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Review

Urban Overheating and Cooling Potential in Australia: An Evidence-Based Review

Komali Yenneti [1,2], Lan Ding [3], Deo Prasad [3], Giulia Ulpiani [4,*], Riccardo Paolini [3], Shamila Haddad [3] and Mattheos Santamouris [3]

1 School of Architecture and Built Environment, Faculty of Science and Engineering, University of Wolverhampton, West Midlands WV1 1LY, UK; komaliy@wlv.ac.uk
2 Australia India Institute, University of Melbourne, Parkville, VIC 3010, Australia
3 High Performance Architecture Research Cluster, Faculty of Built Environment, UNSW Sydney, Sydney, NSW 2052, Australia; lan.ding@unsw.edu.au (L.D.); d.prasad@unsw.edu.au (D.P.); r.paolini@unsw.edu.au (R.P.); s.haddad@unsw.edu.au (S.H.); m.santamouris@unsw.edu.au (M.S.)
4 Industrial Engineering and Mathematical Sciences Department, Università Politecnica delle Marche, via Brecce Bianche 1, 60131 Ancona, Italy
* Correspondence: giulia.ulpiani@sydney.edu.au

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Abstract: Cities in Australia are experiencing unprecedented levels of urban overheating, which has caused a significant impact on the country's socioeconomic environment. This article provides a comprehensive review on urban overheating, its impact on health, energy, economy, and the heat mitigation potential of a series of strategies in Australia. Existing studies show that the average urban heat island (UHI) intensity ranges from 1.0 °C to 13.0 °C. The magnitude of urban overheating phenomenon in Australia is determined by a combination of UHI effects and dualistic atmospheric circulation systems (cool sea breeze and hot desert winds). The strong relation between multiple characteristics contribute to dramatic fluctuations and high spatiotemporal variabilities in urban overheating. In addition, urban overheating contributes to serious impacts on human health, energy costs, thermal comfort, labour productivity, and social behaviour. Evidence suggest that cool materials, green roofs, vertical gardens, urban greenery, and water-based technologies can significantly alleviate the UHI effect, cool the ambient air, and create thermally balanced cities. Urban greenery, especially trees, has a high potential for mitigation. Trees and hedges can reduce the average maximum UHI by 1.0 °C. The average maximum mitigation performance values of green roofs and green walls are 0.2 °C and 0.1 °C, respectively. Reflective roofs and pavements can reduce the average maximum UHI by 0.3 °C. In dry areas, water has a high cooling potential. The average maximum cooling potential using only one technology is 0.4 °C. When two or more technologies are used at the same time, the average maximum UHI drop is 1.5 °C. The mitigation strategies identified in this article can help the governments and other stakeholders manage urban heating in the natural and built environment, and save health, energy, and economic costs.

Keywords: urban heat; Australia; UHI effect; mitigation; climate change

1. Introduction

The history of urbanisation is often defined as the history of human development. In the past two centuries, the urban population increased more than 100 times [1]. Today, more than 50% of the world's population lives in cities and forecasts suggest that this number will rise to 70% by 2050 [2]. The burgeoning urban population growth and subsequent urban expansion will greatly affect local and regional climates, urban environmental quality, and public life [3]. Worse, dark coloured building surfaces, roads, pavements, vehicle emissions, and reduced urban green spaces are already contributing to increased atmospheric heat, extreme temperatures, frequent and extended heat spells, and thermal stress.

In Australia, urban overheating has become an increasingly important issue, and urban residents often suffer from excess heat and frequent heatwaves [4,5]. Urban overheating is generally the consequence of the urban heat island (UHI) effect, a local phenomenon caused by city characteristics (urban density, structure, form, and land use), building and paving materials, anthropogenic heat released by vehicle exhausts and building energy use, and the loss of natural features (green areas, water) [5].

Evidence on the UHI effect is available for almost all Australian cities [4]. However, urban overheating in Australia is often triggered by the self-amplifying mechanism of synoptic weather conditions combined with the UHI effect [6]. The significant co-existence of the dualistic atmospheric systems of cool sea breeze from the ocean and hot winds from the inland desert makes the spatiotemporal characteristics of urban overheating highly variable and heterogeneous. As a result, the analysis of the behaviour and formation of urban overheating is very challenging.

Urban overheating and frequent, extreme, and extended heatwaves have significant impact on energy [7], health [8,9], thermal comfort [10], environment [11], and the economy [12]. Advanced technologies and strategies have been developed to mitigate the UHI effect and manage urban heat. The implementation of mitigation techniques and strategies, such as urban greening, green roofs, vertical gardens, cool roofs, and cool pavements, can provide a path for sustainable urban development.

Against this background, the aim of this article was to provide an in-depth evidence-based review on the characteristics of urban overheating, its impacts on human health, energy and economy, and the potential of appropriate mitigation technologies and strategies in Australia.

The analysis of the information presented in this paper is based on data collected from all scientific articles published in peer-reviewed journals, original articles published in accredited media, and original reports published by government agencies and credible research institutions over the last 15 years. The journal articles were searched with a combination of key words such as 'UHI', 'Australia', 'heat mitigation', 'health', 'energy', and 'economy'. Papers with at least a section including the relevant information required for this paper were only considered for final inclusion. All articles and publications that provided spatiotemporal data were included in the study.

This work focuses on canopy layer ground basis observations of the near surface air temperature. Therefore, all publications on boundary layer heat island and surface heat islands using remote sensing, subsurface, and non-urban heat island were excluded. The studies on the UHI effect were separately analysed based on two criteria: (a) the experimental protocol used (standard equipment and weather monitoring stations, mobile traverses around the selected area, and non-standard equipment) and (b) the form and type of the UHI intensity reported. In addition, relevant information on UHI impacts and the potential of mitigation measures were extracted from government reports and other secondary data pathways. The data collected was processed, analysed, and interpreted to provide a meaningful understanding on the UHI effects, impacts, and mitigation in Australia.

After the introduction, the structure of this article is as follows: Section 2 discusses the dynamic characteristics of urban overheating in Australian cities. Section 3 provides evidence on the impact of urban overheating on energy, health, and the economy. Section 4 analyses the potential of different urban heat mitigation strategies. Finally, the article ends with conclusions and policy implications.

