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Executive Final Report

COOL ROOFS COST BENEFIT ANALYSIS

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COOL ROOFS COST BENEFIT ANALYSIS

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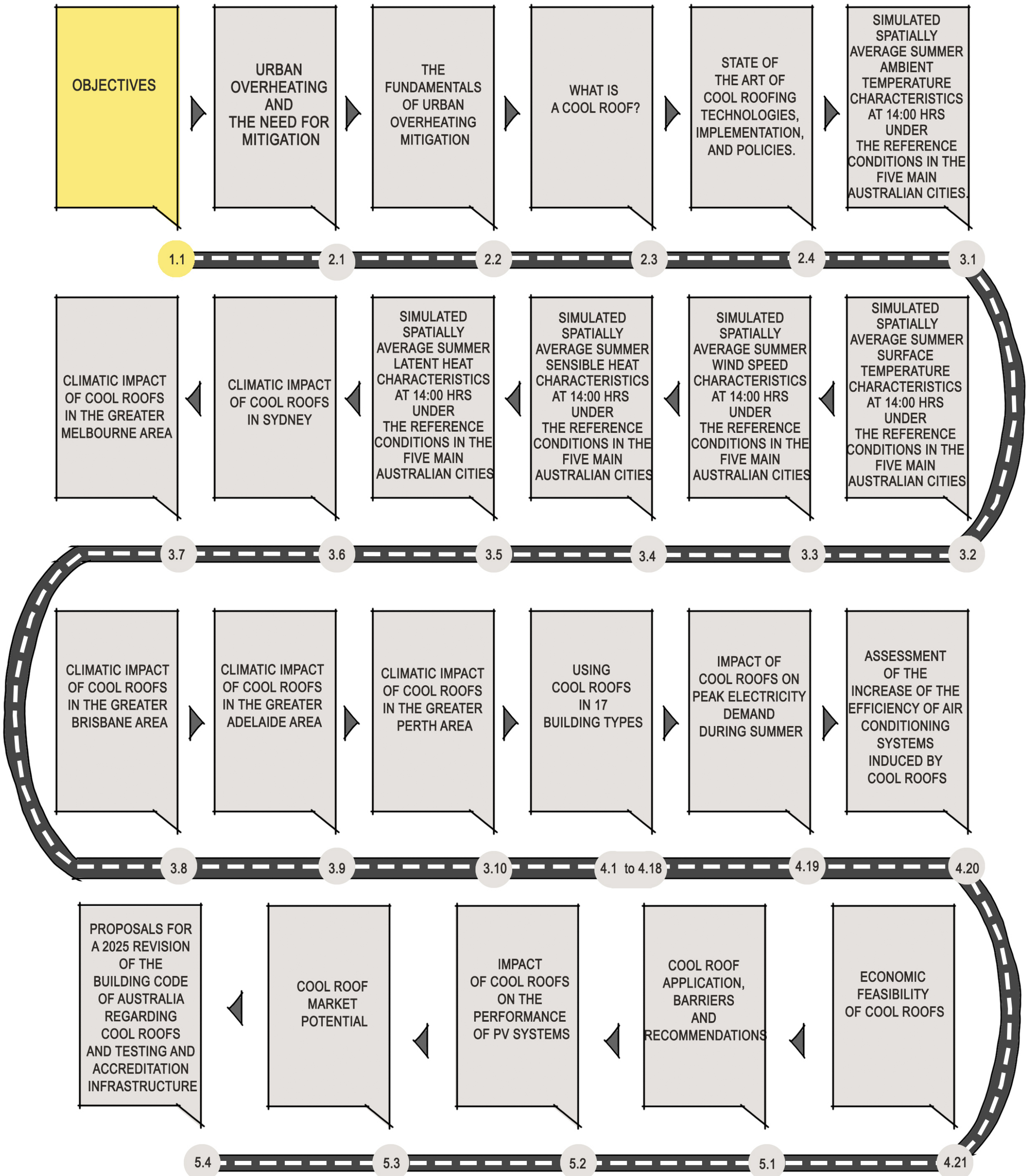

1.1. EXECUTIVE REPORT

1.1.1. OBJECTIVES

Supported by the Department of Industry Science Energy and Resources, DISER, this project carried out by the High Performance Architecture research group of UNSW, aims:

To understand the applicability and cost-benefit of using cool roof technology on buildings in Australia and any barriers to adoption

The specific objectives of the study focus on:

a. The Understanding and evaluation of the current implementation of cool roofs in the world.
b. The climatic potential of cool roofs when implemented in the major Australian cities
c. The energy conservation potential of cool roofs on the cooling energy demand of buildings
d. The capacity of cool roofs to reduce the peak electricity demand in the major Australian cities
e. The impact of cool roofs on the energy efficiency and performance of air conditioners

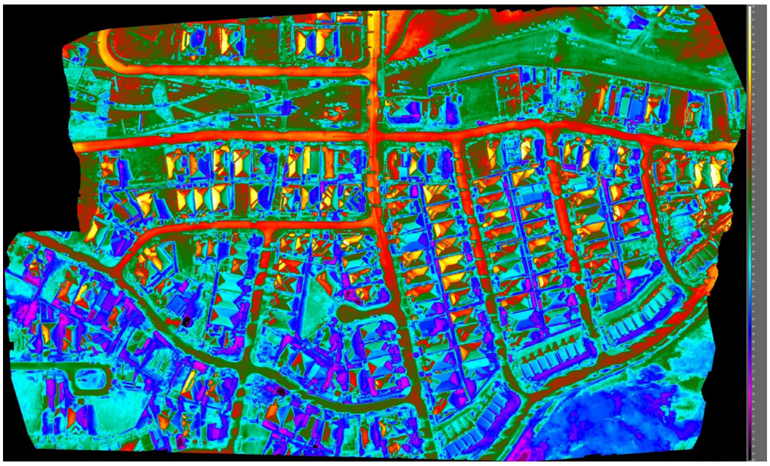

Figure 1.1 Infrared orthophoto taken with a drone flight over a residential area in South Western Sydney

f. The potential impact of cool roofs to improve the performance of roof integrated photovoltaics
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i. The investigation of the existing barriers and the industry needs and perspectives, and
j. Recommendations and Proposals on the changes needed to be made to promote the implementation of cool roofs in Australia

The study has investigated in detail all topics related to the above objectives. Twelve different specific research tasks have been carried out as shown in the roadmap of the project shown in Figure 1.2, plus the analysis and the evaluation of the current implementation of cool roofs in the world.

The final report is composed by 14 specific volumes describing in detail the methodology followed, the results and the main conclusions of the whole study

In the following pages of this executive report, a comprehensive presentation of the main findings of each of the research tasks is presented.

The research team of UNSW is grateful to DISER for their trust and tremendous help and support during this study.

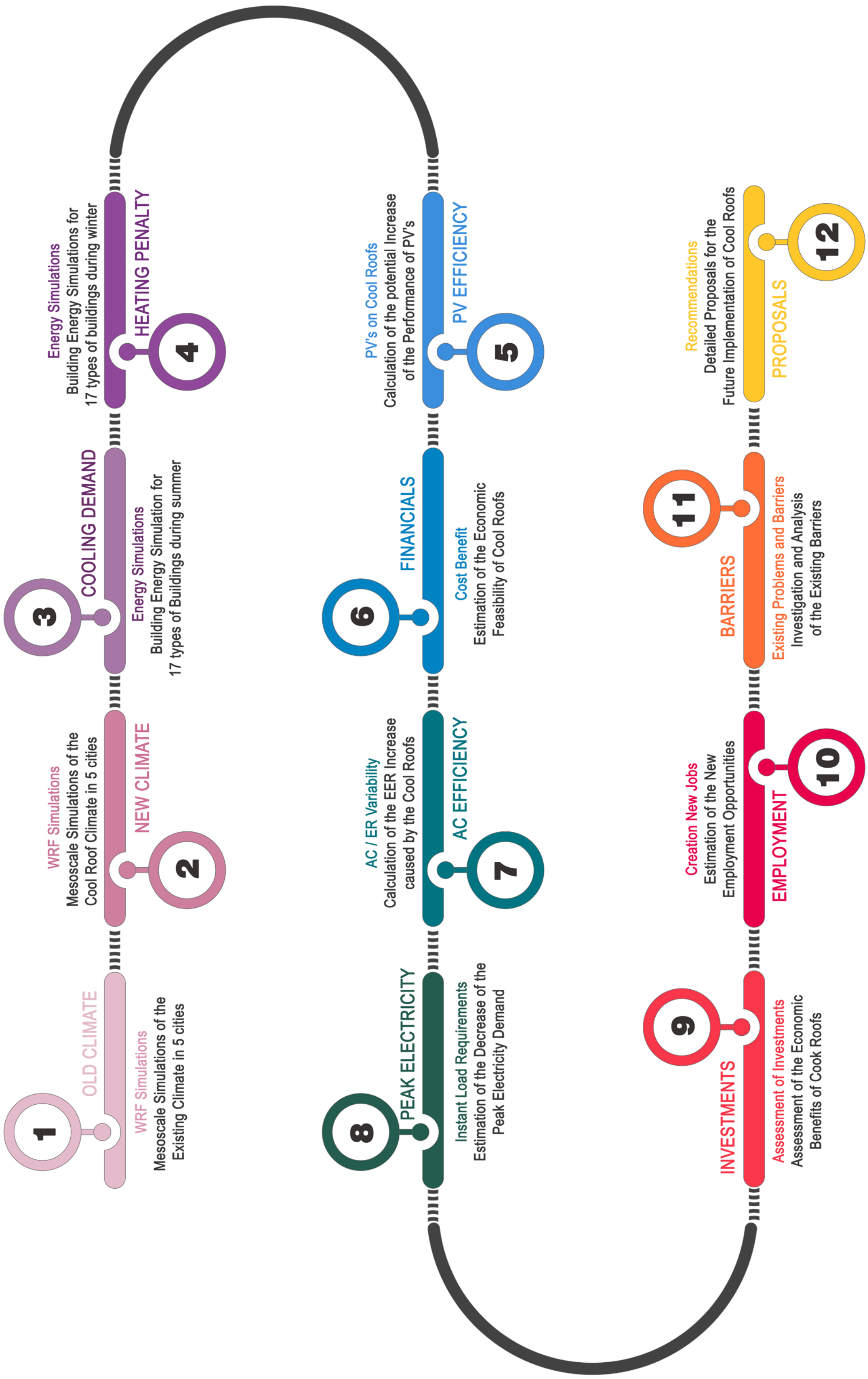
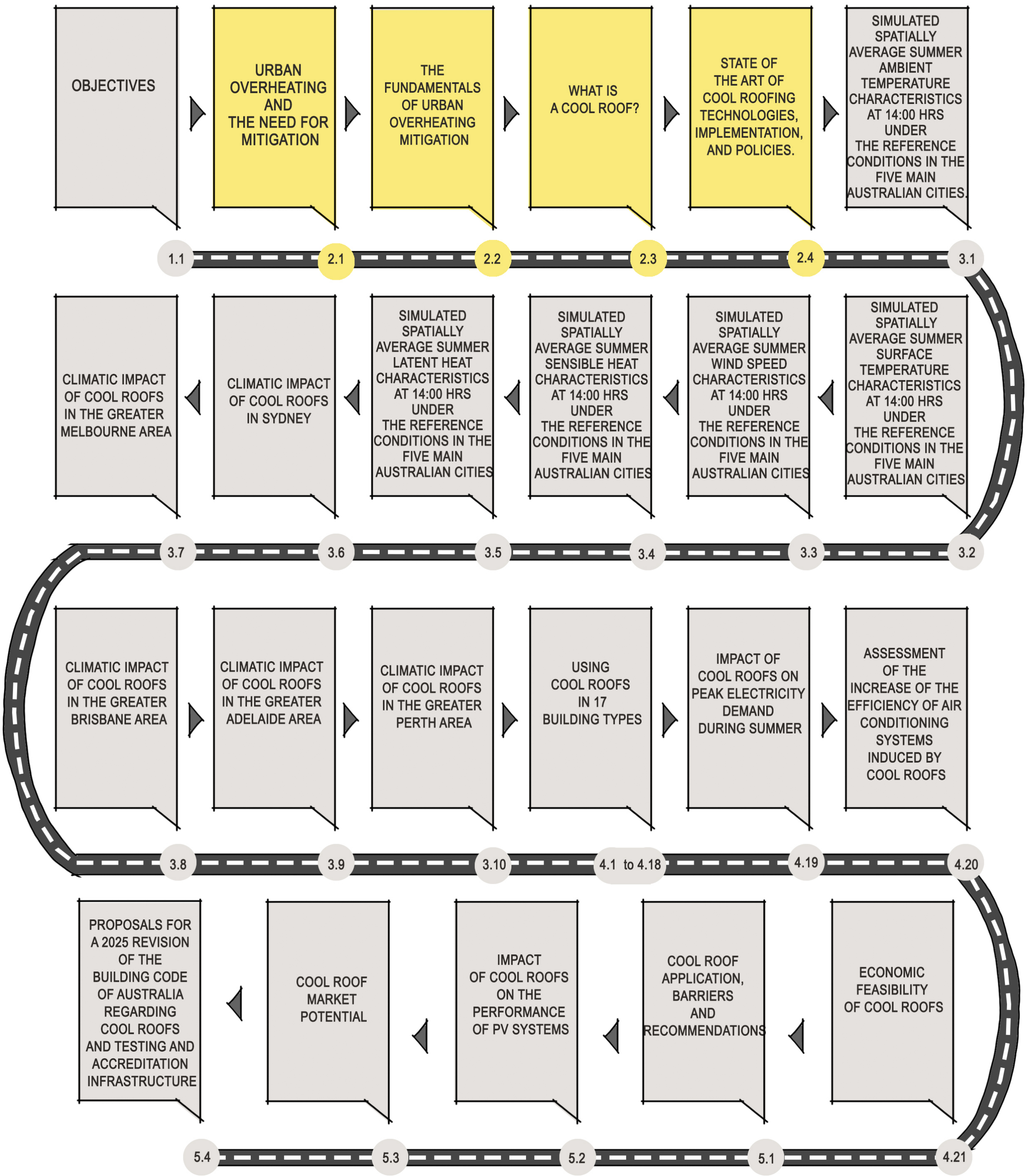


Figure 1.2 Roadmap and different Research Tasks of the study

2. WHAT WE KNOW ABOUT COOL ROOFS



2.1. URBAN OVERHEATING AND THE NEED FOR MITIGATION

Because of global warming and increasing urbanisation, Australians are experiencing hotter summers with a consistent trend over the last decades. This overheating is costing Australians more in electricity bills and their lifestyle and health. Hotter cities lead to increased heat-related mortality and hospitalisation for vulnerable populations and jeopardise the possibility of living outdoors enjoying the Australian way of life with sports and other recreational activities.

Urban areas are typically warmer than adjacent non-urban areas, especially during the early evening and night. This phenomenon is known as the urban heat island effect, and it manifests in every built environment, throughout the year, with different magnitude depending on the general climate conditions. Therefore, in winter, urban heat islands contribute to keeping cities warmer, reducing energy needs for heating. At the same time, in summer, the electricity consumption for air conditioning is higher in an urban building than in a hypothetical identical building located out of the city. This is not surprising, and it happens because a climate is the result of the interactions and responses to external influences (e.g., solar radiation) of the system composed of the atmosphere (air), hydrosphere (water), lithosphere (Earth's surface), and biosphere (definition from the American Meteorological Society). Therefore, changing land cover from rural to urban inherently alters the local climate, with influences waning with increasing distance from the built environment.

In particular, wind speed is reduced within built environments because buildings constitute obstacles to wind circulation, which reduces the penetration of the sea breeze in coastal cities (or any cool airflow), and thus hinders convective cooling. Further, urban areas display predominantly impervious surfaces such as street pavements and roofing materials that, unlike rural soil, do not retain rainfall that can later evaporate, cooling the air. Reduced vegetative land cover in comparison with rural areas also means less transpiration from plants cooling the air.

One of the most relevant differences is that cities are covered by many dark surfaces with high solar absorbance, such as street pavements, many roofing materials, and even photovoltaic panels. Street pavements in asphalt concrete or modified-bitumen roofing membranes, for instance, absorb 95% of the incident solar radiation, increasing the material's surface temperature. The hot surface releases heat — like a heat lamp — and mostly increases the urban temperature by convection. In simple terms, the hot urban surface transfers heat to the urban atmosphere like the bottom of a pot on a kitchen stove transfers heat to the water within it. The higher the surface temperature of the roof or pavement, the greater the heat transfer from it to the ambient air. More heat is dissipated with forced convection (e.g., wind or a fan). Moreover, the urban air is also warmed by heat released by human activities (anthropogenic heat), such as exhaust air from air conditioners and heat from condensing units and vehicles, predominantly.

However, urban overheating is not caused only by urban heat islands. Advection plays an important role in coastal cities, relevant to most Australian capital cities. Especially during heatwave conditions, warm wind from the interior prevails over the sea breeze from the coast, thus reducing the penetration of the latter and worsening urban overheating in synergy with the urban heat island effect.

The first known measurements of the magnitude of the urban heat island effect were performed by Luke Howard in London in 1813. Later, with technological advances in sensing, urban climatology bloomed, with documentation of urban heat islands in hundreds of cities worldwide, displaying consistent heat island features, overall, but at different magnitudes and patterns.

In Australian cities, urban overheating can lead to significant differences between coastal and inland areas, often exceeding 5–6°C during heatwaves, and between urban and non-urban surroundings, which can lead to an additional 2–3°C within urban areas inland compared with adjacent rural areas (Figures 2.1, 2.2). In some areas, such as in Penrith, the ambient temperature can reach peaks of more than 45°C during summer, with extremely low relative humidity exposing the population to the risk of dehydration and urban trees to water-stressed conditions, hindering their health and cooling potential. Urban overheating is documented in all Australian cities.

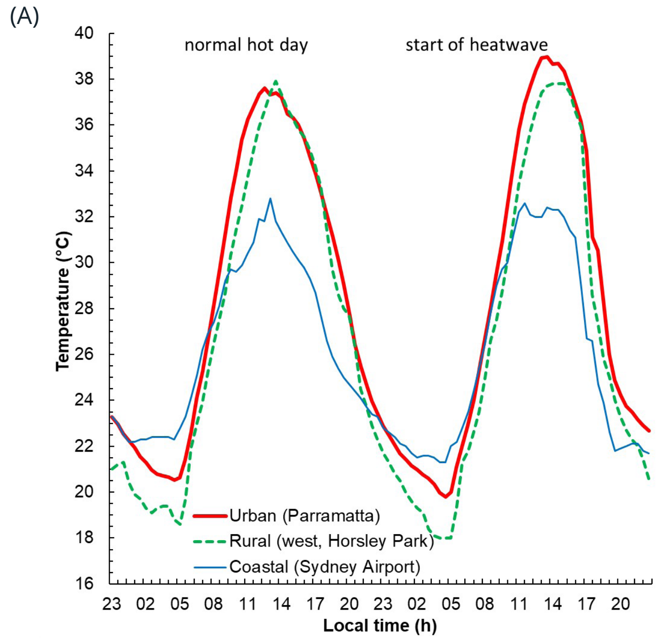


Figure 2.1 (A) Hourly course of urban overheating: a typical hot day followed by a heatwave day in Greater Sydney. The solid red line shows the average ambient temperature in the local government area of Parramatta (average of 20 stations – data from UNSW, Parramatta Urban Overheating Project), while the dashed green and solid blue lines are the ambient temperatures out of the urban area in Horsley Park and coastal area at Sydney Airport, respectively (data from BOM). During the first day (non-heatwave), the ambient temperature within Parramatta is similar to that in Horsley Park during the central hours of the day. During a heatwave day, warm wind from inland contributes to building a synergy between heatwave and urban heat island, leading to higher urban temperatures even during daytime. Urban heat adds to the coastal-inland differences.

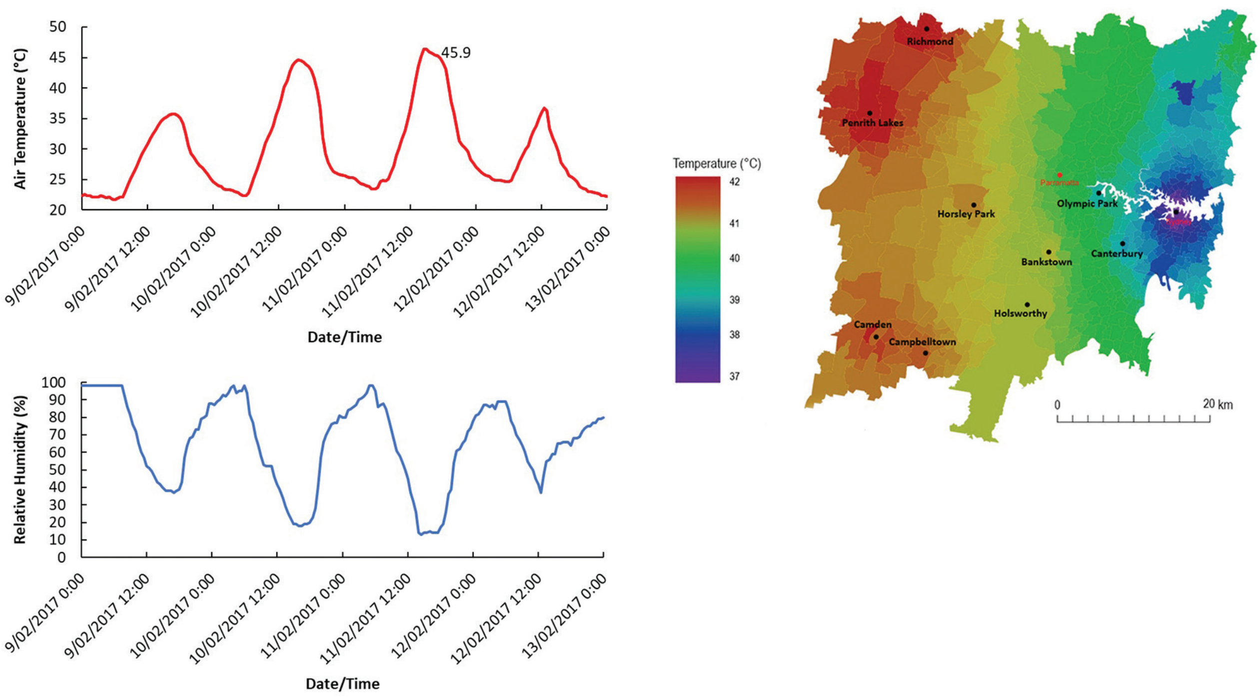


Figure 2.2 Heatwave of February 2017. Data for Penrith and spatial distribution across the Greater Sydney (data from Bureau of Meteorology, analysis by UNSW).

2.2. THE FUNDAMENTALS OF URBAN OVERHEATING MITIGATION

Mitigation of urban overheating can be achieved only upon diagnosing the specific causes of local overheating in the regional and global context. These may differ city by city. For instance, in Sydney, the role of advection from the inland (warm westerly winds), especially during heatwaves, is very strong. In other non-coastal cities (e.g., Milan, Italy) or even coastal cities where there is no relevant pressure difference between coast and inland (e.g., Darwin), this contribution to urban overheating is minor or absent.

Urban overheating is typically mitigated by acting on the mechanisms causing it (Figure 2.3). While many studies assessed the potential to improve urban ventilation and avert blocking the sea breeze (e.g., evaluating the impact of coastal high-rise buildings), it is seldom possible to implement substantial changes in wind-permeability of an established urban texture. Therefore, the mitigation technologies that are most commonly investigated try to avert the dynamics of the energy balance of cities that lead to overheating:

- Solar reflective roofs and pavements: They reduce solar absorption and thus retain a lower surface temperature under the sun, thus reducing the turbulent sensible heat released into the urban environment.
- Urban vegetation: It increases cooling by evaporation from the soil and transpiration from the plant, which uses most of the absorbed solar radiation for purposes that do not increase the temperature of leaves. Urban trees also increase shading and thus reduce the amount of solar radiation reaching street pavements, vehicles, and buildings.
- Water technologies: Irrigation, water misting and water fountains.
- Street shading with artificial materials.

The effectiveness and performance of heat mitigation technologies have been widely investigated in more than 220 projects worldwide, assessed in a metanalysis, documenting an average peak ambient temperature reduction of approximately 2°C with conventional heat mitigation technologies (cool roofs, trees, evaporative cooling). This research focuses on solar reflective roofing, also known as cool roofs, as they can be directly applied to buildings.

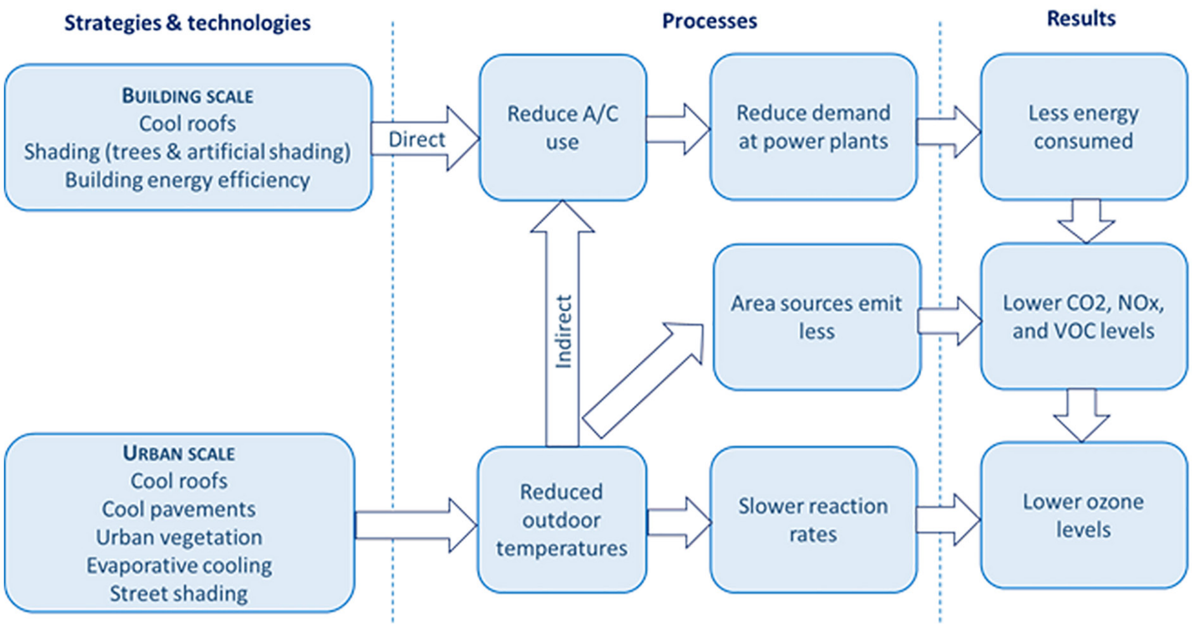


Figure 2.3. Impact of shade trees, cool roofs, and cool pavements on energy use and air quality (smog). Redrawn from Akbari et al. (2001) Solar Energy 70: 295-310.

2.3. WHAT IS A COOL ROOF?

A cool roof is a roof with high solar reflectance (i.e., low solar absorbance) and high thermal emittance. The solar reflectance defines how much the incident solar radiation is absorbed by the surface, while the thermal emittance defines how much the surface emits thermal radiation in comparison with an ideal blackbody, thus describing how much heat is dissipated via radiation in the thermal wavelength range.

As the solar reflectance (or albedo) of a surface approaches 1 (or 100%), the surface reflects all incident sunlight, and thus it retains a surface temperature close to the ambient temperature. Only laboratory optical samples have a solar reflectance nearing 0.99, while an ordinary white paint has a solar reflectance of ~0.80–0.85 and a black paint or black roofing membrane has a solar reflectance of 0.05 (i.e., it absorbs 95% of solar radiation).

The thermal emittance of most materials is approximately 0.90, with the exception of smooth uncoated metals that have an emissivity lower than 0.20, and sandblasted uncoated metal sheeting with an emissivity in the range between 0.40 and 0.60. Coated metals can have high emissivity if the coating is sufficiently thick. The higher the emissivity, the lower the surface temperature. Because of this, cool roofs can stay cool in the sun (Figures 2.4–2.6).

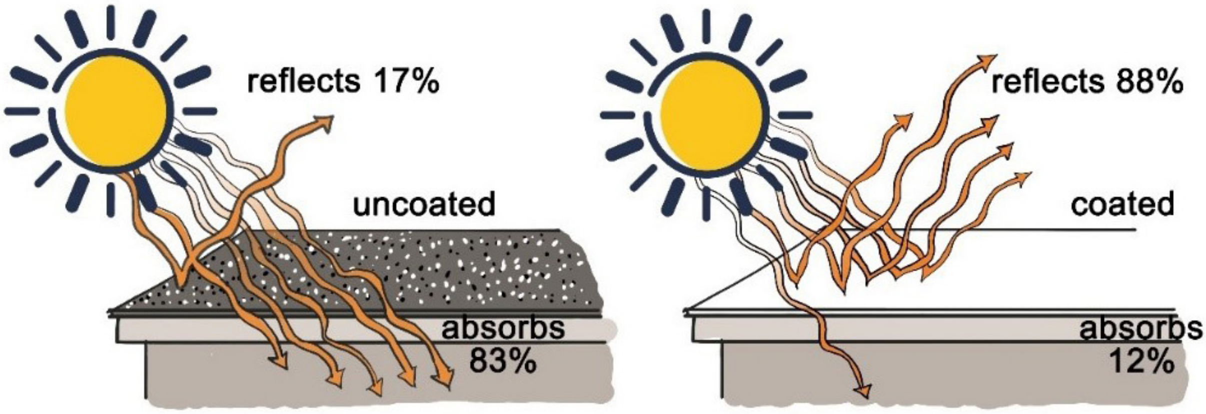


Figure 2.4 Reflection and absorption of sunlight by a conventional dark roof compared with a cool roof (solar reflective).

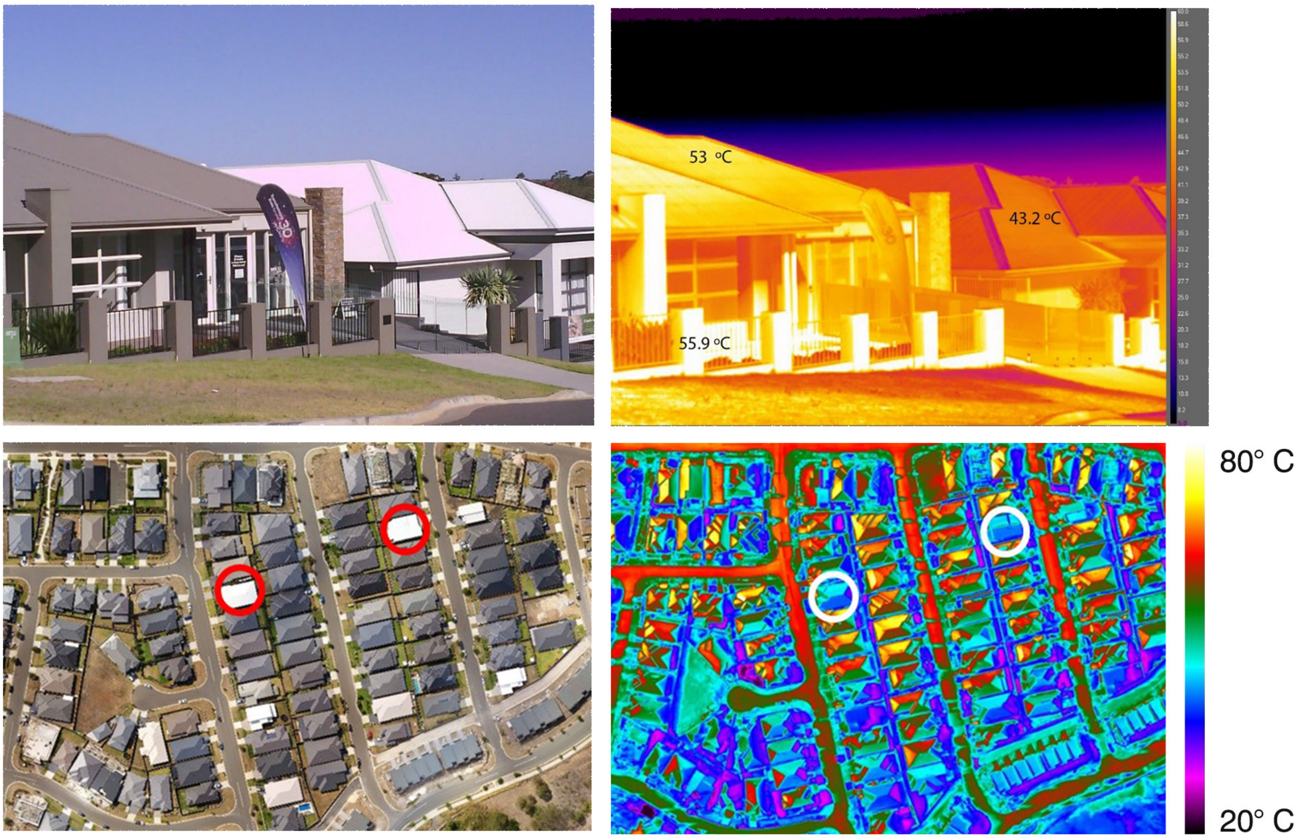


Figure 2.5 Comparison between a dark (SR = 0.15) and a white cool roof (SR = 0.75). Measurements were taken in the Campbelltown area (NSW) in February 2018, in the late afternoon, with Tair = 37.1 °C, RH = 10%, and wind speed = 5.2 m/s.

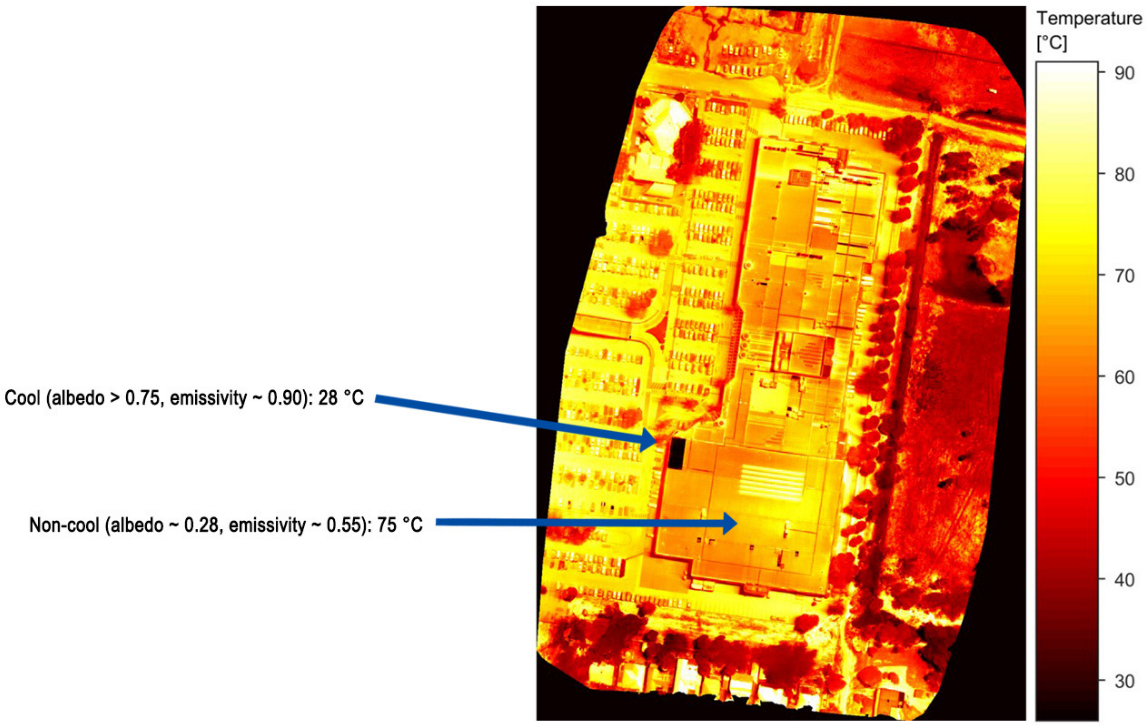


Figure 2.6 Surface temperatures of a shopping mall in Nowra, NSW. The temperature distribution is measured using a drone-mounted thermal camera during relatively calm wind conditions (CRC LCL rp1037 project).

FAQS ON COOL ROOFS

Is it a new idea?

No; reflective coatings have always been used in warm countries to keep buildings cool.

What is the minimum solar reflectance for a roof to be considered cool?

There is no strictly defined limit. For flat or low-sloped cool roofs, the initial (unaged) solar reflectance is greater than 0.65, and the thermal emittance is greater than 0.80.

Does a cool roof cost more?

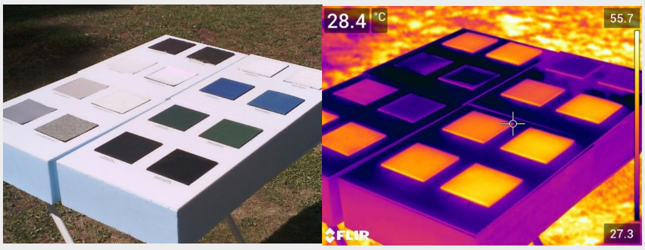
The cost of a cool roof is usually comparable to that of conventional roofing. Only some materials have a small cost premium.

View of Santorini, source: https://www.pexels.com/photo/landscape-view-of-greece-during-day-time-161815/

Are all cool roofs white?

No. A variety of technologies has been developed to deliver solar-reflective surfaces in any colour, although white cool roofs are the most reflective. Here, we present a review of the best solar reflective technologies documented in the scientific literature.

Approximately half of all sunlight is in the invisible “near-infrared” spectrum. Standard light-coloured surfaces strongly reflect both visible and near-infrared solar radiation, while standard dark coloured surfaces reflect poorly in both spectra. Coloured surfaces that strongly reflect near-infrared radiation are called “cool colours.”



Properties of cool roofs

The main physical properties and metrics that are used to characterise cool roofs are explained below.

Solar reflectance (SR) is a measure of the ability of a surface to reflect solar radiation and represent the ratio of reflected to incident solar radiation. Also referred to as albedo, it designates the reflectance of a surface in any direction (i.e., hemispherical) over the solar spectral range (280 – 2800 nm), including specular and diffuse reflection components. It is measured on a scale of 0 to 1 (or 0 – 100%).

Solar absorptance (SA) is a measure of the ability of a surface to absorb solar radiation and represents the fraction of absorbed to incident solar radiation. It is measured on a scale of 0 to 1 (or 0 – 100%). If a surface is opaque, solar absorptance equals 1 – solar reflectance.

Infrared or thermal emittance (TE): Infrared emittance is a measure of the ability of a surface to release absorbed heat by emitting thermal radiation. It specifies how well a surface radiates energy away from itself as compared with a black body operating at the same temperature. Infrared emittance is measured on a scale from 0 to 1 (or 0 – 100%). High thermal emittance helps a surface cool by radiating.

Solar Reflectance Index (SRI): is an index that combines both solar reflectance and infrared emittance in a single value and indicates how “cool” a material is. SRI quantifies how hot a flat surface gets relative to a standard black (reflectivity 5%, emittance 90%) and a standard white surface (reflectivity 80%, emittance 90%). The calculation of this index is based on a set of equations (given in ASTM E1980) that require values of solar reflectance and infrared emittance for specific environmental conditions. The SRI has a value of zero (for the standard black surface) and of 100 (for the standard white surface).

Given the definition of the SRI, materials with very low solar reflectance and thermal emittance can have negative SRI values, and very reflective materials can have an SRI greater than 100.

2.4. WHAT WE KNOW ABOUT COOL ROOFS

2.4.1. INTRODUCTION

Here, we report on the state of the art of reflective roofing technologies, widely known as cool roofs, and the advances in the new generation of cool roofing materials. The main categories of products commercially available and the general market trends are discussed. Then, we present the benefits at the building and at the urban scale of cool roofs in terms of energy savings and ambient temperature reductions. We also report on the limitations and disadvantages of the technology.

Further, we document policies and programs that support the adoption of cool roofs in North America (USA, Canada, and Mexico) and the European Union, including the performance assessment and testing framework implemented by the Cool Roofing Rating Council (CRRC) in the USA, and European Cool Roofs Council (ECRC) in Europe. Finally, we present some relevant projects implementing and assessing the performance of cool roofs. Thus, in this executive summary, we offer a synthesis of the contents presented in detail in the extended report.

2.4.2. COOL ROOFING TECHNOLOGIES

Many cool roofing materials are commercially available such as coatings, membranes, built-up roofs, metal roofs, tiles and asphalt shingles, and there is a cool option for almost every type of roof. Several types of cool roofing technologies have been progressively developed:

- White cool roofs: This has been the first generation of cool roofs with white pigments. Typically, they display solar reflectance greater than 0.80. Conventional whites using titanium dioxide as a pigment have decreasing reflectance in the near infrared. Optimised white cool roofs with greater backscattering in the near infrared have been developed, achieving solar reflectances greater than 0.90.
- Cool coloured materials: Cool coloured materials may have the same colour as conventional materials but present higher SR because they highly reflect in the non-visible near infrared (NIR) part of the solar spectrum, thanks to careful selection of non-absorptive pigments, binder, and additives. For instance, a cool black coating (SR = 0.27) will stay 10°C cooler compared to a conventional black coating (SR = 0.05). They are used on steep-sloped roofs or other visible surfaces to meet the aesthetic/design preferences for darker colours and prevent potential visual discomfort.
- Fluorescent cool coloured materials: They stay cooler under the sun as they re-emit some of the absorbed solar radiation as invisible NIR radiation (fluorescence effect).
- Thermochromic materials: These are dynamic materials that change their solar reflectance (colour) reversibly as a function of temperature, having high solar reflectance (white or light-coloured appearance) in summer and low solar reflectance (dark coloured appearance) during the cold period, minimising the heating penalty and optimising energy performance throughout the year. The first generation of these materials suffered from significant ageing, as they faded and lost their reversibility after some time when exposed to outdoor conditions. However, a new generation of such materials is under development.

Installing a cool roof on a new or existing building can significantly improve the energy efficiency resulting in cooling energy savings that may range from 2% to 44% ...

- Phase Change Materials (PCMs) coupled to cool roofs: PCMs can store and release large amounts of heat in latent form when they change their physical state (from solid to liquid and vice versa) and have been incorporated into cool materials. During the daytime, the PCM absorbs part of the heat through the melting process and at night, the PCM solidifies and releases the stored heat. The net effect is a reduction of the daytime surface temperature of the material and increased durability due to lower temperature swings.
- Retroreflective materials: These materials reflect direct radiation towards the source (the sun), thus avoiding glare issues and reflection of solar radiation towards other buildings. This type of technology can be helpful for pitched roofs or façade elements in densely built environments.
- Daytime radiative coolers: Daytime radiative cooling is one of the most promising cool material technologies due to its high cooling potential. These materials have an SR approaching 1 (i.e., almost perfect reflection) and a TE also close to 1 in the atmospheric window (8-13 μm). Instead, they have a very low TE in the rest of the 4 – 80 μm thermal infrared spectrum to maximise long-wave radiative loss to the sky. Thus, they may have a negative thermal balance, decreasing surface temperatures to values below the air temperature, and cooling the urban atmosphere.

2.4.3. BENEFITS OF COOL ROOFS AT BUILDING SCALE

Installing a cool roof on a new or existing building can significantly improve the energy efficiency resulting in cooling energy savings that may range from 2% to 44% and peak cooling energy savings between 3% and 35% depending on local climate, radiative properties of the building envelope, building characteristics, type and use. These reductions result in cost savings and prevent unwanted electricity shutdowns during heatwaves. Moreover, in buildings without air conditioning, the reduced heat transfer from the cooler roof results in lower indoor air temperatures ranging on average from 1 – 3°C and improved thermal comfort conditions. This is a significant social benefit, especially for low-income households suffering from energy poverty and exposure to extreme overheating conditions and heat-related health risks. In addition, a cool roof is likely to have a longer lifetime, resulting in reduced waste going to landfills due to the significantly lower surface temperatures and the reduced diurnal temperature fluctuations compared to a conventional dark roof. A large cool roof surface area (e.g., on commercial or industrial buildings) has been found to decrease local air temperatures 0.5 – 1.5 m above the roof, thereby further decreasing rooftop HVAC energy consumption due to lower intake temperature. Finally, building owners can see increased property value from energy efficiency measures such as cool roofs that lead to lower energy consumption and lower running costs. Finally, cool roofs present an attractive solution as cooling savings are expected to be even more important in future climatic conditions due to global warming and because of the environmental benefits they provide in terms of mitigating the urban heat island effect, improving outdoor thermal comfort and air quality and decreasing heat-related mortality.

2.4.4. BENEFITS AT CITY AND REGIONAL SCALE

Cities are especially vulnerable to the impacts of climate change: extreme heatwaves, flooding, water scarcity and droughts can impact health, infrastructure, local economies, and quality of life of city habitants. The land cover for housing, roads and car parks increases the absorption of energy from the sun, and it contributes to higher urban temperatures, thus generating the urban heat island effect. At the same time, natural drainage is decreased, which, particularly during heavy rains, can lead to urban floods. Through appropriate and resilient urban design, the impacts of climate change can be reduced using green infrastructures such as forests, parks, wetlands, and cool materials for walls, roofs, and pavements. Such approaches also lead to significant co-benefits, including improved air quality, energy savings, support for biodiversity, enhanced quality of life, and employment opportunities.

Benefits of using cool materials include:

- Mitigate the urban heat island effect: Cool materials can help in the mitigation of the urban heat island effect. The main characteristics of a cool material are high reflectivity and emissivity of the visible and IR light spectrum. Because of these characteristics, a great percentage of the radiation returns instantly to the environment instead of being absorbed by the building elements. Cool roofing works in synergy with other mitigation technologies. By reducing peak temperatures, they help to preserve the health of urban trees, which extremely high temperatures and water-stress conditions can damage. Also, the cooling performance of vegetation, thanks to transpiration, drops dramatically above a species-specific threshold, which for many trees species is approximately 40°C. Therefore, reducing ambient temperature contributes to keeping operational the urban green infrastructure.
- Mitigate heat-related mortality and illnesses: By reducing the peak ambient temperature, cool roofs reduce heat-related mortality and morbidity during heatwaves, which in Australian cities is correlated with the peak daytime temperature.
- Social benefits: Energy poverty has a severe impact on the quality of life of low-income households. Existing statistics show that low-income families in Europe live in houses characterised by lower thermal and environmental standards. Cool roofs can improve the indoor comfort of low-income households, especially during summer overheating and reduce heat-related mortality. Also, the improvement of outdoor comfort conditions contributes to citizens' health and wellbeing, allowing outdoor recreational activities and socialisation in the public space.

2.4.5. MAIN DISADVANTAGES AND PROBLEMS

Here we summarise the main disadvantages and issues and how they have been traditionally addressed.

Heating penalty: Cool roofs may cause an increase in demand for building heating in the winter. This heating penalty is usually offset by the cooling energy savings in the summer. Cool roof impact is reduced during winter as less solar radiation arrives on the roof to be absorbed or reflected, due to increased cloud cover, lower solar radiation intensity, fewer hours of sunshine and snow cover. Installing a cool roof on a residential building in 27 cities worldwide with varying climatic conditions resulted in a heating penalty of 0.2 – 17 kWh/m^2 year, less important than the cooling load reduction (9 – 48 kWh/m^2 year). Cool roofs are more advantageous in locations with long cooling seasons and a short or no heating season. Cooling energy use and cost savings greatly outweigh potential heating energy use and cost penalties for warmer climates with significant amounts of solar radiation on the roof. In colder climates, cool roofs may cause heating load increases, and factors such as local energy prices should be considered to determine if a cool roof is a cost-effective solution. Optimising roof albedo in combination with insulation levels for specific climatic conditions and buildings can cost-effectively reduce energy consumption for heating and cooling. For buildings with high internal gains, such as commercial or industrial buildings, that might result in significant cooling loads throughout the year, the installation of a cool roof is beneficial even in colder climatic conditions.

