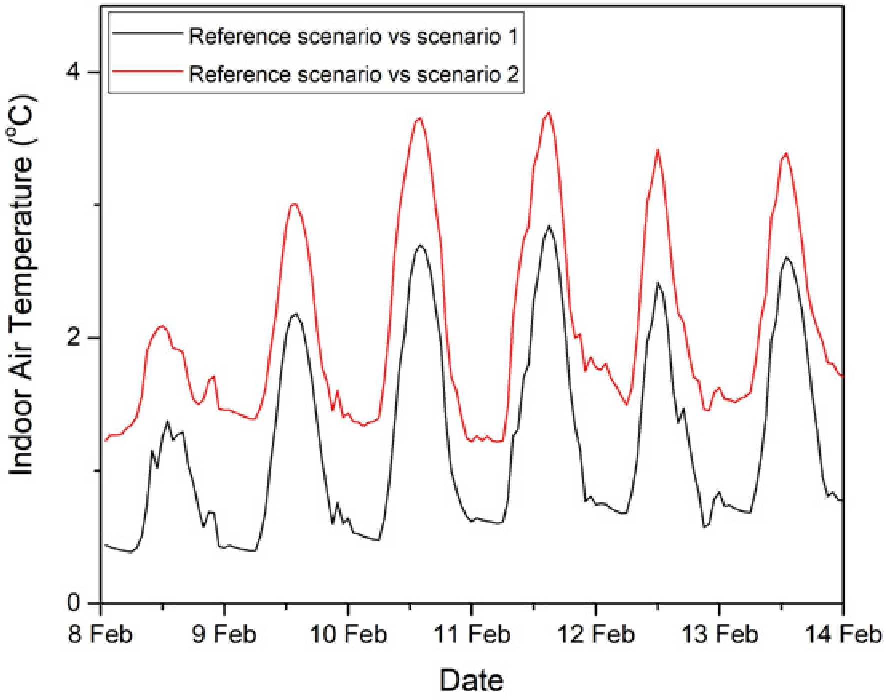


Figure 6. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free-floating conditions during a typical summer week in *Observatory station* using weather data simulated by WRF.

> For Scenario 1 (building-scale), the maximum indoor temperature reduction is estimated to be 2.8 °C and 2.9 °C in Observatory and Richmond stations, respectively.

> For Scenario 2 (combined building- and urban-scale), the maximum indoor temperature reduction increases up to 3.7 °C and 3.7 °C in Observatory and Richmond stations, respectively.