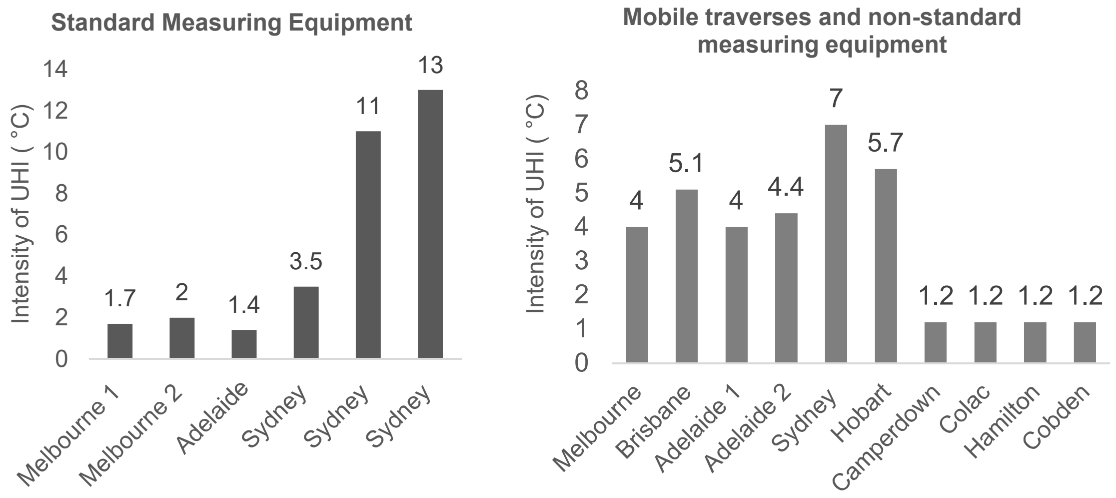
2. The Magnitude and Characteristics of Urban Overheating

The UHI effect is a key phenomenon of local climate change, wherein the temperatures in inner cities are usually higher than the sorrounding rural areas. It is exhibited when "a significant difference in temperature can be observed within a city or between a city and its suburbia and/or its sorrounding rural areas, and areas of maximum temperature can expectedly be found within the densest part of the urban area" [13] (p. 73). Evidence on the intensity of UHIs is available for almost all major cities in Australia (Table 1).

Table 1. The intensity of the urban heat island (UHI) effect in Australian cities and regions.

No.	City	Population Density (People/sq.km: 2016)	Intensity of the Heat Island (°C)	Details of Data Sources	Reference
1	Melbourne	17,506	annual average: 1.4	one urban and one rural weather stations	[14]
			annual average (depending on summer or winter): 0.5–2	one central business district (CBD) and three sorrounding non-CBD area weather stations	[15]
			average mean maximum intensity: 4	mobile traverse from the western fringe, approximately 2 km south of the city center, through the CBD to the northern fringe	[16]
			annual average: 1.4	two urban and two rural reference stations	[17]
2	Sydney	1171	maximum intensity: 11	six meteorological stations distributed across the city	[4]
			maximum intensity: 13	eight different stations within the city	[6]
3	Alice Springs	85	UHI is evident at night. Average intensity: 4.1	ten sensors installed within the city center	[5]
4	Camperdown	4362	average intensity: 1.2	mobile transect from a position in the rural area through town center to a rural area on the other side of the town	[16]
5	Colac	520			
6	Hamilton	480			
7	Hobart	131	maximum intensity: 5.7	mobile sensors	[18]
8	Darwin	703	maximum intensity: 2	weather station at airport	[19]
9	Perth	317	UHI is evident at night. maximum intensity: 0.8	one urban, two urban fringe and three rural stations	[20]
10	Adelaide	400	UHI is evident at night. maximum intensity: 1.3	one urban, two urban fringe and two rural stations	[20]

It should be noted that different measurement methods capture different magnitudes of the urban-reference temperature differences (Figure 1). The average intensity using standard measuring methods (weather monitoring stations) varies between 1.0 °C and 13.0 °C, while the average intensity using non-standard methods (e.g., mobile measurements, micro-scale sensor based measurements) is between 1.0 °C and 7.0 °C. The magnitude of the UHI effect using mobile transects or other non-standard methods is higher than that by using standard measurement stations. Mobile transects and non-standard measurement methods are commonly used to measure UHI in densely populated urban areas, while fixed weather monitoring stations are used in thermally undisturbed areas.



(**a**) (**b**)

Figure 1. The intensity of the UHI effect in Australian cities and regions (**a**) using standard measuring equipment; and (**b**) nonstandard measuring equipment.

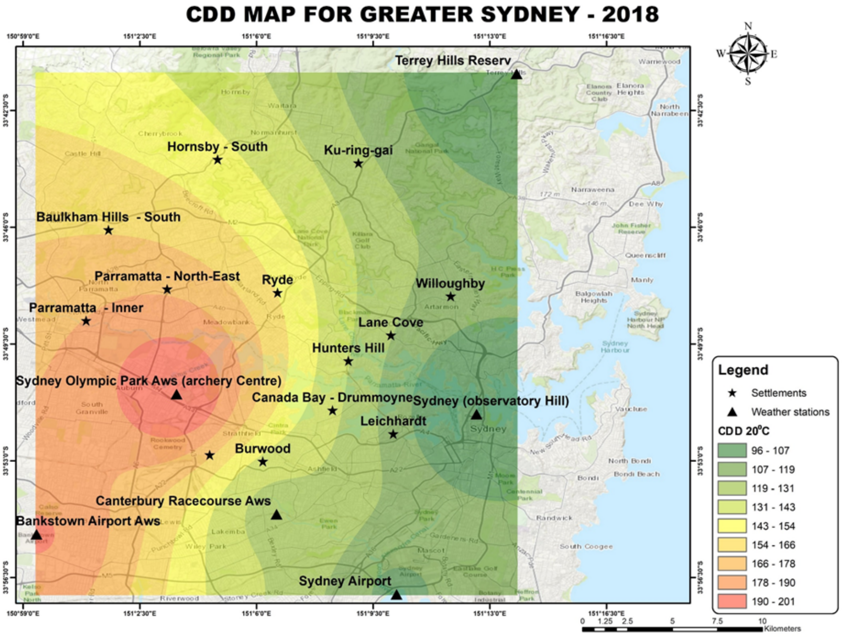
Considering the relatively short duration of the studies based on mobile traverses and non-standard measuring equipment, the UHI intensity reported usually is the maximum temperature difference measured during the entire experiment. However, studies using standard measurement equipment obtained multi-year measurement results on either the annual average, annual average maximum, or absolute maximum UHI intensity or a combination of them (Table 1). The quality and accuracy of the UHI intensity provided by the studies depends on many parameters, such as the duration of the experiment, the number of stations used, the selected experimental protocols, and the accuracy of the measuring equipment [21].

In the next few paragraphs, the characteristics of overheating in Australian cities are discussed. In most parts of the world, the intensity of urban overheating is mainly determined by the UHI effect, a phenomenon caused by city-specific factors (urban expansion, land use, dense built environment, urban layout), anthropogenic heat released by buildings and vehicles, extensive alteration of urban natural spaces (green spaces, water bodies), and the presence of heat sources and sinks [22,23]. However, the magnitude of urban overheating in Australian cities is influenced by both the UHI effect and synoptic weather conditions [21,24,25]. As a result, the spatiotemporal characteristics of urban overheating in Australia, especially in coastal cities, are highly variable and heterogeneous. Moreover, the analysis of the behaviour and formation of urban overheating becomes very challenging.