Durability of cool roofs: Weathering, soiling, biological growth, and chemical and physical stress — collectively referred to as ageing — may reduce the albedo of reflective materials, which increases their surface temperature (Figure 2.7). The main contributors to the loss in reflectance are the deposition of soot (black carbon), which is prevalent in polluted areas or after bushfires, and biofouling. The latter may be significant in hot and humid areas. Natural exposure programs conducted in the United States, Europe, China, Japan, and Brazil have shown that, after ageing, a low-sloped roof with an initial solar reflectance of 0.80 may have an aged solar reflectance of 0.50-0.60. The thermal emittance, instead, is not significantly affected by ageing. Factors such as slope and surface roughness affect the resistance to soiling. In fact, not all cool roofing products are equally affected by ageing and a new generation of cool roofing materials with anti-soiling properties has been developed and tested.

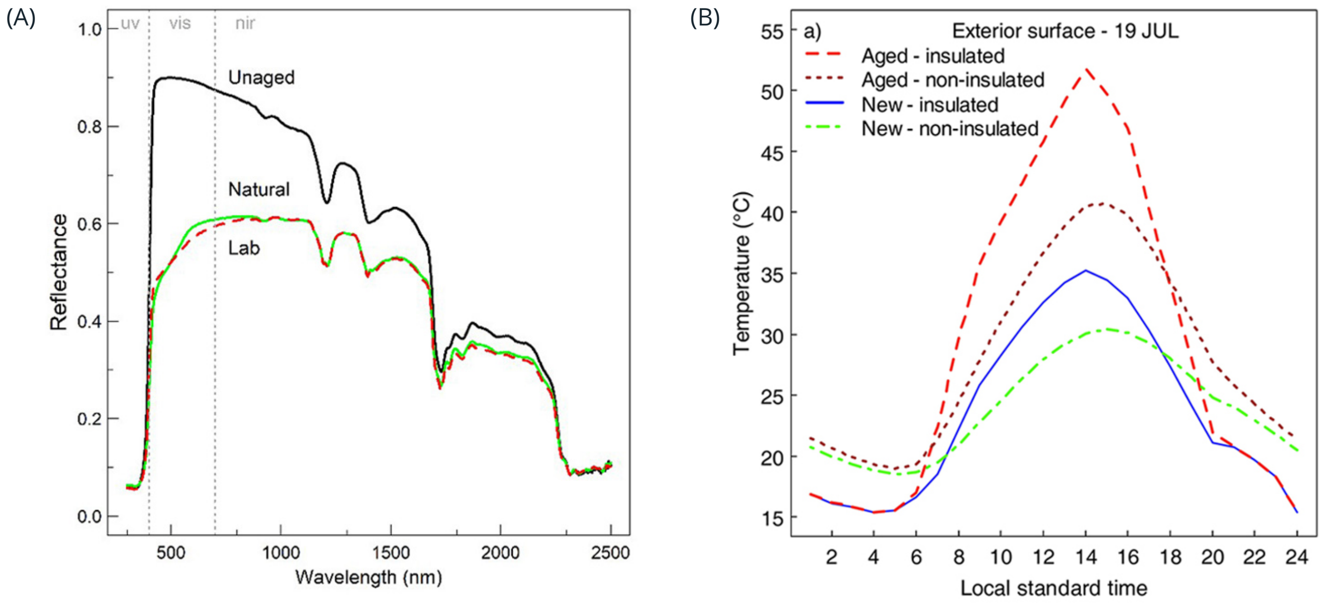


Figure 2.7 (A) Spectral reflectance of an unaged (solid black) and a naturally (3-years) and lab exposed white roofing membrane with initial reflectance of 0.76. (B) Daily course of exterior surface temperatures in insulated and uninsulated conditions in Milan, Italy (summer) of an aged white membrane (albedo = 0.56) and a white new membrane (albedo = 0.80) over 20 cm of expanded polystyrene and uninsulated roofs.

Condensation management: Another potential negative impact of cool roofs is that they can be more susceptible to moisture accumulation and risk of condensation when used in colder climates. Condensate may affect the building envelope's energy efficiency (reduced thermal resistance) and potentially cause environmental and health concerns to the building occupants (e.g., mould growth). Cool roof surfaces may be more susceptible to algae or mould growth in warm, humid climatic conditions. However, a properly designed cool roof can significantly improve the moisture performance of the roofing assembly and, at the same time, provide energy efficiency and environmental benefits.

Integration with architectural heritage and aesthetic preferences: Cool roofs should always be considered in the context of their surroundings as light from a bright white roof may reflect into the windows of neighbouring taller buildings, potentially causing building users glare and visual discomfort and unwanted heat. Moreover, white roofs may not meet the building owners' aesthetic/design preferences for darker colours in cases where the roof is visible from the street level. In all such cases, cool coloured materials can be used.

A summary of advantages and disadvantages is offered in Figure 2.8.

... a properly designed cool roof can significantly improve the moisture performance of the roofing assembly and, at the same time, provide energy efficiency and environmental benefits.

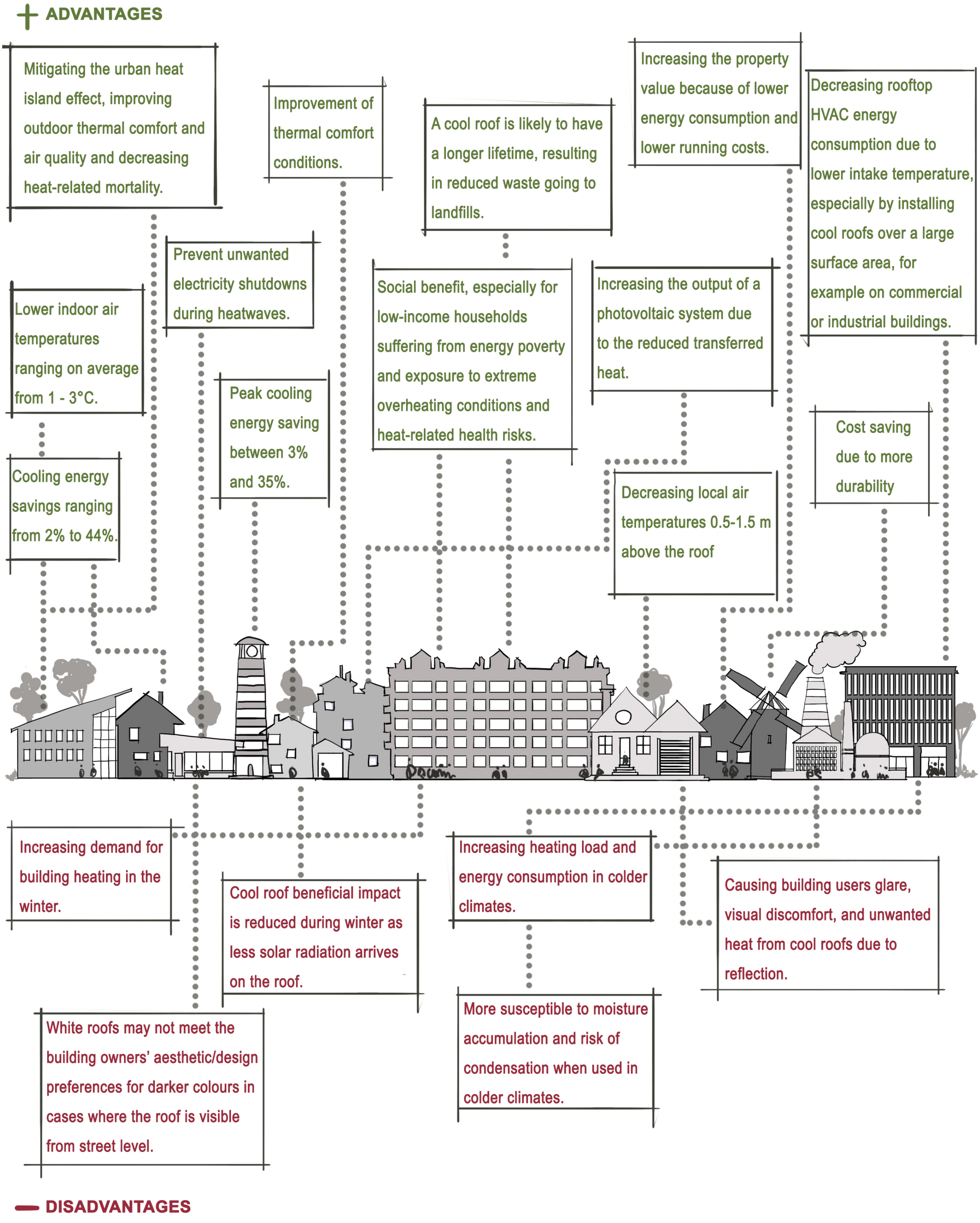


Figure 2.8 Summary of advantages and disadvantages of cool roofing technologies.

2.4.6. PERFORMANCE ASSESSMENT AND MONITORING: TESTING AND ACCREDITATION FRAMEWORK & INFRASTRUCTURE

The performance of cool roofs is determined by their SR and TE. Alternatively, the SRI can be used, which is an index that combines both SR and TE in a single value and indicates how “cool” a material is. The SR, depending on the material and the specific application, can be measured using a spectrophotometer equipped with an integrating sphere, a reflectometer or a pyranometer. Infrared emittance can be measured with an emissometer or a Fourier transform infrared (FTIR) spectrometer.

The SRI is calculated based on measured SR and TE values. Ageing of cool roof products can be evaluated via a) natural weathering, i.e. exposure of samples to outdoor ambient conditions at weathering test sites for a period of at least three years; b) artificial weathering with the use of weathering chambers that accelerate the degradation of materials in a reasonably fast time; and c) a laboratory accelerated aging method that incorporates features of soiling and weathering and simulates three years of natural soiling in a few days. Good practice procedures for all these measurements, methods and calculations are defined by various international, U.S. and European standards.

The Cool Roofing Rating Council in the U.S. and the European Cool Roofing Council (ECRC) in the EU operate rating programs for the radiative properties of roofing products. Their purpose is to provide a uniform and credible system for rating and reporting radiative properties (i.e. SR, TE, and SRI) of roofing products by granting them a label, indicating one or more radiative property ratings reported by accredited/approved testing laboratory reports. In the framework of these two (independent) programs, manufacturers and sellers have the opportunity to label roofing products with the measured values of their initial and aged radiative properties. These properties are determined and verified through testing by accredited/approved testing laboratories and a process of random testing of rated products. Any roofing product can be tested as long as it complies with the specifications and requirements defined in the product rating manual. The product rating program does not specify minimum or target values for any radiative property.

Suboptimal and ineffective products in the market. The following factors may contribute to sub-optimal or poor performance of cool roofs: a) the installation of unsuited roofing materials, such as simple white paint instead of a cool roof coating: b) the lack of (credible) performance data that prevents the selection of appropriate products (e.g. products with poor ageing performance or sub-optimal initial radiative properties such as low infrared emittance); c) installation failures when manufacturers’ instructions are not followed. These failures can be minimised if credible cool roof performance data are available and by following the manufacturers’ installation and maintenance instructions closely.

Figure 2.9 Causes of poor performance of cool roofs.

2.4.7. COOL ROOF POLICIES

Worldwide, policies on the adoption of cool roofs have been modelled on those developed and applied in the USA, where cool roofs were first introduced in building codes, while their use in vernacular architecture in the Mediterranean and other areas largely precedes formal building codes). In the U.S., model codes for commercial and multi-family residential buildings, such as ASHRAE 90.1 and the IECC, require cool roofs in warmer climate zones. These model codes are widely adopted across the U.S. Individual states may adopt their own requirements for cool roofs (e.g., California Title 24). Where allowed by state law, municipalities may also adopt requirements for cool roofs via their building codes (e.g., New York, Chicago, Denver, and Washington DC). Localities may also encourage cool roofs via the adoption of green codes. Green codes often allow for measures to be justified by their broader environmental benefits and their potential effect on building energy consumption. Programs such as the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) and ASHRAE 189.1 encourage cool roofs to reduce urban heat island effects.

There are a wide variety of incentives and voluntary programs encouraging the use of cool roofs as well. These programs may overlap with existing energy efficiency incentive schemes or may be specific to heat mitigation (e.g., Louisville, Kentucky's cool roof rebate program). There are also several international efforts to accelerate the use of cool roofs for thermal comfort, improved health, and energy savings. The Million Cool Roofs Challenge is a philanthropic initiative to create local champions for cool roofs in ten countries experiencing an acute lack of access to cooling services. The champions are existing organisations, universities, and companies that demonstrate local performance, build the supply chain for cool roof materials, implement cool roofs at scale, and advocate for supportive policies, programs, and targets. The Challenge, which concludes in November 2021, is introducing cool roofs into new markets and helping to test a variety of business/implementation plans for scaling the market.

The CRRC has been a critical component in the growth of the cool roof marketplace across all building sectors and is explicitly cited in most U.S. model, state, and municipal codes. Similarly, the development of the cool roof market in Europe is being spearheaded by the ECRC. The ECRC was founded in 2011 to develop scientific knowledge and research in relation to cool roof technology and to promote the use of cool roof products and materials in Europe, including developing a product rating programme for such products and materials. The introduction of cool roofs in European member states has been implemented at the national level, with the first programs developed in Greece and Italy. In several European countries, cool roofs are generally supported with incentives like any other building efficiency intervention, and in Greece and Italy, their use is specifically promoted for public buildings. In Italy, for all buildings, designers are required to perform an assessment of the benefit of a cool roof (solar reflectance greater than 0.65 for flat roofs or 0.30 for pitched roofs).

2.4.8. COOL ROOFS ADOPTION AND MARKET PENETRATION

Cool roof products have been available in the United States for certain categories since the early 1980s. In the late 1990s, cool roofs were added as a credit option to several major energy codes, notably California Title 24 and ASHRAE 90.1 and cool roofs remain a compliance option for many energy efficiency standards and incentives. Starting in 2001, Chicago adopted a cool roof policy that explicitly referenced cool roofs' ability to mitigate urban heat islands. Increased adoption of model energy codes that require cool roofs by states and municipalities has helped drive the commercial, multi-family, and institutional markets, particularly in the Southern U.S. The increasing use of green certifications, most notably LEED, has also been beneficial for cool roof adoption, particularly among higher value building classes.

Cool roof implementation faces a number of obstacles that have slowed progress. Heat mitigation is rarely pursued in a coordinated fashion, in favour of an approach spread across many agencies and actors. Awareness of cool roof options and benefits, particularly in the residential market, remains relatively low in North America. The structure of the market, specifically residential roofing, is quite diffuse and hard to change with policy. There remains a lack of regulatory frameworks for properly valuing and adopting cool roofs, as well as a lack of public and private financing for those investments.

The global cool roof coatings market size was estimated to be worth USD 3.59 billion in 2019 and is expected to register a revenue-based CAGR of 7.1% over the forecast period. The rising adoption of green building codes by the emerging economies across the globe is anticipated to further fuel the demand for cool roof coatings. North America held the largest market share of more than 34% in terms of revenue in 2019. Increasing awareness regarding building energy consumption, coupled with the implementation of the LEED green building certification initiative, is likely to drive the regional demand for cool roof coatings. The Asia Pacific is projected to be the fastest-growing region in the near future on account of the increasing acceptance of green building codes. The growing construction industry in the emerging economies of Asia Pacific and increased infrastructure spending by the governments of India and China are the key factors responsible for driving product demand over the forecast period. The use of cool roof coatings is also growing in Australia, both in new developments and retrofits (Figures 2.10 and 2.11).

Figure 2.10 Example of a field-applied cool roof coating on a commercial building in Victoria (source: energystar.com.au). The application of a cool roof coating also improves the resistance to corrosion.

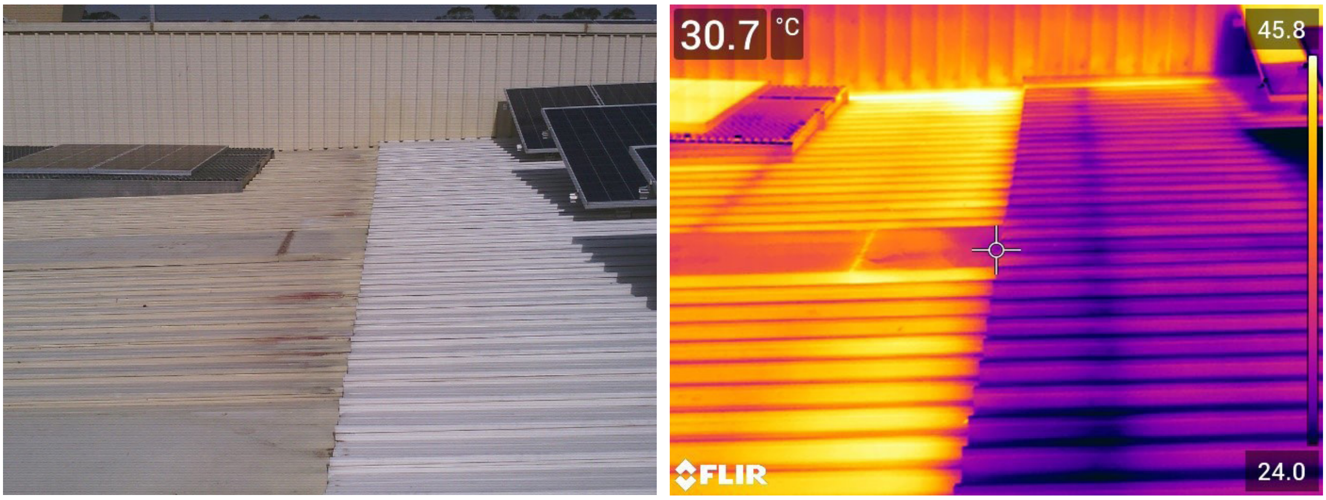
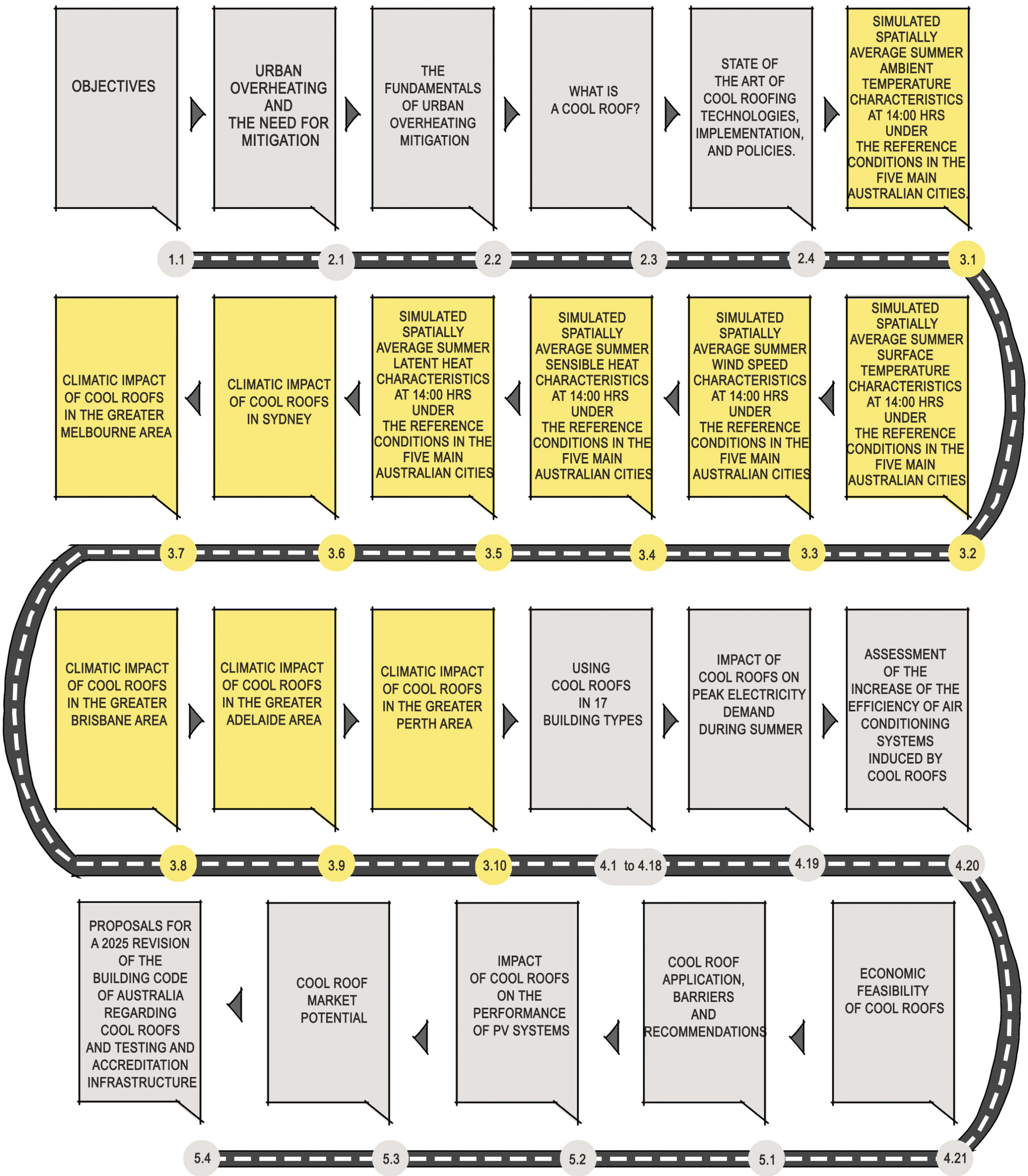


Figure 2.11. Visible and infrared view of an uncoated and coated metal roofing in Wetherill Park, NSW during an autumn morning. Even with mild irradiation, the cool roof is 15°C cooler than the uncoated roof (CRC project rp1037).

3. HOW DO COOL ROOFS AFFECT THE CLIMATE OF AUSTRALIAN CITIES?



3.1. SIMULATED SPATIALLY AVERAGE SUMMER AMBIENT TEMPERATURE CHARACTERISTICS AT 14:00 HRS UNDER THE REFERENCE CONDITIONS IN THE FIVE MAIN AUSTRALIAN CITIES

3.1.1. MAIN CHARACTERISTICS

The range and the frequency of the calculated spatially average ambient temperature at 14:00 hrs as calculated by the Weather Research and Forecasting (WRF) mesoscale model, under the reference conditions in the five cities, are shown below (Figures 3.1 and 3.2). We use a full mesoscale climatic model for the major Australian cities using the weather research forecasting model (WRF v4.3), which is an advanced, commonly used numerical climate model. The model is created to simulate the distribution of the main climatic conditions in the city under all climatic, synoptic, and land use conditions. The developed mesoscale model is used to calculate the hourly distribution of the main climatic parameters under the existing heatwave conditions and one mitigation scenario. The albedo or emissivity as a single fraction was applied uniformly to all urban grid cells. The cool materials were examined by test case of 100% cool surfaces (on the roof only) with changing albedo and emissivity fractions for roofs at the urban scale. We performed extensive analysis to analyse the performance of the cool roof scenario and its cooling potential. The main conclusions and observations follow.

a. The spatially average median ambient temperature in the five cities varies between 32°C to 37°C. The median value is considerably higher in Perth (close to 37°C), followed by Brisbane (close to 34.5°C), Sydney (close to 33°C), Adelaide (close to 32.5°C), and Melbourne (close to 32°C).
b. During the simulation period, the spatially average absolute maximum ambient temperature at 14:00 hrs during the simulation period exceeds 45°C in Sydney and Brisbane. The absolute maximum in Perth is much lower and close to 42°C while in Melbourne, it is close to 40.5°C, and in Adelaide around 39.2°C.
c. On one day, a very high spatially average maximum ambient temperature, close to 45°C, can be observed in Melbourne, and the value is statistically considered as an outlier. An outlier close to 41°C can also be observed in Adelaide.
d. The spatially average absolute minimum temperature is in Adelaide, 26°C, followed by Melbourne, 26.6°C, Sydney, 27.5°C, Brisbane 29°C and Perth 30°C. Temperatures below 25°C can be observed in Adelaide for two days and are considered as outliers.
e. The more frequent level of the spatially average ambient temperature in the five cities is slightly lower than the calculated median ambient temperature, except for Perth, where both the median and the more frequent temperature values are close to 37°C.
f. Melbourne presents the lower magnitude of the more frequent spatially average ambient temperature, 29°C, followed by Adelaide 32°C, Sydney 32.5°C, Brisbane 33.5°C, and Perth 37°C.
g. While Perth presents the highest value of the more frequent spatially average ambient temperature, the frequency of appearance of ambient temperatures exceeding 37°C, is quite low as the distribution curve presents a very rapid decrease above its maximum. A similar shape of the frequency distribution curve is obtained for Adelaide.

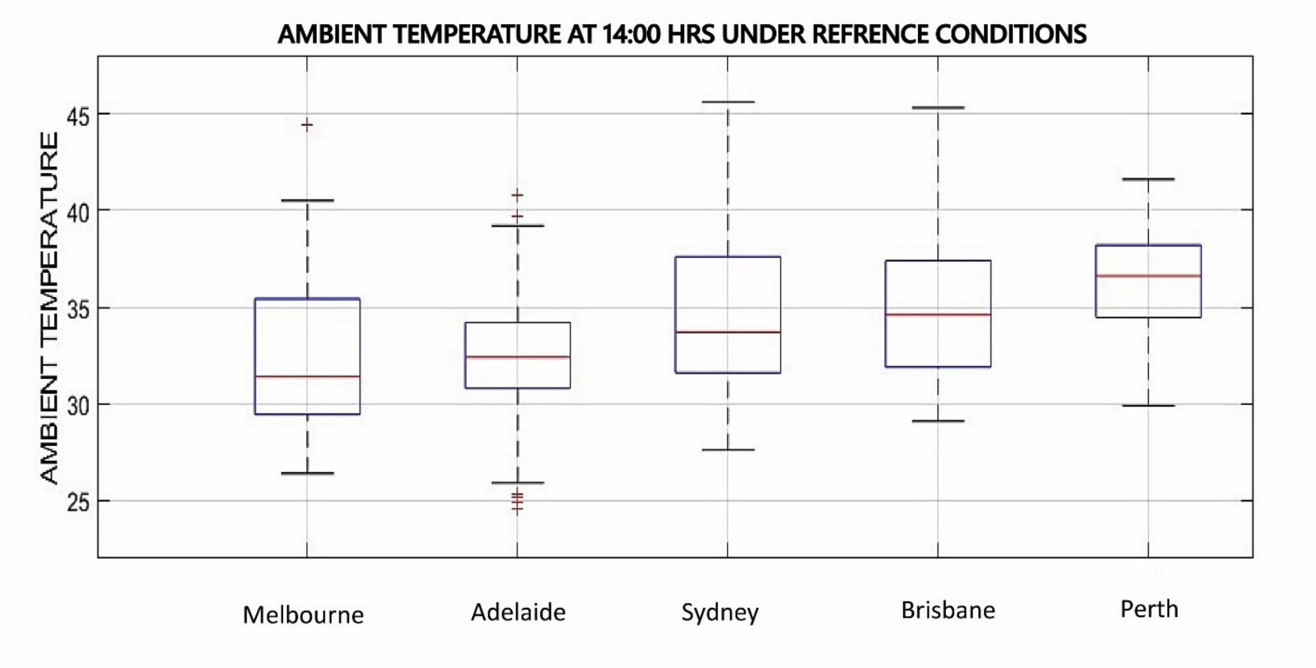


Figure 3.1 Variability of the summer ambient temperature at 14:00 hrs in the five main Australian cities under the reference conditions as calculated by WRF for January and February.

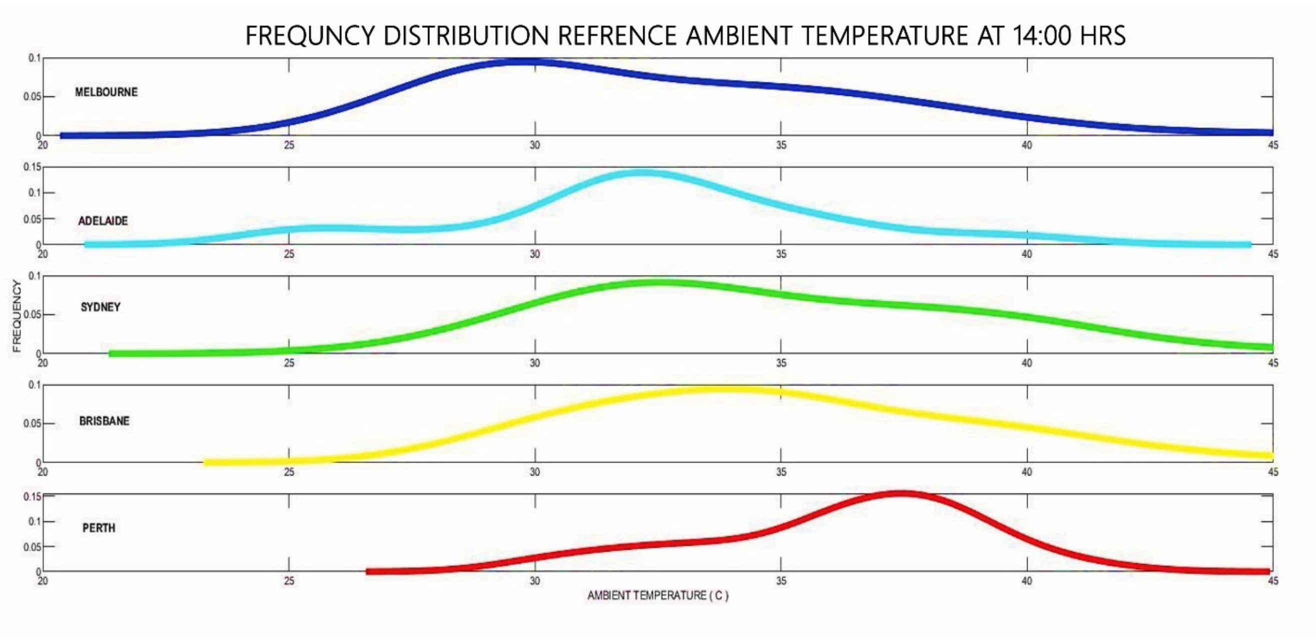


Figure 3.2 Frequency distribution of the summer ambient temperature at 14:00 hrs in the five main Australian cities under the reference conditions as calculated by WRF for January and 14:00 hrs February.

3.2. SIMULATED SPATIALLY AVERAGE SUMMER SURFACE TEMPERATURE CHARACTERISTICS AT 14:00 HRS UNDER THE REFERENCE CONDITIONS IN THE FIVE MAIN AUSTRALIAN CITIES

3.2.1. MAIN CHARACTERISTICS

The range and the frequency of the calculated spatially average surface temperature at 14:00 hrs as calculated by the WRF mesoscale model, under the reference conditions in the five cities, are shown below (Figures 3.3, 3.4 and 3.5). The main conclusions and observations follow

a. The spatially average median surface temperature in the five cities varies between 37°C to 43°C. The median value is considerably higher in Brisbane (close to 42.5°C), followed by Perth (close to 42°C), Sydney (close to 41.5°C), Melbourne (close to 40°C), and Adelaide (close to 37.5°C)
b. The spatially average absolute maximum surface temperature at 14:00 hrs during the simulation period exceeds 55°C in Sydney and 53°C in Melbourne and Brisbane. The absolute maximum in Perth is much lower and close to 46.5°C, and in Adelaide around 45°C.
c. The spatially average absolute minimum surface temperature is in Adelaide, 31°C, followed by Melbourne, 34°C, Brisbane, 27.5°C, Brisbane 36°C, Sydney 37°C and Perth 37.5°C. Temperatures around and below 30°C, are observed in Adelaide for two days and are considered as outliers
d. The more frequent level of the spatially average surface temperature in the five cities is slightly lower than the calculated median surface temperature, except for Sydney, where both the median and the more frequent temperature values are close to 41.5°C.
e. Melbourne presents the lower magnitude of the more frequent spatially average ambient temperature at 29°C, followed by Adelaide 32°C, Sydney 32.5°C, Brisbane 33.5°C, and Perth 37°C.
f. As in the case of the ambient temperature, Perth presents the highest value, but the frequency of occurrence of ambient temperatures exceeding 42°C is relatively low, as the distribution curve presents a very rapid decrease above its maximum.
g. There is an almost linear association between the daily spatially average ambient temperature at 14:00 hrs and the corresponding surface temperature (Figure 3.5). While the characteristic curves are quite similar for the five cities, Adelaide and Perth present a higher ambient temperature for the same surface temperature value. This is because of the optical characteristics of the materials used and the specific wind conditions.

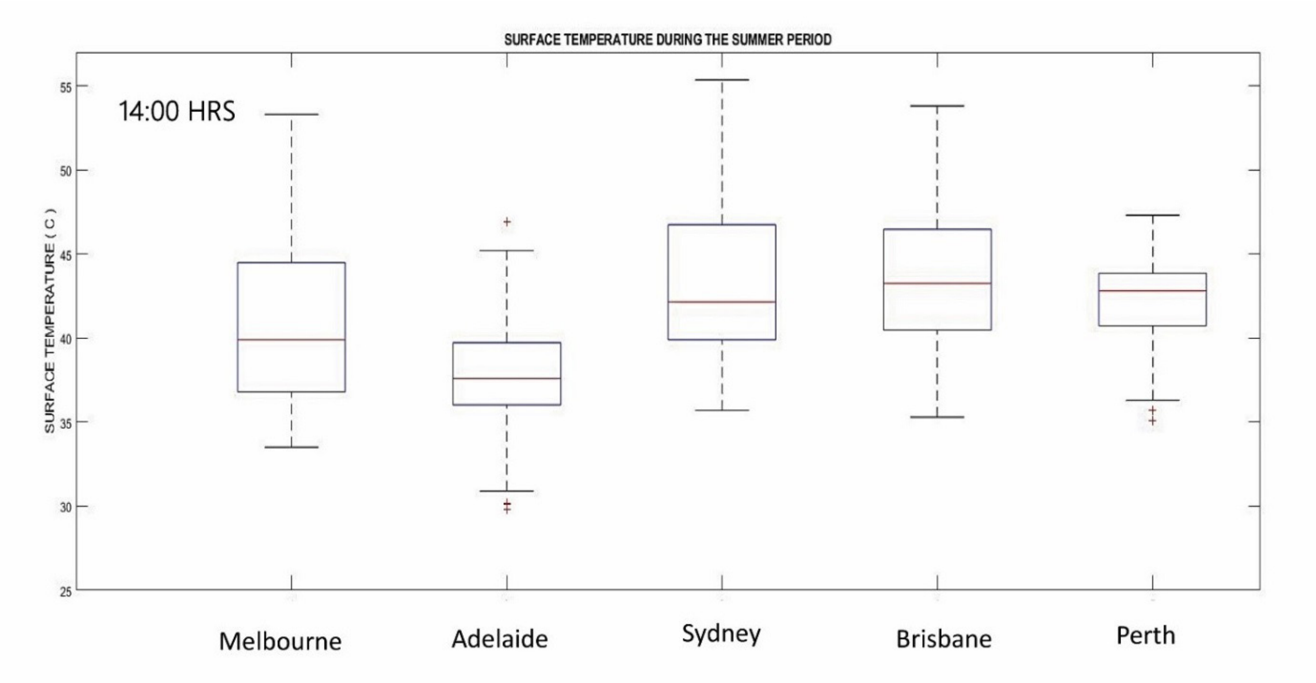


Figure 3.3 Variability of the summer ambient temperature at 14:00 hrs in the five main Australian cities under the reference conditions as calculated by WRF for January and February.

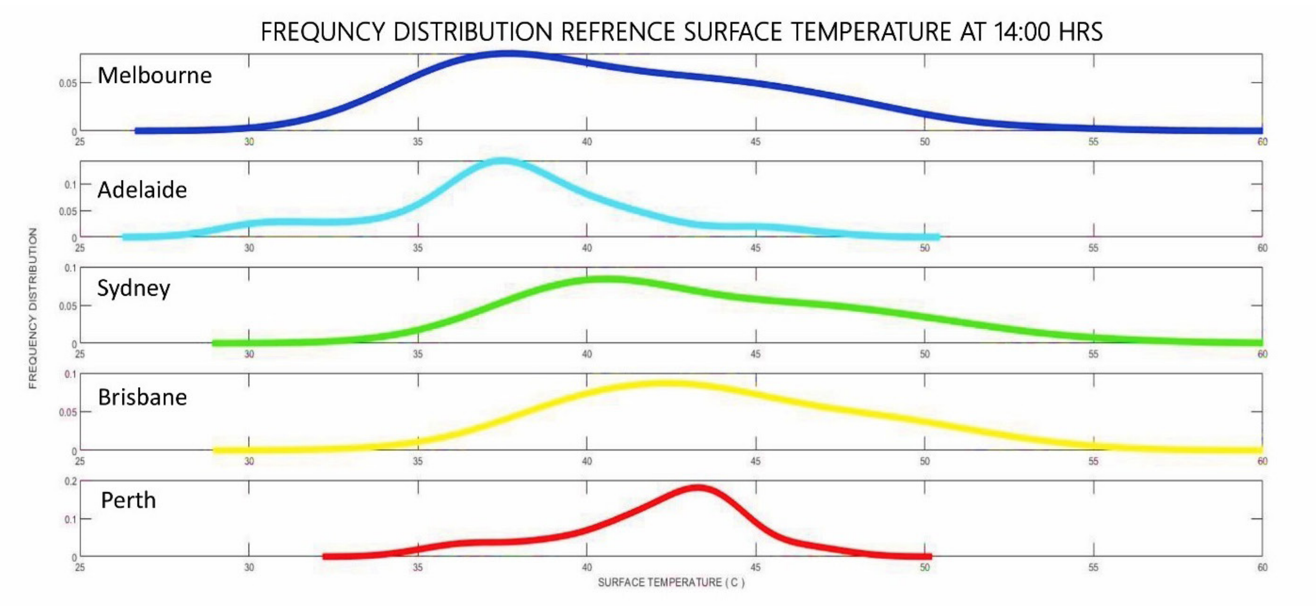


Figure 3.4 Frequency distribution of the summer ambient temperature at 14:00 hrs in the five main Australian cities under the reference conditions as calculated by WRF for January and February

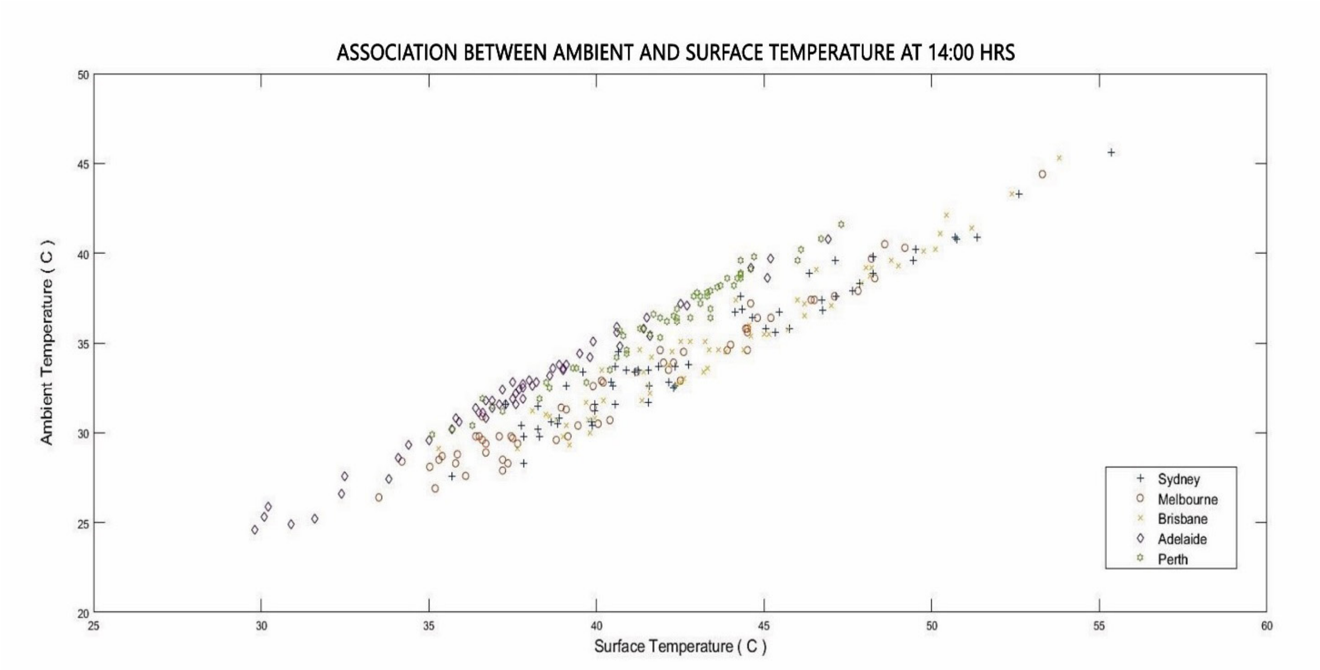


Figure 3.5 Association between the spatially average surface temperature at 14:00 hrs and the corresponding ambient temperature in the five cities.

3.3. SIMULATED SPATIALLY AVERAGE SUMMER WIND SPEED CHARACTERISTICS AT 14:00 HRS UNDER THE REFERENCE CONDITIONS IN THE FIVE MAIN AUSTRALIAN CITIES

3.3.1. MAIN CHARACTERISTICS

The range and the frequency of the calculated spatially average wind speed at 14:00 hrs as calculated by the WRF mesoscale model, under the reference conditions in the five cities, are shown below (Figures 3.6 – 3.9). The main conclusions and observations follow

a. The spatially average median wind speed in the five cities varies between 5.5 m/sec to 7.3 m/sec. The median value is considerably higher in Perth, (close to 7.3 m/sec), followed by Brisbane, (close to 7 m/sec), Adelaide, (close to 6.5 m/sec), Sydney, (close to 6.3 m/sec) and Melbourne, (close to 5.5 m/sec).

b. The spatially average absolute maximum wind speed at 14:00 hrs during the simulation period exceeds 8 m/sec in Perth, 7.7 m/sec in Adelaide, and 7.6 m/sec in Sydney. The absolute maximum in Brisbane is lower and close to 7.4 m/sec, and in Melbourne, 6.5 m/sec.

c. The spatially average absolute minimum wind speed is in Perth, 6.3 m/sec, followed by Brisbane, 6.1 m/sec, Sydney, 5.5 m/sec, Adelaide, 5.2 m/sec and Melbourne, 4.6 m/sec.

d. The more frequent magnitude of the spatially average wind speed in the five cities is almost equal to the calculated median wind speed.

e. An almost linear relation between the spatially average wind speed at 14:00 hrs and the corresponding ambient temperature is observed. Higher wind speeds always correspond to higher ambient air temperatures. The slope is quite similar for all cities.

f. In the same way, an almost linear association is found between the spatially average wind speed at 14:00 hrs and the corresponding surface temperature. Higher wind speeds always correspond to higher surface temperatures (The higher urban albedo values decrease the advective flow between the city and its surroundings, improving the cooling potential of reflective materials. It creates a 'regional high', which can reduce both horizontal and vertical wind speed over the city). The configuration of the corresponding curve is quite similar for all cities.

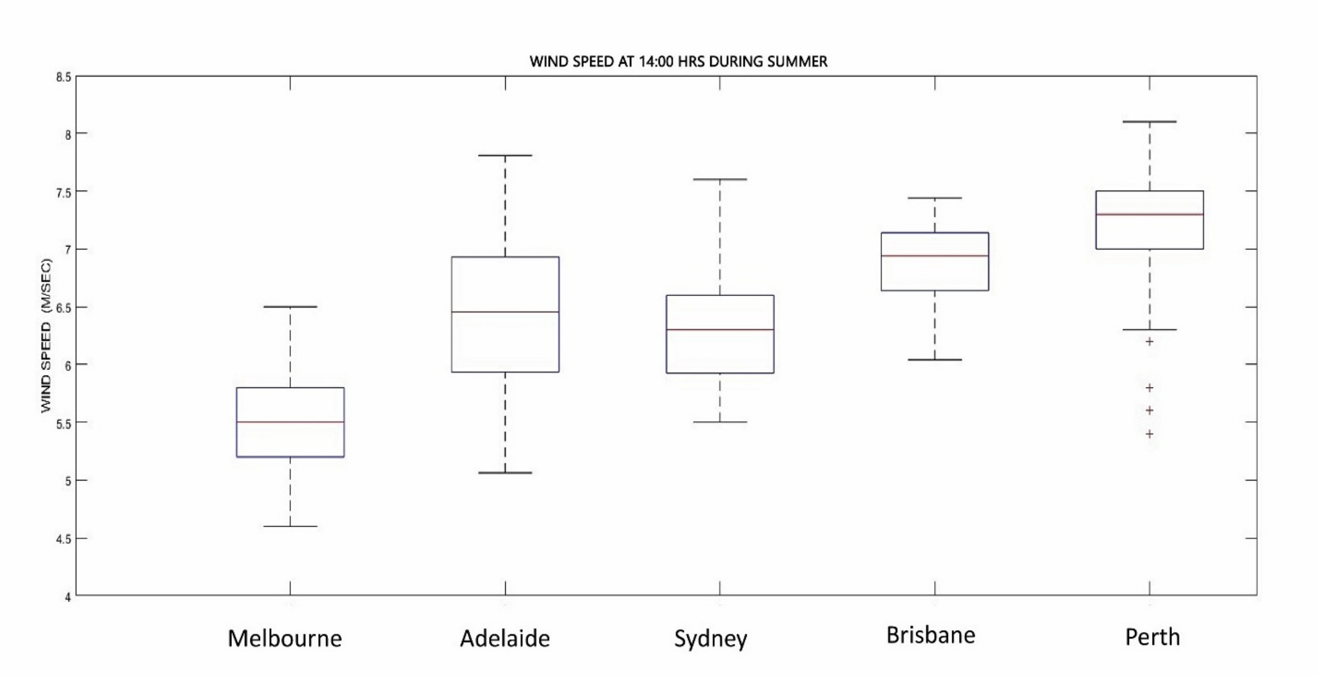


Figure 3.6 Variability of the summer wind speed at 14:00 hrs in the five main Australian cities under the reference conditions as calculated by WRF for January and February.

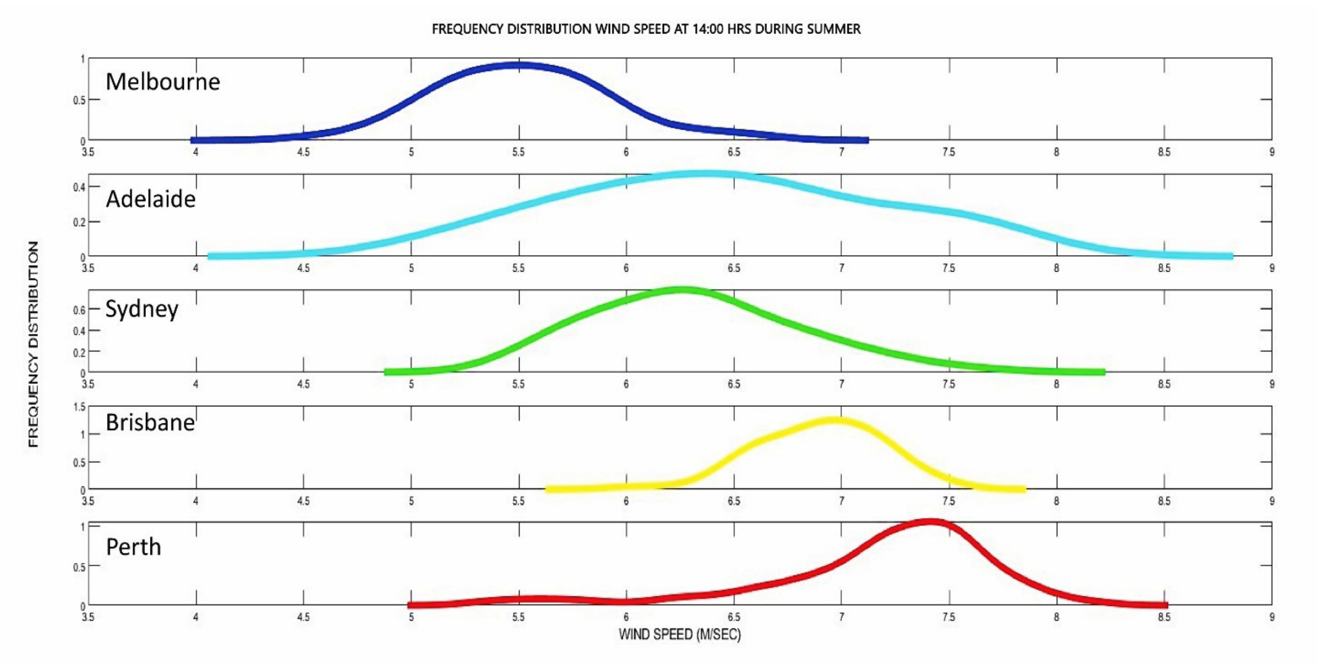


Figure 3.7 Frequency distribution of the summer wind speed at 14:00 hrs in the five main Australian cities under the reference conditions as calculated by WRF for January and February.