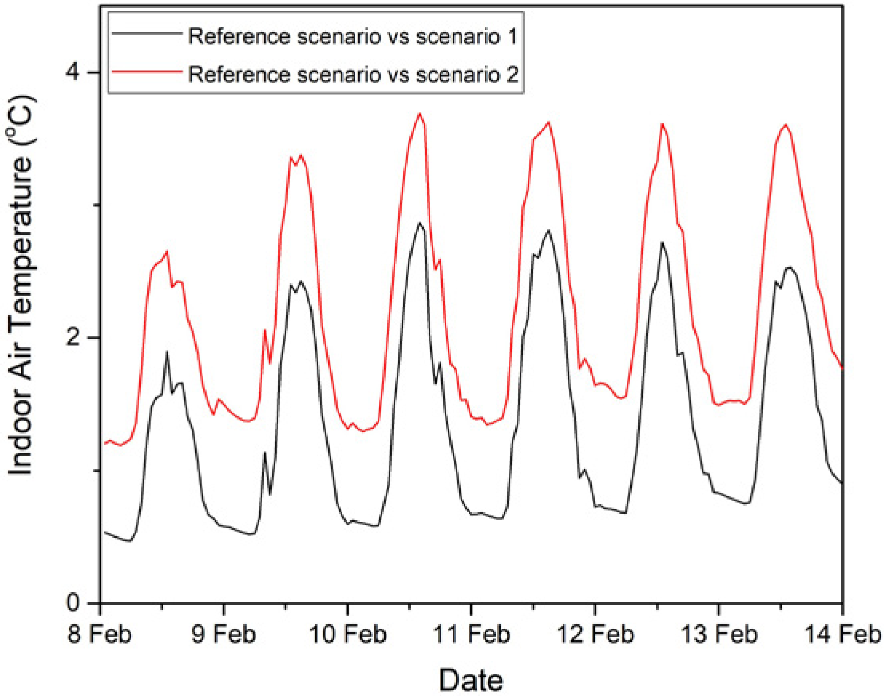


Figure 7. Indoor temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) and reference scenario versus cool roof with modified urban temperature scenario (scenario 2) for a new stand-alone house under free-floating conditions during a typical summer week in *Richmond station* using weather data simulated by WRF.

4

INDOOR AIR TEMPERATURE AND AMBIENT TEMPERATURE FOR FREE-FLOATING CONDITION DURING A TYPICAL COLD PERIOD UNDER TWO SCENARIOS[d]

[d] Reference scenario and scenario; estimated for weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

During a typical winter week, the indoor air temperature is expected to decrease from a range 12.7-23.9 °C in reference scenario to a range 12.5-22.9 °C in scenario 1 in Observatory Hill station.

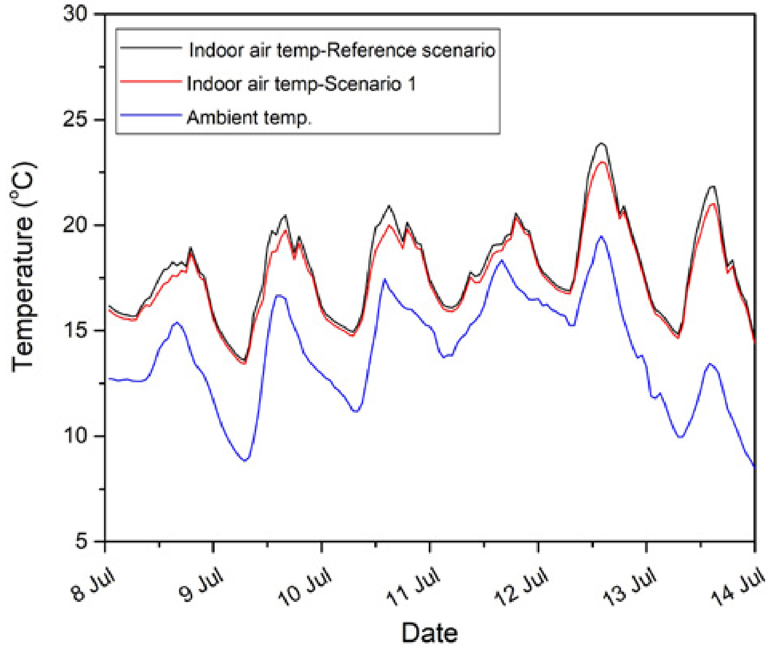


Figure 8. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new existing stand-alone house under free-floating condition during a winter week in *Observatory station* using annual measured weather data.

The indoor air temperature is predicted to reduce from a range 8.8-23.5 °C in reference scenario to a range 8.7-22.8 °C in scenario 1 in Richmond station.