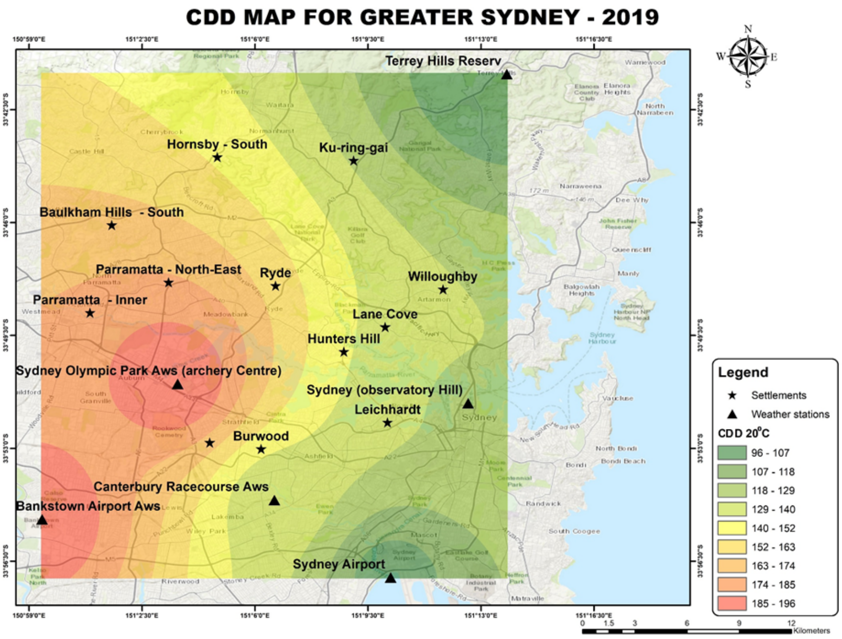
A good example to demonstrate the variability of urban overheating in Australia is Greater Sydney. Despite being located along the coast and close to the ocean, Sydney's average UHI intensity is much higher than other Australian cities (Figure 1). Further, the behaviour of urban overheating changes with time and space. In Sydney, a high degree of thermal imbalances exists between different parts of the city, with temperatures changing daily, monthly, and yearly [4,6].

Results from multiple numerical and experimental studies indicate that the dramatic fluctuations in the intensity of urban overheating in Sydney are related to two major large-scale atmospheric circulation systems: (a) sea breeze and (b) hot desert winds [4,6,24]. The significant co-existence of advective and convective processes related to local weather conditions, along with the UHI effect itself, can affect the spatiotemporal pattern of urban overheating in Sydney [4,6].

Spatially, the absolute intensity of urban overheating increases with increasing distance from the coastline (Figure 2). The average intensity of overheating in the inland western suburbs is at least 2–5 °C higher than the coastal areas in the eastern suburbs [6].



(A)



(B)

Figure 2. Patterns of UHI intensity in Greater Sydney, based on cooling degree days (CDD) (**A**) 2018 (**B**) 2019.

Sydney is strategically positioned on the South Pacific coast, but is also located close to one of the largest desert areas in the world, known as "the Australian arid biome". This inland desert is a cradle of strong hot winds and a massive heat source [6,26]. The sea breeze inhibits hot air advection as it interacts with the UHI circulation and contributes to the cooling effect in the eastern suburbs [6]. This is a pattern commonly observed in other Australian cities, such as Adelaide [27] and Melbourne [21]. On the other side, the stagnation region in the city canyons, coupled with the warm desert winds leads to weaker penetration of cool winds in the western part of the city [4,5].

Temporally, the intensity of urban overheating in the western region is lower at night. As a result, the average night time ambient temperature in western Sydney is lower than in eastern areas [4]. This is particularly due to the high intensity of the nocturnal oasis effect [28], a phenomenon triggered by radiation and convection cooling processes (low density, reduced solar heat gain, and nearness to vegetation areas) [29,30]. However, during the hot summer months, the degree of night-time oasis phenomenon reduces in the western suburbs due to strong warm winds from the inland areas [28]. At the same time, the cooling effect of the sea breeze from the ocean alleviates the heat island effect and lowers the temperature in the eastern suburbs [4]. These two climatic processes (heat island effect and oasis effect) are the main influencing factors of the discrepancies in temperature distribution in summer [4,6].

The constant dynamic struggle between the sea breeze (cooling mechanism) and the warm dry air (heating mechanism) from inland during the summer season further complicate urban overheating characteristics in Sydney [31,32]. Compared with other hot arid cities around the world (e.g., Ghardaia in Algeria) [33], the characteristics of urban overheating in Sydney are unique and undergo significant changes in space and time; the city center is cooler during the day than in the fringe areas of the city, and warmer at night [29].

Alice Springs is another city that represents Australia's hot desert climate. Urban overheating in Alice Springs presents a constant pattern and is mainly governed by city-specific variables [5]. Existing evidence shows that the inner city area is warmer than the sorrounding desert environment at night and cooler in the morning [5]. Similar to Alice Springs, the night-time UHI was observed in other cities (Adelaide and Perth). Clearly, a presence of 'daytime cool island' effect has been observed in the city, which can be explained by the shading of buildings, vegetation and trees (especially in the eastern parts of city areas), and shading of solar radiation. Urban cool island (UCI) effect has been also observed in other cities located in similar hot dry climates [30]. Moreover, a higher intensity of UHI during the day has been observed from afternoon to evening. The large amount of heat stored in the urban fabric, unobstructed solar radiation contributing to diurnal heat island and a desert mass inland are the main reasons for the UHI increase in the afternoon in Alice Springs [5]. The delay in urban cooling via the slow heat release from the urban fabric and the long-wave radiation loss from the urban canopy may be related to higher nocturnal UHI amplitude [5].

The intensity of urban overheating in other Australian cities (such as Darwin, Adelaide, and Melbourne) can also be explained by city-specific variables. In Darwin, heat retention within the urban canopy, high humidity, low wind speed, and lack of sea breezes exacerbate urban overheating [34]. The form, layout, structure, morphology, and anthropogenic heat greatly influence the advection rate. Compared with other areas of the city, the low-rise open layout areas have lower diurnal temperatures [34].

Last but not least, evidence from recent research confirms that global climate change further exacerbates urban overheating [24,35]. Over the past 100 years, the average temperature of the earth has risen by about 0.7 °C, while the average temperature of Australia has risen by about 0.9 °C [36]. Interestingly, a large part of this temperature increase (close to 0.7 °C) occurred after 1950. Further, the hottest years in Australian modern history (since 1910) occurred in the past two decades [37]. Climate change projections also indicate that under 1990 baseline conditions and business as usual (BAU), by 2030 and 2100, the temperature rise in Australia will be 1.5 °C and 4.5 °C, respectively [36]. Even under strong carbon emission reduction scenarios, the average temperature increase will be about

2 °C by 2100 [38]. These changes are expected to increase the average and maximum temperatures in summer, the frequency of heatwaves, hot days, and warm nights [25,37,39].

Heatwaves and extreme high-temperature events are some of the most significant effects of El Niño Southern Oscillation (ENSO) and global climate change. Thus, the increasing frequency of heatwaves is an important issue in Australia. There is no consensus on the definition of heatwaves because people in different regions have different climatic adaptive capacities [40–42]. However, in Australia, a heatwave is pronounced if the absolute maximum temperature threshold (35 °C) is exceeded for two to five consecutive days [43].