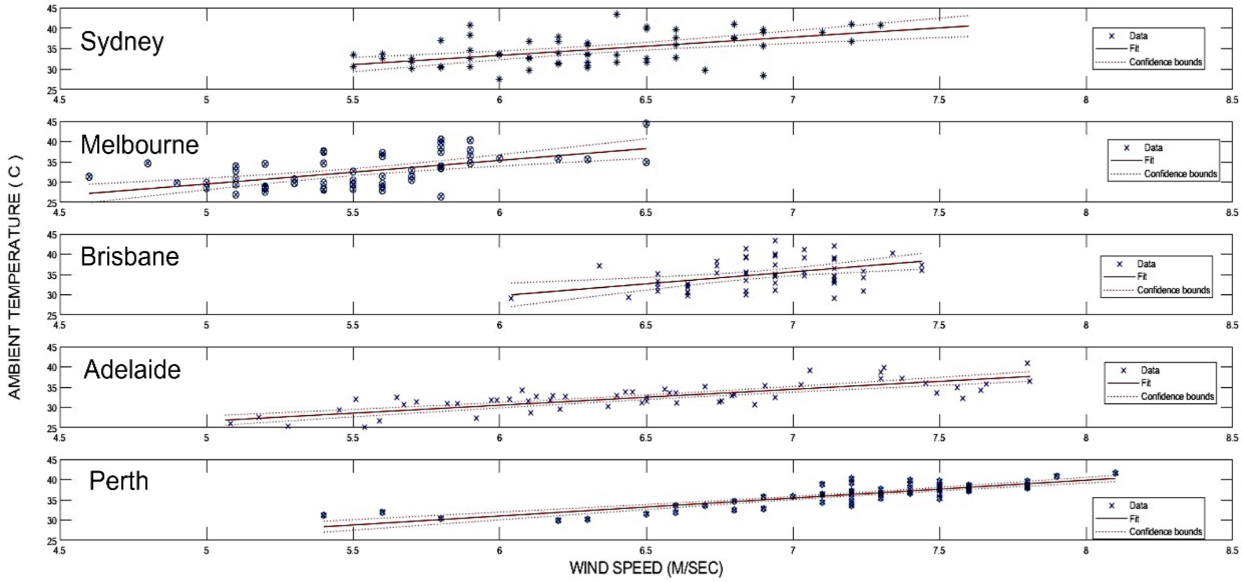


Figure 3.8 Association between the spatially average wind speed at 14:00 hrs and the corresponding ambient temperature in the five cities.

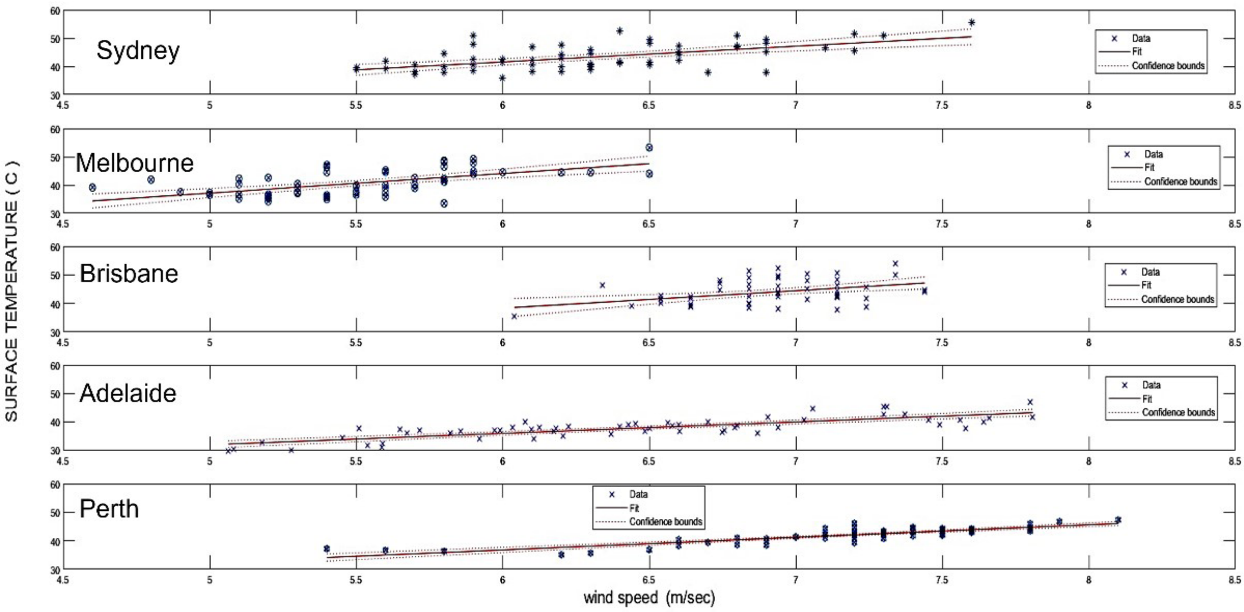


Figure 3.9 Association between the spatially average wind speed at 14:00 hrs and the corresponding surface temperature in the five cities.

3.4. SIMULATED SPATIALLY AVERAGE SUMMER SENSIBLE HEAT CHARACTERISTICS AT 14:00 HRS UNDER THE REFERENCE CONDITIONS IN THE FIVE MAIN AUSTRALIAN CITIES

3.4.1. MAIN CHARACTERISTICS

The range and the frequency of the calculated spatially average sensible heat[1] at 14:00 hrs as calculated by the WRF mesoscale model, under the reference conditions in the five cities, are shown below (Figures 3.10 – 3.14). The main conclusions and observations follow.

a. The spatially average median sensible heat released in the five cities varies from 370 W/m^2 to 550 W/m^2. The median value is considerably higher in Perth (close to 550 W/m^2), followed by Adelaide (close to 470 W/m^2), Melbourne and Brisbane (close to 460 W/m^2) and Sydney (close to 400 W/m^2).

b. The spatially average absolute maximum sensible heat released at 14:00 hrs pm during the simulation period exceeds 630 W/m^2 in Perth, 580 W/m^2 in Adelaide and Melbourne, 570 W/m^2 in Brisbane and 510 W/m^2 in Sydney.

c. The spatially average absolute minimum released sensible heat is 510 W/m^2 in Perth, followed by Brisbane and Adelaide at 470 W/m^2, while Melbourne is close to 310 W/m^2 and Sydney, 250 W/m^2.

d. The more frequent level of the spatially average released sensible heat in the five cities is almost equal to the calculated median sensible heat.

e. The influence of wind speed on the released sensible heat differs between the cities. In Brisbane increase in the wind speed decreases the released sensible heat slightly; in Sydney, the variability of the sensible heat as a function of the wind speed is almost negligible, while for the remainder of the cities, a positive linear association is observed.

f. The influence of the surface temperature on released sensible heat differs between the cities. In Brisbane and Sydney, an increase in surface temperature seems not to affect the released sensible heat, while for the balance of the cities, a positive linear association is observed.

g. The influence of the ambient temperature on the released sensible heat differs between the cities. In Brisbane and Sydney, an increase in the ambient temperature seems not to affect released sensible heat, while for the rest of the cities, a positive linear association is observed.

1 Sensible heat refers to heat that people can feel or sense. This is the heat that can be measured with a thermometer. Sensible heat is the energy required to change the temperature of a substance without causing a phase shift. A temperature change can result from the absorption of sunlight by the soil or the air itself. The heat can also be released by direct conduction (by contact with warmer air).

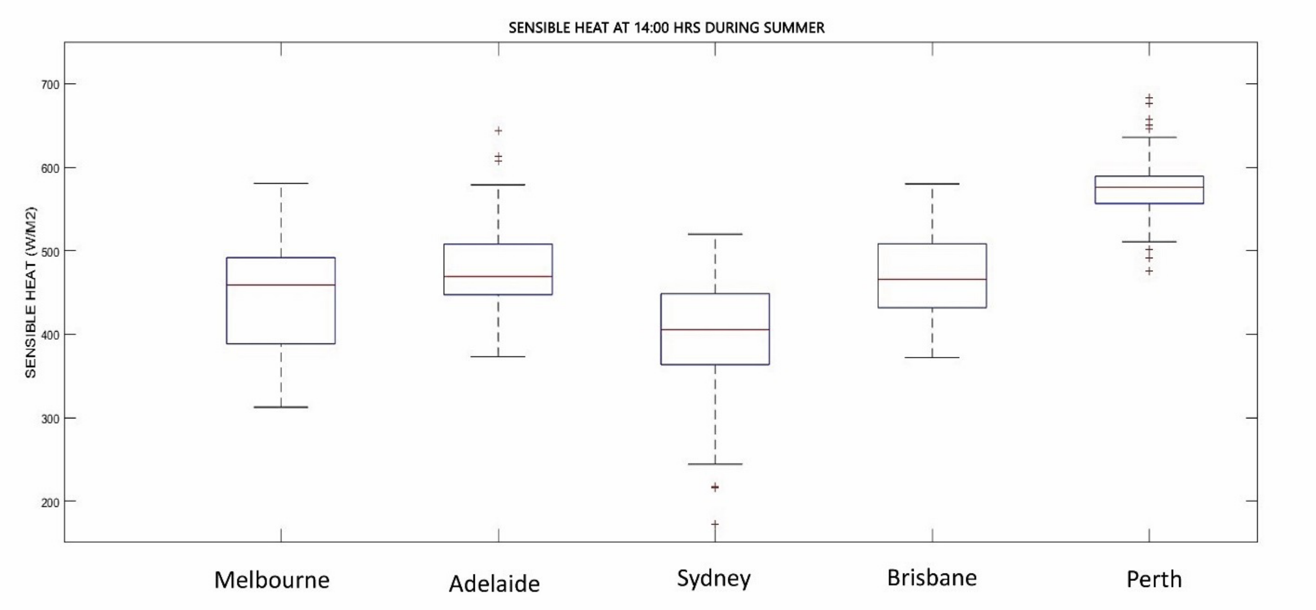


Figure 3.10 Variability of the summer sensible heat at 14:00 hrs in the five main Australian cities under the reference conditions as calculated by WRF for January and February.

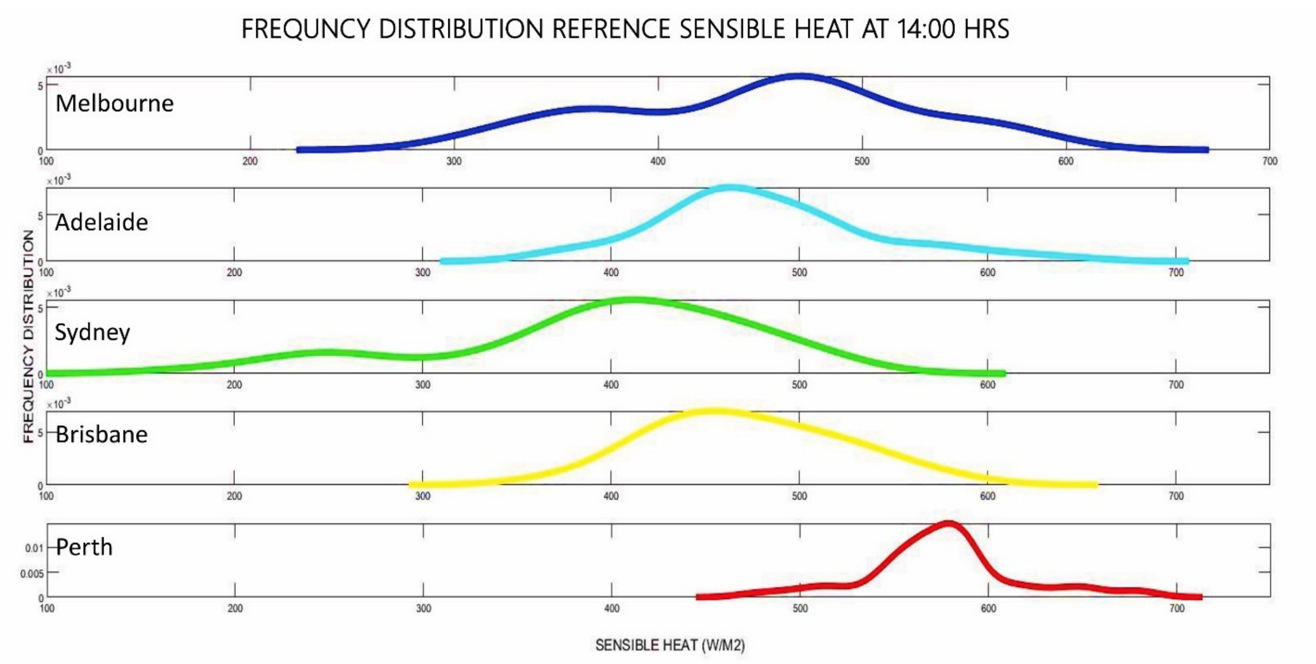


Figure 3.11 Frequency distribution of the summer sensible heat at 14:00 hrs in the five main Australian cities under the reference conditions as calculated by WRF for January and February.

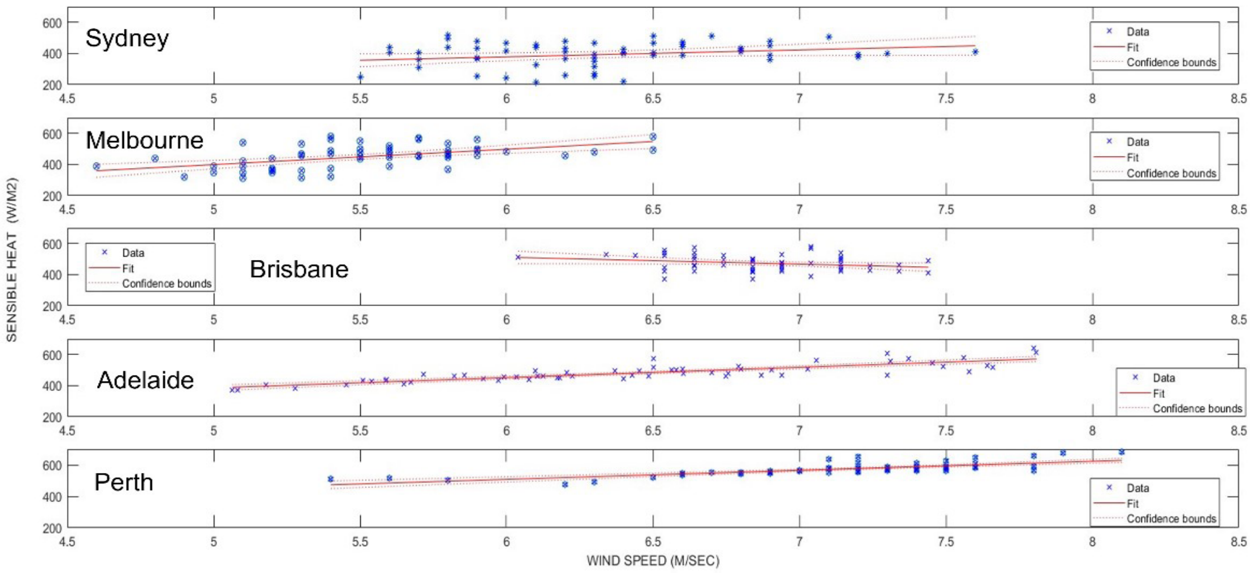


Figure 3.12 Association between the spatially average wind speed at 14:00 hrs and the corresponding release of sensible heat in the five cities.

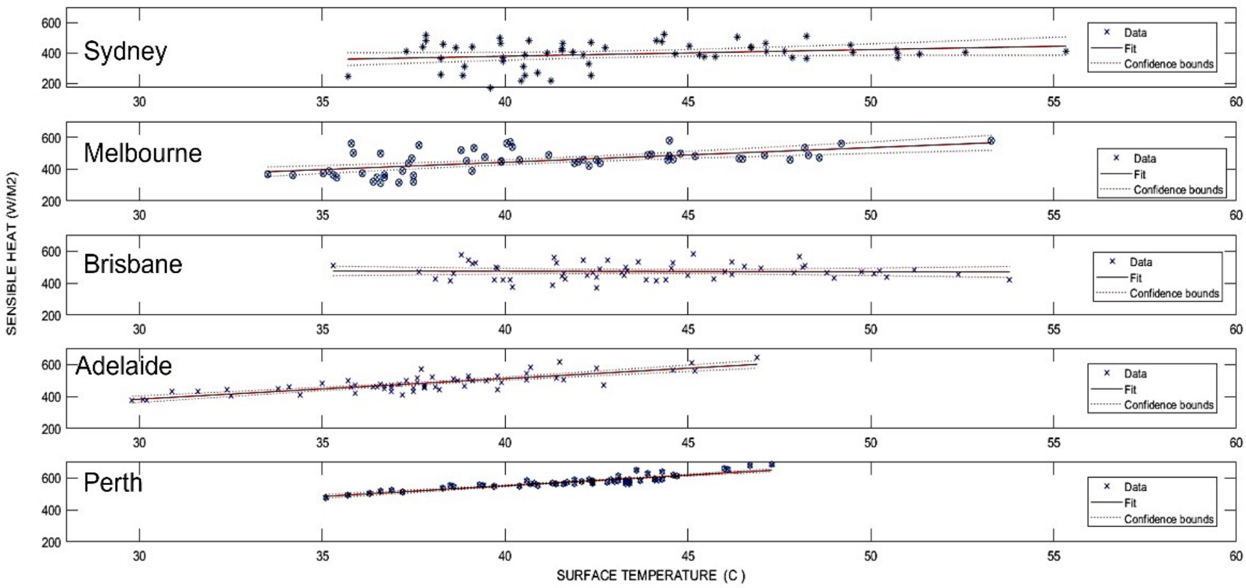


Figure 3.13 Association between the spatially average surface temperature at 14:00 hrs and the corresponding release of sensible heat in the five cities.

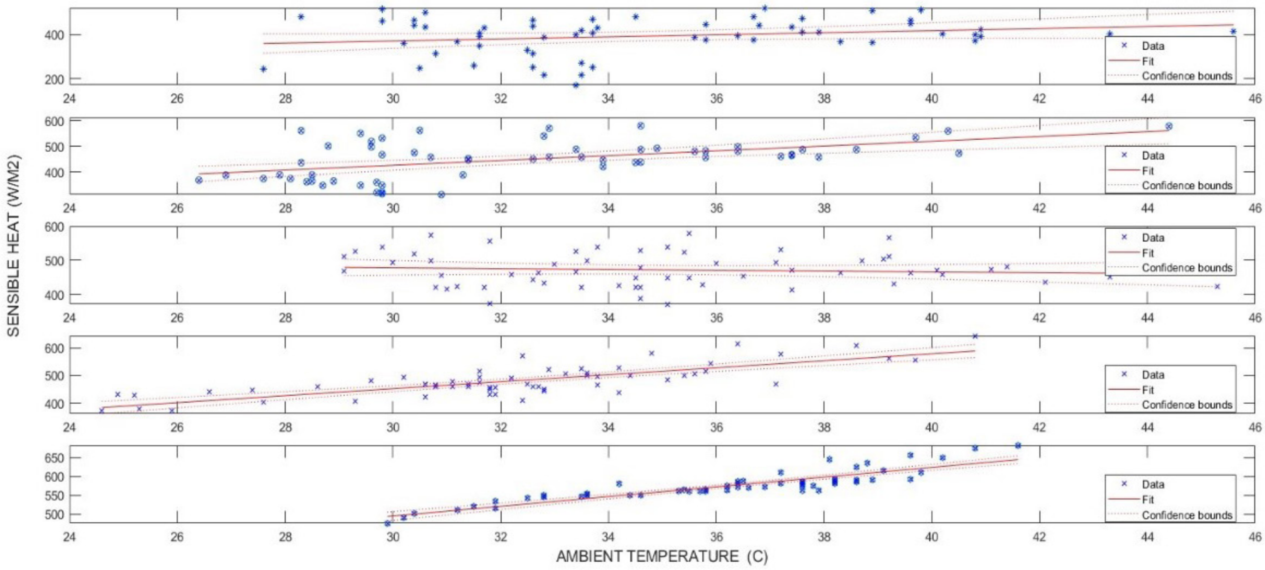


Figure 3.14 Association between the spatially average ambient temperature at 14:00 hrs and the corresponding release of sensible heat in the five cities.

3.5. SIMULATED SPATIALLY AVERAGE SUMMER LATENT HEAT CHARACTERISTICS AT 14:00 HRS UNDER THE REFERENCE CONDITIONS IN THE FIVE MAIN AUSTRALIAN CITIES

3.5.1. MAIN CHARACTERISTICS

The range and the frequency of the calculated spatially average latent heat[2] at 14:00 hrs as calculated by the WRF mesoscale model, under the reference conditions in the five cities, are shown below (Figures 3.15 – 3.17). The main conclusions and observations are as follows.

a. The spatially average median latent heat released in the five cities is rather low and varies between 35 W/m^2 and 23 W/m^2. The median value is considerably higher in Perth and Melbourne (close to 35 W/m^2), followed by Sydney and Brisbane (close to 22-23 W/m^2)

b. The spatially average absolute maximum latent heat released at 14:00 hrs during the simulation period exceeds 40 W/m^2 in Perth, Adelaide, and Melbourne. In Sydney and Brisbane, it is close to 30 W/m^2.

c. The spatially average absolute minimum released sensible heat is 30 W/m2 in Perth, followed by Melbourne and Adelaide (26-27 W/m^2), while Sydney and Brisbane are close to 7 W/m^2.

d. The more frequent level of the spatially average released latent heat in the five cities is almost equal to the calculated median sensible heat.

e. Ambient temperature presents a weak association with the magnitude of the released latent heat. Higher ambient temperatures correspond to slightly higher latent heat fluxes.

f. The association between wind speed and related heat released, is very similar to the association of wind speed and sensible heat for each city. In Brisbane, the increase of the wind speed reduces the released latent heat slightly. In Sydney, the variability of latent heat as a function of the wind speed is almost negligible, while for the remaining cities, a positive linear association is observed.

2 Latent heat refers to the energy absorbed or released by a substance during a change in its physical state (phase) that occurs without changing its temperature.

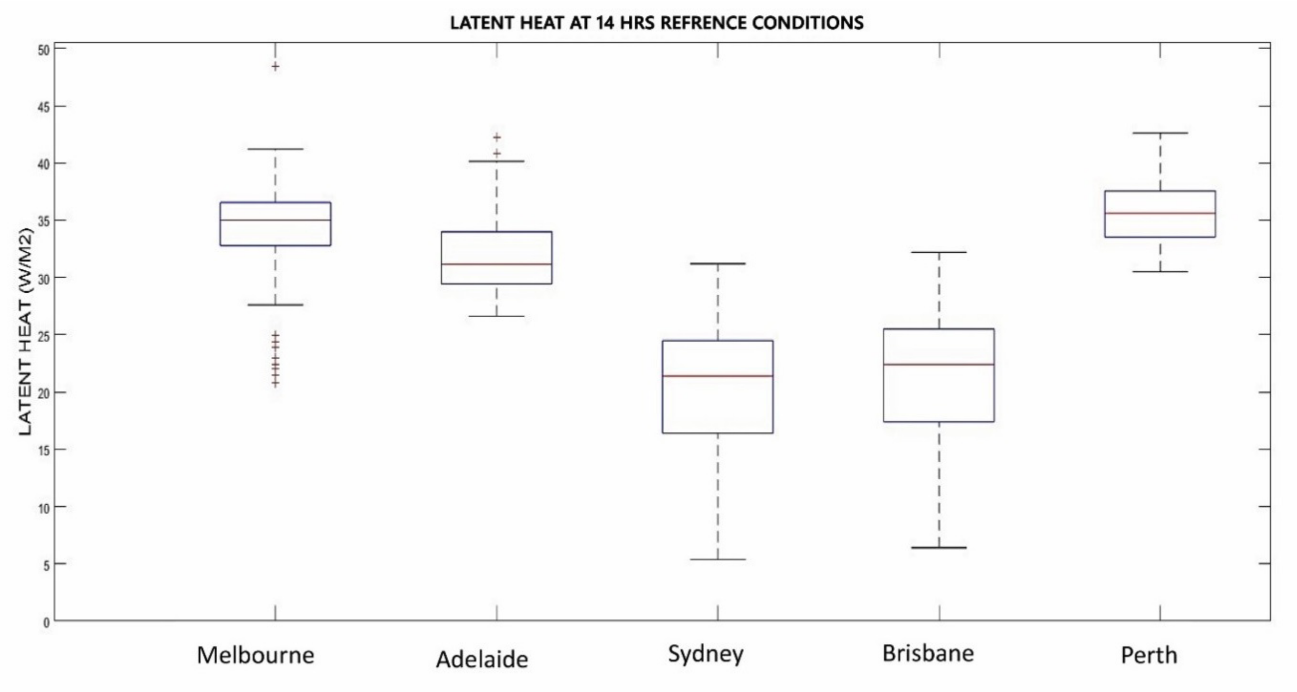


Figure 3.15 Variability of the summer latent heat at 14:00 hrs in the five main Australian cities under the reference conditions as calculated by WRF for January and February.

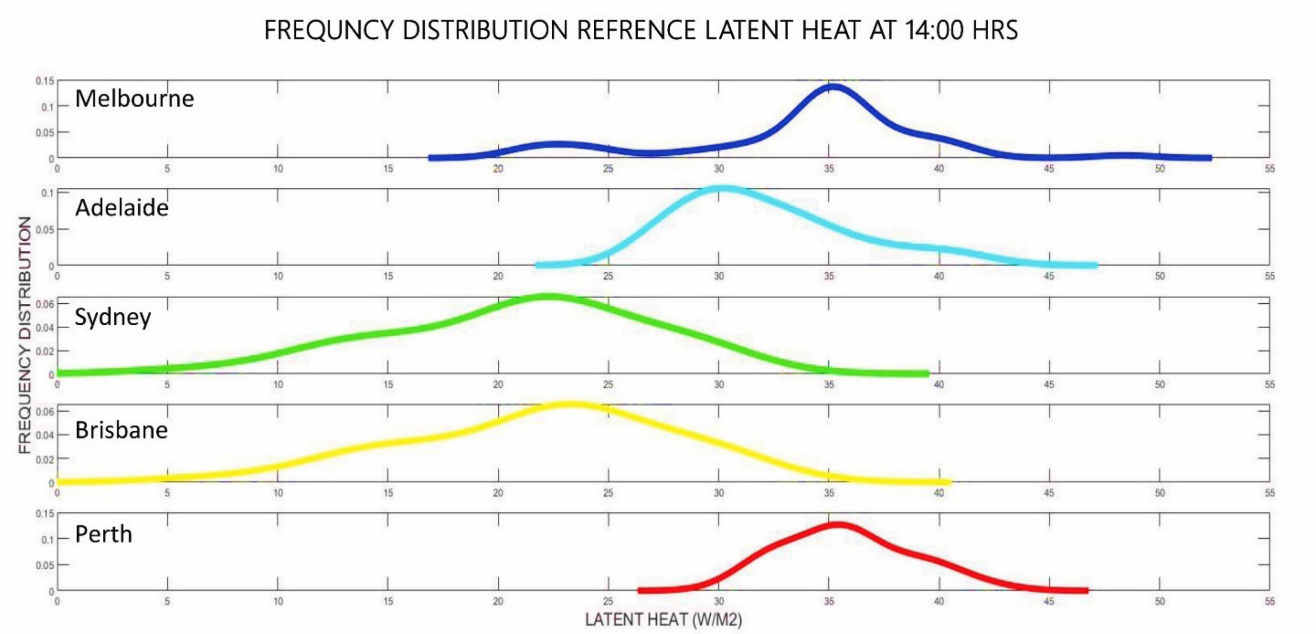


Figure 3.16 Frequency distribution of the summer latent heat at 14:00 hrs in the five main Australian cities under the reference conditions as calculated by WRF for January and February.

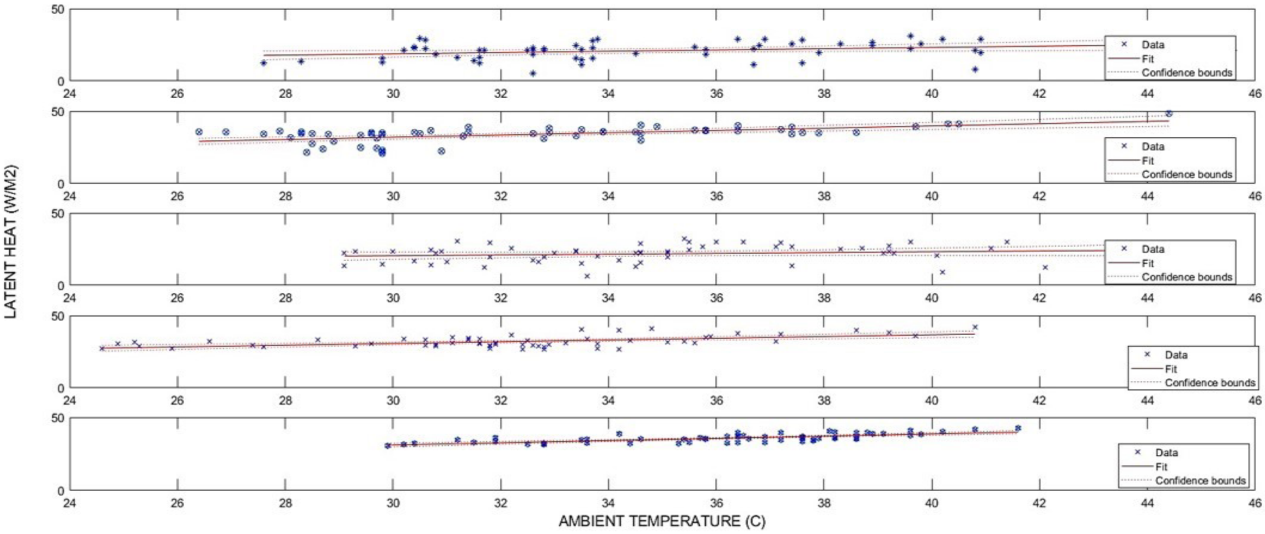


Figure 3.17 Association between the spatially average ambient temperature at 14:00 hrs and the corresponding release of latent heat in the five cities.

3.6. CLIMATIC IMPACT OF COOL ROOFS IN SYDNEY

3.6.1. CONTEXT OF THE STUDY

A full simulation of the climatic conditions in the Greater Sydney area has been performed to assess the spatial and temporal variation of the main climatic parameters that affect urban overheating and the levels of thermal comfort.

Simulations are performed for two complete summer months, using the accurate mesoscale model, WRF, with a grid resolution of 500 x 500 m, as shown in Figure 3.18.

Two climatic scenarios are investigated:

Reference Scenario: aiming to simulate the spatial and temporal variability of the main climatic parameters under the reference conditions, (no use of cool roofs)

Cool Roofs Scenario: as the above reference scenario but assuming that all roofs in domain d03 of Figure 3.18 are reflective (cool roofs).

The reflectance of the roofs was considered equal to 0.15 and 0.8 under the reference and cool roof scenarios, respectively. The emissivity of the roofs was equal to 0.85 for both scenarios.

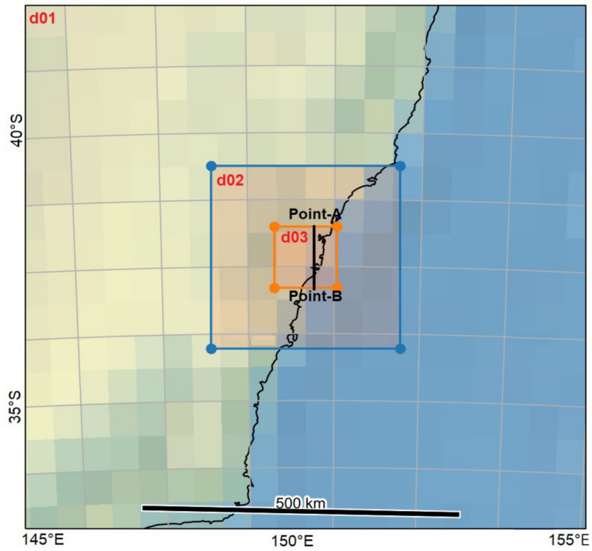


Figure 3.18 The WRF domain shows (a) dynamic downscaling with domain 1 (d01) as the outermost parent domain with 4,500 m grid spacing; domain 2 (d02) with 1,500 m grid spacing and, an innermost domain 3 (d03) with 500 m grid spacing; (b) the innermost d03 with 500 m grid spacing encompasses Greater Sydney. The Point-A (left) and Point-B (right) are the points used for drawing horizontal-vertical cross-sections to analyze meteorological conditions.

The predictions of the reference scenario were validated against measured climatic data from four meteorological stations, in Penrith, Observatory Park in Sydney, Sydney Airport and Olympic Park, and are found to be in excellent agreement (see Figure 3.19).

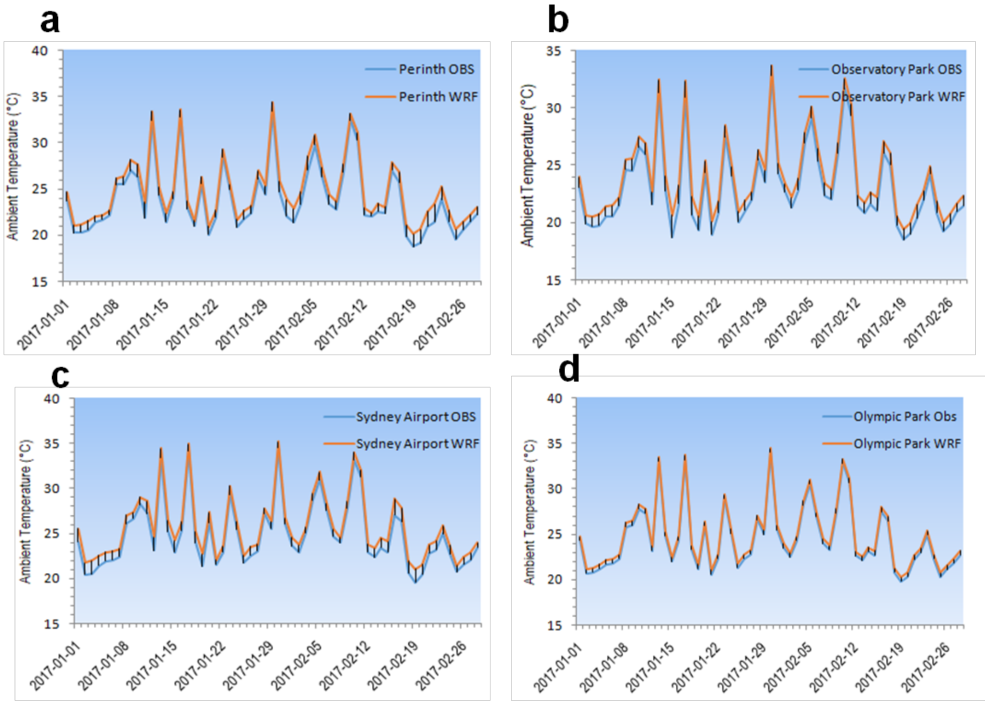


Figure 3.19 Comparison of the simulation results with observation data on average for 59 days.

3.6.2. REFERENCE CLIMATIC CONDITIONS

Ambient Temperature

The magnitude of urban overheating in Sydney is very significant.

During a representative summer day, the peak ambient temperature in Sydney, presents a very important spatial distribution. During the peak day period, 14:00 hrs, the eastern and coastal parts of the city benefit from the flow of the cool sea breeze presenting up to 10°C lower ambient temperature than the western part of the city, which is highly influenced by the warm westerly winds from the arid inland areas, Figure 3.20.

The spatial distribution of the cooling degree hours in Sydney during the summer period demonstrates the magnitude of overheating in Western Sydney. Cooling degree hours measure how much, and for how long, outside air temperature is higher than 26°C, and serve as a rough indication of regional climatic severity. While the total cooling degree hours during January and February in the city's eastern part do not exceed 1,100, Western Sydney has almost 3 to 4 times the cooling degree hours, that is, 3,300 in Penrith and 4,000 in Richmond (Figure 3.21).

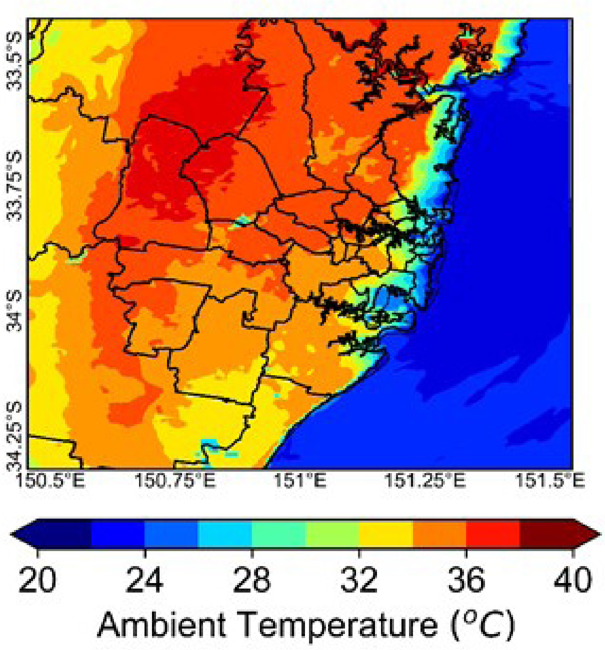


Figure 3.20 Spatial distribution of the ambient temperature in Sydney at 14:00 hrs during a representative summer day under the reference conditions as calculated by the WRF simulations.

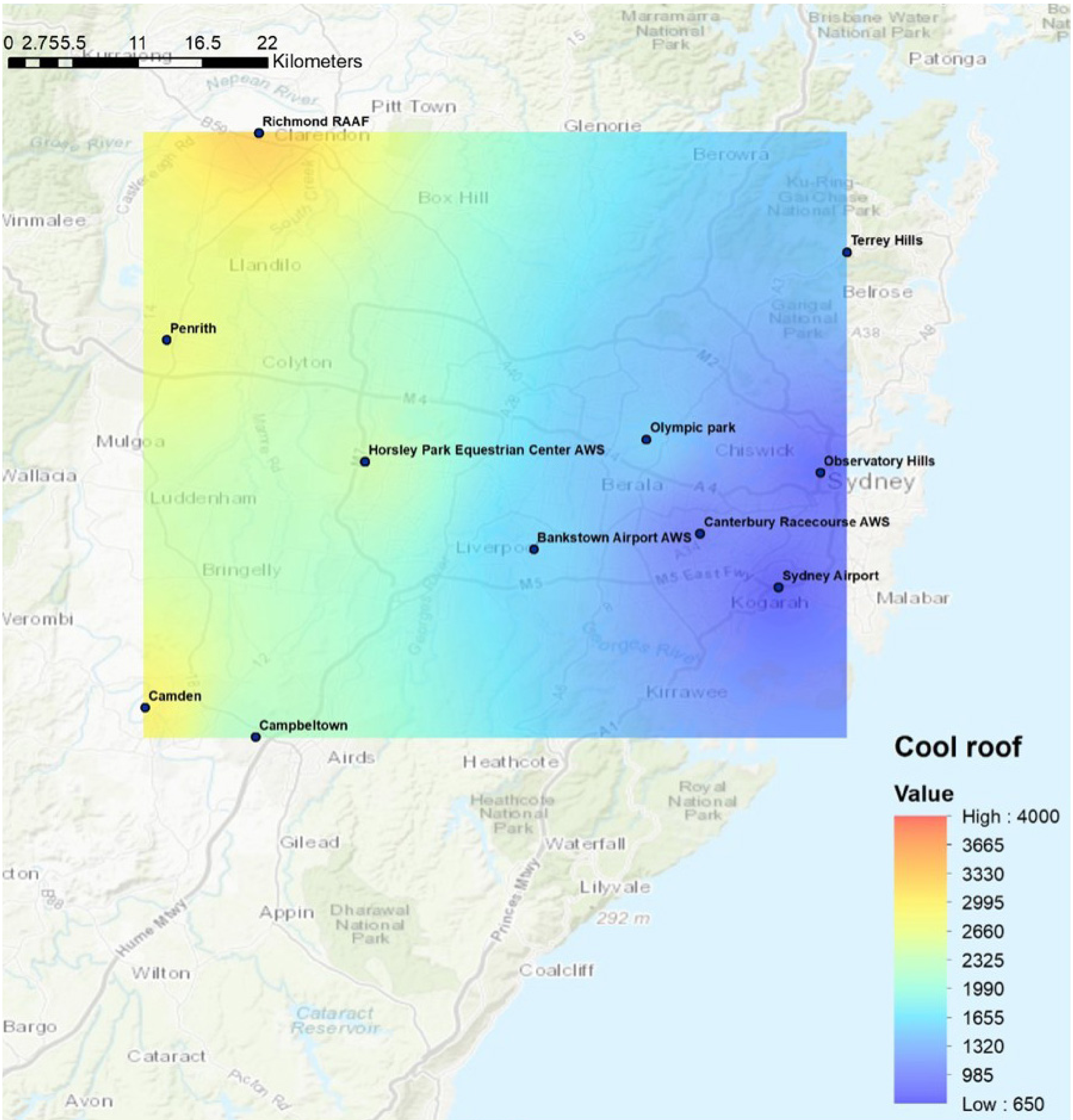


Figure 3.21 The sum of cooling degree hours in January and February at the 11 reference stations in Sydney.

Surface Temperature

Surface temperature distribution during the daytime is high in specific zones of the city, approaching 50°C, and like the ambient temperature, presents a significant spatial distribution, Figure 3.22.

The surface temperature at 2 pm can be as high as 50°C as a function of the optical properties of the materials used. Highly absorbing dark roofs and pavements present the highest surface temperature, while light coloured reflective surfaces may present up to 20°C lower surface temperature. Green spaces present quite a low surface temperature; however, this is highly affected by the characteristics of the specific urban greenery zones.

High surface temperatures release much higher sensible heat to the atmosphere, increasing the ambient temperature and intensifying the magnitude of urban overheating. The maximum released sensible heat at 14:00 hrs is close to 410 W/m^2.

High ambient and surface temperatures, especially in the western part of the city, correspond to very uncomfortable climatic conditions affecting the energy consumption of buildings, peak electricity demand, heat related mortality and morbidity and survivability of the low-income population.

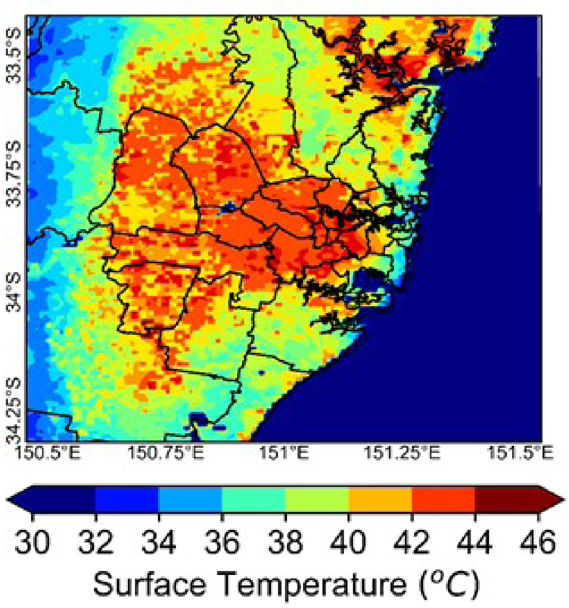


Figure 3.22 Spatial distribution of the surface temperature in Sydney at 14:00 hrs during a representative summer day under the reference conditions as calculated by the WRF simulations.

Wind Speed

Wind speed in Sydney is determined by the characteristics of the sea breeze in the coastal area and the western winds flowing from the direction of the arid inland areas. During the daytime and mainly in the afternoon hours, the sea breeze significantly cools down the eastern suburbs to the eastern part of Paramatta, while western winds dominate in the rest of the Sydney basin. The average wind speed (W_{speed}) is 8.8 m/s, 9.4 m/s and 8.9 m/s at 06:00 hrs local time (LT), 14:00 hrs LT and 18:00 hrs LT, respectively over the city.

Figure 3.23 shows the magnitude and the direction of the wind during a representative summer day at 06:00 hrs, 14.00 hrs and 18:00 hrs LT.

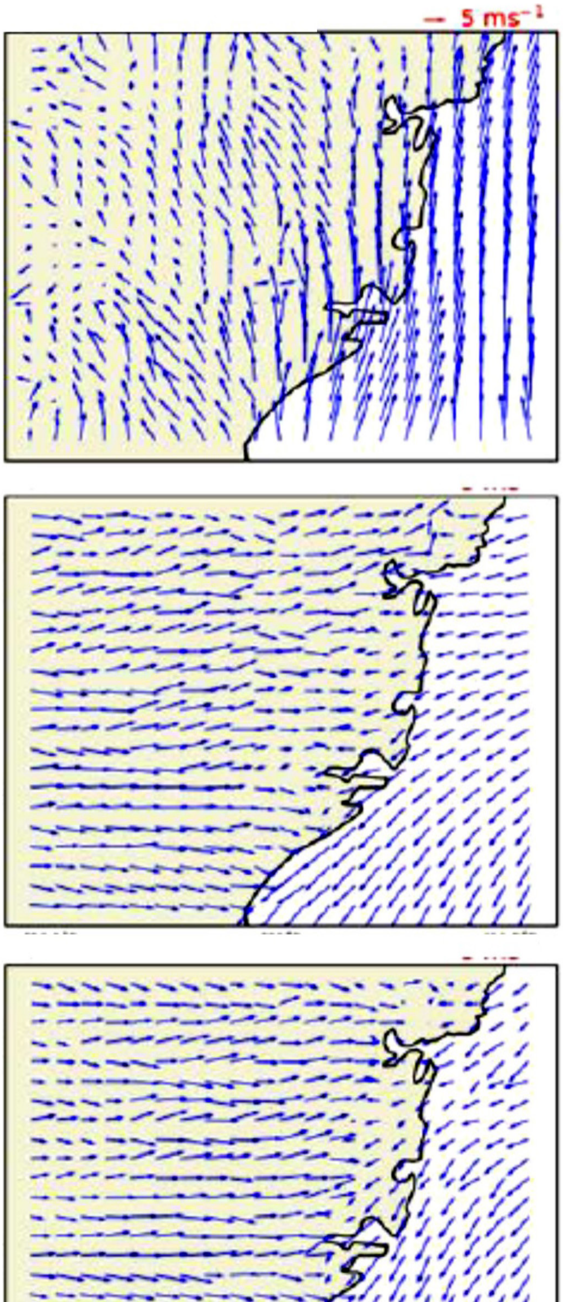


Figure 3.23 Spatial distribution of the wind speed and direction in Sydney at 06:00 hrs, (upper), 14:00 hrs (middle) and 18:00 hrs (lower), during a representative summer day under the reference conditions as calculated by the WRF simulations.

3.6.3. MODIFIED CLIMATIC CONDITIONS — INSTALLATION OF COOL ROOFS

The installation of the cool roofs at the city scale affects the local climate acutely. It decreases both the ambient and surface temperature mainly during the daytime, decreases the strength of the wind speed and the advection of heat from the arid inland areas and contributes strongly to reducing the magnitude of urban overheating in the city.