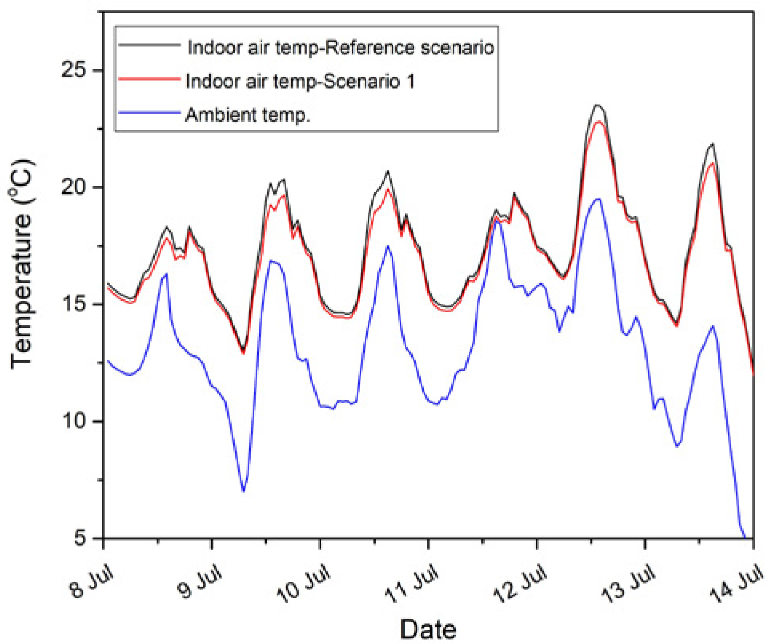


Figure 9. Indoor air temperature and ambient temperature for two scenarios including reference scenario and reference with cool roof scenario (scenario 1) for a new existing stand-alone house under free-floating condition during a winter week in *Richmond station* using annual measured weather data.

For Scenario 1, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.1 and 1.0 °C in Observatory and Richmond stations, respectively.

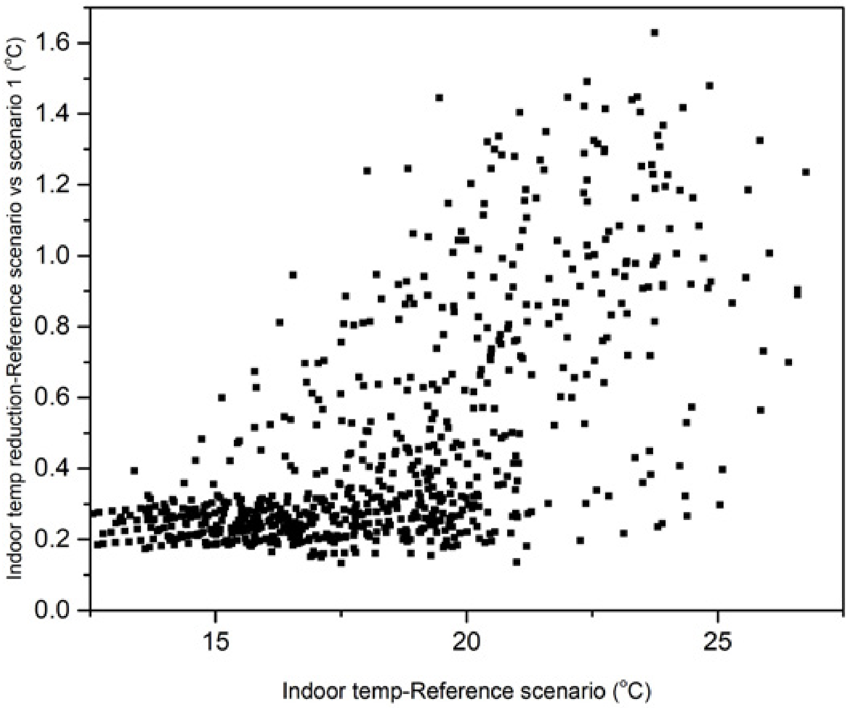


Figure 10. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house under free-floating conditions during a typical winter month in *Observatory station* using annual measured weather data.

Temperature decrease mainly happens during the non-heating period when indoor temperature is higher than the threshold.