The combined effect of heatwaves and local climate change is argued to increase summer temperatures in Australia [24,35,44]. Yet, in-depth studies on changes in the intensity of overheating during heatwaves and the possible synergies between these two phenomena are very limited [24]. For example, recent research in Sydney argues that there is a strong relationship between heatwaves and the degree of overheating: the difference between the maximum average UHI intensity during heatwaves and non-heatwave period was found to be at least 8 °C [24]. In addition, the UHI effect is enhanced and more pronounced during the day (noon). Moreover, in Sydney, the synergies between overheating and heatwaves can also be attributed to specific synoptic weather conditions in the city [24]. The advective heat flux from desert winds, as well as anthropogenic and sensible heat fluxes, can be considered as key reasons for overheating during heatwaves [24].

These results are consistent with studies carried out in other coastal cities [45,46], although there are large differences between heatwave and non-heatwave periods in Sydney. Further, the results are different from studies based on non-coastal cities [47,48], where no changes or reductions in overheating patterns were found during heatwaves. In studies comparing rural and non-coastal areas, the phenomenon of urban heating was more pronounced at night [49–51].

Among other weather extremes, Australia is particularly susceptive to and whose frequency is being exacerbated by climate change are bushfires. A recent publication [52] demonstrated that long-lasting bushfire seasons may alter the overheating pattern in the city of Sydney. In the study, the authors compared the UHI intensity during the bushfire event in 2019/2020 to that recorded during the same period over the previous 20 years. Results from the study show that bushfires were responsible for the disappearance of cool island events and the exacerbation of UHI events over the median. The interlacement between UHI and urban pollution is indeed very intimate and expected to deteriorate in the future [53].

3. Impacts of Urban Overheating

Urban overheating is a major local climate change phenomenon in Australia. As mentioned in the previous section, the average UHI in Australian cities is as high as 4–6 °C, and in some metropolitan cities, it exceeds 10 °C. Consequently, this local climate anomaly may seriously affect urban sustainability and human well-being, and the interrelationship between urban overheating and its impact on various aspects of human life has been documented for major Australian cities. This section provides a comprehensive review of the impact of urban overheating on public health, energy and the economy.

3.1. Health and Well-Being

In Australia, overheating in cities seriously threatens public health. The Australian Emergency Management Agency and other government organisations have recognised that overheating poses a serious threat to health and well-being. Long-term exposure to extreme temperatures and heat may cause cardiovascular, respiratory, and thermoregulation (cramps, rashes, and heat stroke) related problems, and affect cognitive and emotional abilities [54]. The most at-risk groups include the elderly, children, pregnant women, patients with chronic diseases, people with physical and mental disabilities, and low-income communities.

A considerable body of literature has demonstrated that local climate change and higher urban temperatures, especially during heatwaves, can amplify heat-related mortality and morbidity [38,55–57]. In particular, existing works have found that when the ambient temperatures rise above a certain threshold, mortality and morbidity significantly increase. For example, recent evidence indicates that people living in warmer areas of Western Sydney have a 6% higher risk of heat-related death than those living in colder areas of East Sydney [58]. Furthermore, a 2 °C rise in the maximum threshold temperature (27 °C) can increase the average mortality rate by 5.3% Similar findings were also observed by [59]. In Perth, a degree rise in the temperature threshold of 30 °C increased the mortality rate of patients with cardiovascular-diseases by at least 10% [60]. Studies of a similar nature have also demonstrated a presence of strong synergies between overheating and increase in heat-related mortality in many other Australian cities, such as Brisbane [61] and Adelaide [56].

In terms of morbidity, some comprehensive studies conducted in all capital cities in Australia found that a degree rise in temperature can increase the emergency hospitalisation rate of heart-disease patients by an average of 10%, when the maximum ambient temperature is considered to be 30 °C [60,62]. However, other evidence suggests that results may vary depending on the research methods, spatial, socioeconomic, and climatic variabilities, as well as public adaptation [58]. For example, recent research has shown that Sydney's unique overheating phenomenon can be a major cause of higher morbidity in the western parts of the city [58]. It is further estimated that the incidence of all-cause heat morbidity is between 0.05% and 4.6%, and that during heatwaves, this value is between 1% and 11% [58]. Moreover, a 1 °C increase in daily maximum temperature can increase the incidence of heat-related morbidity by 1.1% to 4.6%, when the threshold temperature is regarded as 27 °C. Other studies conducted in Sydney [63] and Brisbane [64] also observed similar results.

Overall, it is evident that the risk of heat-related mortality and morbidity rises significantly with the rise in threshold temperature and during heatwaves. However, the risk gradient may depend on a variety of factors, such as local climate, age, outdoor and indoor environments, thermal quality of the housing, physiological characteristics of the population, demographic and socioeconomic factors, adaptation, and infrastructure [38,65–67]. For example, for low-income people living in poor and warm parts of the city with poor-quality housing, and lack of resources to maintain thermal comfort (air conditioning), the health risks are very high [68,69]. As a result, low-income people may spend more energy than others, or even live in uncomfortable indoor environmental conditions that may affect their health and well-being [58]. Despite these risks, limited research has explored the relative impact of urban overheating on low-income communities in Australia [70].

3.2. Energy Consumption and Demand

Urban overheating has severely affected the energy consumption and peak electricity demand in Australian cities. Many studies have explored the relationship between urban overheating and energy consumption, and found a positive correlation between the two [71].

Santamouris [7] found that urban energy consumption per person-year increases by 0.73 ± 0.64 kWh/m^2/°C, or 78 ± 47 kWh/°C, while peak electricity demand increases by 0.45–12.3%/°C, depending on AC penetration and setpoint temperature. Evidence from a recent experimental study conducted in Sydney indicated that urban overheating can increase indoor overheating levels by 56% and cooling energy demand by 16% per year [58]. It was further found that the cooling penalties of residential and commercial buildings were 6.4% and 15.6% per year, respectively, or about 1.8 kWh/m^2/°C and 6.7 kWh/m^2/°C per year, respectively. However, the distinct overheating phenomenon in Sydney (Section 2) can have a differential effect on the city's cooling energy demand.

According to a parametric study of the Sydney metropolis, the buildings in western Sydney consume three times as much energy as eastern Sydney [71]. Moreover, the annual cooling energy demand in western Sydney was as high as 140.2 kWh/person/°C, while the cooling penalties for residential and commercial buildings were 45.1 kWh/person/°C and 95.1 kWh/person/°C per year, respectively [58]. The higher energy penalties imposed by the commercial sector can be attributed to the increased use of commercial energy and the relative smaller population in the western region.

Similarly, in the desert city of Alice Springs, the heat island effect (Section 2) also significantly affected the city's cooling energy demand and building consumption. The energy demand, measured in cooling degree days (CDDs), was between 923–475, when the base temperature ranged between 23 °C and 27 °C [5]. This finding indicates that Alice Spring manifests three times the energy demand of Sydney [4].