Ambient Temperature

The installation of cool roofs at the city scale reduces summer peak ambient temperature at 14.00 hrs up to 1.6°C (Figure 3.24). The important temperature difference between the eastern and the western parts of the city still exists, although the magnitude of the temperature difference is lower by about 1.0°C.

The calculated decrease of temperature is more significant for the inner and mid-western parts of the city, as shown in Figure 3.25. The median spatially average temperature drop in Sydney is 0.8°C, respectively, and the maximum one is 1.6°C. For almost 50% of the days, the average ambient temperature drop is between 0.5°C and 1°C, while for 24% of the time is between 1.0°C to 1.5° C and 20% between 0.0°C and 0.5°C.

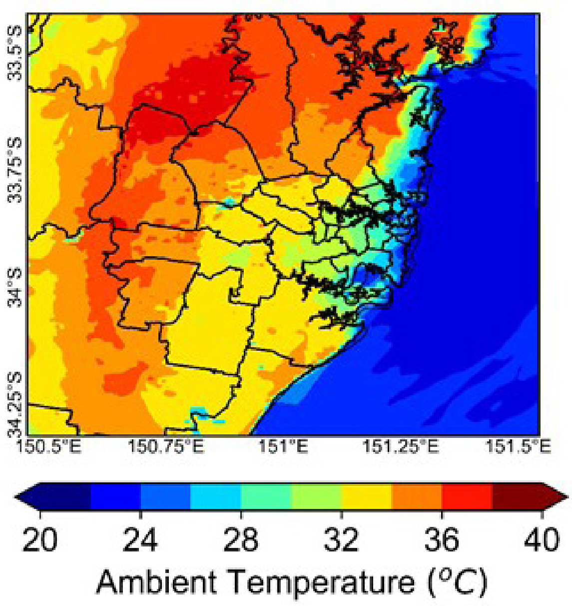


Figure 3.24: Spatial distribution of the ambient temperature in Sydney at 14:00 hrs during a representative summer day when cool roofs are implemented, as calculated by the WRF simulations.

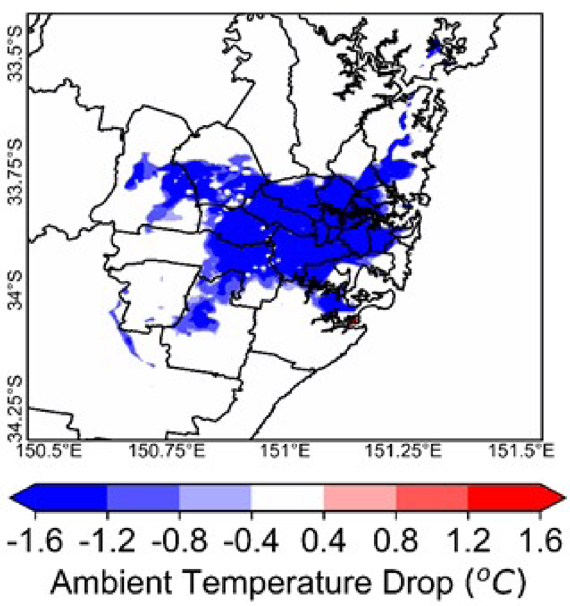


Figure 3.25 Spatial distribution of the ambient temperature drop in Sydney at 14:00 hrs, caused by the installation of the cool roofs, during a representative summer day, as calculated by the WRF simulations.

A very significant drop of the summer cooling degree hours, ranging between 20 to 35% compared to the reference climatic conditions, is observed in Figure 3.26. Eastern Sydney presents a reduction of cooling degree hours close to 350, while in the western part of the city, the decrease may be the double, 750 in Richmond.

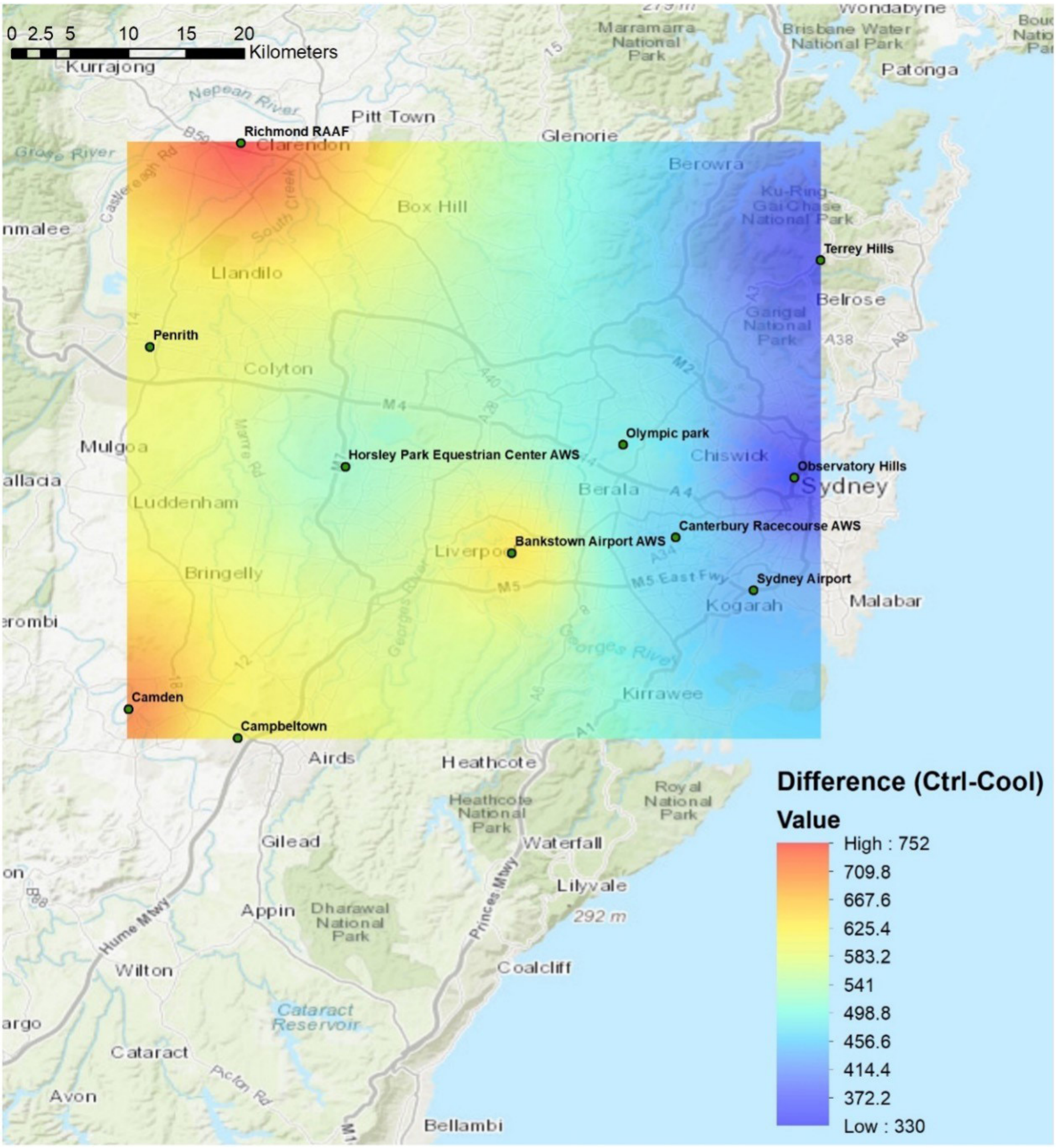


Figure 3.26 The sum of cooling degree hours in Jan and Feb at the 11 stations in Sydney, when cool roofs are implemented at a city scale.

Surface Temperature

While the surface temperature in Sydney continues to be high, cool roofs contribute to a very significant decrease of the surface temperature at 14:00 hrs pm is observed for the whole Sydney area. The median spatially average temperature decreases at 14:00 hrs pm is close to 7°C while its maximum is around 8.5°C and its minimum at 3°C. For 52% of the days, the average surface temperature drop is between 6°C and 8°C, and 19% between 4°C and 6°C.

The significant decrease of the surface temperature results in an important reduction of the sensible heat released by the city that significantly affects the magnitude of the urban overheating. The maximum decrease of the sensible heat flux is 279.8 Wm^{-2} , and the average decrease is 192 Wm^{-2} at 14:00 hrs LT over the CBD and inner west. At 18:00 hrs LT, the maximum and average reduction of summer months of sensible heat flux are 115.0 Wm^{-2} and 60.1 Wm^{-2} over the urban domain. At 18:00 hrs LT, the maximum and average reduction of summer month of sensible heat flux is 115.0 Wm^{-2} and 60.1 Wm^{-2} over the urban domain, Figure 3.29 The median sensible heat drop at 14 pm in Sydney is 210 W/m^2. For 78% of the days the average drop of the sensible heat is between 150 W/m^2 and 250 W/m^2.

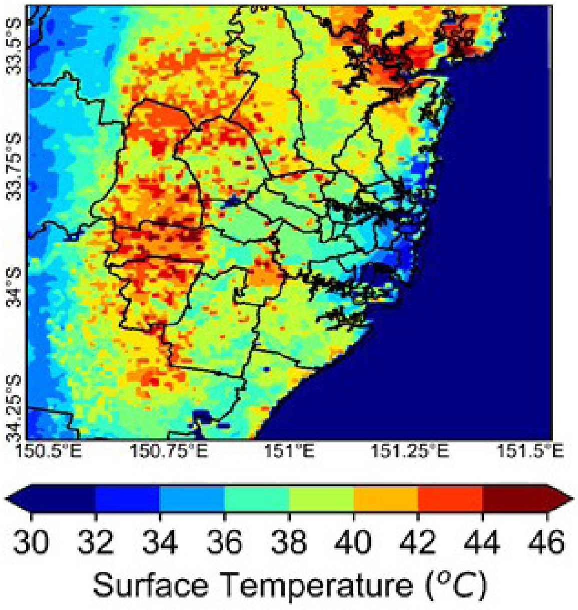


Figure 3.27 Spatial distribution of the surface temperature in Sydney at 14:00 hrs during a representative summer day when cool roofs are installed at city scale, as calculated by the WRF simulations.

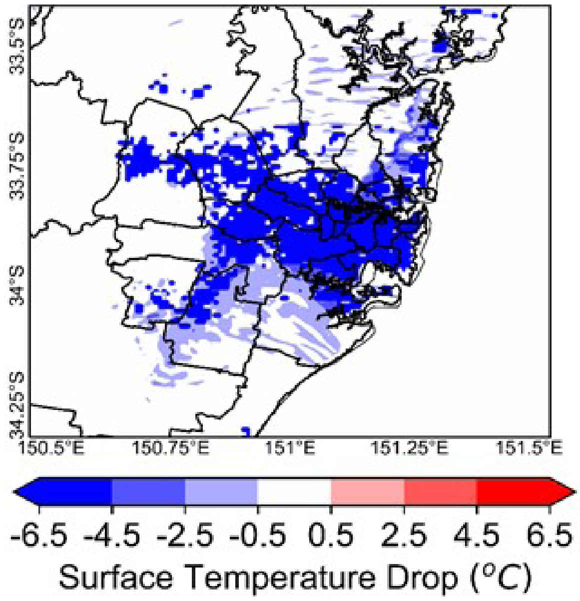


Figure 3.28 Spatial distribution of the surface temperature drop in Sydney at 14:00 hrs during a representative summer day when cool roofs are installed at city scale, as calculated by the WRF simulations.

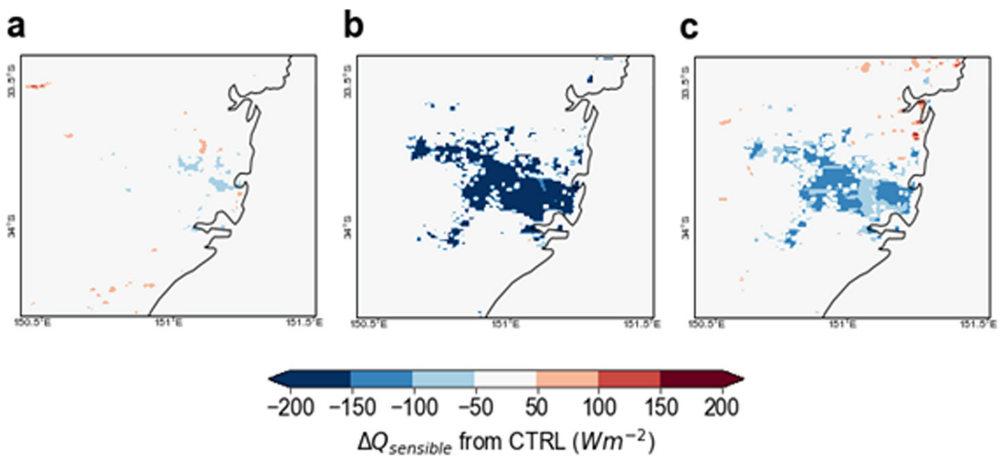


Figure 3.29 Reduction of sensible heat flux at (a) 06:00 LT, (b) 14:00 hrs LT, and (c) 18:00 LT, in Sydney, during a representative summer day when cool roofs are installed at city scale.

Wind Speed

The installation of cool roofs at the city scale greatly affects air circulation in the city. Lower surface temperatures caused by a large-scale deployment of cool roofs decrease the height of the planetary boundary layer (PBL).
The planetary boundary layer is the lowest layer of the atmosphere where the wind is influenced by the city surface and when the thickness is not constant (Figure 3.30). The lower height of the PBL corresponds to reduced wind circulation in the lower parts of the atmosphere and by lower advection of warm winds from the arid inland areas. The magnitude of the PBL height reduction is considerably higher when highly reflective cool materials rather than conventional materials are used at the city scale. The prime causes of PBL depth reduction are a reduction in the absorbed solar radiation and a consequent decrease in the sensible heat flux released and associated turbulence in the lower atmosphere. It is also noted that the increase of the albedo is expected to accelerate static stability at the diurnal scale of the PBL depth. Modification of the albedo reduces the impacts of urban induced warming and decreases the intensity of the convective mixing, thereby reducing the PBL depth, with potential penalties for air pollutant dilution and dispersion over the city domain. The reduction of moisture transport from the urban surface to the vertical layer caused by the installation of reflective materials can also be disadvantageous to cloud formation processes and, as a result, reduce the amount of precipitation in urban areas or their downwind environments.

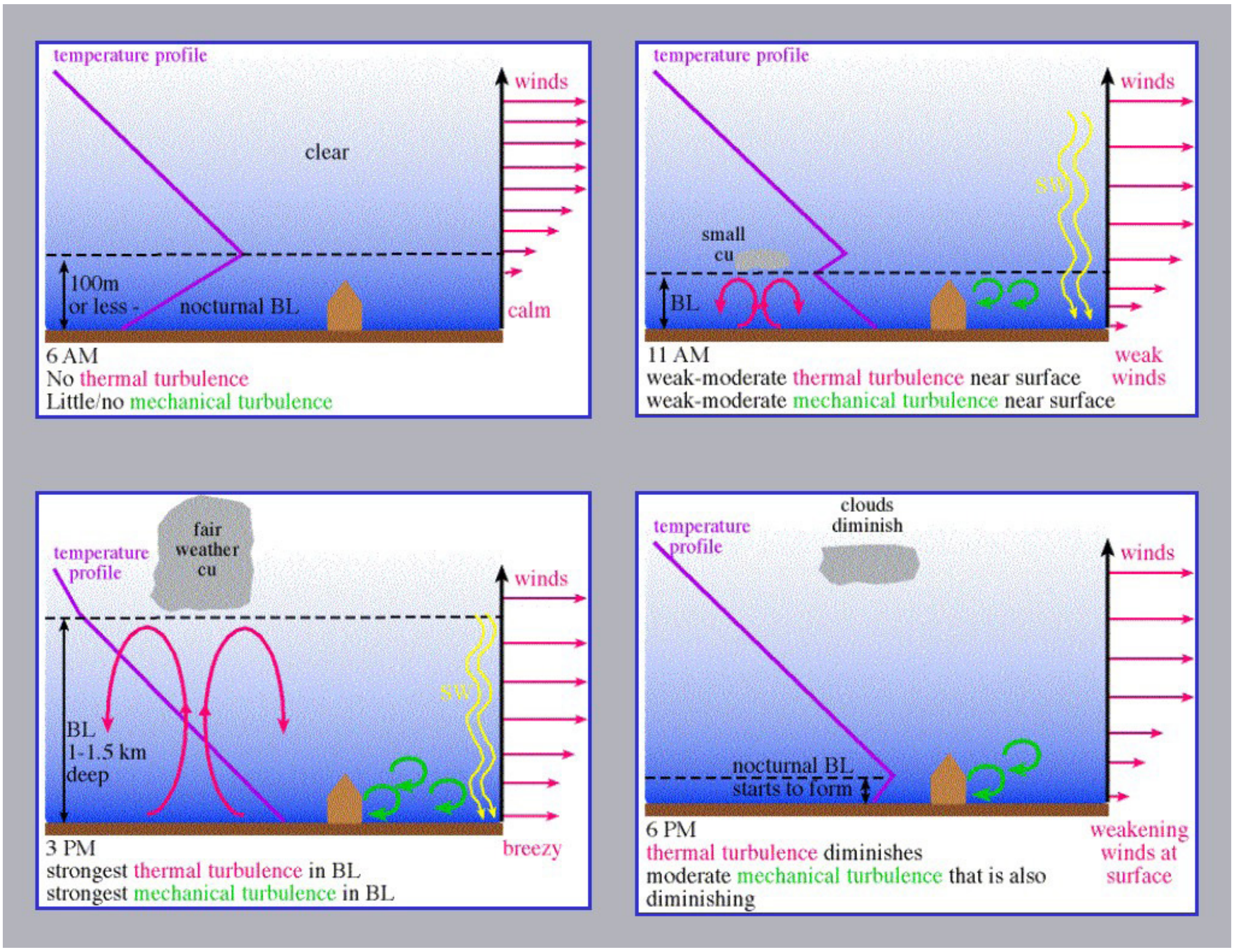


Figure 3.30 Evolution of the planetary boundary layer during a day. Source: Planetary Boundary Layer (www.weather.gov).

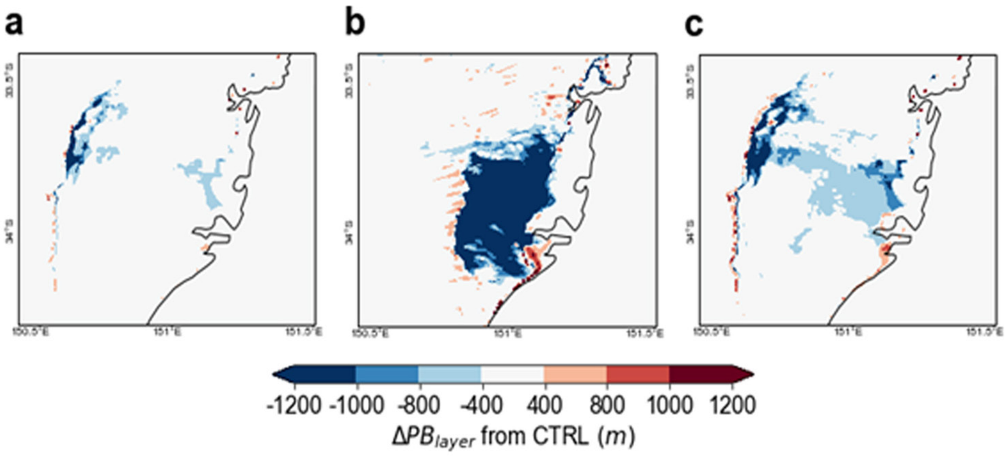


Figure 3.31 Reduction of PBL height at (a) 06:00 hrs LT, (b) 14:00 hrs LT, and (c) 18:00 hrs LT during a typical summer day when cool roofs are installed at city scale.

The deployment of cool roofs over the city scale can affect the pressure gradient between the city and surrounding surface due to a significant drop in ambient temperature up to 2.4°C and wind speed reduced up to 3.9 m/s. The highest decrease of the average wind speed is observed in the western part of the city, it is close to 0.8 m/sec and greatly contributes to decreasing the advective flow of warm air from the desert, Figure 3.32. The median wind speed drop in Sydney, is 0.2 m/sec.

Thus, changes in roof reflectivity, sensible heating, and wind speed result in feedback within the local climate of the city during peak hours (14:00 hrs LT). The higher urban albedo values decrease the advective flow between the city and its surroundings, improving the cooling potential of reflective materials. It creates a 'regional high', which can reduce both horizontal and vertical wind speed over the city. The average decrease of wind speed from the north-west and south-west at 14:00 hrs LT is 2.0 m/s and 1.4 m/s, respectively. Consequently, the increase of albedo may prevent the warm airflow from the adjacent arid inland areas towards western Sydney because of the regional high over the domain. In addition, the impact of the sea breeze is reduced over high-density residential areas (Figure 3.33).

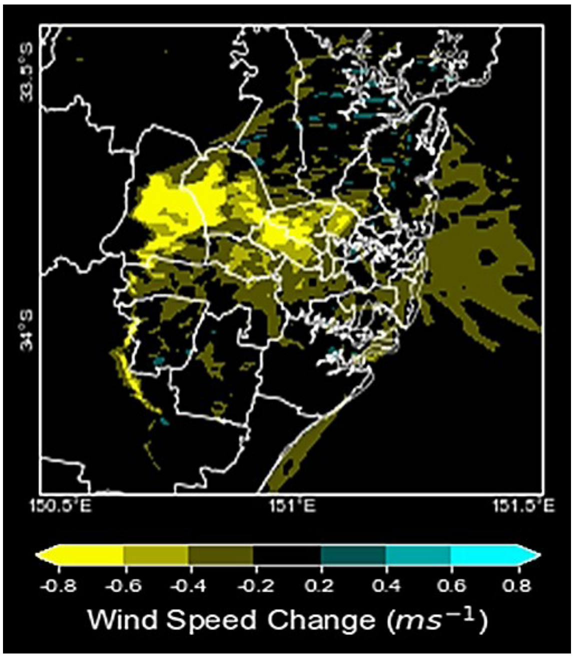


Figure 3.32 Reduction of the wind speed at 14:00 hrs because of the installation of the cool roofs at city scale during a typical summer day.

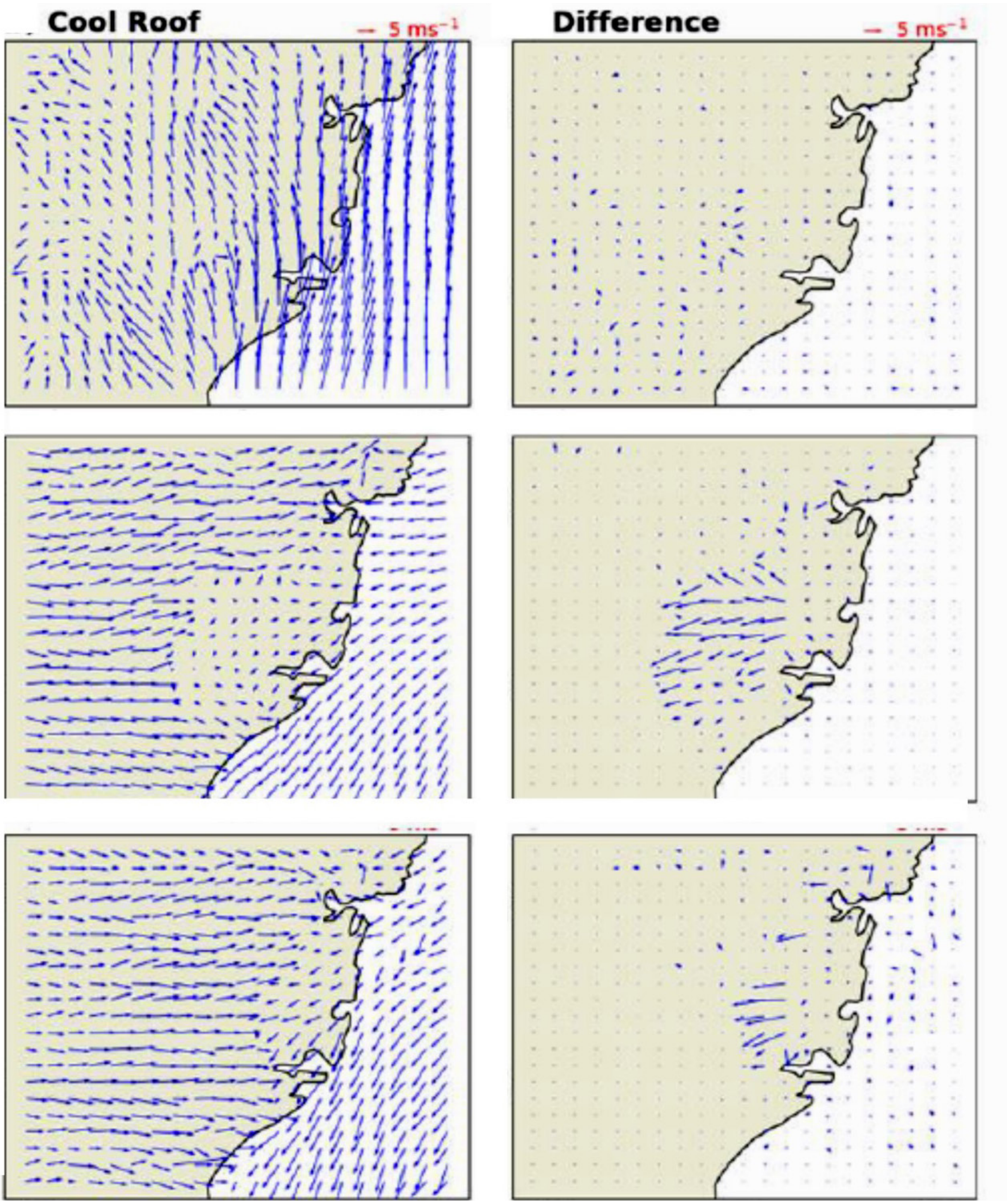


Figure 3.33 Spatial distribution of the wind speed and direction in Sydney at 06:00 am, (upper), 14:00 hrs, (middle) and 18:00 pm (lower), during a representative summer day when cool roofs are installed at city scale and difference of the wind speed against the reference conditions, as calculated by the WRF simulations.

3.7. CLIMATIC IMPACT OF COOL ROOFS IN THE GREATER MELBOURNE AREA

3.7.1. CONTEXT OF THE STUDY

A full simulation of the climatic conditions in the Greater Melbourne area has been performed to assess the spatial and temporal variation of the main climatic parameters that affect urban overheating and the levels of thermal comfort. Simulations are performed for two complete summer months, using the accurate mesoscale model, WRF, with a grid resolution of 500 m x 500 m as shown in Figure 3.34.

Two climatic scenarios are investigated:

Reference Scenario: aiming to simulate the spatial and temporal variability of the main climatic parameters under the reference conditions, (no use of cool roofs).

Cool Roofs Scenario: as the above reference scenario but assuming that all roofs in domain d03 of Figure 3.34 are reflective, that is, cool roofs.

The reflectance of the roofs was considered equal to 0.15 and 0.8 under the reference and cool roof scenarios, respectively. The emissivity of the roofs was 0.85 for both scenarios.

The predictions of the reference scenario were validated against measured climatic data from four meteorological stations, in (a) Avalon, (b) Laverton, (c) Moorabbin Airport, and (d) Cerberus, and are in excellent agreement, Figure 3.35.

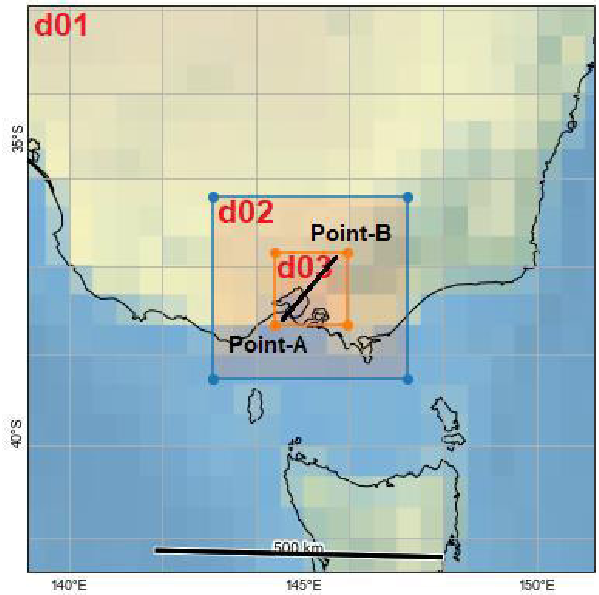


Figure 3.34 The WRF domain shows (a) dynamical downscaling with domain 1 (d01) as outermost parent domain with 4500 m grid spacing, domain 2 (d02) with 1500 m grid spacing and, an innermost domain 3 (d03) with 500 m grid spacing; (b) innermost d03 with 500 m grid spacing which encompasses the Greater Melbourne. Point-A (left) and Point-B (right) are the points used for drawing horizontal-vertical cross-sections to analyze meteorological.

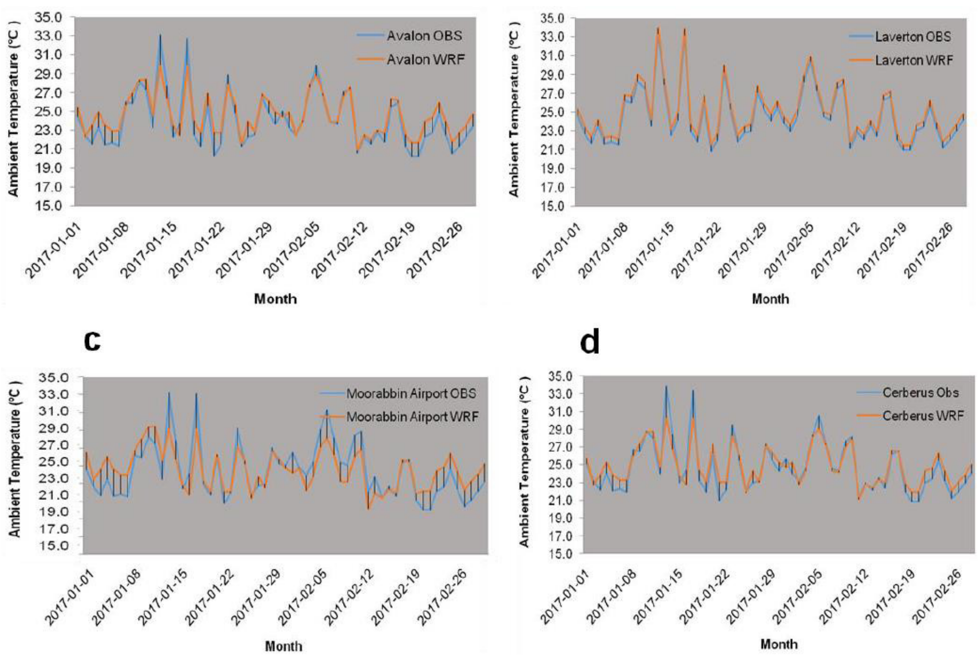


Figure 3.35 Validation of the WRF model and the corresponding observed air temperature for the 24-hour average duration for four local meteorological stations: (a) Avalon, (b) Laverton, (c) Moorabbin Airport, and (d) Cerberus.

3.7.2. REFERENCE CLIMATIC CONDITIONS

Ambient Temperature

The magnitude of urban overheating in Melbourne is very significant. During a representative summer day, the peak ambient temperature in Melbourne presents a very important spatial distribution. During the peak day period, 14:00 hrs, the coastal parts of the city benefit from the flow of the cool sea breeze, bringing 8 – 12°C lower ambient temperature than specific zones in the northern part of the city, which is highly influenced by the warm western winds from the desert, Figure 3.36.

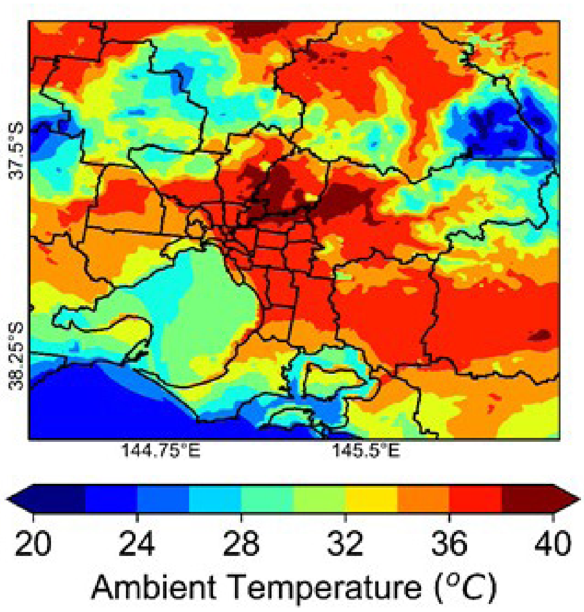


Figure 3.36: Spatial distribution of the ambient temperature in the Greater Melbourne area at 14:00 hrs during a representative summer day under the reference conditions as calculated by the WRF simulations.

The spatial distribution of the cooling degree hours in the Greater Melbourne area during the summer period demonstrates the magnitude of overheating in parts of the northern Melbourne area. Cooling degree hours measure how much, and for how long, outside air temperature is higher than 26°C and serve as a rough indication of regional climatic severity. While the total cooling degree hours during January and February in the coastal part of the city do not exceed 445, parts of northern Melbourne present almost 3 to 4 times higher cooling degree hours, that is, 1350 cooling degree hours at Melbourne Airport, Figure 3.37.

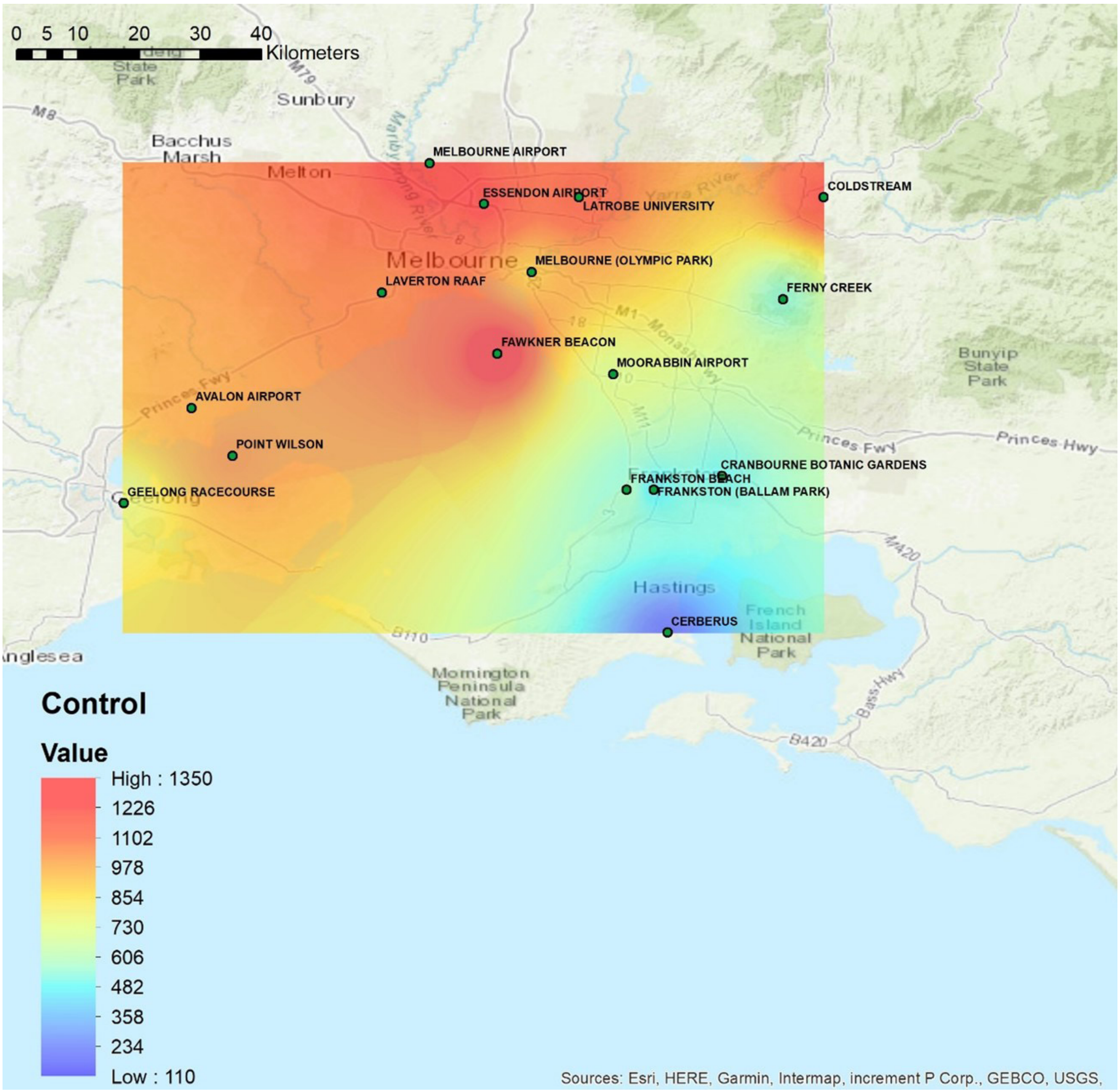


Figure 3.37 The sum of cooling degree hours in January and February at 16 reference stations in the Greater Melbourne area.

Surface Temperature

During the daytime, the surface temperature distribution varies widely across specific zones of the city, approaching 46°C, and the ambient temperature presents a marked spatial distribution (Figure 3.38).

Surface temperature at 14.00 hrs can be as high as 46°C as a function of the optical properties of the materials used. Highly absorbing dark roofs and pavements present the highest surface temperature, while light coloured reflective surfaces may present up to a 15°C lower surface temperature. Green spaces present a quite low surface temperature; however, this is highly affected by the specific characteristics of the urban greenery zones.

High surface temperatures release much more sensible heat to the atmosphere, increasing the ambient temperature and intensifying the magnitude of urban overheating. The maximum released sensible heat at 14.00 hrs is close to 398 W/m^2.

High ambient and surface temperatures, especially in the warm northern part of the city, correspond to very uncomfortable climatic conditions affecting the energy consumption of buildings, peak electricity demand, heat related mortality and the morbidity and survivability of the low-income population.

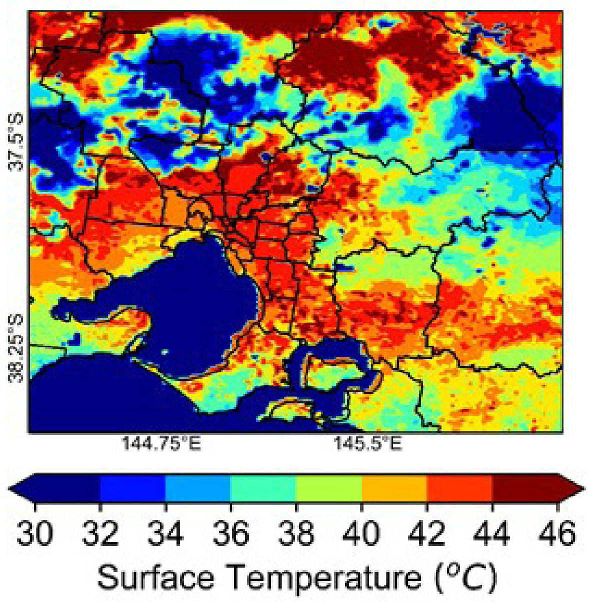


Figure 3.38 Spatial distribution of surface temperature in the Greater Melbourne area at 14:00 hrs during a representative summer day under the reference conditions as calculated by the WRF simulations.

Wind Speed

Wind speed in Melbourne is determined by the characteristics of the sea breeze in the coastal area and winds flowing from the north-west direction of the arid inland areas. During the daytime and mainly in the afternoon hours, the sea breeze cools the coastal suburbs, while it is weaker in the northern parts of the city. The average wind speed (W_{speed}) is 8.9 m/s^{-1}, 10.1 m/s^{-1}, and 9.2 m/s^{-1} during 06:00 hrs LT, 14:00 hrs LT, and 18:00 hrs LT, respectively, over the city.

Figure 3.39 shows the magnitude and the direction of the wind during a representative summer day at 06:00 hrs LT, 14.00 hrs LT and 18:00 hrs LT.

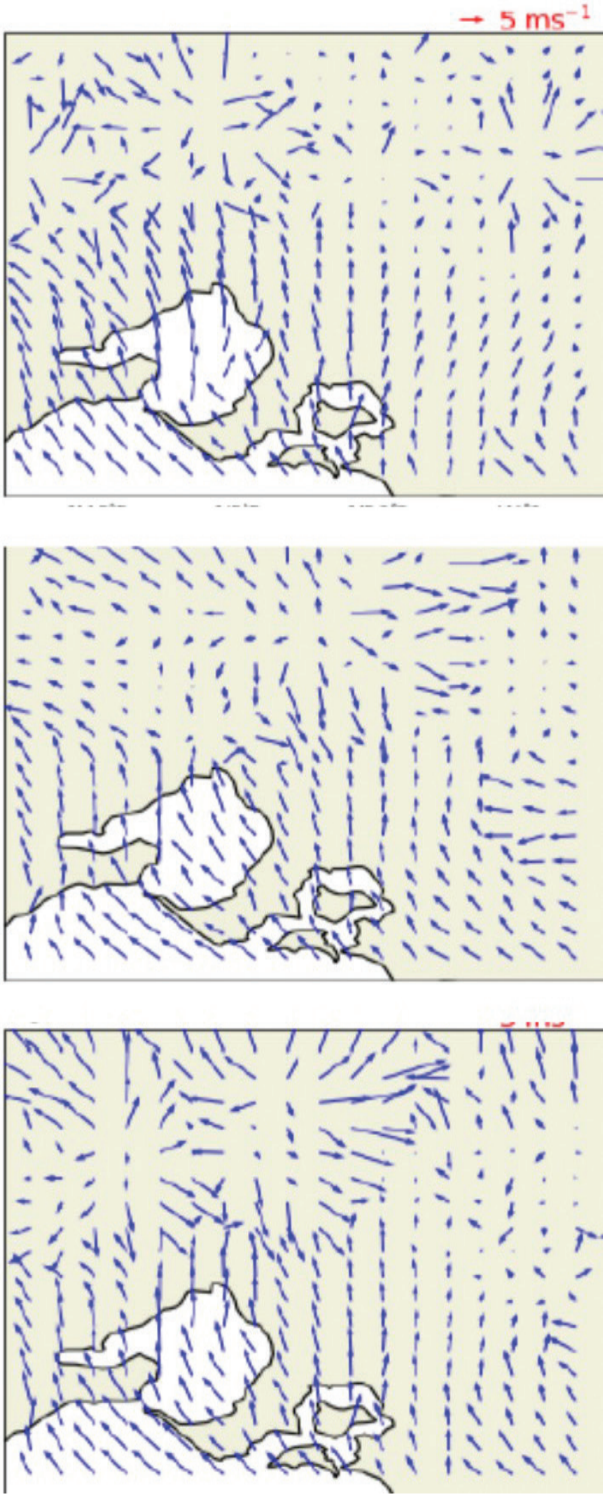


Figure 3.39 Spatial distribution of the wind speed and direction in the Greater Melbourne area at 06:00 hrs, (upper), 14:00 hrs, (middle) and 18:00 hrs (lower), during a representative summer day under the reference conditions as calculated by the WRF simulations.

3.7.3. MODIFIED CLIMATIC CONDITIONS — INSTALLATION OF COOL ROOFS

The implementation of the cool roofs at the city scale affects the local climate seriously. It decreases both the ambient and surface temperature mainly during the daytime, decreases the strength of the wind speed and the possible advection of heat from the desert and contributes highly to reducing the magnitude of urban overheating in the city.

Ambient Temperature

The installation of cool roofs at city scale reduces summer the peak ambient temperature at 14:00 hrs up to 1.6°C, Figure 3.40. The important temperature difference between the coastal and some northern parts of the city still exists, although the magnitude of the temperature difference is lower by about 0.8°C. The spatially average median temperature drop in Melbourne is 0.9 C and the maximum one is close to 1.2°C. For 59% of the days, there is an average ambient temperature drop between 0.6°C and 0.9°C, while 24% corresponds to the range between 0.9°C and 1.2°C.

The calculated decrease of the temperature is more significant for the coastal and inner and mid-northern parts of the city, as shown in Figure 3.41. A very significant drop in the summer cooling degree hours, ranging between 20% to 42% compared to the reference climatic conditions, is observed in Figure 3.42. The coastal part presents a reduction of the cooling degree hours close to 150, while in the northern part of the city, the decrease may be the double, 400 in Melbourne's airport.

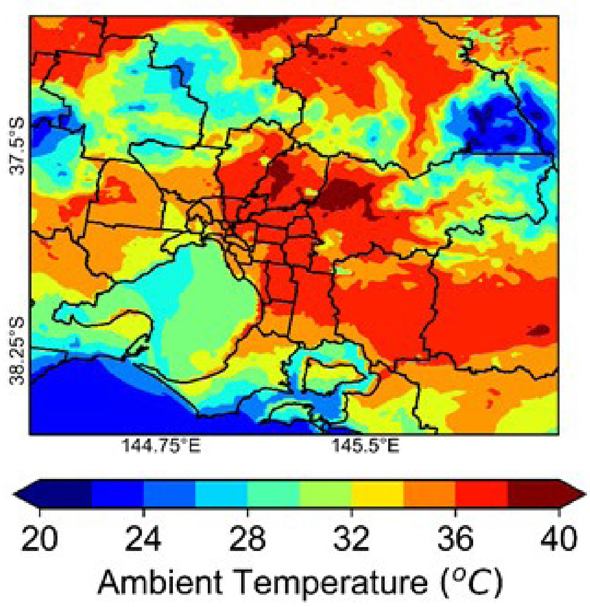


Figure 3.40 Spatial distribution of the ambient temperature in the Greater Melbourne area at 14:00 hrs during a representative summer day when cool roofs are implemented, as calculated by the WRF simulations.

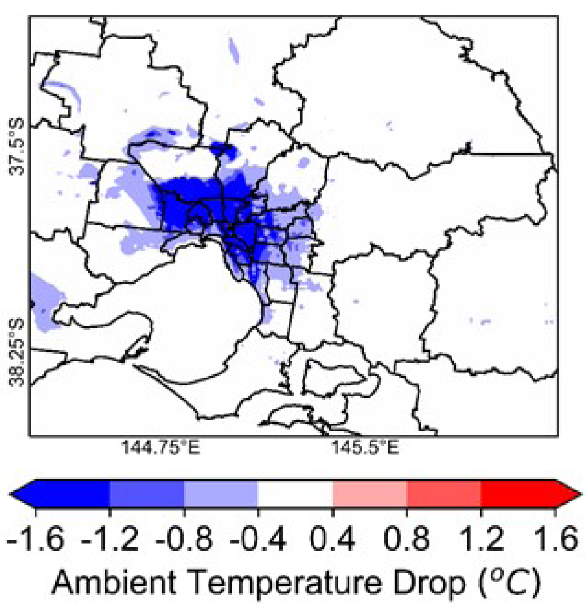


Figure 3.41 Spatial distribution of the ambient temperature drop in the Greater Melbourne area at 14:00 hrs, caused by the installation of the cool roofs, during a representative summer day, as calculated by the WRF simulations.