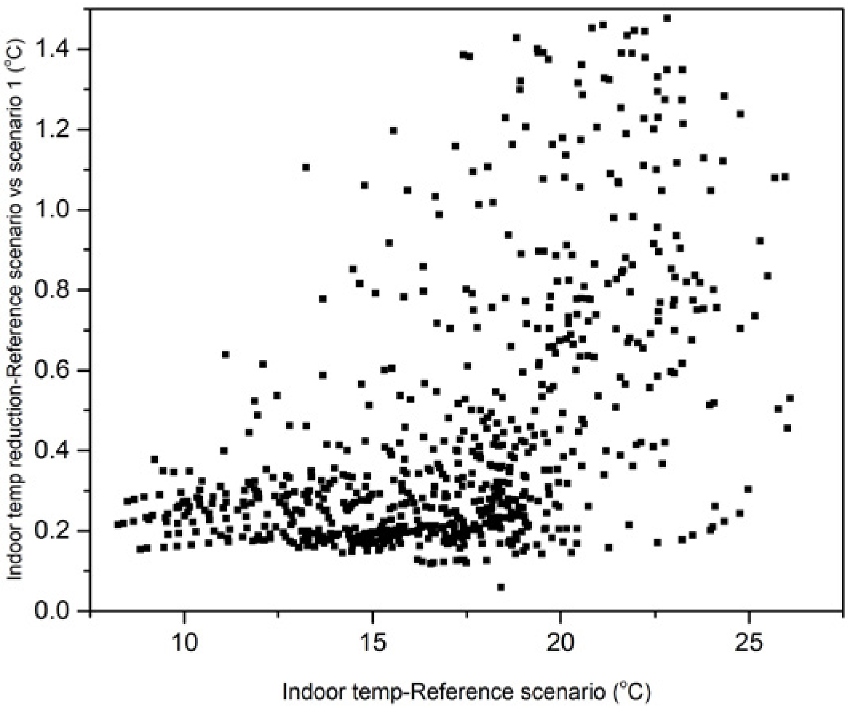


Figure 11. Indoor air temperature difference between reference scenario versus reference with cool roof scenario (scenario 1) for a new stand-alone house under free-floating conditions during a typical winter month in *Richmond station* using annual measured weather data.

5

NUMBER OF HOURS WITH INDOOR AIR TEMPERATURE BELOW 19°C DURING A TYPICAL COLD PERIOD AND ABOVE 26°C DURING A TYPICAL WARM PERIOD[e]

[e] For free-floating condition in weather stations presenting the lowest and highest ambient temperatures in Sydney (i.e. Observatory Hill and Richmond) using annual measured weather data.

Table 5. Number of hours with indoor air temperature below 19 °C in free-floating mode during a typical winter month using annual measured weather data.

During a typical winter month, the total number of hours with an indoor air temperature (<19 °C) is predicted to considerably increase from 429 hours in reference scenario to 478 hours; and from 523 to 562 hours in scenario 1 in Observatory and Richmond stations, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario
Observatory	429	478
Richmond	523	562

Table 6. 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.

During a typical summer month, the total number of hours with an indoor air temperature (>26 °C) is predicted to significantly decrease from 422 hours in reference scenario to 339 and 253 hours under scenario 1 and 2 in Observatory station; and from 456 hours in reference scenario to 415 and 356 hours under scenario 1 and 2 in Richmond station, respectively.

Stations	Reference scenario	Scenario 1 Reference with cool roof scenario	Scenario 2 Cool roof with modified urban temperature scenario
Observatory	422	339	253
Richmond	456	415	356

6

CONCLUSIONS

• It is estimated that both building-scale and combined building-scale and urban-scale application of cool roof can significantly reduce the cooling load of a new standalone house during the summer season.

• In the eleven weather stations in Sydney, the building-scale application of cool roofs can decrease the two summer months total cooling load of a new high-rise apartment from 13.0-16.5 kWh/m^2 to 9.0-12.6 kWh/m^2. As computed, the two summer months total cooling load saving by building-scale application of cool roofs is around 3.3-3.9 kWh/m^2. This is equivalent to approximately 23.2-30.8 % total cooling load reduction in reference with cool roof scenario (scenario 1) compared to the reference case scenario (See Table 1 and 2 and Figures 1 and 2).

• In the eleven weather stations in Sydney, the combined building-scale and urban-scale application of cool roofs is estimated to reduce the two summer months total cooling by 6.1-8.5 kWh/m^2. This is equivalent to 42.4-62.0 % total cooling load reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario (See Table 1 and 2 and Figures 2 and 3).