In general, studies on the impact of urban overheating on energy determined that for every degree rise in threshold temperature (18 °C) increase, the average cooling energy demand will increase by 0.45% to 4.6% [72], while the annual average energy consumption will increase by 0.5% to 8.5% [65]. Worse, the cooling energy demand of urban buildings will be at least 13% higher than similar rural buildings [7]. Considering that Australia's average summer temperature is higher than 27 °C and 90% of the country is urbanised, these figures may seriously affect thermal comfort and well-being [15,73].

3.3. Economy and Productivity

Urban overheating may pose a serious threat to the Australian economy by reducing labour productivity [74]. Yet, there is not sufficient evidence on the synergies and interdependencies between local climate change and the economy. Most of the existing work on local climate change has focused on the relationship between overheating during heatwaves and indoor workplace productivity [38,74] and outdoor workers productivity [75,76].

For example, a study has shown that urban overheating will cause the Australian gross national product (GNP) to drop at least 1.3% per year [77]. A recent study highlighted that due to heat stress, 7% of the Australian population did not go to work at least one day in the year 2013/14 [74]. The study further emphasised that 70% of the population did go to work, but they felt inefficient, and on average, people were exposed to heat stress for at least 10 days a year and lost about 27 work hours per year. If the sample is extrapolated to the entire working population in Australia, the annual productivity loss from thermal stress is $7.92 billion [74]. Existing findings on the economic costs of extreme temperature events varies widely, with estimates ranging from $1.8 billion to $7 billion [74]. These economic and productivity losses make the cost of heat stress comparable to the cost of chronic health problems.

Extreme temperatures and urban overheating, especially during heatwaves [15,78], severely impact other sectors of the economy, such as transport, construction, agriculture, and tourism, in addition social behaviour (e.g., domestic violence, burglary, assault) [15]. However, evidence on the synergies between urban overheating and other sectors of the economy is also inadequate.

4. Impact of Mitigation Strategies on Cooling Cities

To mitigate urban overheating and offset its impact on cities, appropriate mitigation techniques and strategies are available. These measures create a thermally balanced city by increasing the reflectivity of urban areas, reducing anthropogenic heat, and dissipating excess urban heat. In this context, this section comprehensively reviews the progress of research on urban heat mitigation in Australia.

A number of studies have been attempted to estimate the potential of various strategies in urban heat mitigation in Australia. The list and the performance of each study are given in Table 2. The reported studies are based on the following mitigation techniques: (a) reducing the absorption of solar radiation and keeping urban surfaces cool (e.g., cool materials); and (b) increasing evapotranspiration in urban environments (e.g., urban greenery, green infrastructure, and water-based systems). The rest of this section provides a discussion on these strategies and their mitigation performance in Australia.

Table 2. Performance of mitigation strategies reported in Australian cities.

S.No	Mitigation Strategy	Location	Maximum UHI Mitigation Potential	Reference
Urban Green Spaces				
1	Urban greenery	Sydney	1.4	[71]
2	Urban parks	Melbourne	0.3	[79]
3	Urban vegetation	Melbourne	1	[80]
4	Urban vegetation	Melbourne	2	[81]
5	Urban vegetation	Brisbane	1.08	[82]
6	Urban greenery	Alice Springs	0	[5]
7	Urban parks (trees)	Gold Coast (Brisbane)	1.2	[83]
8	Urban parks (grass)	Gold Coast (Brisbane)	0.7	[83]
9	Urban greenery	Adelaide	2	[84]
Green roofs				
10	Green roofs	Adelaide	0.06	[85]
13	Green roofs	Melbourne	1.4	[86]
14	Green roofs	Canberra	0.4	[87]
15	Green roofs	Sydney	0.5	[71]
Green Walls				
16	Green wall	Adelaide	0.25	[85]
17	Living wall	Adelaide	1.5	[88]
Reflective Materials				
18	Cool streets	Sydney	1.4	
19	Cool pavements	Sydney	0.5	[71]
20	Cool roofs	Sydney	0.6	
21	Cool roofs	Melbourne	0.5	[80]
Water				
23	Water sprinklers	Alice Springs	0	[5]
Shading				
24	Street shading	Alice Springs	0	[5]
Combination				
25	Greenery and Reflective materials		0.95	[89]
26	Water and Shading		3	
27	Reflective materials (roofs, pavements, streets)	Sydney	3	[71]
28	Urban vegetation and Cool roofs	Melbourne	0.82	[80]
29	Trees, Reflective materials (roofs and pavements), Evaporative cooling systems and Shading	Alice Springs	1.1	[5]
30	Trees and Green roofs	Melbourne	2.4	[86]
31	Trees and Grass	Canberra	0.8	[87]
32	Reflective materials (buildings and pavement)	Alice Springs	0.9	[5]
33	Reflective materials (roofs, pavements) and trees	Sydney	1.3	[90]

4.1. Use of Water

For centuries, people have been using water as an important strategy to minimise heat stress and cool the sorrounding environment. A waterbody helps regulate temperatures and act as a thermal buffer by reducing heat convection to air above and evaporation [89,91], where absorbed thermal energy converts sensible heat to latent heat with the production of water vapour [92] (p. 1047). Natural water bodies such as lakes, rivers, and wetlands, in addition to artificial water bodies, can reduce the UHI effect and contribute to the UCI effect [93]. Along with natural waterbodies, for decorative and climatic reasons, passive water systems such as small artificial lakes, ponds, and swimming pools have been widely used in public places. Similarly, active or hybrid systems such as evaporation towers, sprinklers, fountains, and water misting technologies are now widely used in public places around the world [89].

A water body is capable of lowering the UHI effect by 1–2 °C, and sorrounding local environments by 2–6 °C [93]. Unfortunately, previous studies in Australia have not fully assessed the possible impact of water bodies on urban temperatures, especially beyond their sorroundings (Figure 3). A trivial number of existing studies demonstrate positive correlation between water and UHI reduction, while the corresponding temperature drop at the local scale is between 4–13 °C [5,94]. For example, in Alice Springs, the use of water sprinklers technology in the CBD had no major effect on sorrounding temperatures, while it contributed to a local maximum mitigation of 13 °C [5]. Similarly, a local maximum reduction of 3.9 °C was observed in Darwin by using evaporative cooling systems [34].

Notwithstanding, the ability of water to influence the UHI effect and the sensible cooling effectiveness (of both dynamic and static water systems) depends on the urban area, the physical and geometric characteristics of the system, its inherent properties, the net effect of radiation balance, atmospheric advection, the climate variables (humidity, wind velocity) that contribute to sensible to latent heat conversion, and its interactions with sorrounding climatic conditions [92,94]. Furthermore, despite their intense local impact, there is little experimental information about the performance of blue installations in Australia.