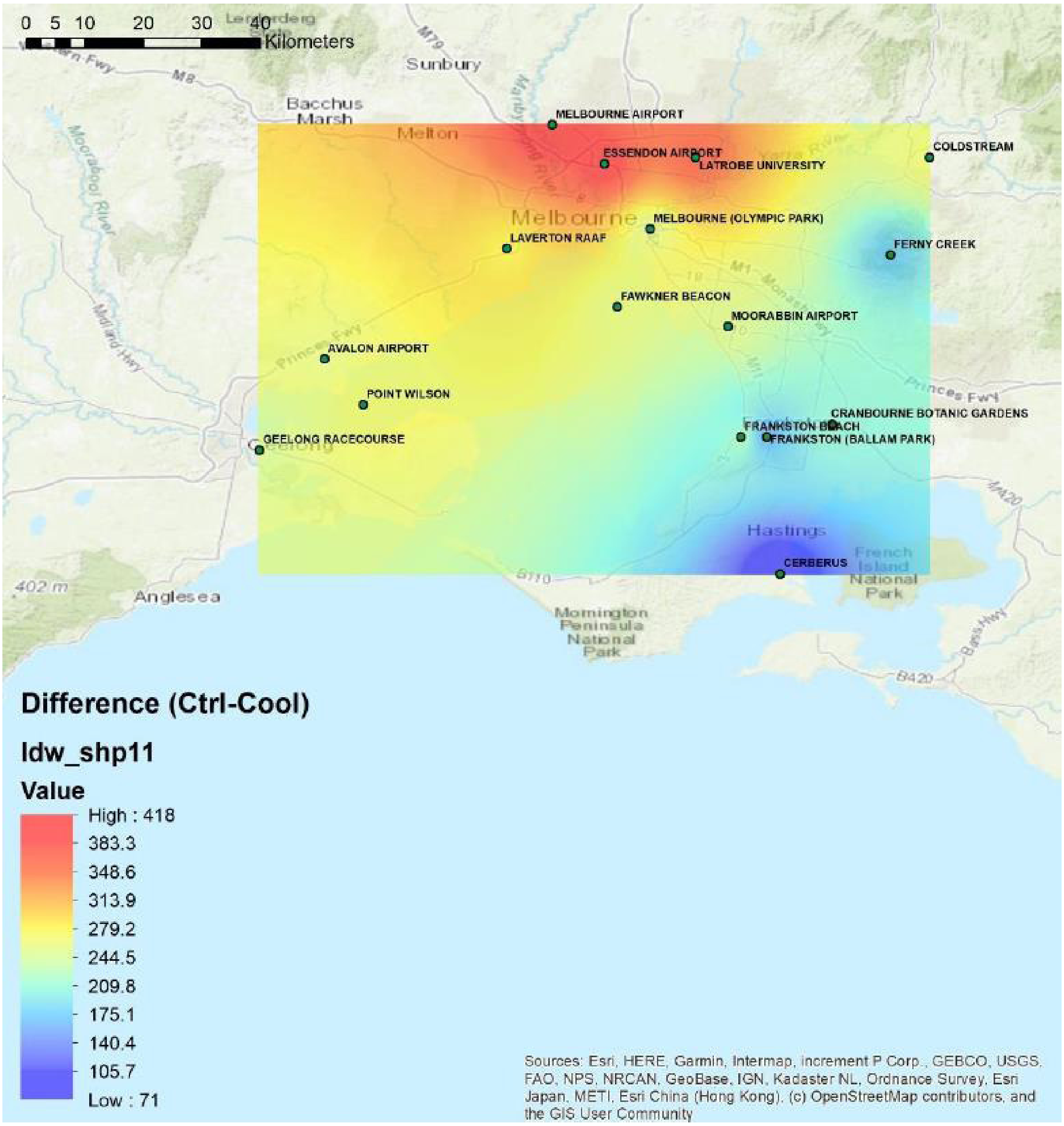


Figure 3.42 The sum of cooling degree hours in January and February at the 11 stations in the Greater Melbourne area, when cool roofs are installed at city scale.

Surface Temperature

While the surface temperature in the Greater Melbourne area continues to be high, cool roofs contribute to a very significant decrease at 14:00 hrs pm for the whole Melbourne area. The peak surface temperature drops at 14:00 hrs is close to 5.0°C (Figures 3.58 and 3.59). The median temperature drop in Melbourne is 3.8°C, and the maximum one is close to 5.5°C. For 58% of the days the average surface temperature drop is between 2°C and 4°C, and 30 between 4°C and 5°C.

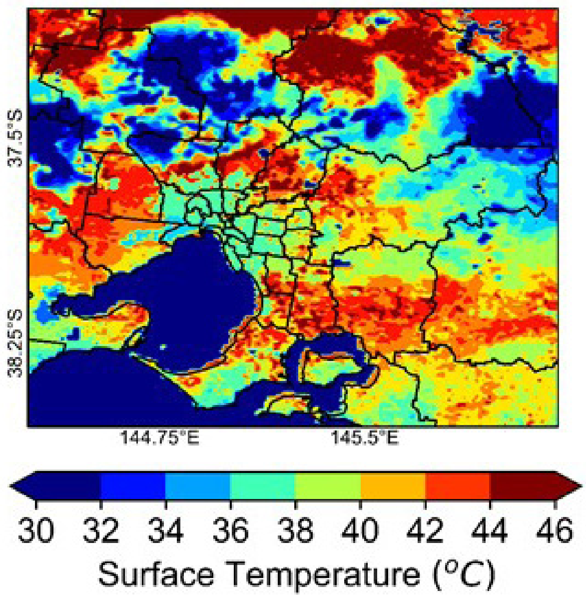


Figure 3.43 Spatial distribution of the surface temperature in the Greater Melbourne area at 14:00 hrs during a representative summer day when cool roofs are implemented at the city scale, as calculated by the WRF simulations.

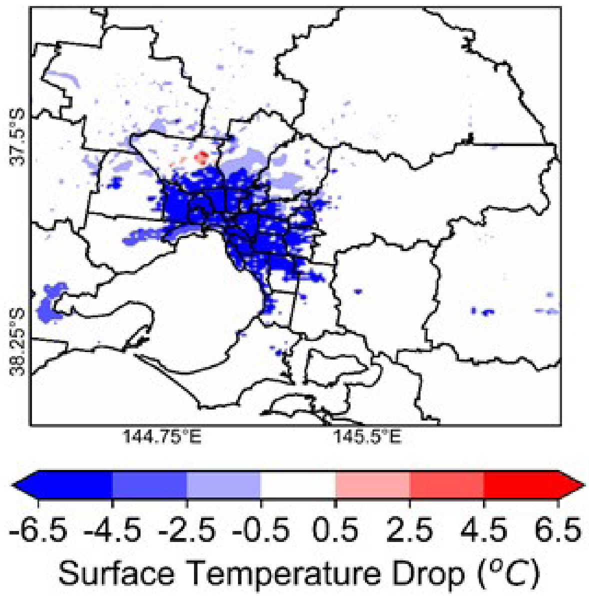


Figure 3.44 Spatial distribution of the surface temperature drop in the Greater Melbourne area at 14:00 hrs during a representative summer day when cool roofs are implemented at the city scale, as calculated by the WRF simulations.

The significant decrease in surface temperature results in an important reduction of the sensible heat released by the city that considerably affects the magnitude of urban overheating. The maximum decrease in the sensible heat flux is 292.8 W/m$^{-2,}$ and the average decrease is 175.1 W/m^{-2} at 14:00 hrs LT over CBD areas of Melbourne city and extends up to Maribyrnong, Moonee Valley, and Moreland. At 18:00 hrs LT, the maximum and average reduction of the summer month of sensible heat flux is 118.0 W/m^{-2} and 59.1 W/m^{-2} over the urban domain, Figure 3.45. The median sensible heat drop at 14:00 hrs in Melbourne is 175 W/m^{2}, and the maximum one is close to 250 W/m^{2}.

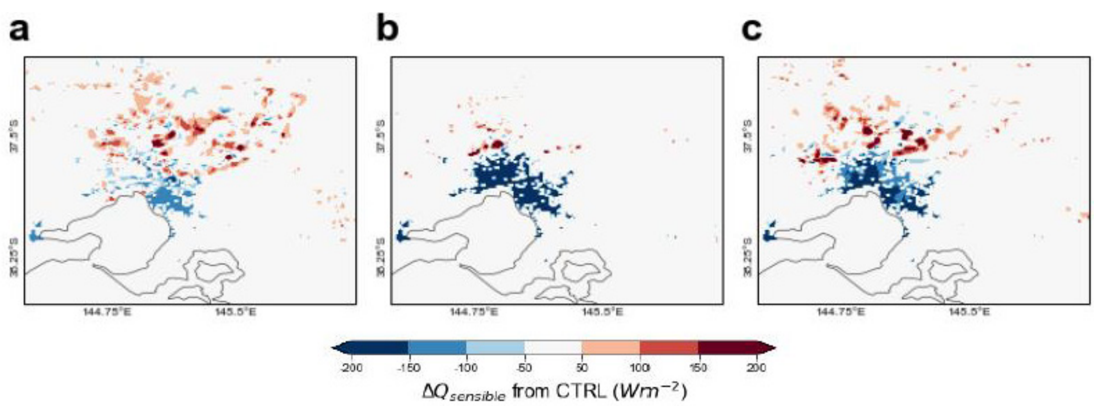


Figure 3.45 Reduction of sensible heat flux at (a) 06:00 LT, (b) 14:00 hrs LT, and (c) 18:00 hrs LT, in the Greater Melbourne area, during a representative summer day when cool roofs are implemented at city scale.

Wind Speed

The installation of cool roofs at city scale greatly affects air circulation in the city for the reasons explained previously. A significant decrease of the PBL caused by the implementation of cool roofs in the Greater Melbourne area is observed, appreciably affecting the magnitude of the wind speed, Figure 3.46. The maximum reduction is associated with peak hours (14:00 hrs LT) over Melbourne, Maribyrnong, Monney Valley, Monash, Knox, Whitehorse, Manningham, and Brimbank. On the other hand, the maximum reduction is reported for the outer west of Melbourne during sunrise and sunset.

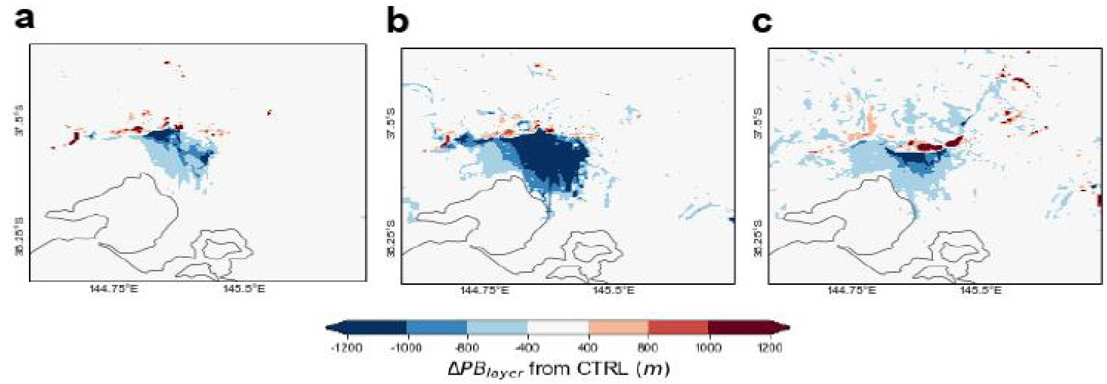


Figure 3.46 Reduction of PBL height at (a) 06:00 hrs LT, (b) 14:00 hrs LT, and (c) 18:00 hrs LT during a typical summer day when cool roofs are implemented at city scale.

The amplification of sea breeze circulation is more variable on a large-scale synoptic background, which modulates the prevailing wind at the near-surface in the city. In the vertical dimension, the height of the PBL in Melbourne is linked closely with the advection of the sea breeze from Port Philip and the local impact of cool materials. However, based on the numerical analysis of the vertical profiles of winds and the specific humidity of cool roofs, the advection of moist air from surrounding areas is unlikely to be the driving mechanism due to the extremely hot and dry conditions during heatwave events. The circulation can be modified when cool roofs are installed at city scale. The cool roof could alter the PBL height and potentially trigger localized circulation over the urban domain of Melbourne. The onset of the sea breeze was delayed to the afternoon (14:00 hrs LT) due to the “regional high” effect within the lower PBL and offshore synoptic wind flow above the PBL. The denser cool air over the urban domain flows towards the suburban area to replenish the buoyant warm air. The cool roof materials can suppress the vertical lifting of urban thermals, transport, and dispersion of low-level motions due to inversion in the hot summer and decelerate the sea breeze front. Therefore, the decrease in the extent of vertical wind speed by 1.5 m/s^{-1} to 3.5 m/s^{-1} induces stronger subsidence over the urban domain where reflective materials are installed.

The surface roughness parameters are not favourable to be useful for pulling the cool air of sea breezes down to the surface due to the mixing effects. Besides, the horizontal wind shear and frontal lifting owing to surface roughness parameters could set back the onset of the sea breeze front in the urban core. The potency of the sea breeze advection is subjected to the dimensions of the city, which generate the urban heating effect. Thus, a cool roof for cities has greatly modified the thermal and dynamic profile in the urban boundary layer and sea breeze circulation. This synoptic flow is opposite to the direction of the sea breeze, and the sea breeze front developed is more prone to the accumulation of secondary pollutants at the back of the front. The location of Port Philip and its geometrical horse-head-shaped enclosed bay on the central coast may change the wind pattern from the open fetch of the nearby ocean. The winds over the city of Melbourne are indicative of the synoptic pattern over the whole bay, but there is a modification of the wind component as one moves southward due to the sea breeze effects of Port Phillip Bay itself. There is also an east-west funnelling in the vicinity of Port Phillip, which increases the frequency of easterlies and westerly components (Figures 3.47 and 3.48).

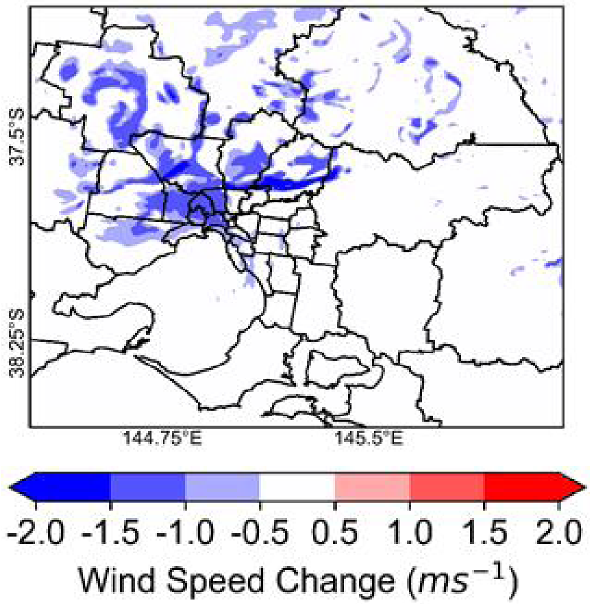


Figure 3.47 Reduction of the wind speed at 14:00 hrs because of the installation of the cool roofs at the city scale during a typical summer day.

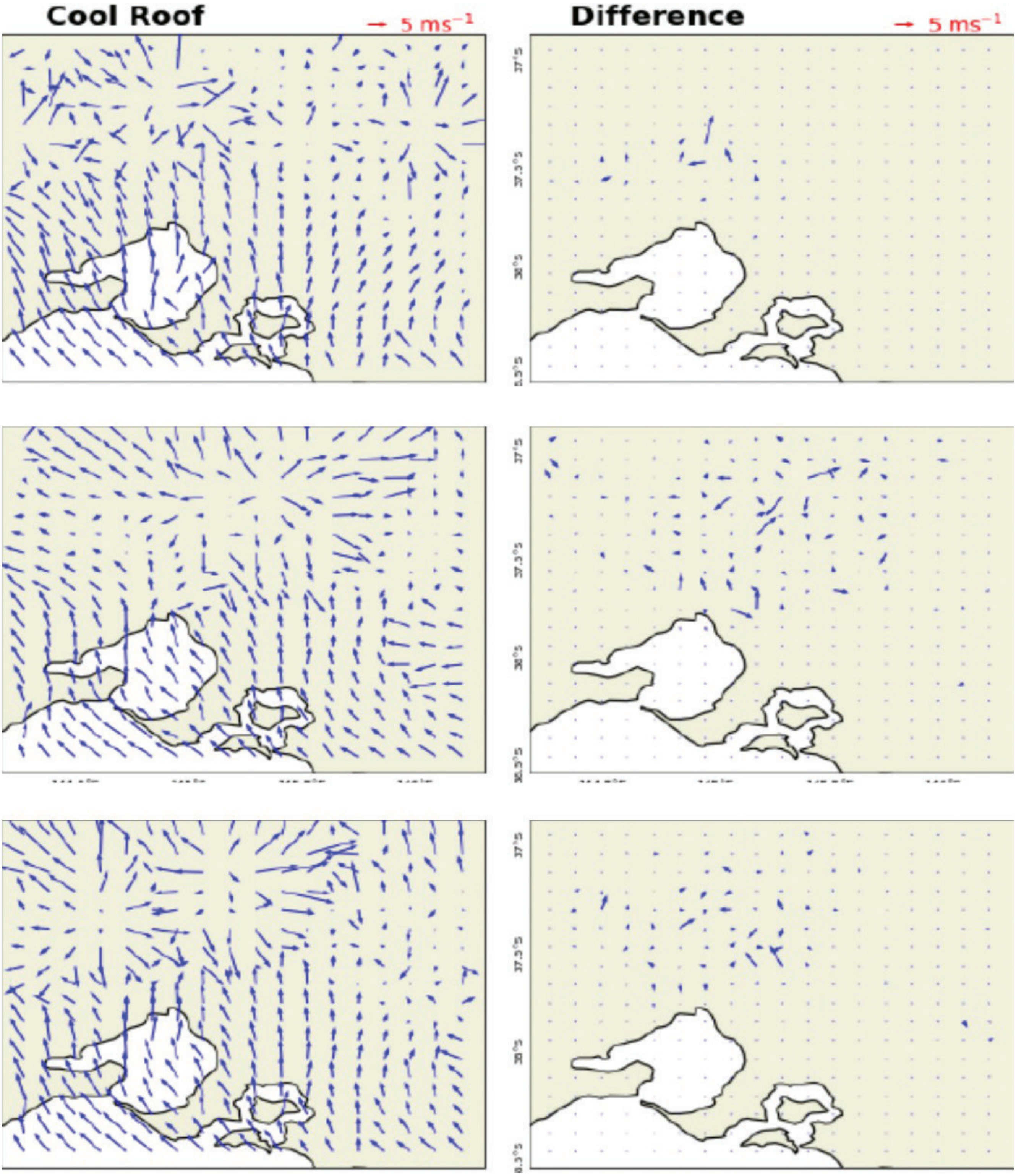


Figure 3.48 Spatial distribution of the wind speed and direction at the Greater Melbourne area at 06:00 hrs, (upper), 14:00 hrs, (middle) and 18:00 hrs (lower), during a representative summer day when cool roofs are implemented at the city scale and difference of the wind speed against the reference conditions, as calculated by the WRF simulations.

3.8. CLIMATIC IMPACT OF COOL ROOFS IN THE GREATER BRISBANE AREA

3.8.1. CONTEXT OF THE STUDY

A full simulation of the climatic conditions in the Greater Brisbane area has been performed to assess the spatial and temporal variation of the main climatic parameters that affect urban overheating and the levels of thermal comfort. Simulations are performed for two complete summer months, using the accurate mesoscale model, WRF, with a grid resolution of 500 m x 500 m as shown in Figure 3.49.

Two climatic scenarios are investigated:

Reference Scenario: aiming to simulate the spatial and temporal variability of the main climatic parameters under the reference conditions, (no use of cool roofs).

Cool Roofs Scenario: as the above reference scenario but considering that all roofs in the domain d03 of Figure 3.49 are reflective, (cool roofs).

The reflectance of the roofs was considered equal to 0.15 and 0.8 under the reference and cool roof scenarios, respectively. The emissivity of the roofs was equal to 0.85 for both scenarios.

The predictions of the reference scenario were validated against measured climatic data from four meteorological stations in (a) Archerfield, (b) Brisbane, (c) Brisbane Airport, and (d) Cape Moreton, and are found to be in excellent agreement (Figure 3.50).

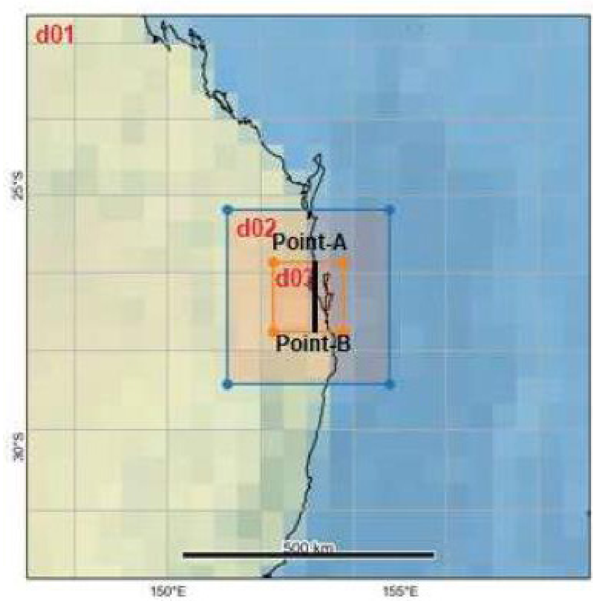


Figure 3.49 The WRF domain shows (a) dynamical downscaling with domain 1 (d01) as outermost parent domain with 4500 m grid spacing, domain 2 (d02) with 1500 m grid spacing and, an innermost domain 3 (d03) with 500 m grid spacing which encompasses the Greater Brisbane. Point-A (left) and Point-B (right) are the points used for drawing horizontal-vertical cross-sections to analyze meteorological conditions.

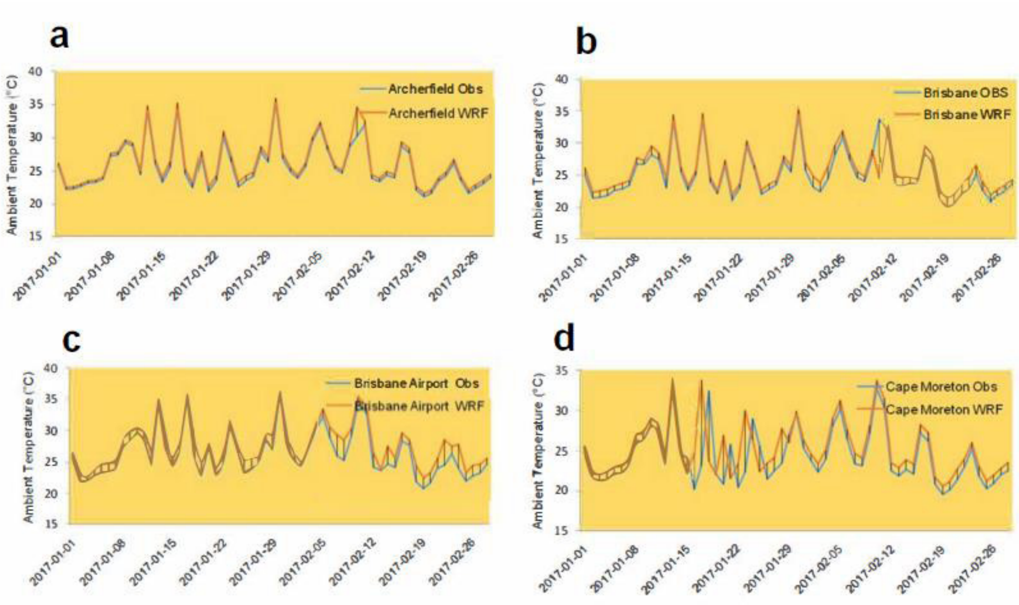


Figure 3.50 Comparison of the simulation results with observation data at 59 days for four local meteorological stations: (a) Archerfield, (b) Brisbane, (c) Brisbane Airport, and (d) Cape Moreton.

3.8.2. REFERENCE CLIMATIC CONDITIONS

Ambient Temperature

The magnitude of urban overheating in the Greater Brisbane area is very significant. During a representative summer day, the peak ambient temperature in Greater Brisbane, presents a very important spatial distribution. During the peak day period, 14:00 hrs, the eastern and coastal parts of the city benefit from the flow of the cool sea breeze bringing up to 10°C lower ambient temperatures compared with the western part of the city.

The spatial distribution of the cooling degree hours in the Greater Brisbane area during the summer period demonstrates the magnitude of overheating in the western part of the city. Cooling degree hours measure how much, and for how long, outside air temperature is higher than 26°C, and serve as a rough indication of the degree of regional climatic severity. While the total cooling degree hours during January and February in the eastern part of the city do not exceed 1050, the western Brisbane zone has almost 4 times the number of cooling degree hours - 4100 in Oakey Aereo and 3900 in Welcamp Airport (Figure 3.52).

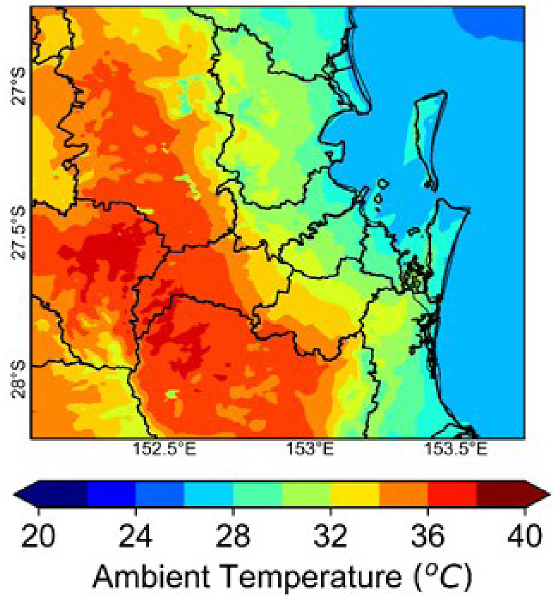


Figure 3.51 Spatial distribution of the ambient temperature in the Greater Brisbane area at 14:00 hrs during a representative summer day under the reference conditions as calculated by the WRF simulations.

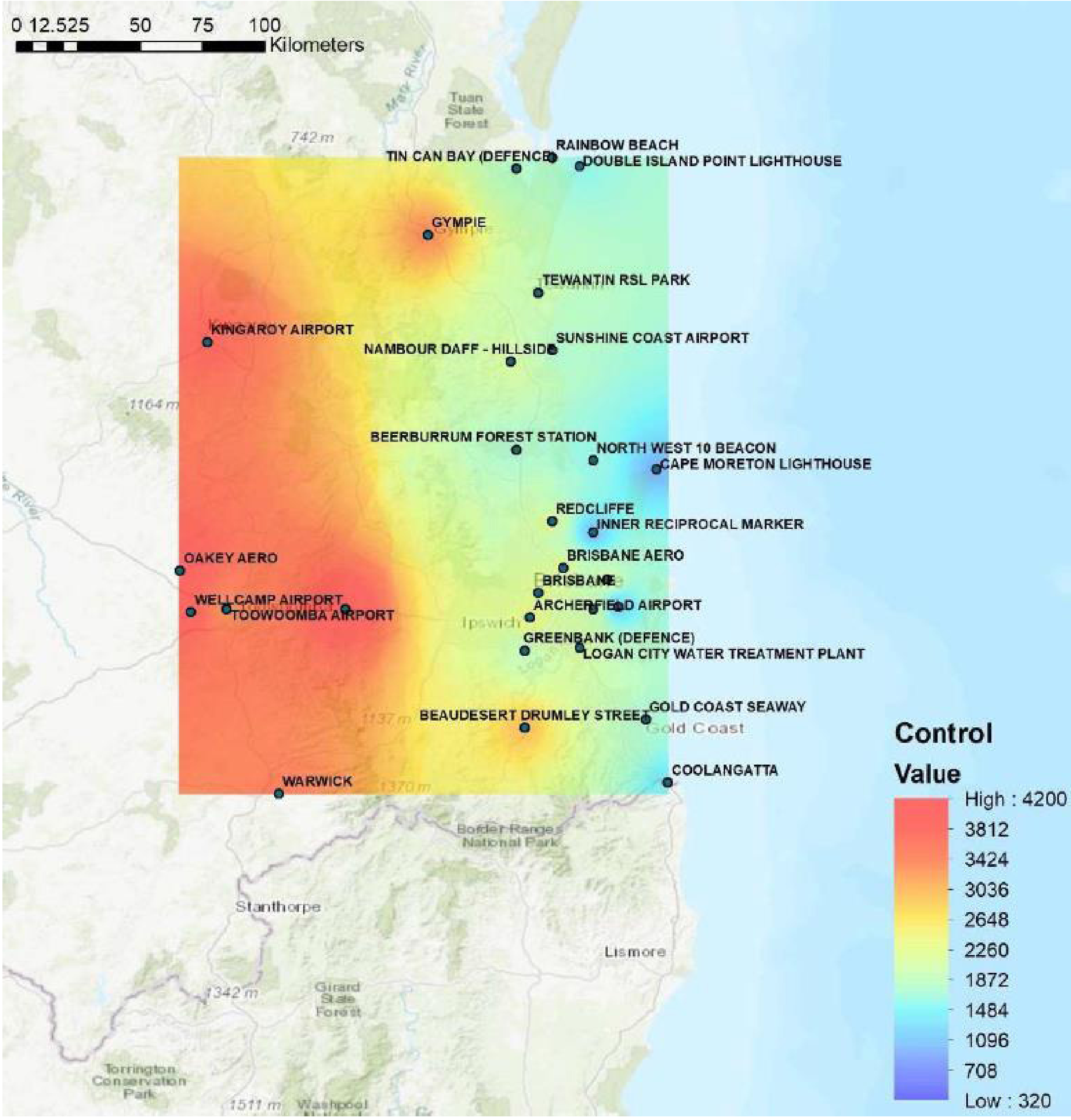


Figure 3.52 The sum of cooling degree hours in January and February at the 31 reference stations in the Greater Brisbane area.

Surface Temperature

The surface temperature distribution during the daytime is high in specific zones of the city, approaching 50°C, and like the ambient temperature, presents a significant spatial distribution (see Figure 3.53). Surface temperature at 14:00 hrs can be as high as 50°C as a function of the optical properties of the materials used. Highly absorbing dark roofs and pavements present the highest surface temperature, while light coloured reflective surfaces may present up to 20°C, lower surface temperatures. Green spaces present a quite low surface temperature, although this is considerably affected by the characteristics of the specific urban greenery zones.

High surface temperatures release much higher sensible heat to the atmosphere, increasing the ambient temperature and intensifying the magnitude of urban overheating. The maximum released sensible heat at 14:00 hrs pm is close to 475 W/m^2. High ambient and surface temperatures, especially in the western part of the city, correspond to very uncomfortable climatic conditions affecting the energy consumption of buildings, peak electricity demand, heat related mortality and morbidity and the survivability of the low-income population.

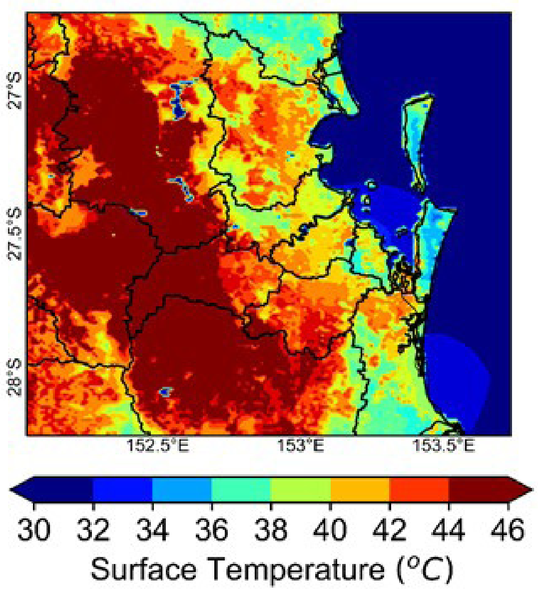


Figure 3.53 Spatial distribution of the surface temperature in the Greater Brisbane area at 14:00 hrs during a representative summer day under the reference conditions as calculated by the WRF simulations.

Wind Speed

Wind speed in the Greater Brisbane area is determined by the characteristics of the sea breeze in the coastal area. During the daytime and mainly in the afternoon hours, the sea breeze strongly affects and cools down the eastern suburbs while it is weaker in the western parts of the city. The average wind speeds (W_{speed}) are 3.9 m/s, 6. 7 m/s and 6.2 m/s during 06:00 hrs LT, 14:00 hrs LT and 18:00 hrs LT, respectively, over the city. Figure 3.54 shows the magnitude and the direction of the wind during a representative summer day at 06:00 hrs, 14:00 hrs and 18:00 hrs LT.

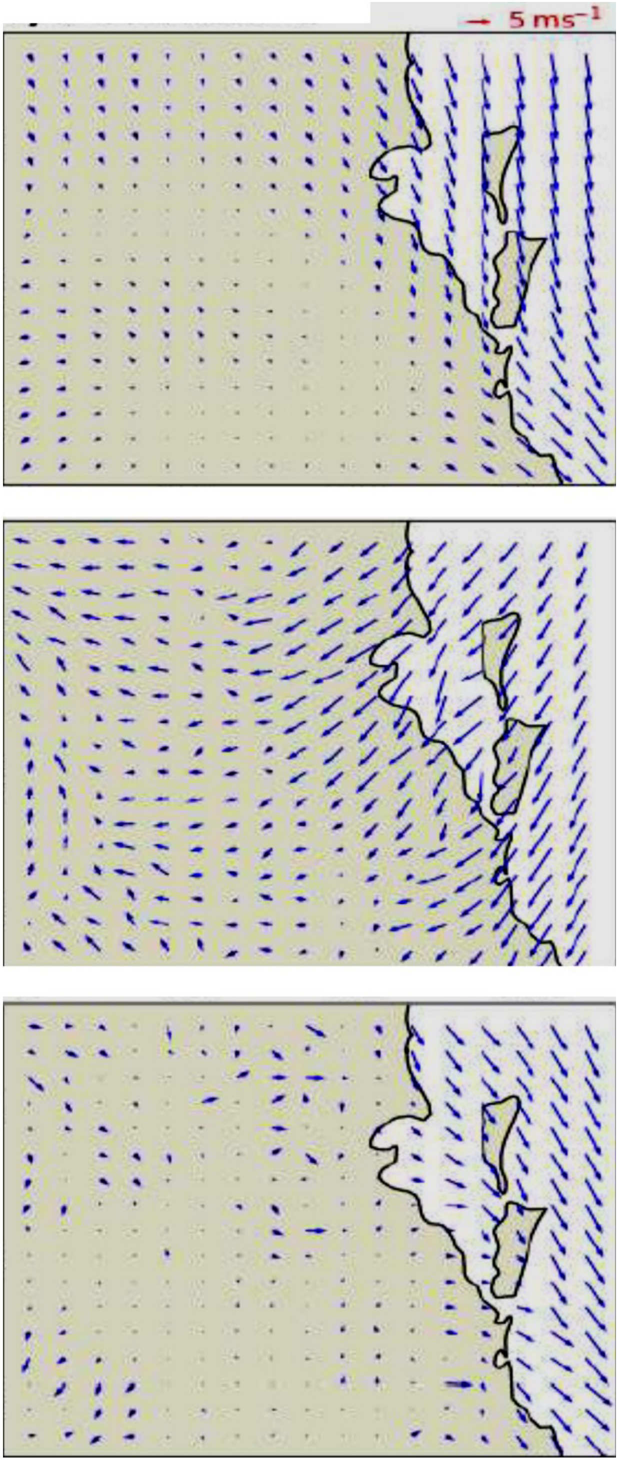


Figure 3.54 Spatial distribution of wind speed and direction in the Greater Brisbane at 06:00 hrs, (upper), 14:00 hrs, (middle) and 18:00 hrs (lower), during a representative summer day under the reference conditions as calculated by the WRF simulations.

3.8.3. MODIFIED CLIMATIC CONDITIONS – INSTALLATION OF COOL ROOFS

The installation of the cool roofs at the city scale greatly affects the local climate. It decreases both the ambient and surface temperature mainly during the daytime and contributes greatly to reduce the magnitude of urban overheating in the city.

3.8.3.1 Ambient Temperature

The installation of cool roofs at the city scale reduces the summer peak ambient temperature at 14:00 hrs, on average by up to 1.7°C, Figure 3.55. The important temperature difference between the eastern and the western parts of the city still exists, although the magnitude of the temperature difference is lower. The maximum drop in ambient temperature caused by cool roofs is calculated for Brisbane with the median spatially averaged temperature decrease being close to 1.7°C while its maximum is around 2.3°C and its minimum at 0.9°C. About 37% of the days present an average drop between 1.8°C and 2.1°C, 32% between 1.5°C and 1.8°C, and 12% between 0.9°C and 1.2°C.

The calculated decrease of the temperature is more significant for the inner and mid-western part of the city as shown in Figure 3.56. A very significant drop of the summer cooling degree hours, ranging between 20 to 60% compared to the reference climatic conditions, is observed (Figure 3.57).

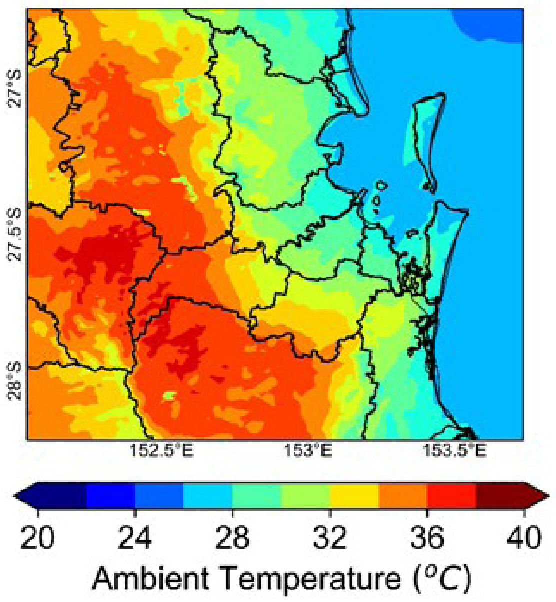


Figure 3.55 Spatial distribution of the ambient temperature in the Greater Brisbane area at 14:00 hrs during a representative summer day when cool roofs are installed, as calculated by the WRF simulations.

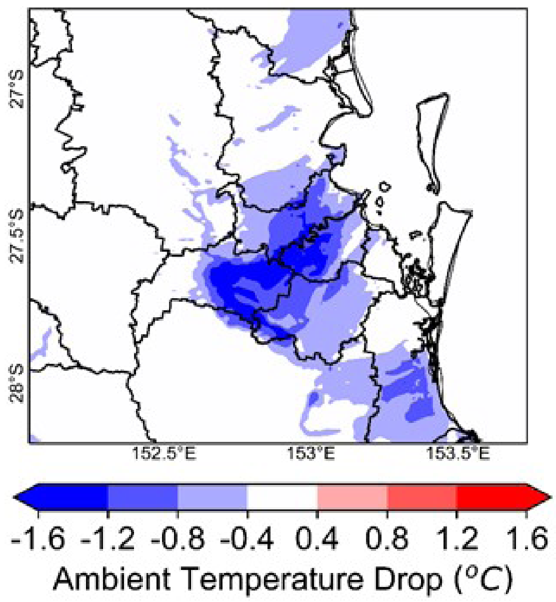


Figure 3.56 Spatial distribution of the ambient temperature drop in the Greater Brisbane area at 14:00 hrs, caused by the installation of cool roofs, during a representative summer day, as calculated by the WRF simulations.

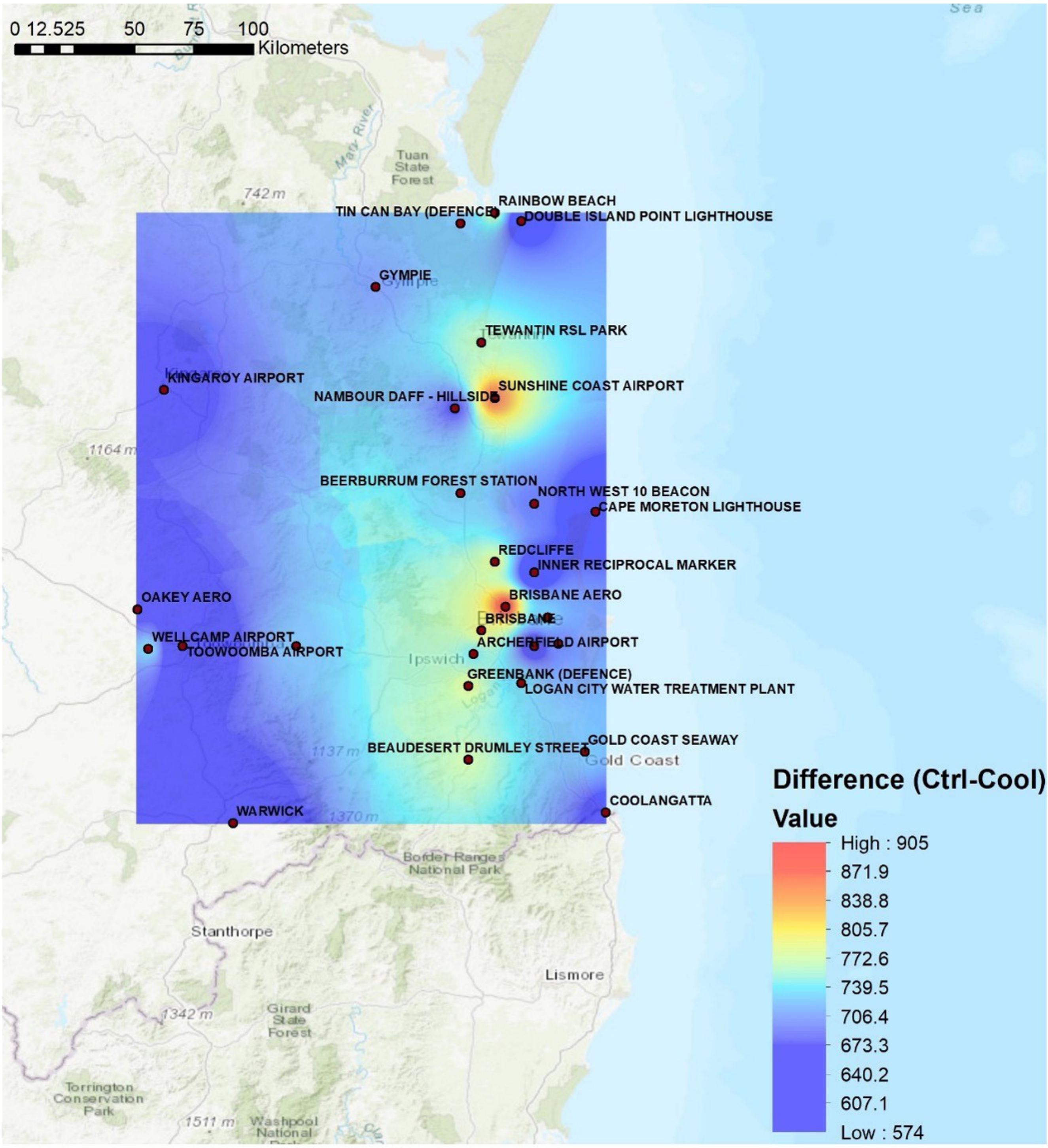


Figure 3.57 The sum of cooling degree hours in Jan and Feb in the 31 stations in the Greater Brisbane area, when cool roofs are implemented at the city scale.

Surface Temperature

While the surface temperature in the Greater Brisbane area continues to be high, cool roofs contribute to a very significant decrease of the surface temperature at 14:00 hrs for the whole Greater area. The peak surface temperature drops at 14:00 hrs is close to 5.0°C (Figures 3.58 and 3.59). The median spatially average temperature drop in Brisbane at 14 pm is 3°C, respectively, and the maximum one is close to 5°C, respectively. For 80% of the days, the average surface temperature drop is between 2°C and 4°C.

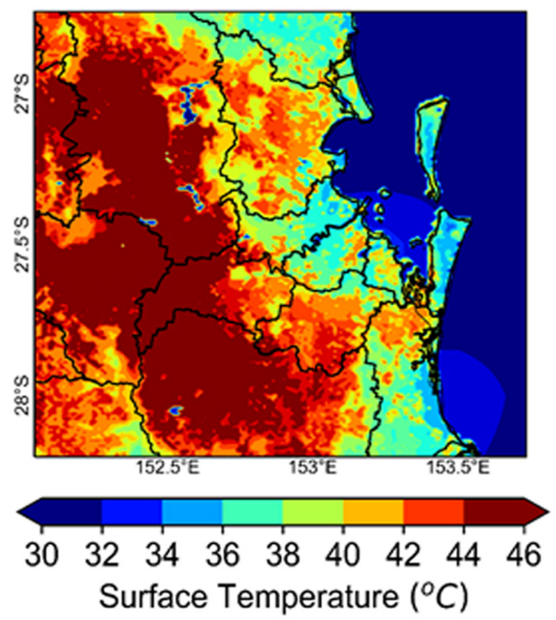


Figure 3.58 Spatial distribution of the surface temperature in the Greater Brisbane area at 14:00 hrs during a representative summer day when cool roofs are implemented at the city scale, as calculated by the WRF simulations.

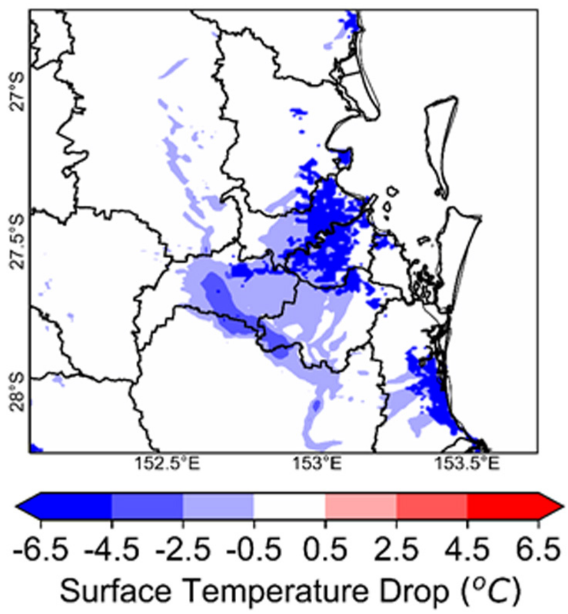


Figure 3.59 Spatial distribution of the surface temperature drop in the Greater Brisbane area at 14:00 hrs during a representative summer day when cool roofs are installed at city scale, as calculated by the WRF simulations.

The significant decrease of surface temperature results in an important reduction of the sensible heat released by the city that greatly affects the magnitude of the urban overheating. The maximum decrease in the sensible heat flux is 175.0 W/m^2 over the urban domain (Hamilton, Doboy, Morningside and the Central), and the average decrease is 160.0 W/m^2 at 14:00 hrs LT over the central part of the city. In the high density residential urban area, the maximum and average reduction of sensible heat flux are about 184.6 W/m^2 and 169.2 W/m^2 respectively at 14:00 hrs LT in the summer month compared to the control case. At 18:00 hrs, the maximum and average reduction of the summer month of sensible heat flux is 69.9 Wm-2 and 63.8 W/m-^{2}, respectively, over the urban domain (Figure 3.60). The maximum drop of released sensible heat at 14:00 hrs in Brisbane brought about by the cool roofs is close to 240 W/m^2 while its maximum is around 280 W/m^2 and its minimum is 130 W/m^2. For 83% of the days, the average drop of the sensible heat is between 180 W/m^2 and 280 W/m^2.

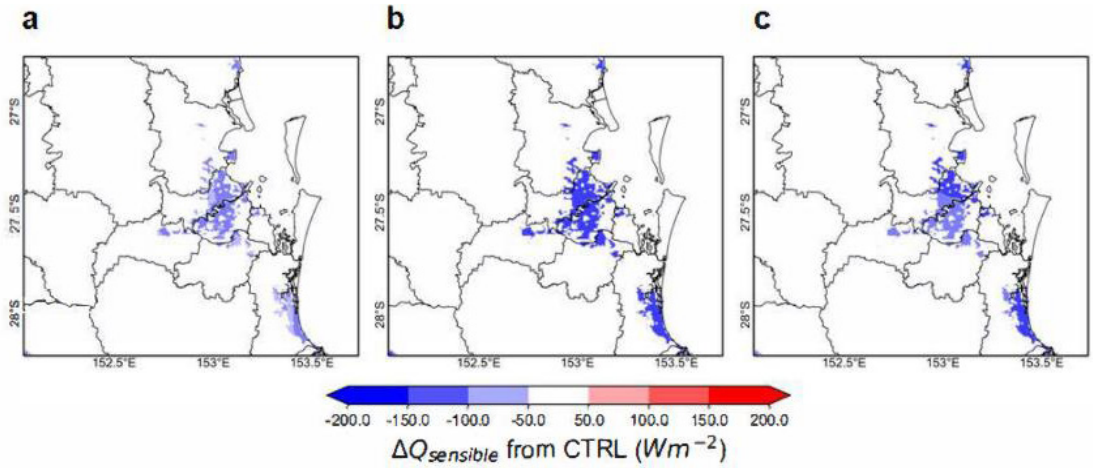


Figure 3.60 Reduction of sensible heat flux at (a) 06:00 hrs LT (b) 14:00 hrs LT, and (c) 18:00 hrs LT, in the Greater Brisbane area, during a representative summer day when cool roofs are implemented at city scale.