• The annual cooling and heating simulation using annual measured weather data illustrate that the annual heating penalty (0.7-1.6 kWh/m^2) is lower than the annual cooling load reduction (5.7-7.8 kWh/m^2). As calculated, the annual cooling load saving by building-scale application of cool roofs is around 25.7-38.7%. The annual total cooling and heating load saving by building-scale application of cool roofs ranges between 4.2 and 6.5 kWh/m^2 (~10.2-18.6%) (See Table 3 and 4).

• During a typical summer week and under free floating condition, the indoor air temperature of the reference scenario ranges between 24.1-38.0 ^{o}C and 24.0-41.1 ^{o}C in Observatory and Richmond stations, respectively. When cool roofs are applied at a building scale (scenario 1), the maximum indoor temperature reduction is estimated to be 2.8 and 2.9 ^{o}C in Observatory and Richmond stations, respectively. The indoor air temperature reduction is foreseen to increase further to 3.7 and 3.7 ^{o}C by combined building-scale and urban-scale application of cool roofs (scenario 2) in Observatory and Richmond stations, respectively (See Figures 4-7).

• During a typical summer week, the ambient air temperature is predicted to decrease from a range between 19.2 and 39.8 ^{o}C in reference scenario to a range between 18.1 and 38.9 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Observatory station. The ambient temperature reduction in cool roof and modified urban temperature scenario (scenario 2) compared to the reference scenario is approximately 0.6-1.6 ^{o}C. Similarly, the ambient temperature is predicted to decrease from 17.2-44.7 ^{o}C in reference scenario to 15.9-43.6 ^{o}C in cool roof and modified urban temperature scenario (scenario 2) in Richmond station. The estimated ambient temperature reduction is 0.7-1.7 ^{o}C in Richmond station (See Figures 4 and 6).

• During a typical winter week and under free floating condition, the indoor air temperature is expected to decrease from a range between 12. 7 and 23.9 ^{o}C in reference scenario to a range between 12.5 and 22.9 ^{o}C in reference with cool roof scenario (scenario 1) in Observatory Hill station (See Figure 8).

Similarly, the indoor air temperature is predicted to slightly reduce from a range between 8.8 and 23.5 °C in reference scenario to a range between 8.7 and 22.8 oC in reference with cool roof scenario (scenario 1) in Richmond station (See Figures 8 and 9).

• During a typical winter month and under free floating condition, the average maximum indoor air temperature reduction by building-scale application of cool roofs is predicted to be just 1.1 °C and 1.0 °C for both Observatory and Richmond stations, respectively. Positively, temperature decrease happens mainly during the non-heating period when indoor temperature is higher than the threshold (See Figures 10 and 11).

• During a typical winter month and under free floating condition, the total number of hours with an indoor air temperature below 19 °C is predicted to considerably increase from 429 hours in reference scenario to 478 hours in reference with cool roof scenario (scenario 1) in Observatory station. The estimations for Richmond stations also show a slightly increase in total number of hours below 19 °C from 523 hours in reference scenario to 562 hours in reference with cool roof scenario (scenario 1) (See Table 5).

• During a typical summer month and under free-floating condition, use of cool roofs is predicted to significantly decrease the number of hours above 26 °C. As computed, the number of hours above 26 °C is 422 hours under the reference scenario in Observatory station, which significantly decreases to 339 and 253 hours under the reference with cool roof scenario (scenario 1) and cool roof and modified urban temperature scenario (scenario 2), respectively. The simulations in Richmond station also illustrate a significant reduction in number of hours above 26 °C from 456 hours in reference scenario to 415 in reference with cool roof scenario (scenario 1) and 356 hours in cool roof and modified urban temperature scenario (scenario 2), respectively (See Table 6).

B17

UNSW - SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

Sydney, NSW 2052
Australia

Phone
+61 (02) 9385 0729

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au

SCHOOL OF BUILT ENVIRONMENT
High Performance Architecture

UNSW SYDNEY, NSW 2052
Australia

Phone
+61 (02) 9385 1000

Email
m.santamouris@unsw.edu.au

Website
https://www.unsw.edu.au