4.2. Urban Green Technologies and Strategies

Urban greenery is one of the key elements of a sustainable city. Greenery can alleviate urban temperatures, cool the sorrounding environment, and influence the urban microclimate through (a) shading the building surfaces, deflecting solar radiation, reducing the heat convection to the air above occupied spaces, thereby reducing space cooling energy, and any resulting anthropogenic heat emissions that have the potential to increase thermal energy released back into the urban climate; (b) evapotranspiration, a process where water absorbed through roots of plants is evaporated into the air through their leaves by absorbing energy from solar radiation, which keeps themselves cool through the photosynthesis and the sorrounding air by latent heat absorption; and (c) acting as wind shields and contributing to wind pattern changes [95–97]. In addition, greenery can improve thermal comfort and human health, promote psychological balance, and make cities more attractive [89]. Urban greenery may be part of urban landscapes, parks, streets, hedges, open spaces, and integrated into buildings through green roofs [98] and green walls/vertical gardens [99].

Many studies have been conducted on the mitigation potential of various types of urban greenery in Australian cities. The full list and the mitigation potential evaluated in each study is provided in Table 2. In total, 11 studies evaluated the potential of increased tree canopy cover, 7 studies analysed the potential cooling effect of green and planted roofs and walls, and 2 studies identified the performance of combinations of various types of greenery. In general, different forms of urban greenery can provide a mitigation potential in the range of 0.3–2.5 °C, with an average value of 1.0 °C (Figure 4). A further discussion on the mitigation potential of each of the urban greenery strategies is provided in the following paragraphs.

4.2.1. Urban Green Spaces

In tropical and subtropical climate regions, such as Australia, increasing the number of trees and hedges is a cost-effective mitigation strategy [100]. Based on a comparative analysis of five selected cities in different climate zones, Brown et al. [101] concluded that shading and canopy cover are by far the most effective cooling strategies in Australia. Evidence from existing research show that increasing the tree canopy cover can reduce the UHI by 0.3–2 °C, with an average value of 1.07 °C. However, the temperature differences vary both spatially and temporally.

Spatially, a detailed study conducted in Melbourne found that increasing canopy coverage from 27% to 40% can reduce the UHI by 1 °C [80], while increasing the percentage of outdoor pavements integrating greenery has a maximum cooling potential of 1.4 °C in Sydney [71]. By reviewing the existing studies in Melbourne [79] and Brisbane [83], it can be summarised that urban parks are 0.3–1.2 °C cooler than a sorrounding non-green area.

The performance of urban greenery at the local level is comparable to the global mitigation potential. Findings from Alice Springs revealed that increasing tree canopy cover can contribute to a maximum local temperature drop by 1 °C [5], while shading on all main streets in the city center can reduce the local temperature by 1.3 °C in Darwin [34].

Temporally, experimental results from different cities establish that a high percentage of tree canopy cover correlates strongly with cooler nocturnal temperatures in Australia (Figure 3). Research from Melbourne show that when tree canopy coverage was 5–10%, there was no large temperature difference between day and night, while the difference increases by 0.6 °C at 40% vegetation cover [80]. Similar results were also observed in Brisbane [82] and Adelaide [84].

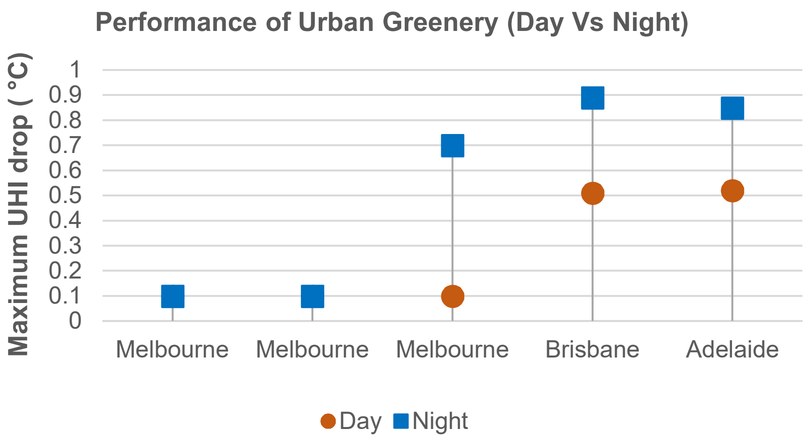


Figure 3. Performance of urban greenery (day vs. night).

While trees and hedges have significant potential in urban heat mitigation, their performance is highly localised and is affected by complex factors, such as vegetation type, canopy density, height of leaves above the ground, leaf area index (LAI), water content, water availability, evapotranspiration, distance between buildings and trees, thermal balance in sorrounding areas, urban density, and local weather conditions [97,102]. Similarly, the performance of urban parks depends on factors such as the characteristics of the area, the features of urban park, types of trees, and wind speed. According to [103], the impact of urban parks is limited to one park width, and the cooling gradient outside the park varies from 0.1 to 1.5 °C/100 m. To design large urban green spaces, such as parks, that have the greatest cooling effect in hot summer weather, landscape architects and city planners need to understand the relative impact of various design interventions.

4.2.2. Green Roofs

A green roof is a building roof with fully or partially covered vegetation. Green roofs are usually categorised into three types: intensive roofs (with small trees and shrubs), semi-intensive roofs (with small herbaceous plants, ground covers, grasses, and shrubs), and extensive roofs (covered with thin vegetation layers) [96,104]. Green roofs can mitigate urban heat, improve urban environmental quality, and have many other environmental and economic benefits. However, it must be recognised that green roofs (and also green walls) have disadvantages, such as high initial investment, high maintenance cost, and requirement of more structural strength to support extra load [105].

Evidence from existing research demonstrates that green roofs have a mitigation potential of 0.06–1.4 °C (Figure 4). According to an experimental survey of a typical urban area in Adelaide, covering 30% of the total roof area of all buildings with green roofs during a typical warm summer can reduce UHI by 0.06 °C and the daily energy consumption by 2.57 W/m^2/day [85]. Similarly, [86] documented that the cooling potential of green roofs in Melbourne is 1.4 °C. [71] reported that green roofs can reduce the UHI in Sydney by 0.5 °C, while the heat mitigation potential of green roofs in Canberra is 0.4 °C [87]. Given the small number of studies, more research on the thermal performance of green roofs is warranted.

4.2.3. Green Walls

Green walls have been around for a long time as hanging gardens or climbing plants. Today, green walls, also known as living walls, vertical gardens, and bio-walls, are an important category of natural urban sustainability solutions.

Green walls can be divided into two categories: (i) green façades and (ii) living wall systems [106]. A green façade can be designed to be direct or indirect, wherein a direct green façade is a type of traditional green wall with evergreen or deciduous climbers connected directly to the building's surface, while an indirect green façade consists of a vertical structure supported by trellis or steel cables for climbing plants [107]. On the other hand, a living wall is a modern vertical greening system and requires complex planting boxes, pre-vegetation, and pre-fabricated support structures to promote plant growth [108]. The application of modular panels in living walls helps plants obtain sufficient nutrients to survive. The success of a green wall depends on several factors, such as the choice of plants and vegetation (local and non-local), an irrigation system, wall orientation, and design conditions.

Despite their environmental and economic benefits, there is little information about the performance of green walls in Australia. Thermal performance analysis of a living wall in Adelaide show that, in summer, a living wall can mitigate UHI by 1.5 °C [88], while another study found that green walls has a maximum UHI mitigation performance of 0.25 °C [85]. Nevertheless, Australia's green wall industry is still in its infancy, and new case studies are needed to resolve many research gaps.