Wind Speed

The installation of the cool roofs at city scale greatly affects air circulation in the city for the reasons explained previously. A significant decrease of the PBL caused by the installation of cool roofs at the Greater Brisbane area is observed, significantly affecting the magnitude of the wind speed (Figure 3.61). The maximum reduction occurs at peak hour (14:00 hrs LT) over the central part of Brisbane city.

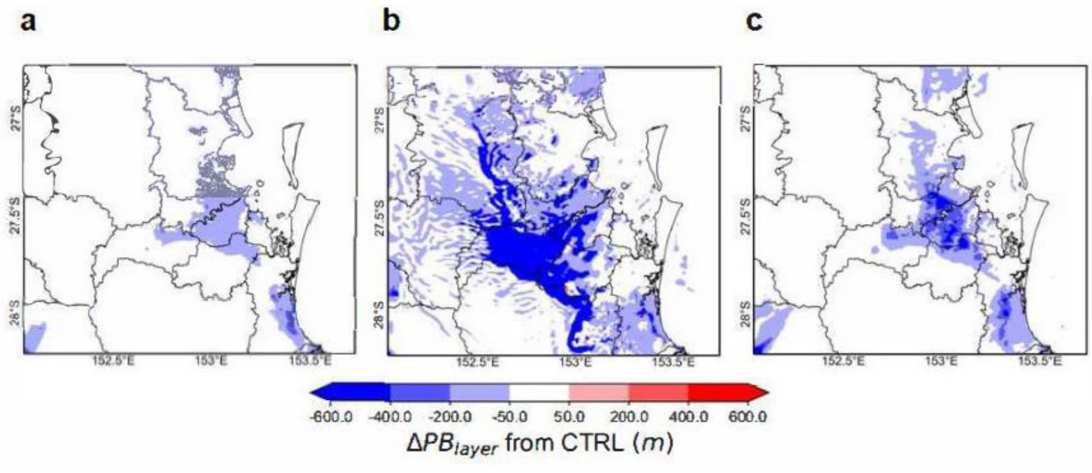


Figure 3.61 Reduction of PBL height at (a) 06:00 hrs LT, (b) 14:00 hrs LT, and (c) 18:00 hrs LT during a typical summer day when cool roofs are implemented at city scale.

The impact of cool materials on the open-air surface and ambient temperature, which is associated with urban heating and thermal flow conditions, has been widely reported. Under low wind speed, an additional thermal gradient was observed over Brisbane city. The term, thermal wind, describes the vertical change in the geostrophic wind in a baroclinic atmosphere at a synoptic scale. However, under the low inflow circumstance, wind velocity was simply prejudiced by the geometry of buildings, thermal differences, and buoyancy flow. After heating the rooftop and pavements, wind velocity increased while turbulent concentration decreased due to a small scale thermal gradient. This strength could make pollutant transportation more rapid to withdraw pollutants from mixing. This situation also occurs over several parts of Brisbane city (e.g. Marchant, Central, The Gabba, Paddington, Walter Taylor, Coorparoo, Holland Park, Tennyson, Jamboree, and Moorooka) when the wind speed is low and the ambient and surface temperature is very high. Under these conditions, there is a substantial temperature difference between the cool roofs and the warm pavements that generate small scale local thermal winds at the neighbourhood scale. Thus, when wind velocity is low, the effect of the roof and surface material is clearly shown in the thermal wind environment in the vicinity of the roof surface to warm pavements with an increase of wind velocity and a decrease in turbulent energy, as illustrated in Figure 3.62 and Figure 3.63.

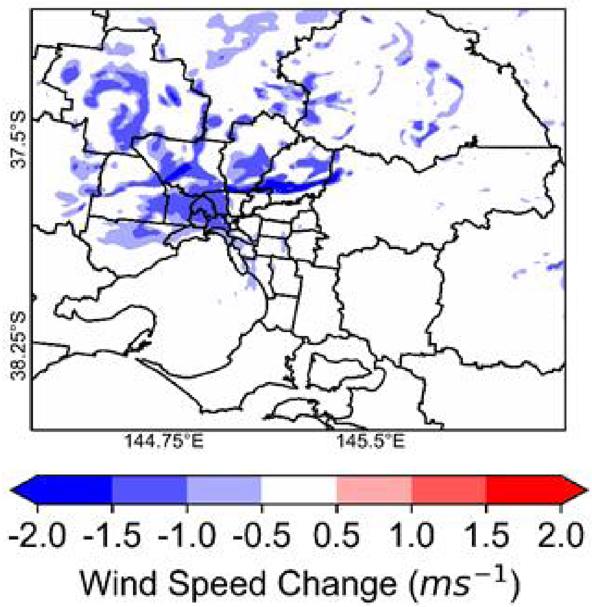


Figure 3.62 Reduction of the wind speed at 14:00 hrs pm because of the installation of cool roofs at city scale during a typical summer day.

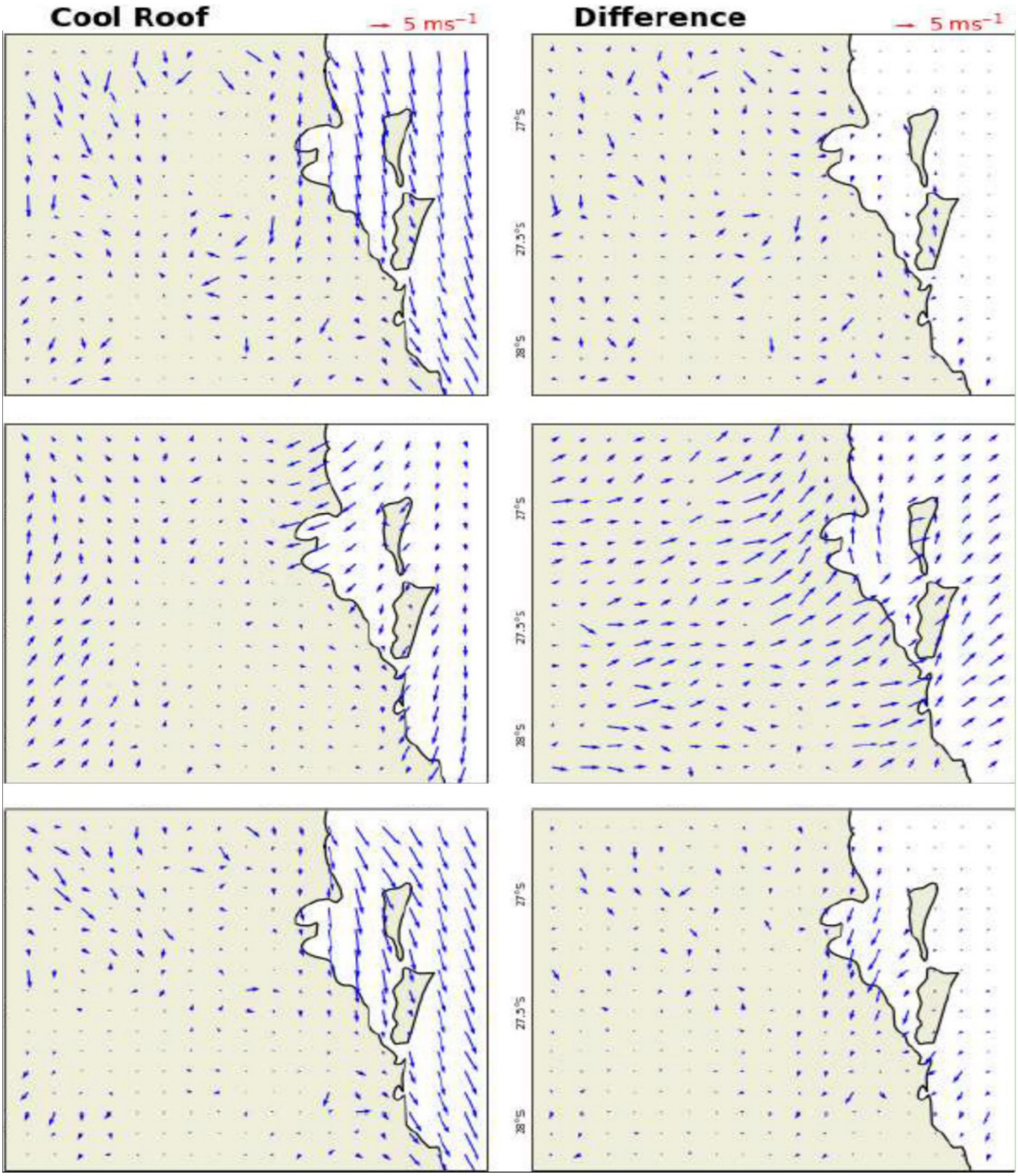


Figure 3.63 Spatial distribution of wind speed and direction in the Greater Brisbane area at 06:00 hrs, (upper), 14:00 hrs, (middle) and 18:00 hrs (lower), during a representative summer day when cool roofs are implemented at city scale and there is a difference in wind speed compared with the reference conditions, as calculated by the WRF simulations.

3.9. CLIMATIC IMPACT OF COOL ROOFS IN THE GREATER ADELAIDE AREA

3.9.1. CONTEXT OF THE STUDY

A full simulation of the climatic conditions in the Greater Adelaide area has been performed to assess the spatial and temporal variation of the main climatic parameters that affect urban overheating and the levels of thermal comfort. Simulations are performed for two complete summer months, using the accurate mesoscale model, WRF, with a grid resolution of 500 m x 500 m as shown in Figure 3.64.

Two climatic scenarios are investigated:

Reference Scenario: aiming to simulate the spatial and temporal variability of the main climatic parameters under the reference conditions, that is, no use of cool roofs.

Cool Roofs Scenario: as the above reference scenario but assuming that all roofs in domain d03 of Figure 3.64 are reflective, cool roofs.

The reflectance of the roofs was considered equal to 0.15 and 0.8 under the reference and cool roof scenarios, respectively. The emissivity of the roofs was equal to 0.85 for both scenarios.

The predictions of the reference scenario were validated against measured climatic data from four meteorological stations in (a) Adelaide Airport, (b) Parafields Airport, (c) Nourlunga, and (d) Roswarthy, and are found to be in excellent agreement (see Figure 3.65).

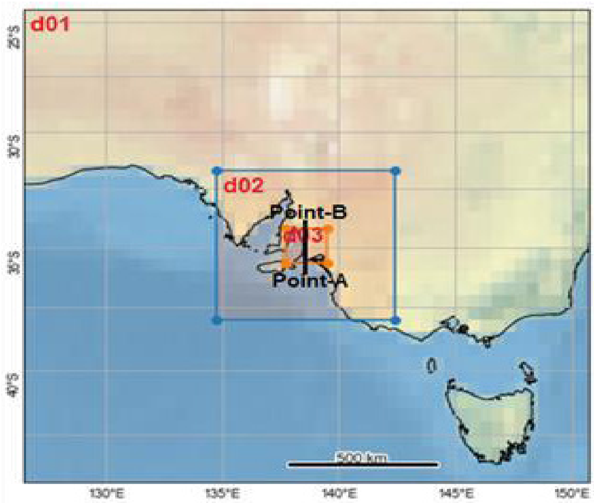


Figure 3.64 The WRF domain shows (a) dynamical downscaling with domain 1 (d01) as the outermost parent domain with 4500 m grid spacing, domain 2 (d02) with 1500 m grid spacing and, an innermost domain 3 (d03) with 500 m grid spacing; (b) innermost d03 with 500 m grid spacing which encompasses the Greater Adelaide. Point-A (left) and Point-B (right) are the points used for drawing horizontal-vertical cross-sections to analyze meteorological conditions.

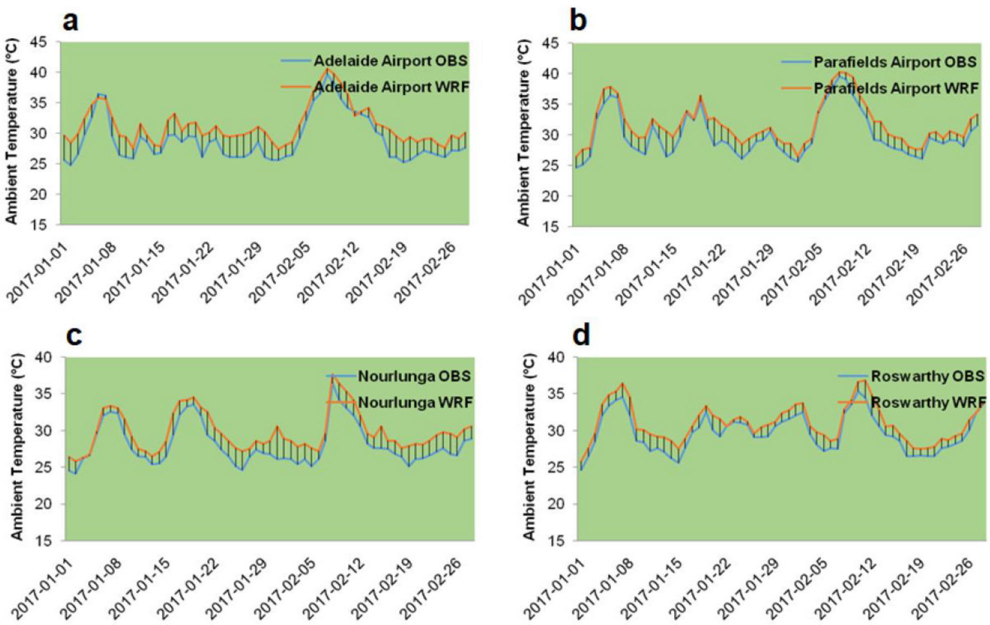


Figure 3.65 Comparison of the simulation results with observation data at average for 59 days for four local meteorological stations: a) Adelaide Airport, (b) Parafields Airport, (c) Nourlunga, and (d) Roswarthy.

3.9.2. REFERENCE CLIMATIC CONDITIONS

Ambient Temperature

The magnitude of urban overheating in the Greater Adelaide area is not as significant as in Sydney, Brisbane and Melbourne. During a representative summer day, the peak ambient temperature in the city of Adelaide illustrates a non-significant spatial distribution. The maximum temperature difference between the different urban zones does not exceed 3°C. Much lower ambient temperatures are observed in the northern part of the city mainly because of its altitude (Figure 3.66).

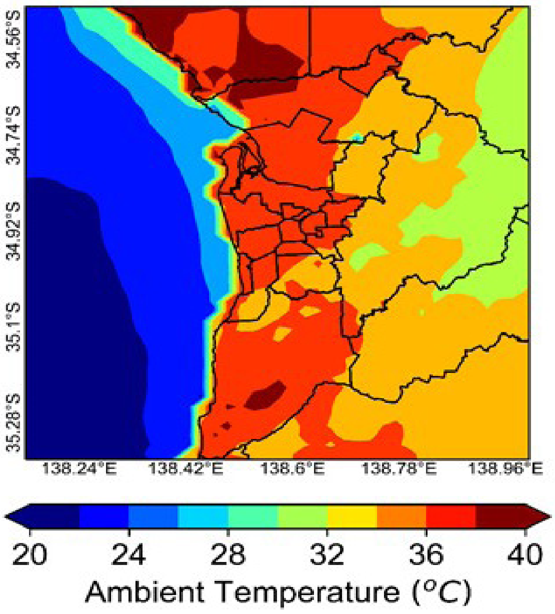


Figure 3.66 Spatial distribution of the ambient temperature in the Greater Adelaide area at 14:00 hrs during a representative summer day under the reference conditions as calculated by the WRF simulations.

The spatial distribution of the cooling degree hours in the Adelaide area during the summer period is not very significant. Cooling degree hours measure how much, and for how long, outside air temperature is higher than 26°C, and serve as a rough indication of the regional climatic severity. The total cooling degree hours during January and February in the main city vary between 500 and 1000, but in certain suburban and rural areas out of the main city, cooling degree hours may be as high as 3500, mainly because of the influence of warm winds from the dry interior (Figure 3.67).

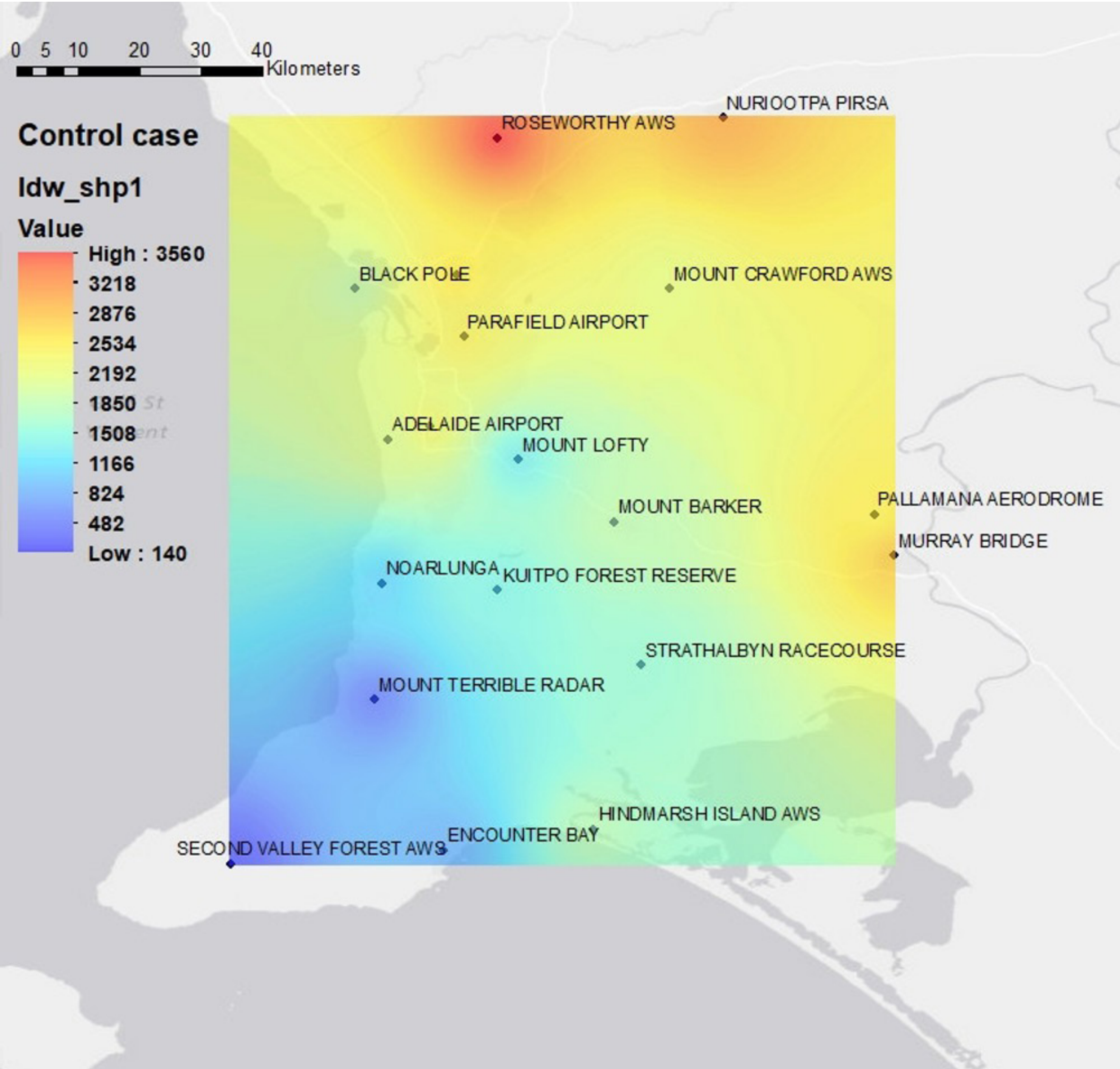


Figure 3.67 The sum of cooling degree hours in January and February of the reference cases in the 19 stations in the Greater Adelaide area.

Surface Temperature

The surface temperature distribution during the daytime is high in specific zones of the city, approaching 46°C, and presents a quite significant spatial distribution, as in Figure 3.68. Surface temperature at 14:00 hrs can be as high as 46°C as a function of the optical properties of the materials used. Highly absorbing dark roofs and pavements present the highest surface temperature, while light coloured reflective surfaces may present up to 15°C lower surface temperature. Green spaces present a quite low surface temperature, although this is strongly affected by the characteristics of the specific urban greenery zones.

High surface temperatures release much more sensible heat to the atmosphere, increasing the ambient temperature and intensifying the magnitude of urban overheating. The maximum released sensible heat at 14:00 hrs is 472.3 W/m^2 and 336.1 W/m^2 at 18:00 hrs LT, the average sensible heat flux is 99.8 W/m^2.

High ambient and surface temperatures, especially, correspond to very uncomfortable climatic conditions affecting the energy consumption of buildings, peak electricity demand, heat related mortality and morbidity and the survivability of the low-income population.

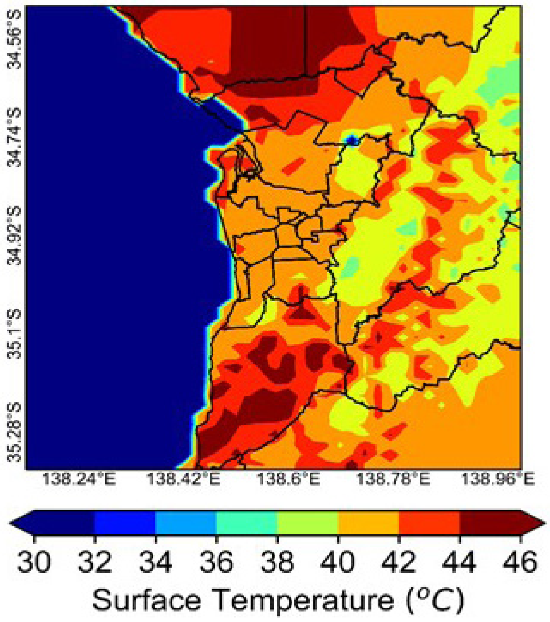


Figure 3.68 Spatial distribution of the surface temperature in the Greater Adelaide area at 14:00 hrs during a representative summer day under the reference conditions as calculated by the WRF simulations.

Wind Speed

Wind speed during summer in the Greater Adelaide area is determined primarily by the local landscape. The average wind speed (W_{speed}) during the simulation period is 2.7 m/s, 6.4 m/s and 5.2 m/s during 06:00 hrs LT, 14:00 hrs LT and 18:00 hrs LT, respectively, over the city. Figure 3.69 shows the magnitude and the direction of the wind during a representative summer day at 06:00 hrs, 14:00 hrs and 18:00 hrs LT.

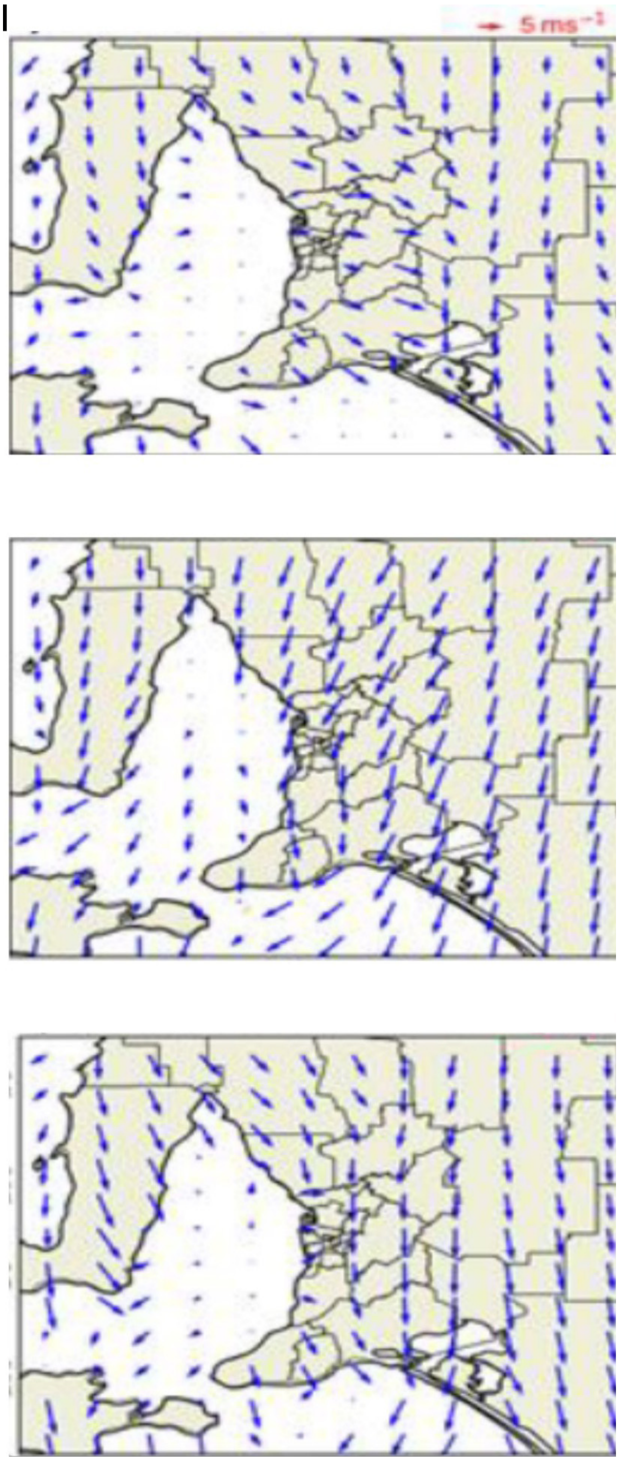


Figure 3.69 Spatial distribution of the wind speed and direction in the Greater Adelaide at 06:00hrs, (upper), 14:00 hrs, (middle) and 18:00 hrs (lower), during a representative summer day under the reference conditions as calculated by the WRF simulations.

3.9.3. MODIFIED CLIMATIC CONDITIONS — INSTALLATION OF COOL ROOFS

The installation of cool roofs at city scale affects the local climate significantly. It decreases both the ambient and surface temperature mainly during the daytime and contributes strongly to reducing the magnitude of urban overheating in the city.

Ambient Temperature

The implementation of cool roofs at city scale reduces summer the peak ambient temperature at 14:00 hrs pm up to 1.5°C, Figure 3.70. The important temperature difference between the various regions of the city still exists, although the magnitude of the temperature difference is lower. The median temperature drop in Adelaide is 1.1°C, and the maximum one is close to 1.6°C. Almost 41 % corresponds to temperature drops between 0.8°C and 1.0°C and 36 % between 1.2 and 1.4°C.

The calculated decrease of the temperature is more significant in the main part of the city, as shown in Figure 3.71. The daily average reduction of the ambient temperature at 14:00 hrs pm for the Greater Adelaide area during the summer period is close to 1.1°C. A very significant drop of the summer cooling degree hours, ranging between 18% to 44% compared to the reference climatic conditions is observed, as in Figure 3.72. The highest percentage reduction is observed in the Second Valley area.

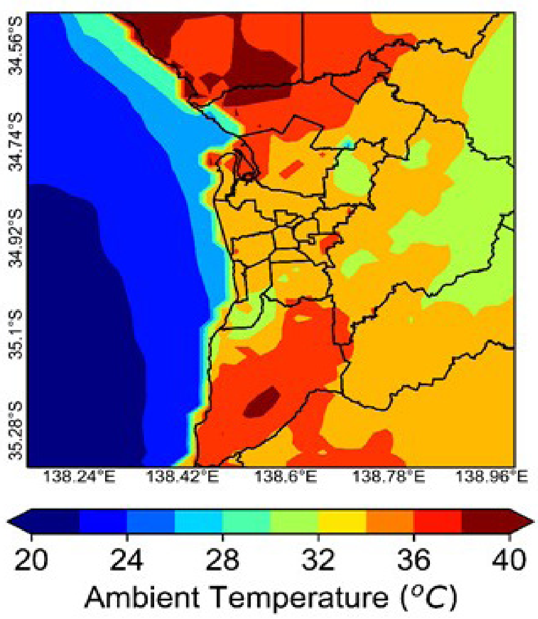


Figure 3.70 Spatial distribution of the ambient temperature in the Greater Adelaide area at 14:00 hrs during a representative summer day when cool roofs are installed, as calculated by the WRF simulations.

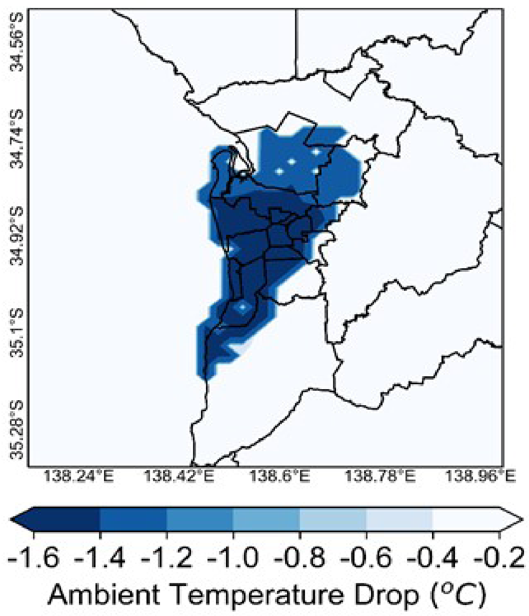


Figure 3.71 Spatial distribution of the ambient temperature drop in the Greater Adelaide area at 14:00 hrs, caused by the installation of the cool roofs, during a representative summer day, as calculated by the WRF simulations.

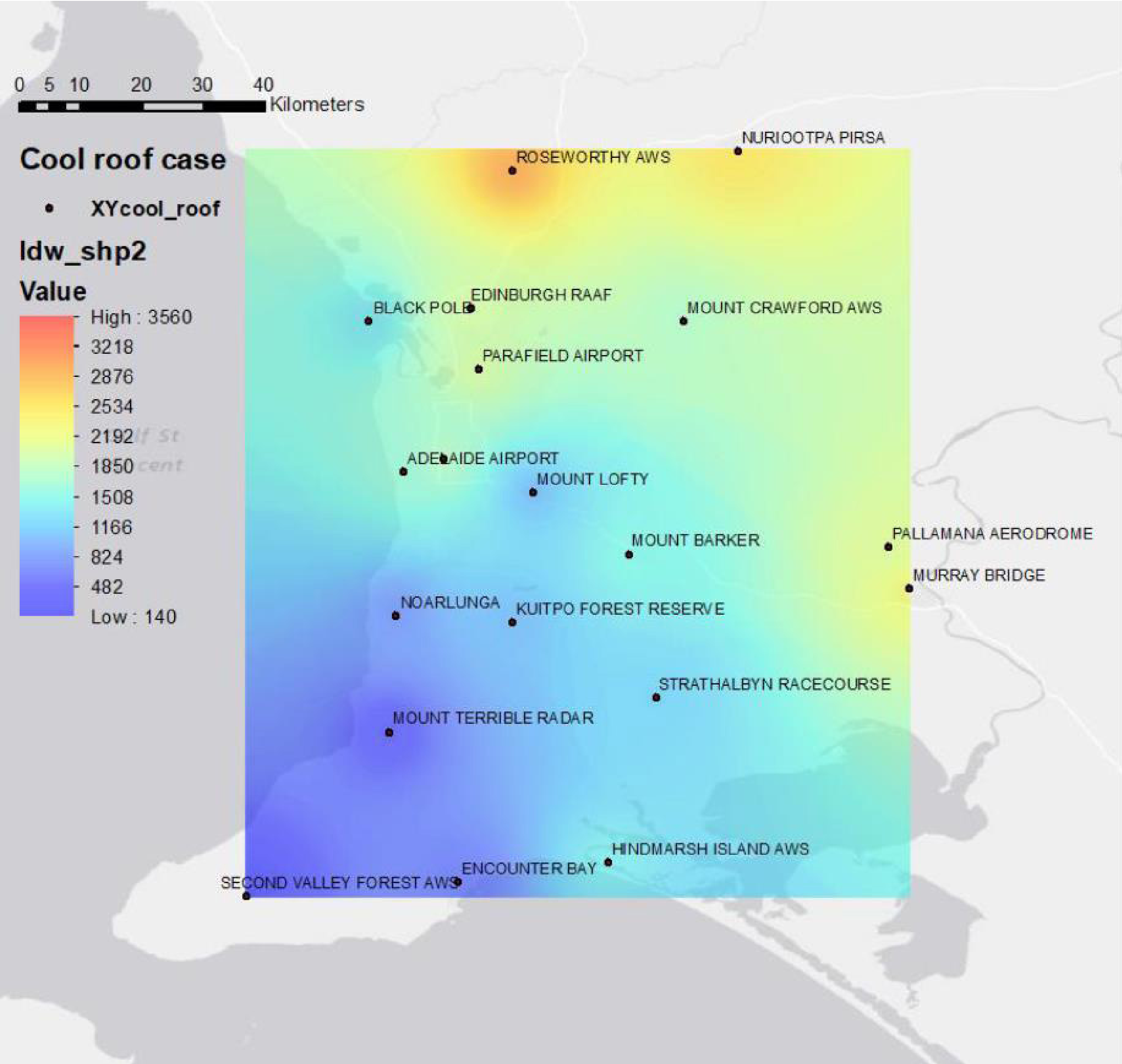


Figure 3.72 The sum of cooling degree hours in January and February in the 19 stations in the Greater Adelaide area, when cool roofs are implemented at city scale.

Surface Temperature

While the surface temperature in the Greater Adelaide area continues to be considerably high, cool roofs contribute to a significant decrease of the surface temperature at 14:00 hrs for the whole Greater Adelaide area. The peak surface temperature drop at 14:00 hrs, is close to 6.0°C as in Figures 3.73 and 3.74. The median temperature drop in Adelaide is 5.5°C and the maximum one is close to 6.0 °C. For almost 75% of the days, the average surface temperature drop is between 5.1°C and 6°C.

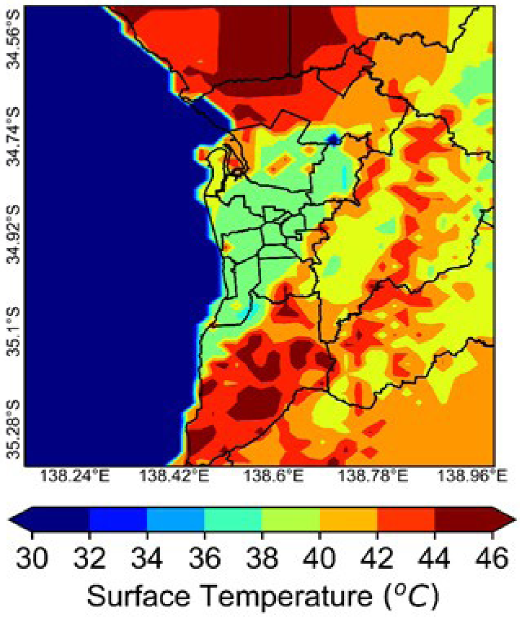


Figure 3.73 Spatial distribution of the surface temperature in the Greater Adelaide area at 14:00 hrs during a representative summer day when cool roofs are installed at city scale, as calculated by the WRF simulations.

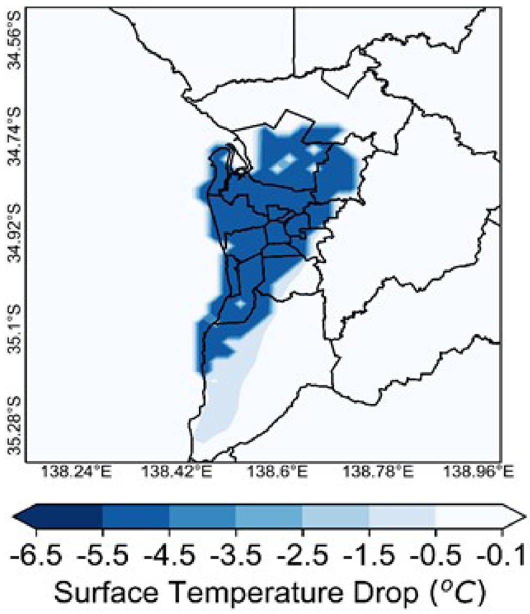


Figure 3.74 Spatial distribution of the surface temperature drop in the Greater Adelaide area at 14:00 hrs during a representative summer day when cool roofs are installed at city scale, as calculated by the WRF simulations.

The significant decrease of the surface temperature results in an important reduction of the sensible heat released by the city that greatly affects the magnitude of urban overheating. The maximum decrease in the sensible heat flux is 171.3 W/m^2, and the average decrease is 145.2 W/m^2 at 14:00 hrs LT over the urban domain (Port Adelaide Enfield, Charies Sturt, Prospect, Norwood, Payneham & St Peters, West Torrens and Holdfast Bay). In the high-density residential urban area, the maximum and average reduction of sensible heat flux are about 179.5 W/m^2 and 153.0 W/m^2 respectively at 14:00 hrs LT in a summer month compared to the control case. At 18:00 hrs LT, the maximum and average reduction in the summer month sensible heat flux is 79.4 W/m^2 and 64.7 W/m^2 over the urban domain Figure 3.75. The median sensible heat drop in Adelaide is 160 W/m^2 and 140 W/m^2 and the maximum one is close to 180 W/m^2.

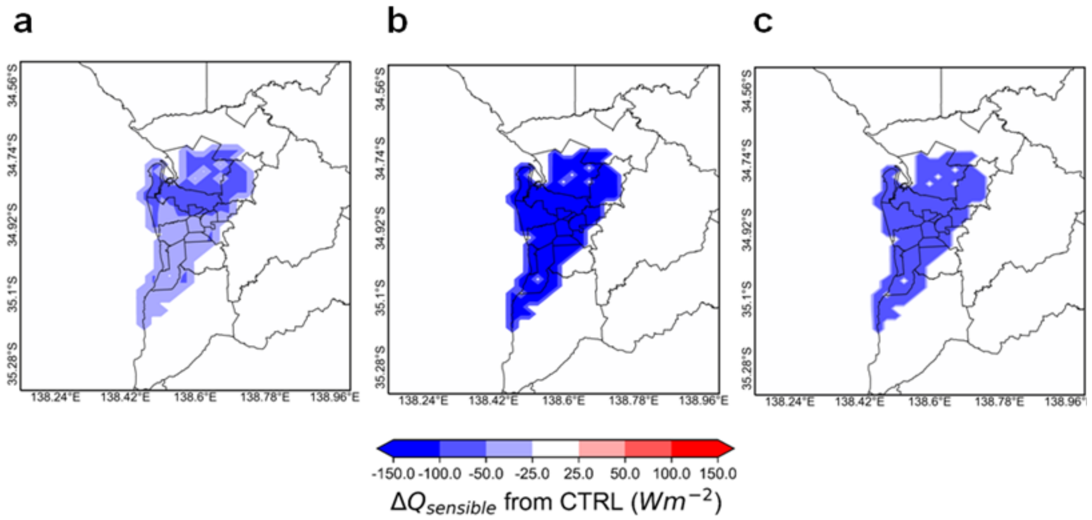


Figure 3.75 Reduction of sensible heat flux at (a) 06:00 hrs LT, (b) 14:00 hrs LT, and (c) 18:00 hrs LT, in the Greater Adelaide area, during a representative summer day when cool roofs are installed at the city scale.

Wind Speed

The installation of the cool roofs at city scale greatly affects air circulation in the city for the reasons explained previously. A significant decrease of the PBL caused by the installation of the cool roofs in the Greater Adelaide area is observed, significantly affecting the magnitude of the wind speed (Figure 3.76). The maximum reduction is associated with the peak hour (14:00 hrs LT) over the central part of Adelaide city.

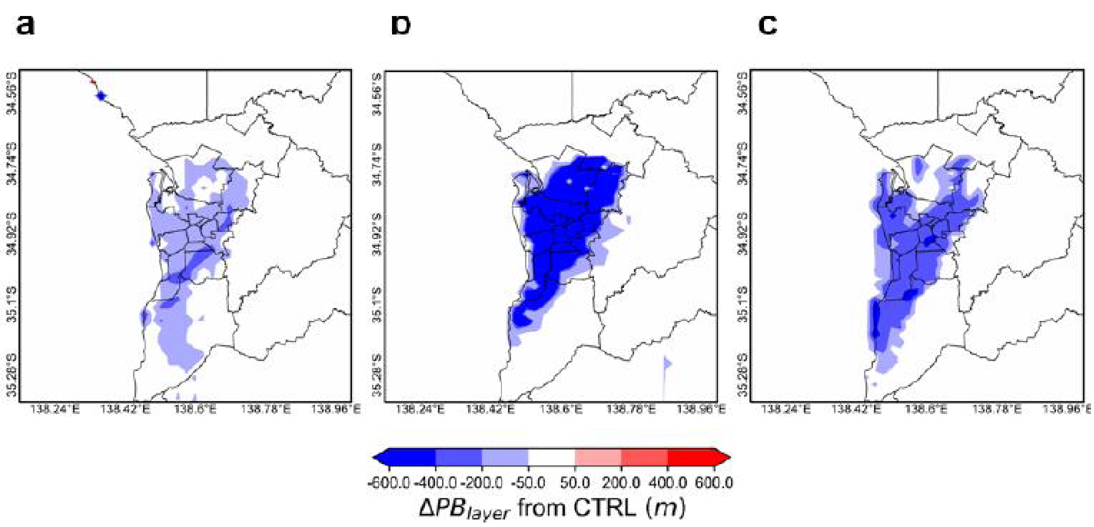


Figure 3.76 Reduction of PBL height at (a) 06:00 hrs LT, (b) 14:00 hrs LT, and (c) 18:00 hrs LT, in the Greater Adelaide area, during a representative summer day when cool roofs are installed at the city scale.

The cool roof could alter the PBL height and potentially trigger localized circulation over the urban domain of Adelaide. Results also indicate that the onset of the sea breeze was delayed to the afternoon (14:00 hrs LT) due to the "regional high" effect within the lower PBL and offshore synoptic wind flow above the PBL. The denser cool air over the urban domain flows towards the suburban area to replenish the buoyant warm air. The cool roof materials can suppress the process of vertical lifting of urban thermals, transport and dispersion of low-level motions due to inversion in the hot summer and decelerate the sea breeze front. Consequently, the decrease in the extent of vertical wind speed by 1 to 2 m/s induces stronger subsidence over the urban domain where reflective materials are installed. The surface roughness parameters do not facilitate to pull the cool air of sea breezes down to the surface due to the mixing effects. In addition, the horizontal wind shear and frontal lifting owing to surface roughness could setback the onset of the sea breeze front in the urban core. The potency of the sea breeze advection is subjected to the dimension of the city, which influences the urban heating effect. Thus, cool roofs for cities have greatly modified the thermal and dynamic profile in the urban boundary layer and also sea breeze circulation patterns. This synoptic flow prevails in the opposite direction of the sea breeze, and the sea breeze front developed is more prone to the accumulation of secondary pollutants in the back of the front (see Figure 3.77 and Figure 3.78).

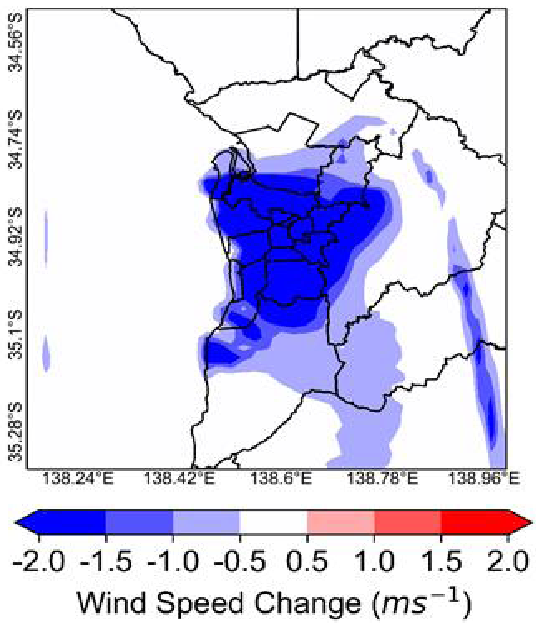


Figure 3.77 Reduction of the wind speed at 14:00 hrs pm because of the installation of the cool roofs at city scale during a typical summer day.

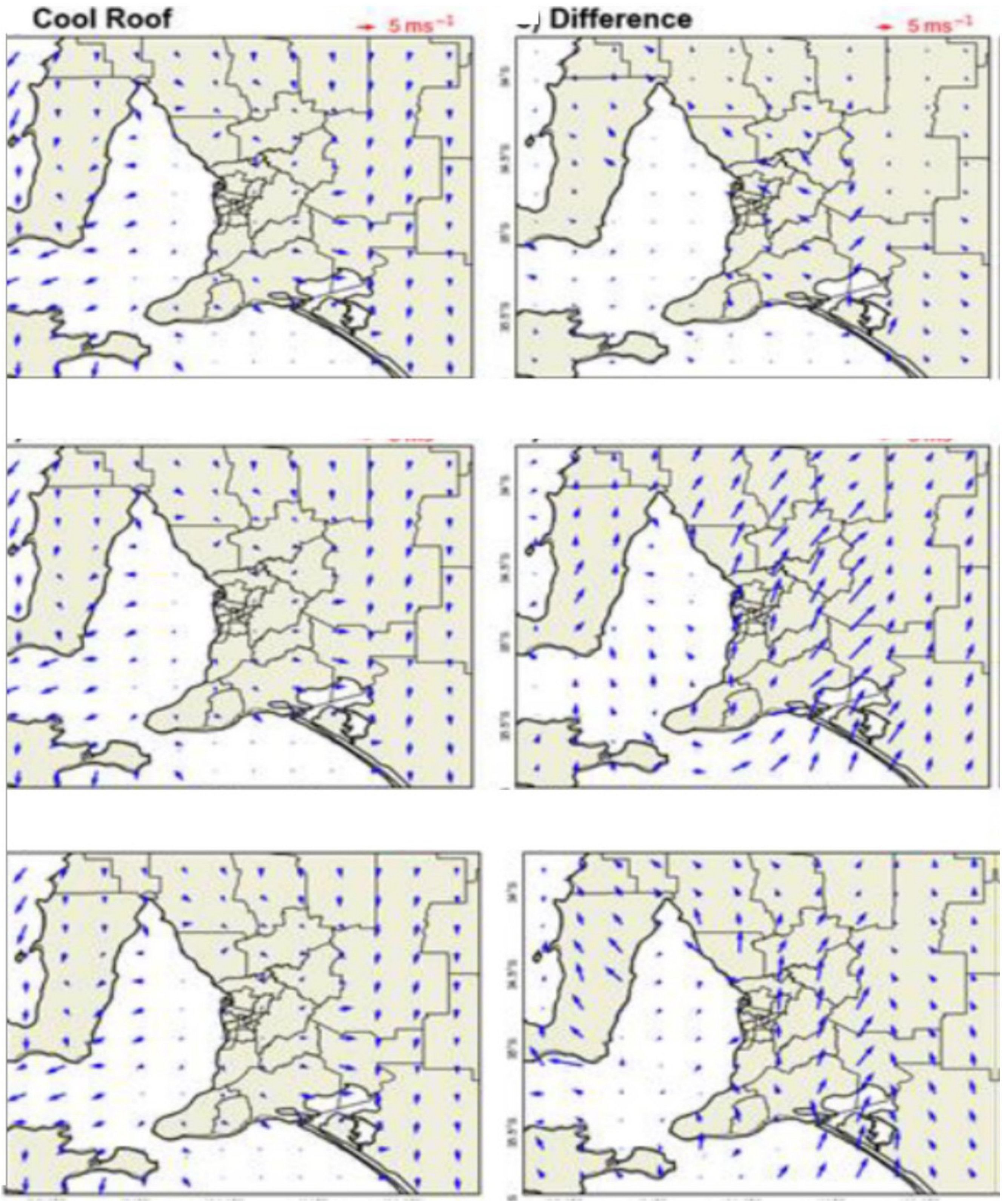


Figure 3.78 Spatial distribution of the wind speed and direction at the Greater Adelaide area at 06:00hrs, (upper), 14:00 hrs, (middle) and 18:00 hrs (lower), during a representative summer day when cool roofs are installed at city scale. Differences in wind speed are estimated in relation to the reference conditions, as calculated by the WRF simulations.

3.10. CLIMATIC IMPACT OF COOL ROOFS IN THE GREATER PERTH AREA

3.10.1. CONTEXT OF THE STUDY

A full simulation of the climatic conditions in the Greater Perth area has been performed to assess the spatial and temporal variation of the main climatic parameters that affect urban overheating and the levels of thermal comfort. Simulations are performed for two complete summer months, using the accurate mesoscale model, WRF, with a grid resolution of 500 m x 500 m as shown in Figure 3.79.

Two climatic scenarios are investigated:

Reference Scenario: aiming to simulate the spatial and temporal variability of the main climatic parameters under the reference conditions with no use of cool roofs.

Cool Roofs Scenario: as the above reference scenario but assuming that all roofs in the domain d03 of Figure 3.79 are reflective cool roofs.

The reflectance of the roofs was considered equal to 0.15 and 0.8 under the reference and cool roof scenarios, respectively. The emissivity of the roofs was equal to 0.85 for both scenarios. The predictions of the reference scenario were validated against measured climatic data from four meteorological stations, a) Perth Airport, b) Perth, c) Gosnells, and d) Swanbourne and are found to be in excellent agreement (Figure 3.80).

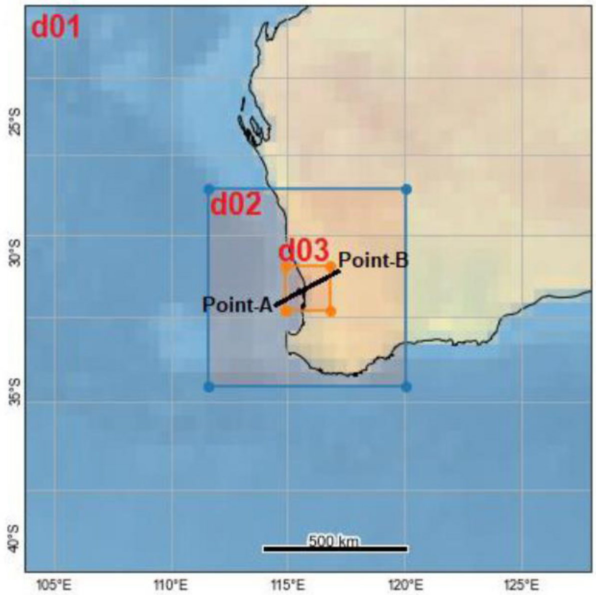


Figure 3.79 The WRF domain shows (a) dynamical downscaling with domain 1 (d01) as outermost parent domain with 4500 m grid spacing, domain 2 (d02) with 1500 m grid spacing and, an innermost domain 3 (d03) with 500 m grid spacing; (b) innermost d03 with 500 m grid spacing which encompasses the Greater Perth. Point-A (left) and Point-B (right) are the points used for drawing horizontal-vertical cross-sections to analyze meteorological conditions.

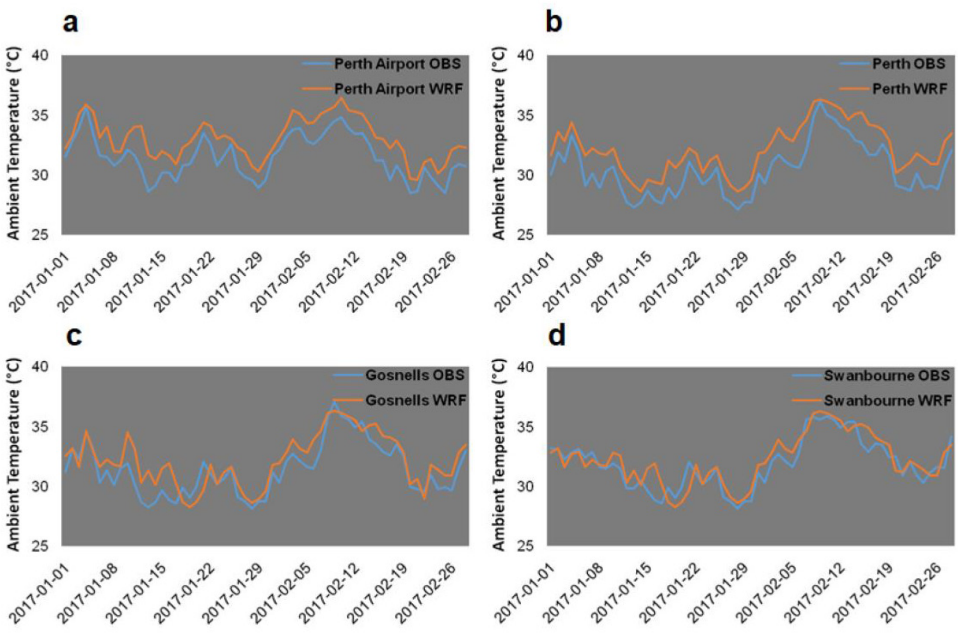


Figure 3.80 Comparison of the simulation results with observation data at average for 59 days for four local meteorological stations a) Perth Airport, b) Perth, c) Gosnells, and d) Swanbourne.

3.10.2. REFERENCE CLIMATIC CONDITIONS

Ambient Temperature

The magnitude of urban overheating in the Greater Perth area is significant and may reach up to 6°C. During a representative summer day, the peak ambient temperature in the city of Perth, presents a significant spatial distribution. The maximum temperature difference between the different urban zones may exceed 6°C. Much lower ambient temperatures are observed in the coastal area of the city as shown in Figure 3.81.

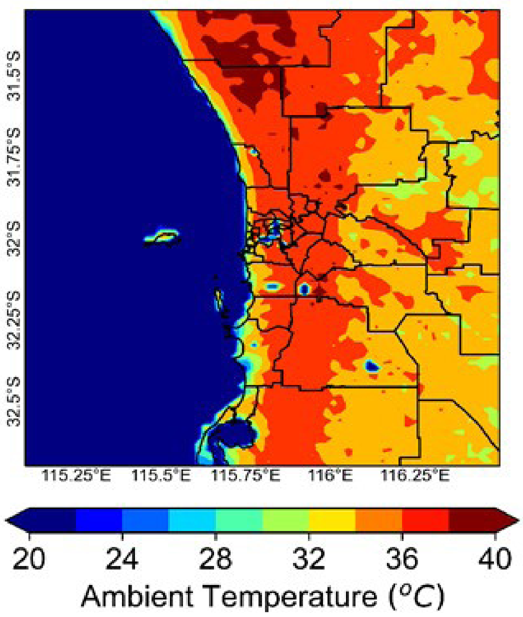


Figure 3.81 Spatial distribution of the ambient temperature in the Greater Perth area at 14:00 hrs during a representative summer day under the reference conditions as calculated by the WRF simulations.

The spatial distribution of the cooling degree hours in the Perth area during the summer period is significant. Cooling degree hours measures how much, and for how long, outside air temperature is higher than 26°C, and serves as a rough indication of regional climatic severity. The total cooling degree hours during January and February in the main city vary between 300–800, but in certain suburban and rural areas in the north-eastern part of the area, cooling degree hours may be as high as 2600 (Figure 3.82).

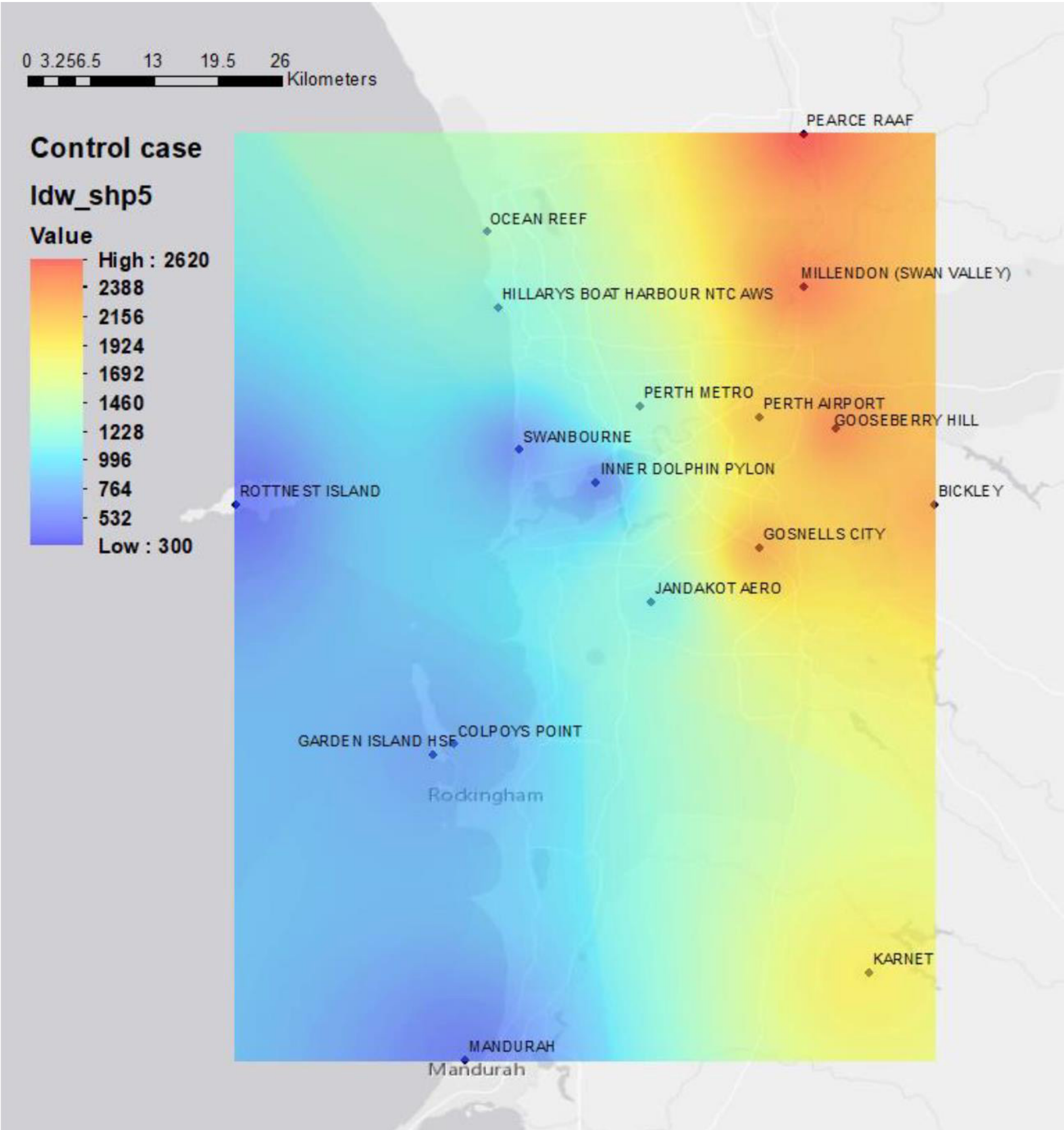


Figure 3.82 The sum of cooling degree hours in January and February at the 19 reference stations in the Greater Perth area.

Surface Temperature

The surface temperature distribution during the daytime, is high in specific zones of the city, approaching 46°C, and presents a quite significant spatial distribution as seen in Figure 3.83 Surface temperature at 14:00 hrs can be as high as 46°C as a function of the optical properties of the materials used. Highly absorbing dark roofs and pavements present the highest surface temperature, while light coloured reflective surfaces may present up to 15°C, lower surface temperature. Green spaces present a quite low surface temperature although this is strongly affected by the characteristics of the specific urban greenery zones.

High surface temperatures release much more sensible heat to the atmosphere, increasing the ambient temperature and intensifying the magnitude of urban overheating. The maximum released sensible heat at 14:00 hrs is 472.3 Wm^{-2} and 336.1 Wm^{-2} at 18:00 hrs LT, the average sensible heat flux is 99.8 Wm^{-2}.

High ambient and surface temperatures, especially, correspond to very uncomfortable climatic conditions affecting the energy consumption of buildings, peak electricity demand, heat related mortality and morbidity and the survivability of the low-income population.

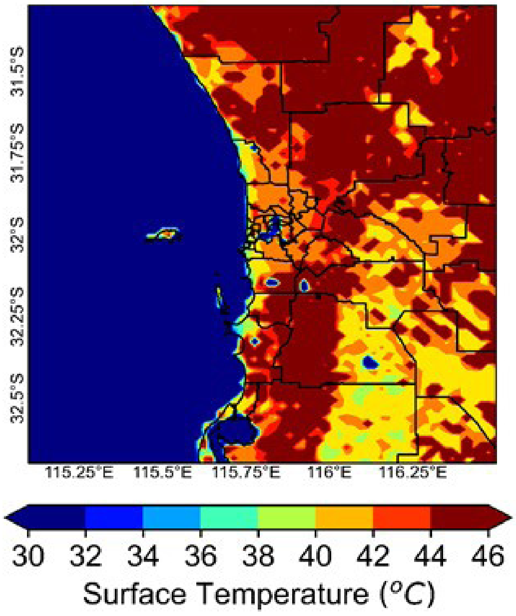


Figure 3.83 Spatial distribution of the surface temperature in the Greater Perth area at 14:00 hrs during a representative summer day under the reference conditions as calculated by the WRF simulations.

Wind Speed

Wind speed during summer in the Greater Perth area is determined mainly by the strength of the sea breeze affecting the coastal area and the north eastern winds affecting the inner parts of the city. The average wind speeds (W_{speed}) during the simulation period are 4.4 m/s, 7.2 m/s and 6.1 m/s at 06:00 hrs LT, 14:00 hrs LT and 18:00 hrs LT respectively over the city. Figure 3.84 shows the magnitude and the direction of the wind during a representative summer day at 06:00 hrs, 14:00 hrs and 18:00 hrs LT.

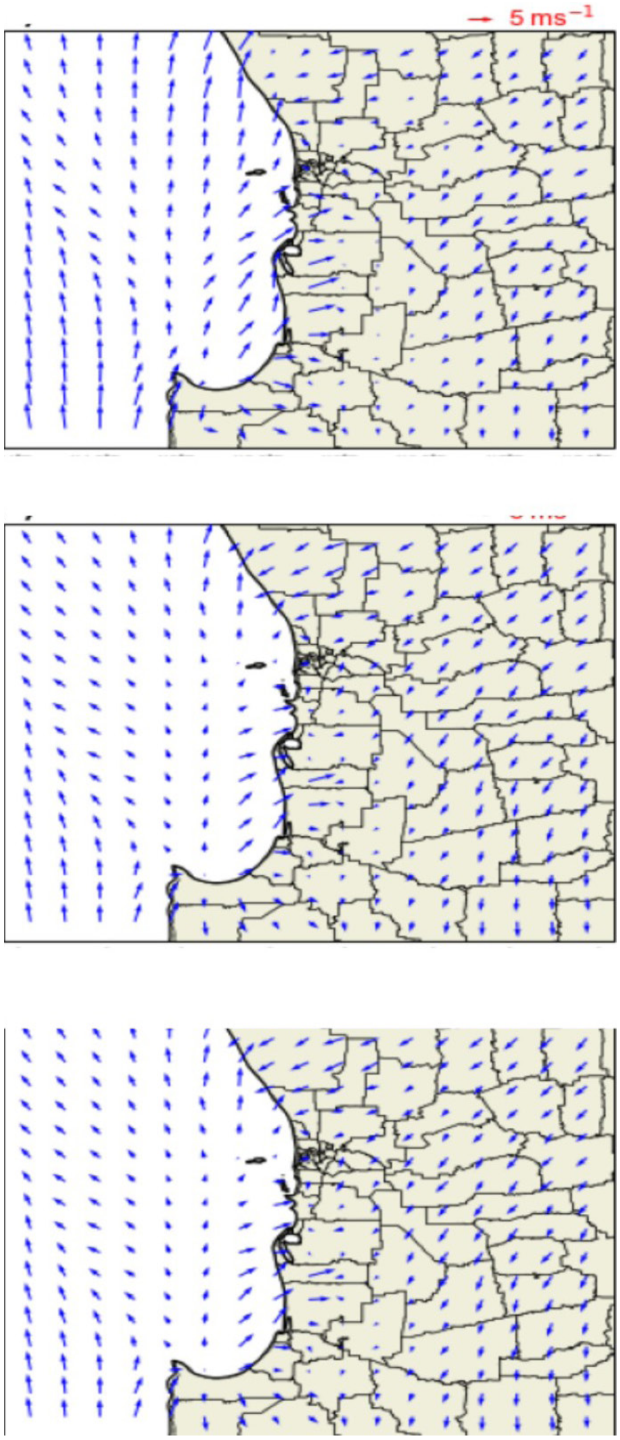


Figure 3.84 Spatial distribution of the wind speed and direction in the Greater Perth at 06:00hrs, (upper), 14:00 hrs, (middle) and 18:00 hrs (lower), during a representative summer day under the reference conditions as calculated by the WRF simulations.

3.10.3. MODIFIED CLIMATIC CONDITIONS — INSTALLATION OF COOL ROOFS

The installation of the cool roofs at the city scale greatly affects the local climate. It decreases both the ambient and surface temperature mainly during the daytime and contributes considerably to reduce the magnitude of urban overheating in the city.

Ambient Temperature

The installation of cool roofs at the city scale reduces the summer peak ambient temperature at 14:00 hrs by up to 1.5°C (Figure 3.85). The important temperature difference between the various regions of the city still exists, although the magnitude of the temperature difference is lower.

The calculated decrease of temperature is more significant in the main part of the city as shown in Figure 3.86. The daily average reduction of the ambient temperature at 14:00 hrs for the Greater Adelaide area during the summer period, is close to 1.2°C. The median temperature drop in Perth is 1.2°C, and the maximum is close to 1.7°C.

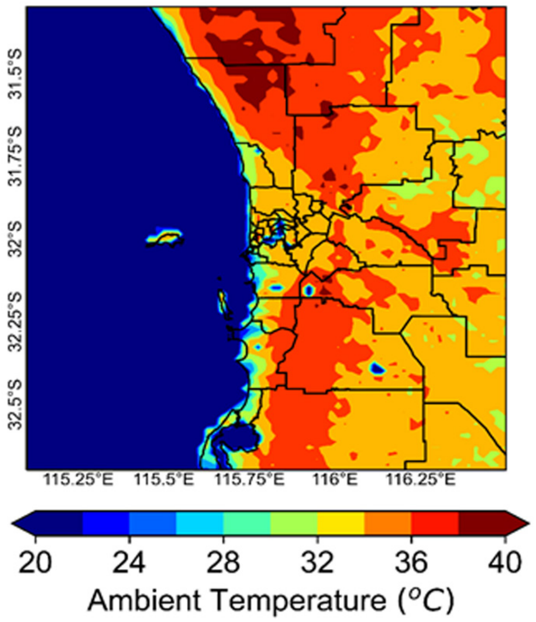


Figure 3.85 Spatial distribution of the ambient temperature in the Greater Perth area at 14:00 hrs during a representative summer day when cool roofs are installed, as calculated by the WRF simulations.

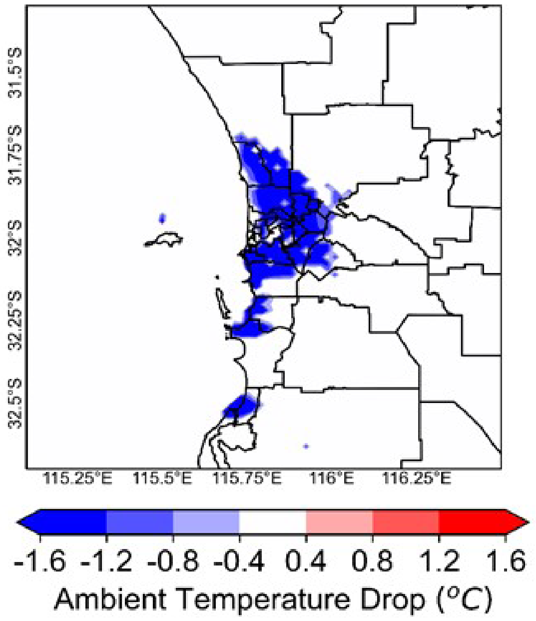


Figure 3.86 Spatial distribution of the ambient temperature drop in the Greater Perth area at 14:00 hrs, caused by the installation of cool roofs, during a representative summer day, as calculated by the WRF simulations.

A very significant drop of the summer cooling degree hours, ranging between 18% to 39% compared to the reference climatic conditions can be observed in Figure 3.87. The highest percentage reduction is seen in the Garden Island area.

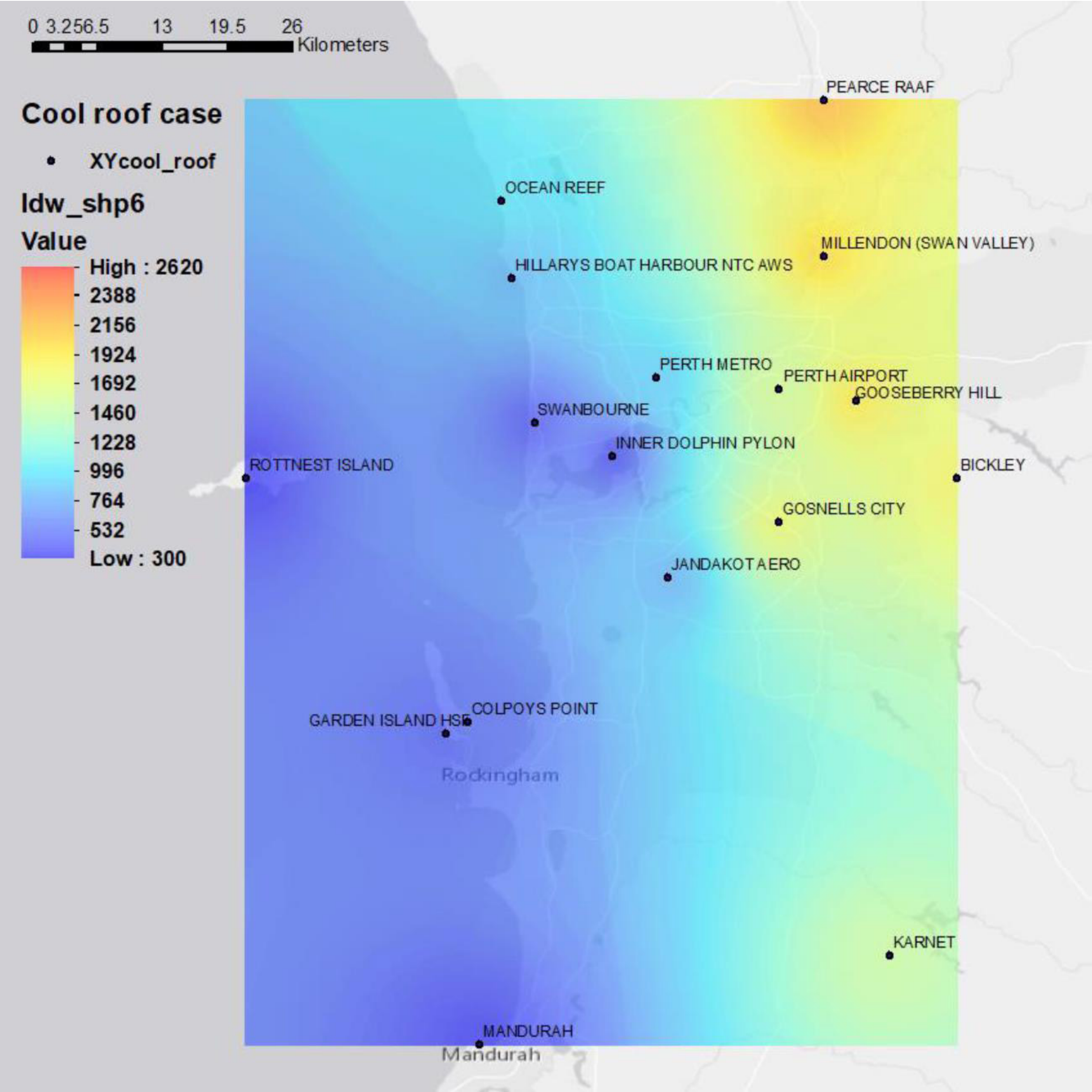


Figure 3.87 The sum of cooling degree hours in January and February in the 19 stations in the Greater Perth area, when cool roofs are installed at city scale.

Surface Temperature

While the surface temperature in the Greater Perth area continues to be considerably high, cool roofs contribute to a significant decrease of the surface temperature at 14:00 hrs for the whole Greater Perth area. The peak surface temperature drops at 14:00 hrs is close to 5.0°C (Figures 3.58 and 3.59). The median temperature drop in Perth is 5.4°C and the maximum is close to 6.0°C. For 94% of the days, the average surface temperature drop is between 5°C and 6°C.

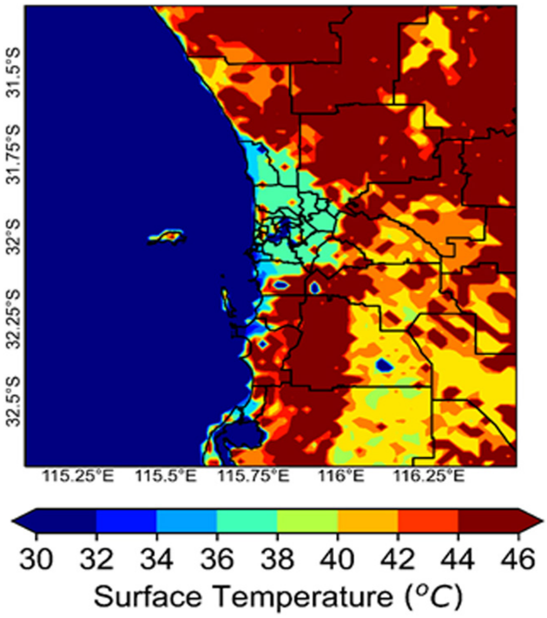


Figure 3.88 Spatial distribution of the surface temperature in the Greater Perth area at 14:00 hrs pm during a representative summer day when cool roofs are installed at city scale, as calculated by the WRF simulations.

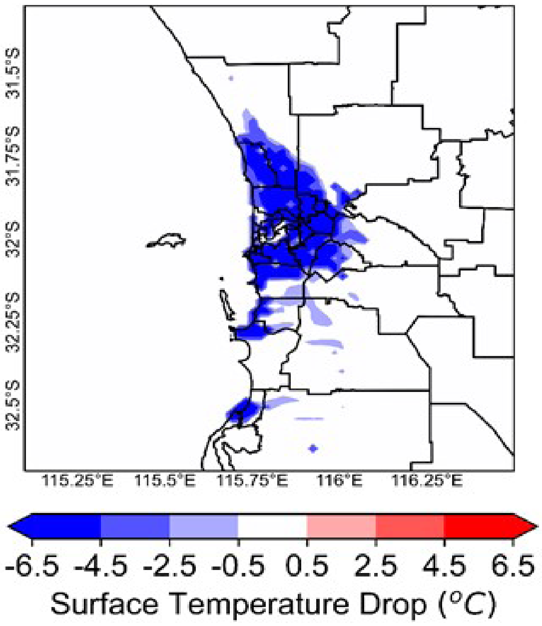


Figure 3.89 Spatial distribution of the surface temperature drop in the Greater Perth area at 14:00 hrs during a representative summer day when cool roofs are installed at the city scale, as calculated by the WRF simulations.

The significant decrease of the surface temperature results in an important reduction of the sensible heat released by the city that significantly affects the magnitude of urban overheating. The maximum decrease in sensible heat flux is 179.6 Wm^2 and the average decrease is 154.8 Wm^2 at 14:00 hrs LT over the urban domain (Fremantle, Perth CBD, Osborne park, and some parts of Thornlie and Joondalup). In the high-density residential urban area, the maximum and average reduction of sensible heat flux is about 187.7 Wm-^{2} and 161.7 Wm^2 at 14:00 hrs LT during a summer month compared to the control case. At 18:00 hrs LT, the maximum and average reduction during the summer month of sensible heat flux is 91.6 Wm^2 and 72.7Wm^2 over the urban domain (Figure 3.90). For 95% of the days, the average drop of sensible heat is between 150 W/m^2 and 250 W/m^2.

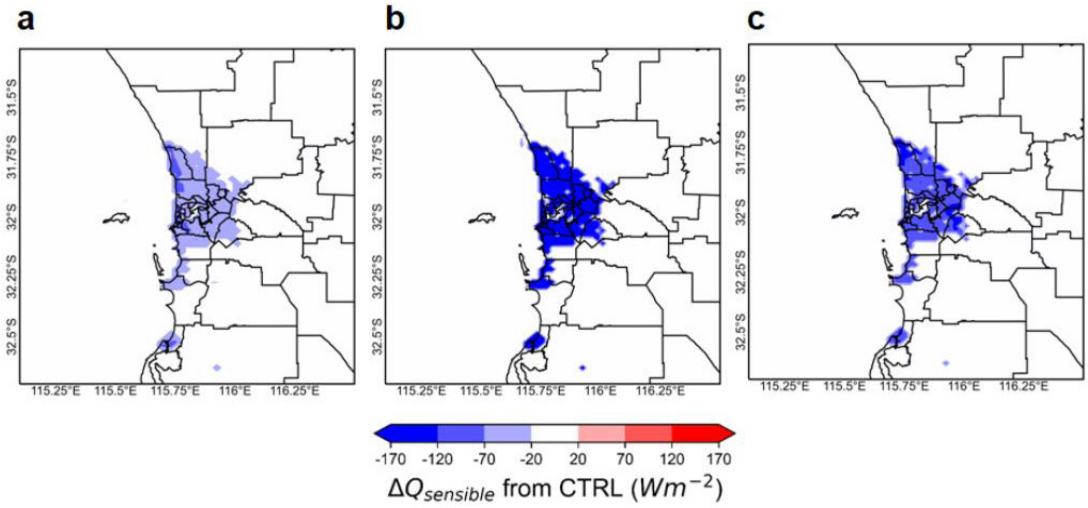


Figure 3.90 Reduction of sensible heat flux at (a) 06:00 hrs LT, (b) 14:00 hrs LT, and (c) 18:00 hrs LT, in the Greater Perth area, during a representative summer day when cool roofs are installed at city scale.

Wind Speed

The installation of cool roofs at city scale greatly affects air circulation in the city for the reasons explained previously. A significant decrease of the PBL caused by the installation of the cool roofs in the Greater Perth area is observed, significantly affecting the magnitude of the wind speed as shown in Figure 3.91. The maximum reduction is associated with the peak hour (14:00 hrs LT) over the central part of Perth city.

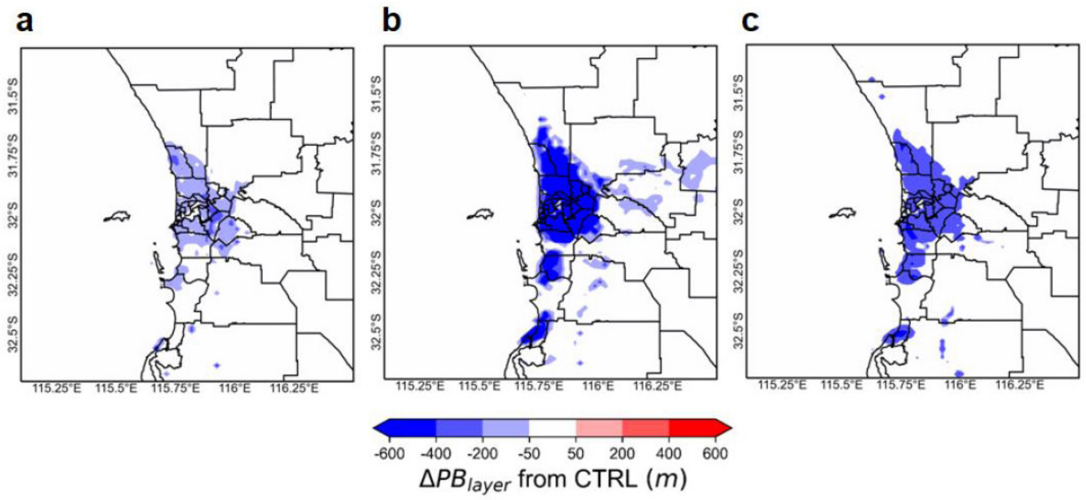


Figure 3.91. Reduction of PBL height at (a) 06:00 hrs LT, (b) 14:00 hrs LT, and (c) 18:00 hrs LT during a typical summer day when cool roofs are installed at city scale.

The amplification of sea breeze circulation is dependent on the large-scale synoptic background, which plays an important role in modulating the prevailing wind at the near surface. In the vertical dimension, report revealed the height of the PBL in Perth is linked closely with the advection of the sea breeze. The circulation can be modified when cool roof is installed at city-scale. The cool roof could alter the PBL height and potentially trigger localized circulation over the urban domain of Perth. Results also indicate that the onset of the sea breeze was delayed to afternoon (14:00 hrs LT) due to the "regional high" effect within the lower PBL and offshore synoptic wind flow above the PBL. The denser cool air over the urban domain flows towards the suburban area to replenish the buoyant warm air. The cool roof materials can suppress the process of vertical lifting of urban thermals, transport and dispersion of low-level motions due to inversion in hot summer and decelerate the sea breeze front. Therefore, the decrease in the extent of vertical wind speed by 1 to 2 m/s induces a stronger subsidence over the urban domain where reflective materials are installed. The surface roughness parameters are painstaking to be useful to pull the cool air of sea breezes down to the surface due to the mixing effects. Besides, the horizontal wind shear and frontal lifting owing to surface roughness parameters could setback the onset of sea breeze front in the urban core. The potency of the sea breeze advection is subjected to the dimension of the city which persuades the urban heating effect. Thus, cool roof for cities have greatly modified the thermal and dynamic profile in the urban boundary layer and sea breeze circulation. This synoptic flow prevails in the opposite direction of sea breeze and sea breeze front developed is more prone to the accumulation of secondary pollutant in the back of the front (Figure 3.92, and Figure 3.93).

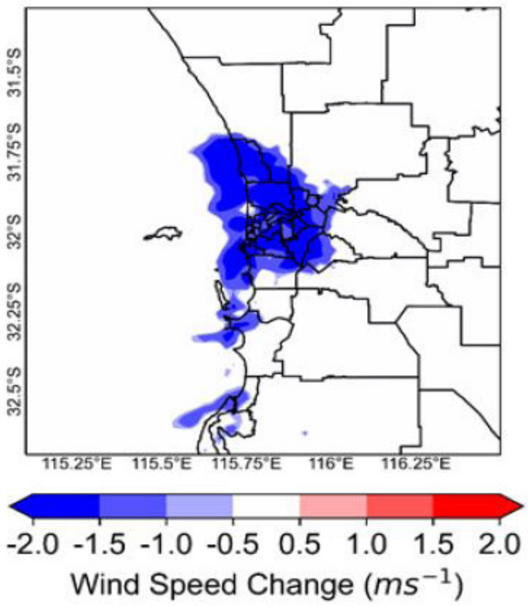


Figure 3.92 Reduction of the wind speed at 14:00 hrs pm because of the installation of the cool roofs at the city scale during a typical summer day.

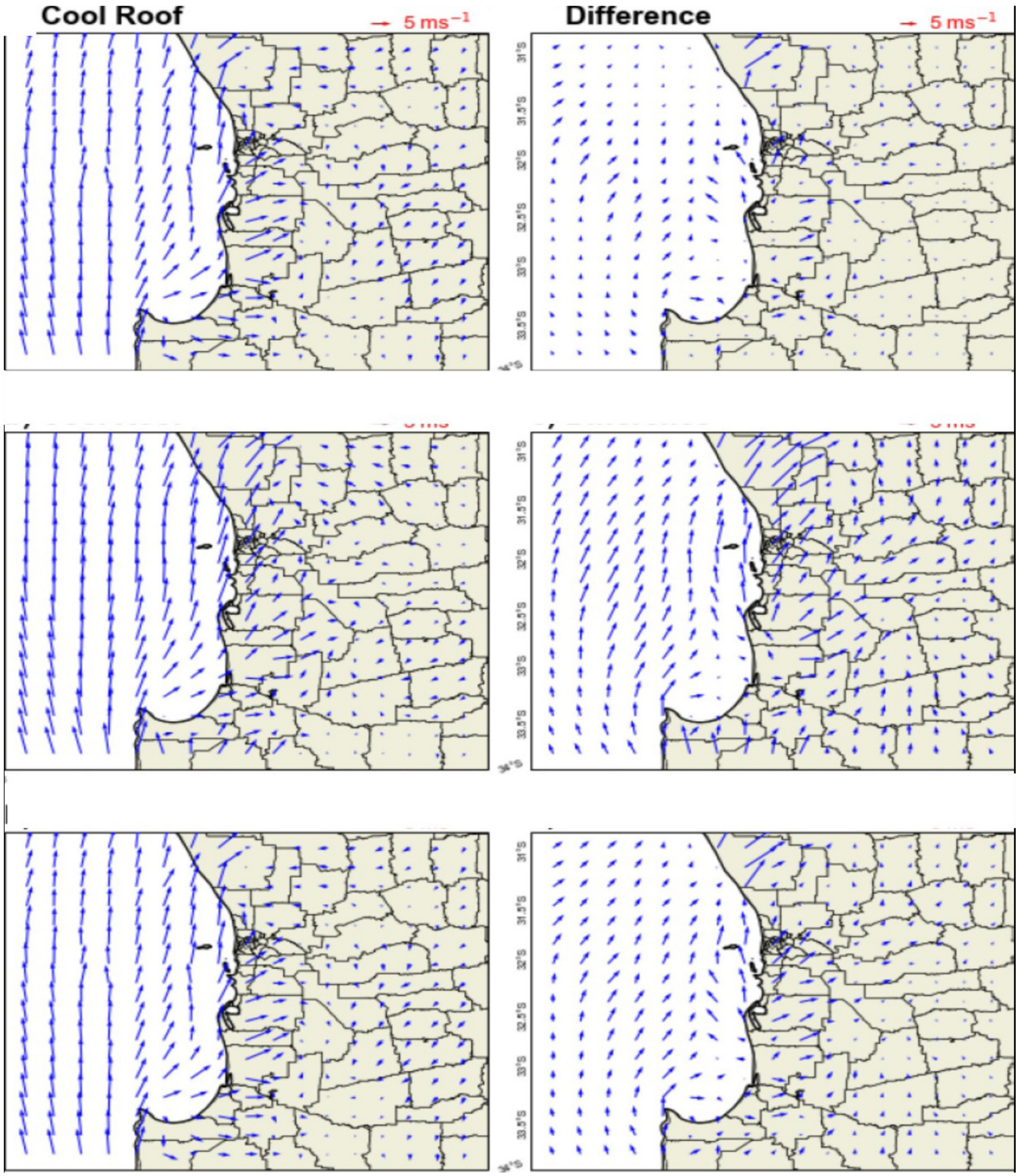


Figure 3.93 Spatial distribution of the wind speed and direction at the Greater Perth area at 06:00 am, (upper), 14:00 hrs pm, (middle) and 18:00 pm (lower), during a representative summer day when cool roofs are installed at the city scale and difference of the wind speed against the reference conditions, as calculated by the WRF simulations.

3.11. CONCLUDING AND COMPARATIVE REMARKS ON THE CLIMATIC IMPACT OF COOL ROOFS IN THE FIVE MAIN AUSTRALIAN CITIES

3.11.1. IMPACT ON AMBIENT TEMPERATURE

Figures 3.94 – 3.95 present the variability of the spatially average ambient temperature drop caused by the installation of the cool roofs at 14:00 hrs during January and February as calculated through the WRF simulations. The main conclusions are:

a. The daily peak ambient temperature drop caused by the installation of cool roofs in the five Australian cities varies between 0.2°C and 2.3°C.

b. The corresponding median temperature drop varies between 0.8°C and 1.7°C, while the maximum drop varies between 1.2°C and 2.3°C. The minimum reduction varies between 0.2°C and 0.8°C.

c. The maximum drop in the ambient temperature caused by cool roofs occurs in Brisbane. The median spatially average temperature decrease at 14:00 hrs is close to 1.7°C while its maximum is around 2.3°C and its minimum is 0.9°C.

d. The median temperature drop in Perth, Adelaide, Melbourne, and Sydney is 1.2°C, 1.1°C, 0.9°C and 0.8°C, respectively and the maximum reduction is close to 1.7°C, 1.6°C, 1.2°C and 1.6°C, respectively.

e. The more probable temperature decrease in all cities is very close to the median value as given above.

f. In Sydney for almost 50% of the days the average ambient temperature drop is between 0.5°C and 1°C, while for 24% of the time it is between 1.0°C to 1.5°C and 20% between 0.0°C and 0.5°C.

g. For Brisbane, 37% of the days present an average drop between 1.8°C and 2.1°C, 32% between 1.5°C and 1.8°C, and 12% between 0.9°C and 1.2°C.

h. For Perth, 54% of the days correspond to an average temperature drop between 1,2°C and 1.4°C, 18% between 0.8°C and 1.0°C, and 10% between 1.0°C and 1.2°C.

i. For Melbourne, 59% of the days correspond to an average temperature drop between 0.6°C and 0.9°C, while 24% corresponds to the range between 0.9°C and 1.2°C.

j. Finally, in Adelaide, 41% of the days corresponds to temperature drops between 0.8°C and 1.0°C and 36% between 1.2 and 1.4°C.

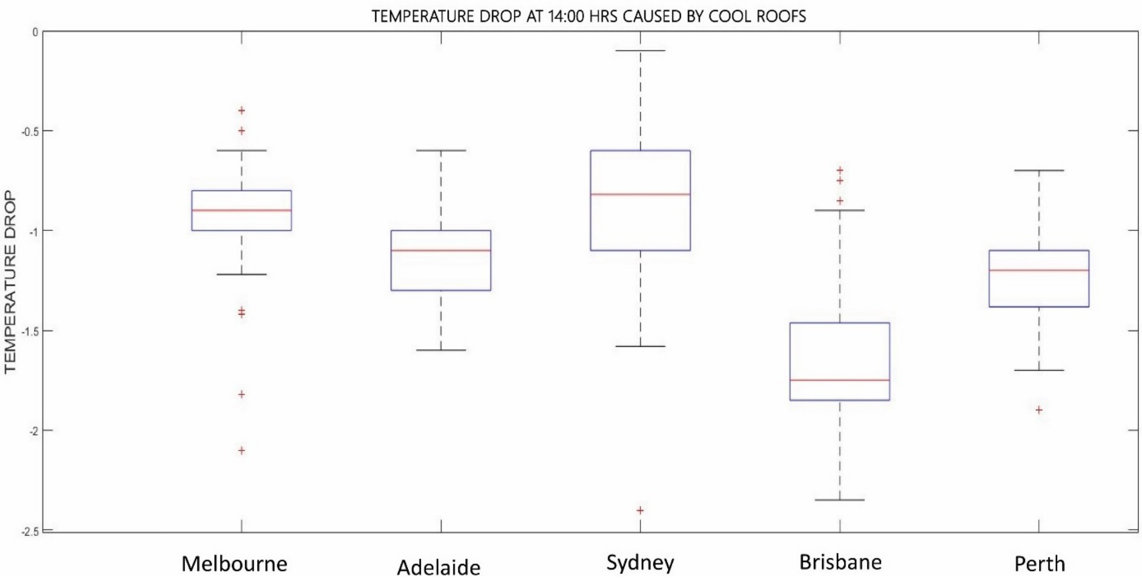


Figure 3.94 Range of the daily and spatially average drop of the ambient temperature at 14:00 hrs in the five main Australian cities during January and February.

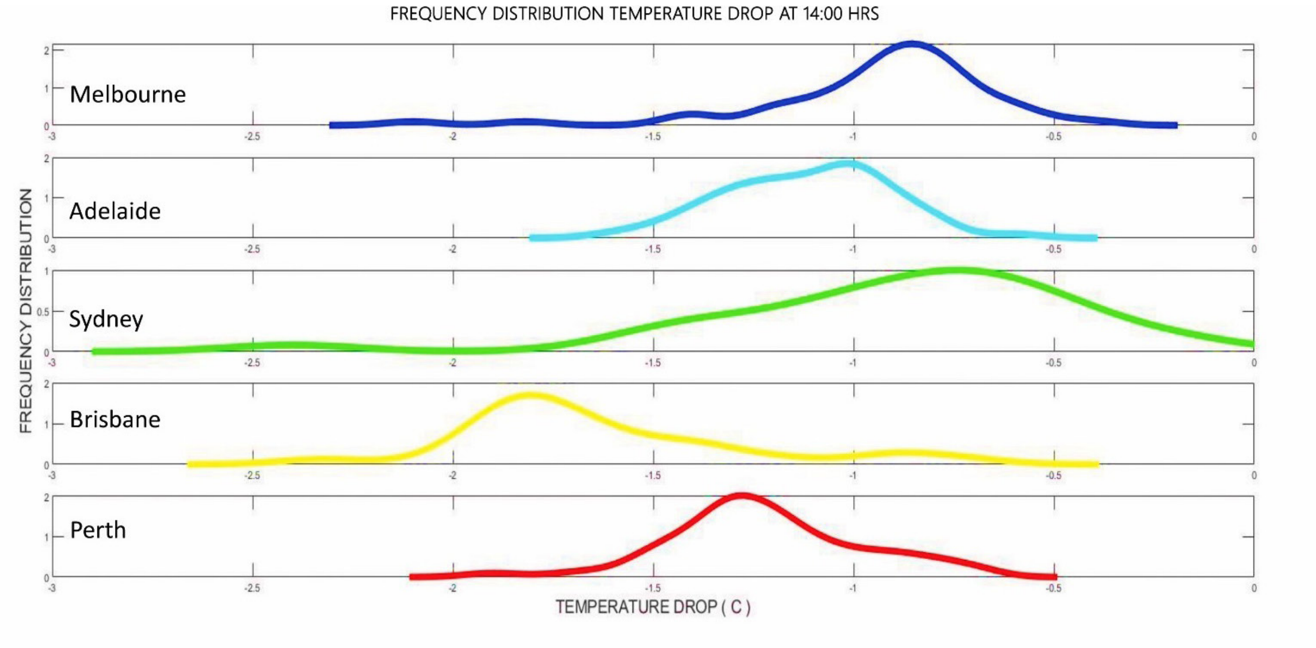


Figure 3.95 Frequency distribution of the daily and spatially average drop of the ambient temperature at 14:00 hrs in the five main Australian cities during January and February.

3.11.2. IMPACT ON SURFACE TEMPERATURE

Figures 3.96 – 3.97 present the variability of the spatially average surface temperature drop caused by the installation of the cool roofs at 14:00 hrs during January and February as calculated through the WRF simulations. The main conclusions are:

a. The daily peak surface temperature drop caused by the installation of cool roofs in the five Australian cities varies between 2°C and 8.5°C.
b. The corresponding median surface temperature drop varies between 3.5°C and 7°C, while the maximum drop varies between 6°C and 8.5°C, and the minimum between 2°C and 5°C.
c. The maximum drop of the surface temperature caused by cool roofs was calculated for Sydney. The median spatially average temperature decrease at 14:00 hrs is close to 7°C while its maximum is around 8.5°C and its minimum is 3°C.
d. The median temperature drop in Adelaide, Perth, Melbourne, and Brisbane is 5.5°C, 5.4°C, 3.8°C and 3°C respectively and the maximum one is close to 6.0°C, 5.9°C, 5.5°C and 5°C, respectively.
e. The more probable temperature decrease in all cities is very close to the median value as given above.
f. In Sydney, for 52% of the days, the average surface temperature drop is between 6°C and 8°C, and 19% are between 4°C and 6°C.
g. In Brisbane, for 80% of the days, the average surface temperature drop is between 2°C and 4°C.
h. In Perth, for 94% of the days, the average surface temperature drop is between 5°C and 6°C.
i. In Melbourne, for 58% of the days, the average surface temperature drop is between 2°C and 4°C, and 30% are between 4°C and 5°C.
j. Finally, in Adelaide, for 75% of the days, the average surface temperature drop is between 5.1°C and 6°C.