4.3. Use of Reflective Materials

Increase in albedo will significantly reduce the UHI effect and extreme temperatures. Advanced materials are commercially available with high emissivity and high reflectivity. These can be applied on roofs, exterior walls of buildings, and outdoor urban spaces (such as pavements). Cool roofs, cool facades, and cool pavements help mitigate UHI, reduce cooling energy consumption in air-conditioned buildings, improve thermal comfort in non-air-conditioned buildings, and improve outdoor air quality and comfort [109,110].

4.3.1. Cool Roofs and Façades

Cool roofs and exterior walls are building components with high solar reflectance and high emissivity coefficient materials. The reflective materials commonly used in buildings are white and can be a single layer or liquid. Typical liquid products are white coatings, elastomers, acrylic, or polyurethane coatings, while single-layer products are EPDM (ethylene propydiene tetrolymer membrane), CPE (chlorinated polyethylene), PVC (polyvinyl chloride), TPO (thermoplastic polyolefin), and CPSE (chlorosulfonated polyethylene) [23]. Akbari and Kolokotsa [96] provide an extensive list of existing cool materials for cool roofs and exterior walls. Furthermore, extensive breakthrough research has been conducted to develop coloured thermochromic materials that become more reflective at higher temperatures [111]. However, more research is needed to develop thermochromic agents as viable and economical cooling materials.

Reflective materials used in buildings can be divided into four categories: (i) natural materials with high solar reflectivity (e.g., white marble), (ii) white synthetic coatings with high reflectivity, (iii) coloured coatings with high reflectivity in the infrared solar spectrum, and (iv) smart coatings such as thermochromic coatings and materials with enhanced optical and thermal properties [65].

Although some studies have been conducted to determine the effect of cool roofs on urban heat, outdoor and indoor comfort, and building energy consumption, research in Australia is still very limited. As such, [71] found that increasing the albedo of all roofs in Sydney can reduce the UHI by 0.6 °C, while [80] reported that an increase in the albedo of 60% of Melbourne's rooftops can lead to a cooling potential of 0.5 °C.

Furthermore, the thermal performance of a cool roof depends on many factors, such as local climatic conditions (solar radiation intensity, humidity, wind speed, and cloud cover), the solar reflectance and thermal emittance of roof materials, heat capacity, and U-value of the roof [65]. Moreover, ageing can remarkably reduce the solar reflectance—and thus the cool roof direct and indirect benefits—even by more than 20% during the first years for cool roofing materials with initial albedo equal to 80%, as documented with natural exposure programs conducted in the US, Europe, Brazil, and Japan [112].

The design, construction and materials of cool roofs are guided by cool roof standards, building codes, grades, and labels. Different building energy efficiency standards including *ASHRAE 90.1 and 90.2* and *International Energy Conservation Code*, have adopted cool roof requirements [109]. In many developed countries, cool roof committees (e.g., the American Cool Roof Ratings Council and the European Cool Roof Council) have been established to promote and standardise cool materials. Although cool roofs can provide important opportunities for Australia to save energy and mitigate urban heat, the lack of cool roof councils or the lack of building regulations with cool roof credits or requirements can pose challenges.

4.3.2. Cool Pavements

Urban pavements, streets, driveways, parking lots, squares, and sports fields cover a large proportion of urban structures, and are mainly composed of highly heat-absorbing surfaces (such as asphalt and concrete). Higher surface temperatures will increase the ambient temperature and exacerbate the UHI effect. In contrast, cool materials can lower the surface temperature of pavements and help alleviate urban overheating [96].

The standard reflective paving materials used are fly ash (concrete additives), chip seal, slurry coatings (also known as "micro-surface layers", "fog coatings", "overlays"), reflective synthetic adhesives and light colours coatings [65]. Important research has been carried out to develop extremely high reflective materials for pavements. Important research has been conducted to develop extremely high reflectivity materials for pavements. These include water-retaining or permeable materials, infrared reflective coatings, heat reflective coatings, colour-changing coatings, nanotechnology additives (for example, emerald coatings), and photovoltaic pavements [113]. Further, Ref. [96,113] provide a list of materials used for pavement and their reflectance values.

In Australia, little work has been conducted on the performance of cool pavements. As such, Ref. [71] found that an increase in the albedo of all streets and pavements in Sydney can mitigate the UHI by 1.4 °C and 0.5 °C, respectively. More analysis is needed to determine the economic feasibility and thermal performance of reflective pavements. In addition, current building standards, public information plans, or incentive plans do not consider reflective surfaces.

4.4. Combined Mitigation Strategies

Evidence from existing research suggests that that the combined use of different mitigation strategies has higher mitigation potential than the contribution of each technology. The combined use of greenery and reflective materials can reduce the maximum UHI by 0.82–0.95 °C [80,89], while the combination of cool roofs and cool pavements can reduce the maximum UHI by 0.9–3 °C [5,71]. Further, the combination of trees and grass [87], as well as trees and green roofs [86], can reduce the maximum UHI by 0.8 °C and 2.4 °C, respectively. The combined use of trees, cool materials, evaporative cooling, shading [5], and water and solar control [89] can reduce the maximum UHI by 1.1 and 3, respectively.

In summary, the above mitigation strategies can significantly offset the impact of UHI and local climate change. The average maximum UHI reduction using only one technology is close to 0.42 °C. When two or more technologies were used simultaneously, the maximum UHI relief increased by an average of 1.59 °C. Urban greenery, especially trees, has a high potential for mitigation. Trees and hedges can reduce the average maximum UHI by 1.08 °C. The average maximum mitigation performance values of green roofs and green walls are 0.26 °C and 0.19 °C, respectively. Reflective roofs and pavements, instead can reduce the average maximum UHI by 0.33 °C. Both green roofs and cool roofs have been found to present high mitigation potential in tropical cities, such as Darwin [19]. However, cool roofs may have a higher mitigation potential compared to green roofs in tropical climates as vegetation can add to latent flux due to evapotranspiration and needs high maintenance and extra load capacity [114]. Advanced water technologies (e.g., misting systems) have a high heat reduction potential in dry and hot climatic areas [94]. In the literature [94], the average maximum temperature reduction is 8 °C, which qualify mist cooling as a tremendous asset against urban overheating at local scale. The highest temperature reductions (>10–15 °C) were reported for hot desert and hot-summer Mediterranean climates [94]. Spray cooling finds a fertile ground for investigation and implementation not just in dry hot climates where evaporation is spontaneously enhanced, but in warm, temperate and humid climates too.

Figure 4 shows the mitigation potential for all reported individual strategies and their combinations.

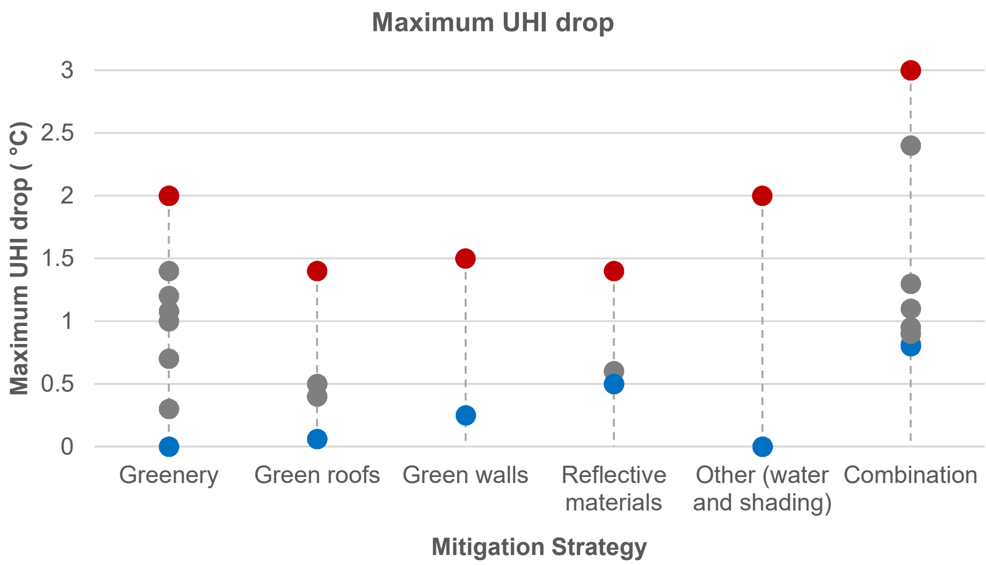


Figure 4. Range of the maximum UHI reduction for all reported mitigation strategies. Blue colour: reported lowest maximum UHI drop value; red colour: reported highest maximum UHI drop value; grey colour: range of maximum UHI drop value between blue and red.

5. Conclusions

Australian cities are warming faster than sorrounding rural areas. The average maximum temperature of the last century has been recorded in the past two decades [36]. Even without global warming, cities are already facing the urban heat island (UHI) effect, where urban areas have become hotter than sorrounding rural areas.

In Australian cities, the intensity of UHI is very significant. The current average intensity varies from 1.0 °C to 13.0 °C. The UHI amplitude changes functionally with the measurement technique adopted. The average intensity using standard method varies between 1.0 °C and 13.0 °C, while the average intensity using non-standard methods is between 1.0 °C and 7.0 °C. Mobile transects and other non-standard measurement methods seem to capture higher UHI intensity as they are commonly used in densely populated urban areas. On the other hand, fixed measuring stations installed in the sorrounding rural areas seem to capture lower UHI intensity as they are used in thermally undisturbed areas.

Urban overheating has different characteristics in different cities and regions of Australia. Urban expansion and reduction of green coverage often lead to the UHI effect. However, the synoptic weather conditions have a greater influence on urban overheating than the UHI itself in many Australian cities. In Sydney, the absolute amplitude of overheating increases as the distance from the coastline increases. The average ambient summer temperatures in the inland western suburbs are at least 2–5 °C higher than the coastal areas of the eastern suburbs [6]. This dramatic fluctuation in the intensity of overheating in Sydney is related to synoptic weather conditions, i.e., sea breeze (cooling mechanism) and hot desert winds (heating mechanism). The sea breeze inhibits hot air advection as it interacts with the UHI circulation and contribute to the cooling effect in the eastern suburbs [6], while the stagnation region in the city canyons, coupled with warm desert winds lead to weaker penetration of cool winds in the western part of the city [4,5]. The intensity of urban overheating in other Australian cities (such as Darwin, Adelaide, Melbourne, and Alice Springs) can be explained by city-specific variables (form, layout, structure, morphology, and anthropogenic heat). Moreover, global climate change and heatwaves have exacerbated overheating in Australian cities [24,35,44].

Urban overheating has caused damage to human health and severely affected energy demand, the economy, and the overall urban sustainability. Between 1993 and 2014, extreme heat has caused more deaths in Australia than floods, hurricanes, lighting, wildfires, and earthquakes combined [37]. Increased temperatures and UHI effects can also harm public health through heat stress and other heat-related diseases. The most vulnerable to overheating are the elderly, young children, chronically ill, mentally ill, outdoor workers, and low-income or socially isolated residents. Existing evidence from different cities in Australia suggests that when the threshold temperature rises by a certain degree, mortality and morbidity will increase. Overall, a 1 °C rise in the threshold temperature (27 °C) can increase the incidence of heat-related morbidity from 1.1% to 4.6% [58,59,64,75].

In addition to causing public health problems, urban overheating also increases urban energy consumption and demand. The overheating of cities will lead to increased energy consumption to meet higher cooling requirements, which will increase greenhouse gas emissions (GHG) and air pollutants. Existing research documented that the average cooling energy can increase by 0.45% to 4.6% per degree rise in threshold temperature of 18 °C [7]. The increase in energy demand will greatly increase the financial burden on governments and may also affect thermal comfort. Worse, urban overheating can affect social behaviour, work and labour productivity, thereby affecting urban development and economic growth [74,76].

Local governments can respond to the impact of urban overheating through emergency plans, outreach activities, and resilient building. However, emergency response and adaptation actions alone cannot save the most vulnerable people. The emergency plans fail to address other interrelated aspects of urban overheating, such as energy disruptions and decreased workplace productivity. Long-term mitigation strategies must be adopted in the natural and built environment to keep residents, buildings and communities cool while also saving energy, health and economic costs.

This article analysed various studies on urban heat mitigation in Australia to support government actions. There is evidence that cool materials, green roofs, vertical gardens, urban greenery, and water-based technologies can significantly alleviate the UHI effect, cool the ambient air, and create a thermally balanced city. Urban greenery, especially trees, has a high potential for mitigation. Trees and hedges can reduce the average maximum UHI by 1.0 °C. The average maximum mitigation performance values of green roofs and green walls are 0.2 °C and 0.1 °C, respectively. Reflective roofs and pavements can reduce the average maximum UHI by 0.3 °C. Water has high heat reduction potential in dry areas [94]. The combined use of greenery and reflective materials can reduce the maximum UHI by 0.8–0.9 °C [80,89], while the combination of cool roofs and cool pavements has a cooling effect in the range of 0.9–3 °C [5,71]. The combination of trees and grass [87], and trees and green roofs [86], can mitigate the maximum UHI by 0.8 °C and 2.4 °C, respectively. The combined use of trees, cool materials, evaporative cooling, shading [5], and water and solar control [89] can reduce the maximum UHI by 1.1 °C and 3 °C, respectively. The average maximum UHI reduction using only one technology is close to 0.4 °C, and the combined use of multiple strategies can reduce the UHI by 1.59 °C, while providing many co-benefits.

The results of this paper can be useful to urban planners and policy makers in reducing urban heat. Governments can use the comprehensive evidence compiled in this article to compare, analyse, and determine the best cooling strategy. Through the use of analytics and a multi-criteria decision-making process, local governments can compare the different mitigation strategies available and determine the most appropriate mitigation strategy. Effective use of evidence in planning and policy is essential to manage urban heat and guide sustainable urban development.

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