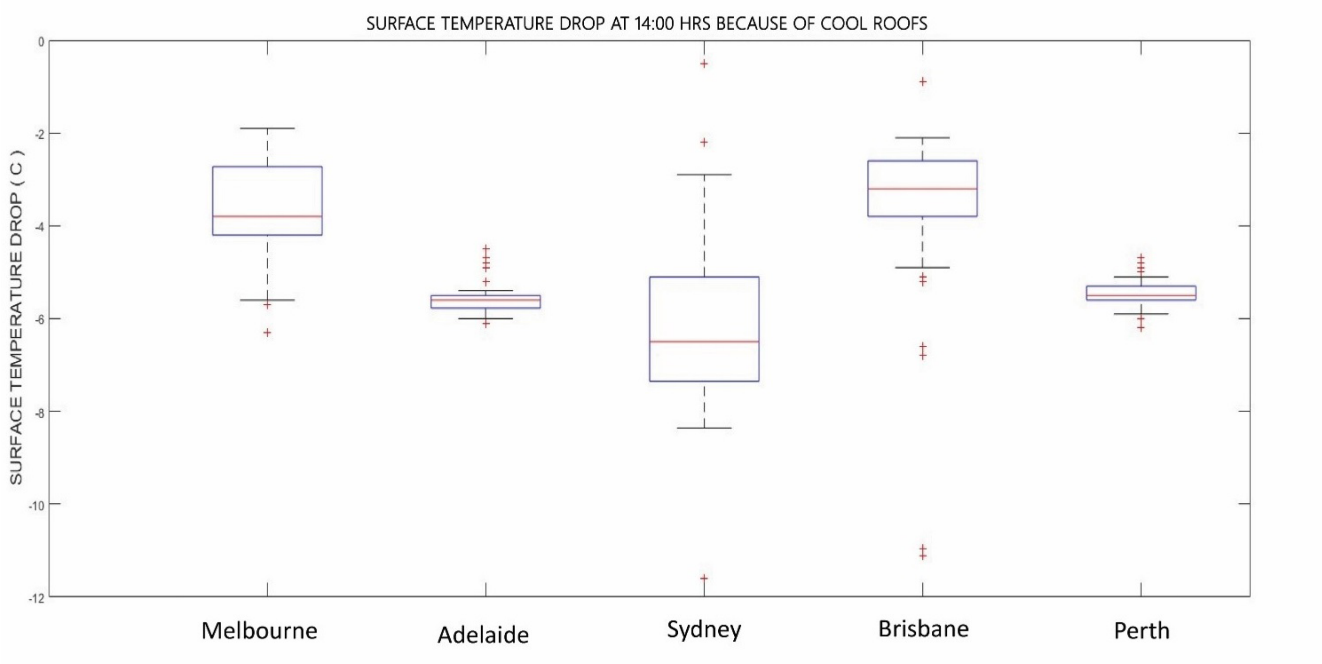


Figure 3.96 Range of the daily and spatially average drop of the surface temperature at 14:00 hrs in the five main Australian cities during January and February.

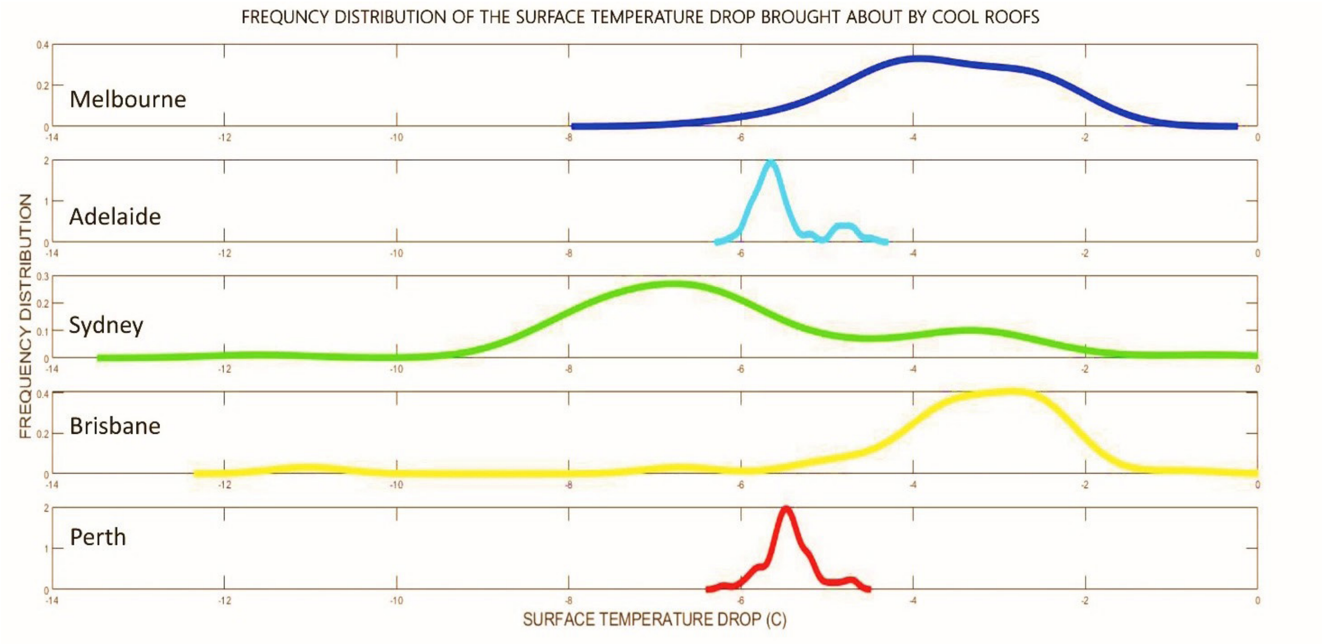


Figure 3.97 Frequency distribution of the daily and spatially average drop of the surface temperature at 14:00 hrs in the five main Australian cities during January and February.

3.11.3. IMPACT ON THE WIND SPEED

Figures 3.98 – 3.99 present the variability of the spatially average wind speed drop caused by the installation of the cool roofs at 14:00 hrs during January and February as calculated through the WRF simulations. The main conclusions are:

a. The daily wind speed change at 14:00 hrs, caused by the installation of cool roofs in the five Australian cities varies between +1.2 m/sec and -3.5 m/sec.
b. The corresponding median wind speed change varies between -0.2 m/sec and -2.2 m/sec, while the maximum drop varies between -0.5 m/sec and -3.5 m/sec, and the minimum between +1.2 m/sec and -1.4 m/sec.
c. The maximum drop of the wind speed caused by cool roofs was calculated for Perth. The median spatially average temperature decrease at 14:00 hrs is close to -2.2 m/sec while its maximum is around -2.5 m/sec and its minimum is -1.8 m/sec.
d. The median wind speed drop in Melbourne, Adelaide, Brisbane and Sydney, is -1.7 m/sec, -1.5 m/sec, -1 m/sec and -0.2 m/sec, respectively and the maximum drop is close to -3,5 m/sec, -2.0 m/sec, 1 m/sec and 0.2 m/sec, respectively.
e. The more probable wind speed change in all cities is very close to the median value as given above.
f. In Sydney, for 64% of the days the average wind speed drop is between 0 m/sec and -0.5 m/sec.
g. In Brisbane, for 69% of the days the average wind speed change is between 0 m/sec and -2 m/sec.
h. In Perth, for 71% of the days the average wind speed change is between -1.8 m/sec and -2.2 m/sec.
i. In Melbourne, for 61% of the days the average wind speed drop is between -1 m/sec and -2 m/sec.
j. Finally, in Adelaide, 92% of the days the average wind speed drop is between -1.2 m/sec and -2 m/sec.

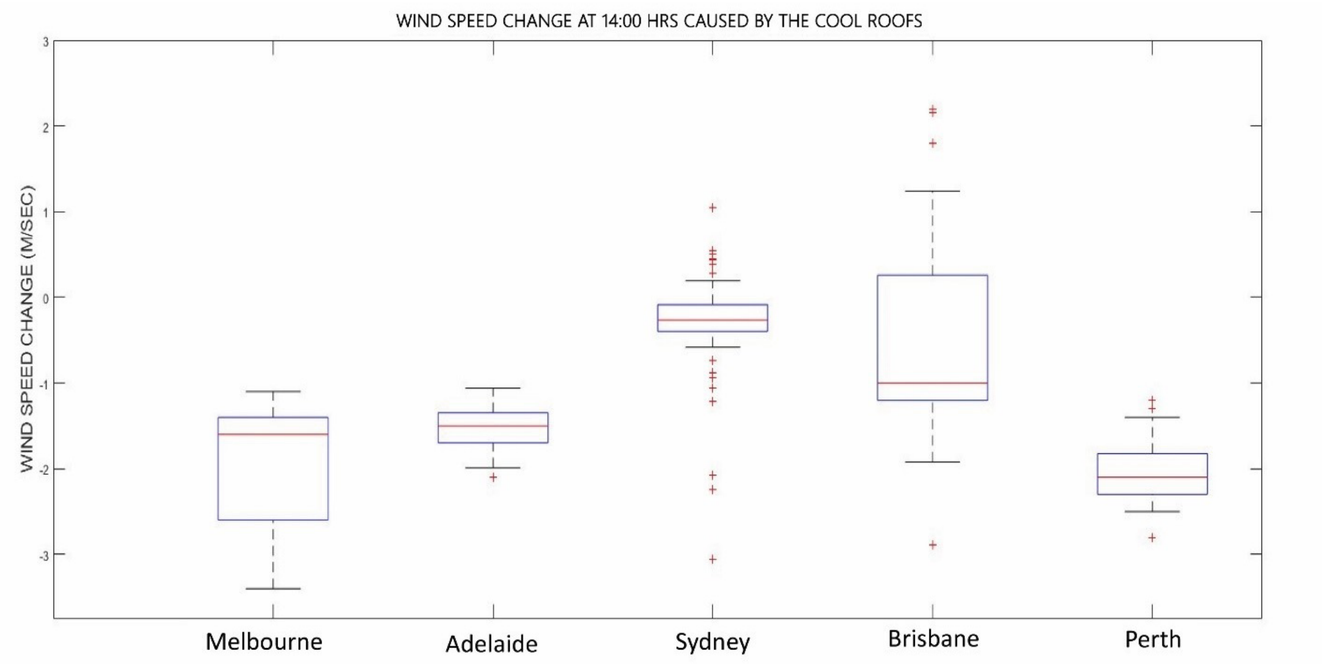


Figure 3.98 Range of the daily and spatially average drop of the wind speed at 14:00 hrs in the five main Australian cities during January and February.

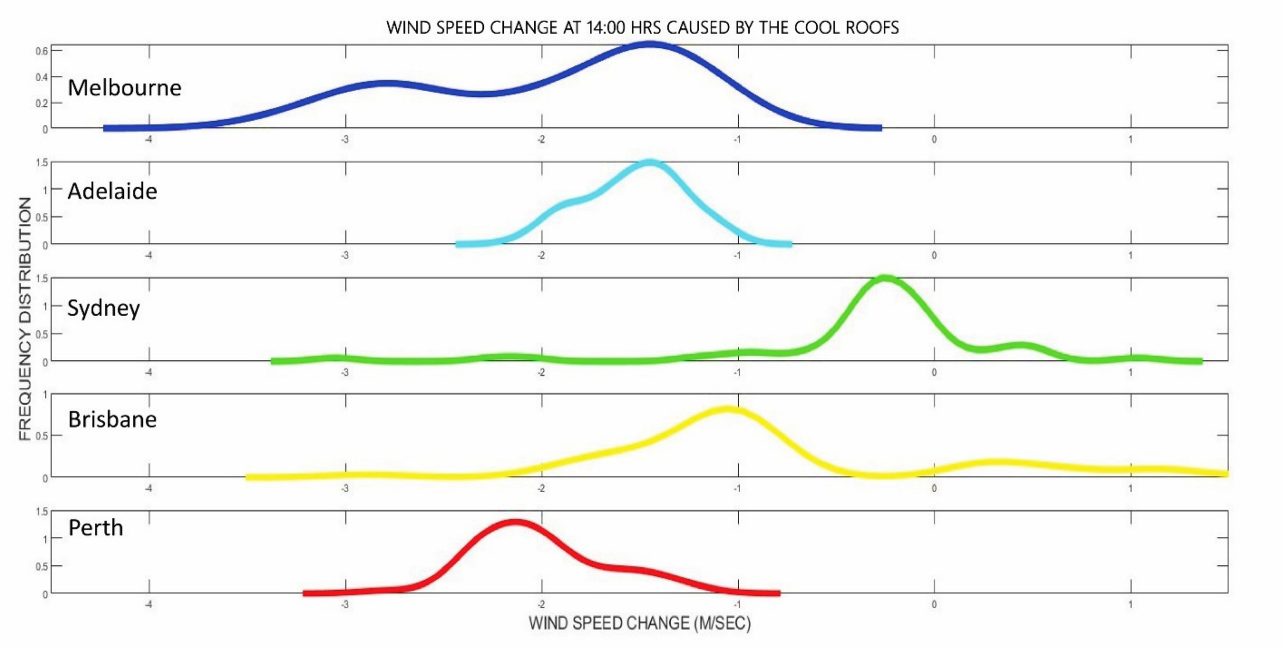


Figure 3.99 Frequency distribution of the daily and spatially average drop of the wind speed at 14:00 hrs in the five main Australian cities during January and February.

3.11.4. IMPACT ON SENSIBLE HEAT

Figures 3.100 – 3.101 present the variability of the spatially average change of the released sensible heat caused by the installation of the cool roofs at 14:00 hrs during January and February as calculated through the WRF simulations. The main conclusions are:

a. The daily change of the released sensible heat at 14:00 hrs, caused by the installation of cool roofs in the five Australian cities, varies between 60 W/m2 and 380 W/m^2.

b. The corresponding median change of the released sensible heat at 14:00 hrs varies between 140 W/m^2 and 240 W/m^2, while the maximum drop varies between 170 W/m^2 and 300 W/m^2, and the minimum between 60 W/m^2 and 140 W/m^2.

c. The maximum drop in released sensible heat at 14:00 hrs caused by the installation of cool roofs was calculated for Brisbane. The median spatially average decrease of sensible heat at 14:00 hrs is close to 240 W/m^2 while its maximum is around 280 W/m^2 and its minimum is 130 W/m^2.

d. The median sensible heat drop in Sydney, Melbourne, Perth, Adelaide and Brisbane, is 210 W/m^2, 175 W/m^2, 160 W/m^2 and 140 W/m^2 respectively and the maximum drop is close to 280 W/m^2, 250 W/m^2, 180 W/m^2 and 170 W/m^2, respectively.

e. The more probable change in sensible heat in all cities is very close to the median value as given above.

f. In Sydney, for 78% of the days, the average drop insensible heat is between 150 W/m^2 and 250 W/m^2.

g. In Brisbane, for 83% of the days, the average drop insensible heat is between 180 W/m^2 and 280 W/m^2.

h. In Perth, for 95% of the days, the average drop insensible heat is between 150 W/m^2 and 250 W/m^2.

i. In Melbourne, for 78% of the days, the average drop insensible heat is between 140 W/m^2 and 180 W/m^2.

j. In Adelaide, 98% of the days, the average drop insensible heat is between 110 W/m^2 and 180 W/m^2.

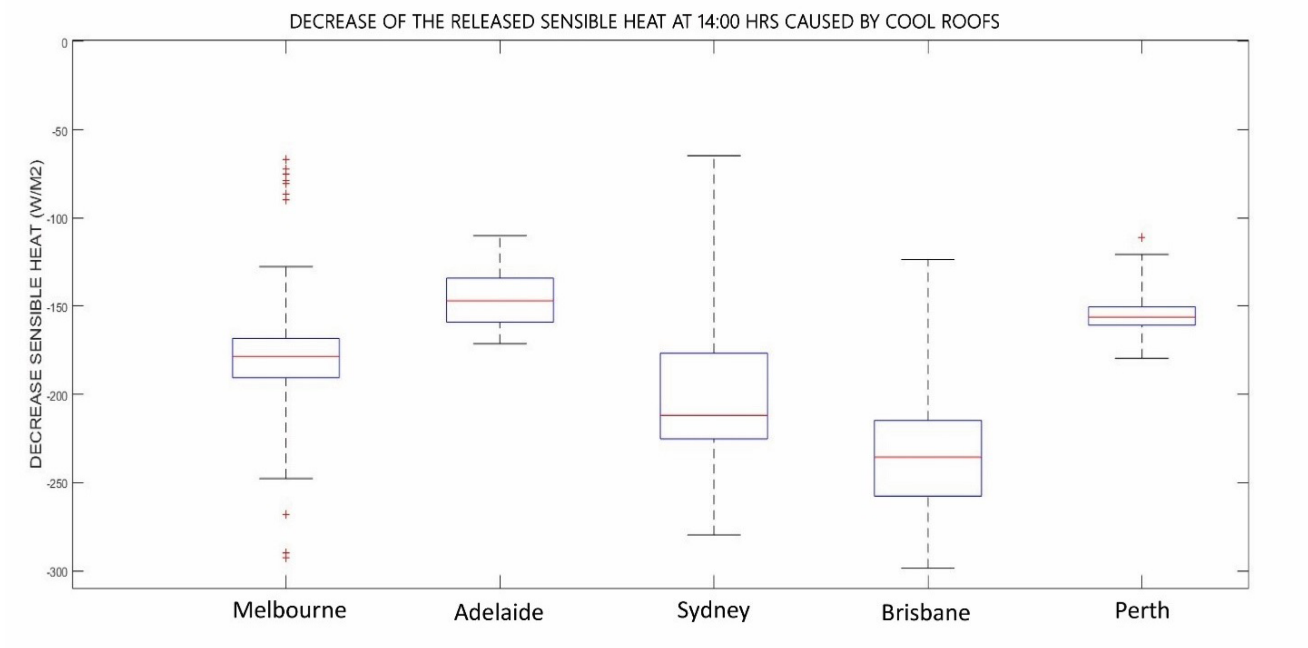


Figure 3.100 Range of the daily and spatially average drop in released sensible heat at 14:00 hrs in the five main Australian cities during January and February.

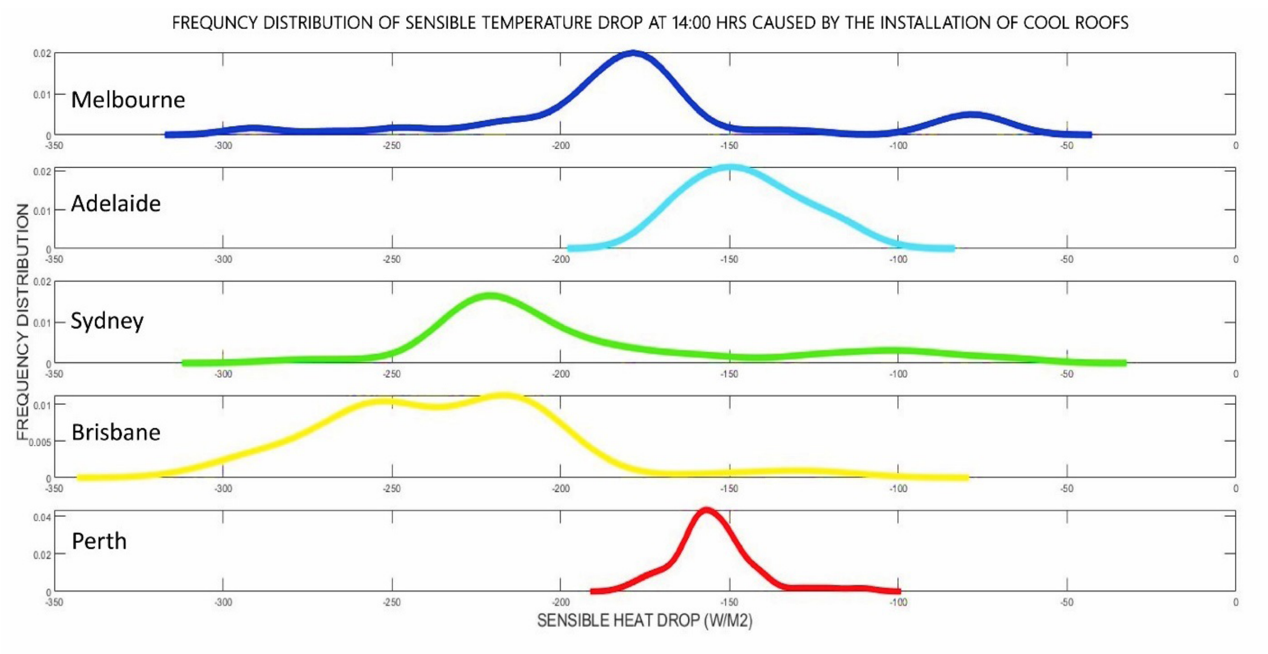


Figure 3.101 Frequency distribution of the daily and spatially average drop in released sensible heat at 14:00 hrs in the five main Australian cities during January and February.

3.11.5. IMPACT ON LATENT HEAT

Figures 3.102-3.103 present the variability of the spatially average change in released latent heat caused by the installation of the cool roofs at 14:00 hrs during January and February as calculated through the WRF simulations. As shown, the change in latent heat is not significant.

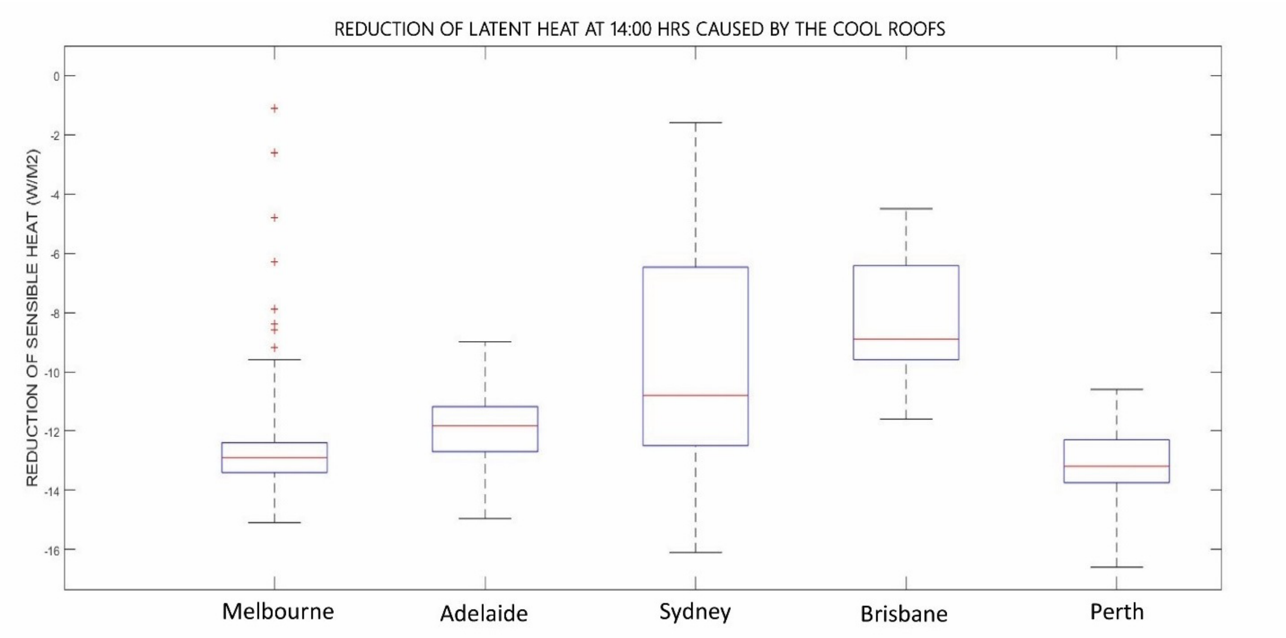


Figure 3.102 Range of the daily and spatially average drop in released latent heat at 14:00 hrs in the five main Australian cities during January and February.

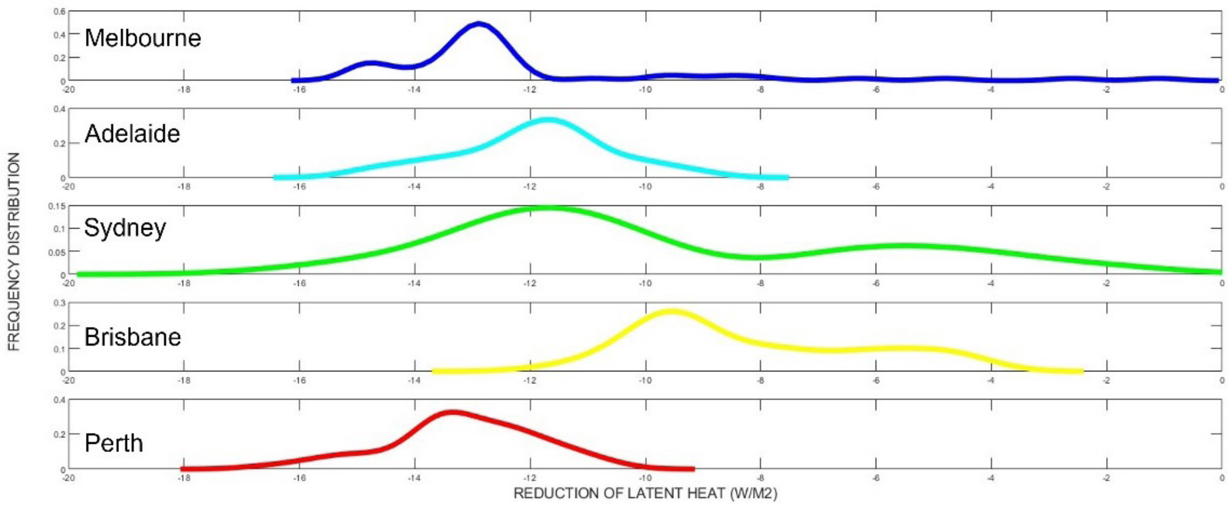
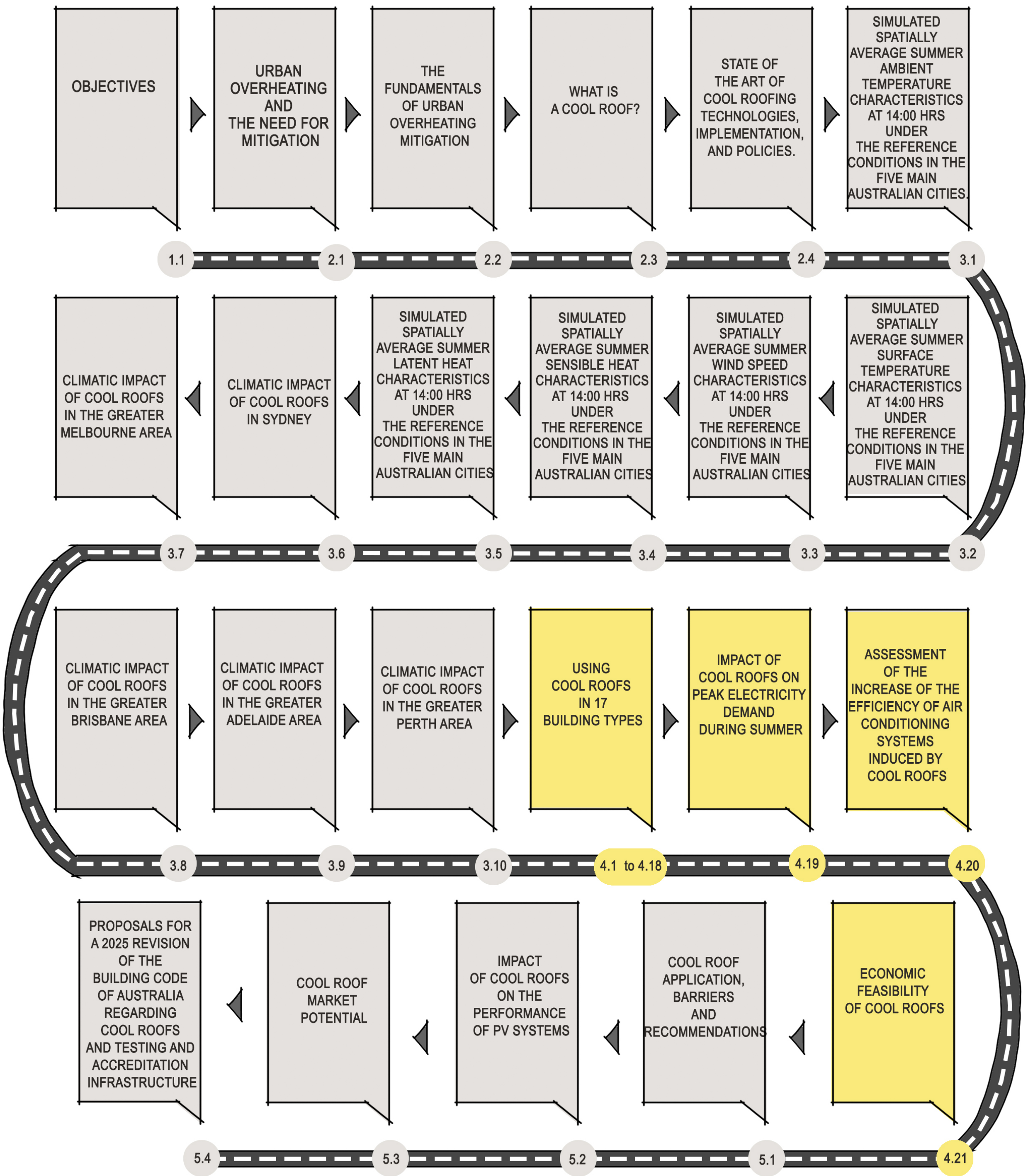


Figure 3.103 Frequency distribution of the daily and spatially average drop in released latent heat at 14:00 hrs in the five main Australian cities during January and February.

4. IMPACT OF COOL ROOFS ON THE ENERGY PERFORMANCE OF BUILDINGS



4.1. CONTEXT

The impact of cool roofs on the energy consumption of 17 types of buildings has been assessed for Adelaide, Alice Springs, Brisbane, Darwin, Hobart, Melbourne, Perth and Sydney.

The seventeen types of buildings considered, include:

1. A low-rise office building without roof insulation — existing building;
2. A high-rise office building without roof insulation — existing building;
3. A low-rise office building with roof insulation — new building;
4. A high-rise office building with roof insulation — new building;
5. A low-rise shopping mall centre — new building;
6. A mid-rise shopping mall centre — new building;
7. A high-rise shopping mall centre — new building;
8. A low-rise apartment building — new building;
9. A mid-rise apartment building — new building;
10. A high-rise apartment building — new building;
11. A typical stand-alone house — existing building;
12. A typical school building — existing building;
13. A low-rise office building with roof insulation — existing building;
14. A high-rise office building with roof insulation — existing building;
15. A low-rise shopping mall centre — existing building;
16. A high-rise shopping mall centre — existing building; and
17. A stand-alone house — new building.

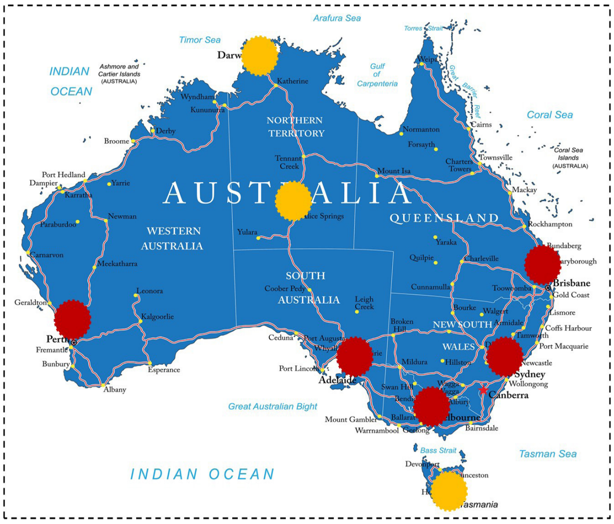


Figure 4.1 Australian Cities where the energy performance of cool roofs is assessed.

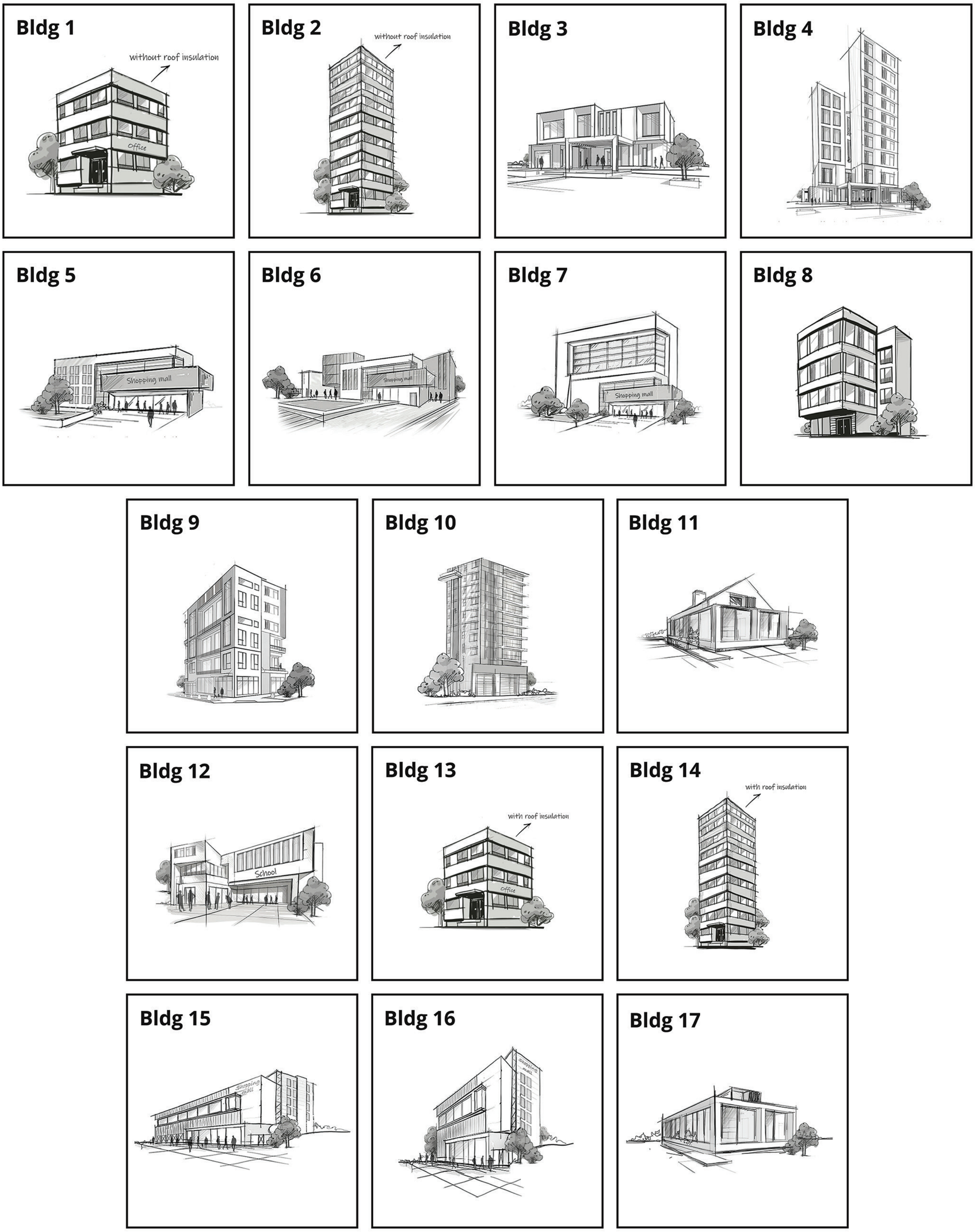


Figure 4.2 Sketches of the 17 buildings considered.

Simulations have been performed under:

— **Thermostatic control conditions.** The heating and cooling load of the buildings has been calculated considering defined indoor temperature set points during the heating and cooling periods. Three operational scenarios are evaluated:

  » Reference scenario: building without a cool roof in a low albedo city;
  » Cool roof scenario 1: building with a cool roof in a low albedo city;
  » Cool roof scenario 2: building with a cool roof in a high albedo city considering a city-wide installation of cool roofs.

— **Free floating conditions.** The indoor temperature of each building is calculated during the whole year, assuming that no auxiliary heating and cooling system is under operation. The three previously mentioned operational scenarios are considered as well.

Simulations have been performed for two types of climatic data:

— **Simulated summer climatic data** as obtained through the mesoscale climatic model for the five main cities and for two summer months, January, and February. Mesoscale simulated data are used to calculate the performance of the 17 buildings under both thermostatic control and free-floating conditions, for the three operational scenarios mentioned above and for a high number of meteorological stations in each city.

— **Measured annual climatic data**, obtained from BOM. Measured data are used to simulate the annual performance of the 17 buildings under thermostatic control conditions and for the reference and the first scenario of cool roofs.

The following material presents the results obtained for each of the 17 types of simulated buildings.

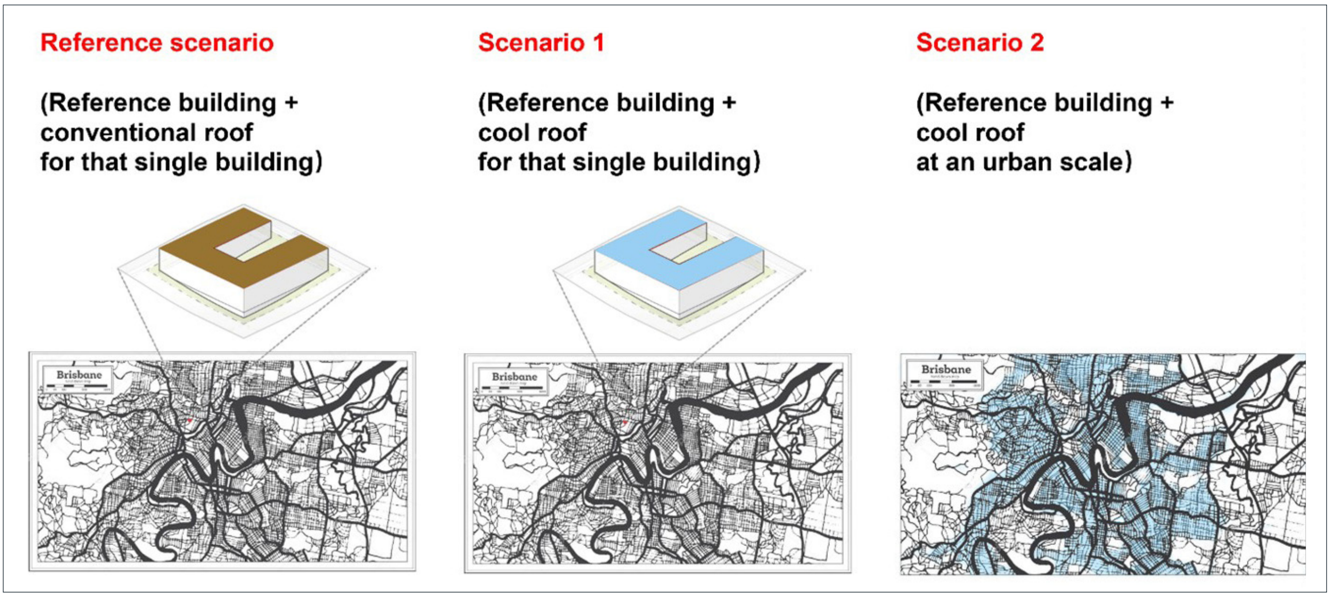


Figure 4.3 Scenarios considered to assess the energy contribution of cool roofs.

4.2. USING COOL ROOFS IN A LOW-RISE OFFICE BUILDING WITHOUT ROOF INSULATION — EXISTING BUILDING, BUILDING TYPE 1

4.2.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

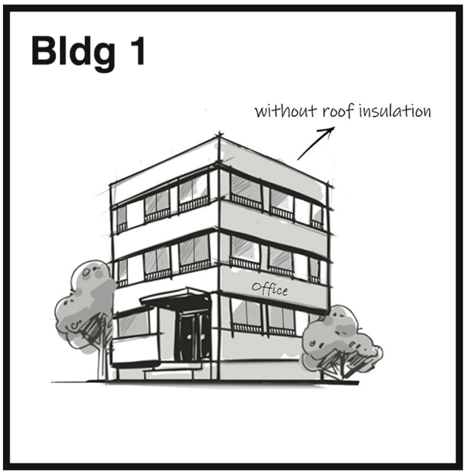


Figure 4.4 Building Type 1: Sketch of a low-rise office building without roof insulation. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of the simulated data and results are given in the extended final report.

A significant spatial difference in the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, in Sydney, the sensible cooling load, (January and February), in the eastern part of the city at Observatory Hill, is close to 19.1 kWh/m^2, while it is almost 57% higher, exceeding 30 kWh/m^2 in the Western part of Sydney, Richmond station. Figure 4.5 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 1, in Sydney under reference conditions.

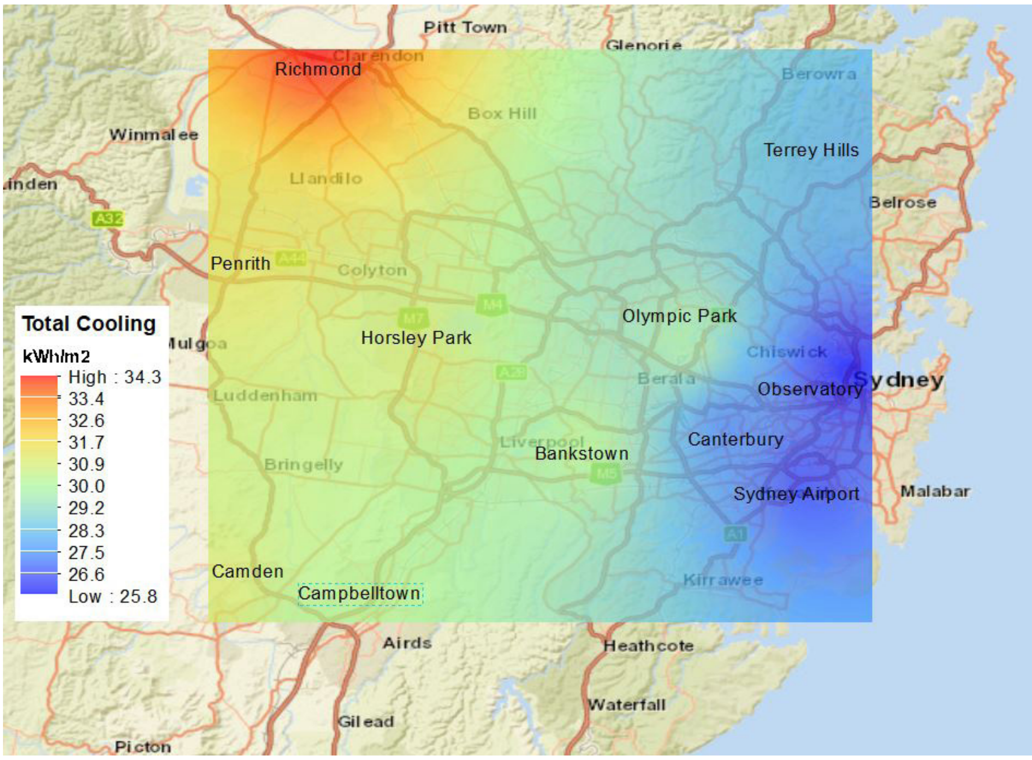


Figure 4.5 Spatial distribution of the total sensible and latent cooling needs of low-rise office building without roof insulation in Sydney under reference conditions.

It is calculated that both building-scale, Scenario 1, and combined building and urban scale application of cool roofs (Scenario 2) can significantly reduce the cooling load of the typical low-rise office building without insulation during the summer season (Figure 4.6). In an individual low rise office building without roof insulation (Scenario 1) the spatially average cooling demand in the five cities decreases between 29.3% and 50%.

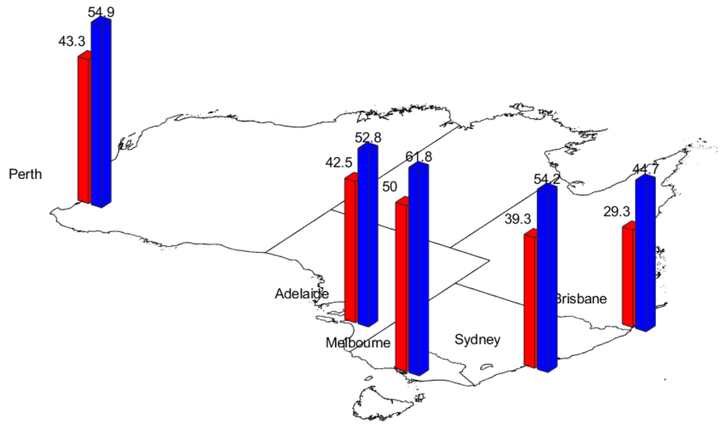


Figure 4.6 Percentage reduction of the cooling demand of a low-rise office building without roof insulation in the five main Australian cities during January and February.

When cool roofs are installed in a low-rise office building without roof insulation both in building and city scale, Scenario 2, the expected energy conservation ranges between 44.7% and 61.8%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings (Scenario 1) is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it is observed that:

- The annual cooling load decreases between 34.1% and 44.4%, Figure 4.7.
- The heating penalty is very low in all cities except for Hobart, where the use of cool roofs is not highly recommended for this type of building.
- Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of cool roofs in an individual low rise office building without roof insulation ranges between 21.4% to 37.7%.

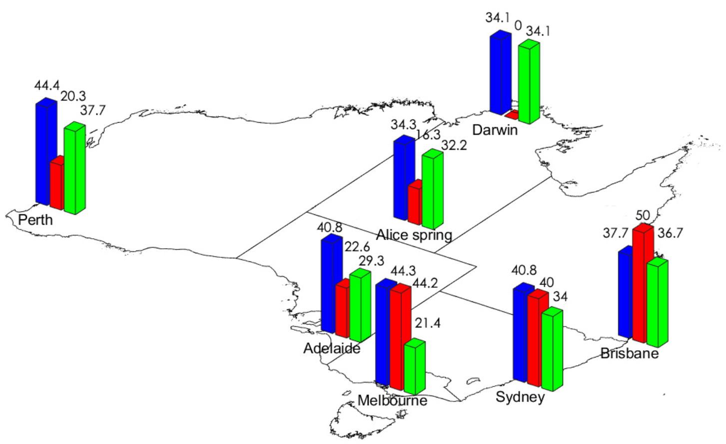


Figure 4.7 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a low-rise office building without roof insulation, at the building scale, Scenario 1.

Under free floating conditions, cool roofs installed in low-rise office buildings without roof insulation, at the building scale (Scenario 1), may reduce the peak summer ambient temperature in the five main cities between 5.1°C and 11.4°C, Figure 4.8. When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 5.9°C and 12°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.4°C and 3.6°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C . In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.8.

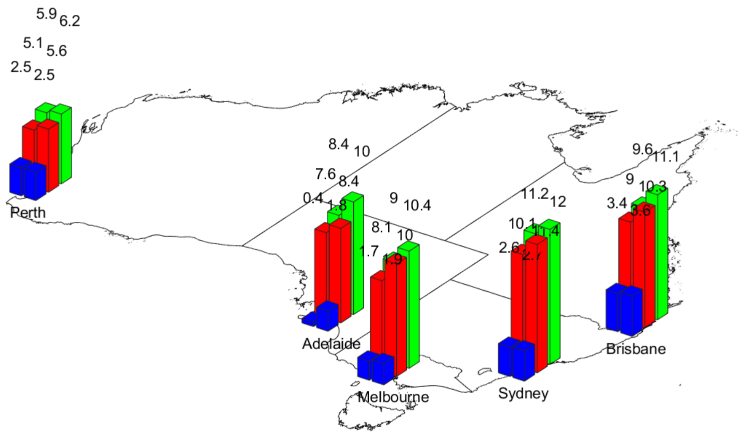


Figure 4.8 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a low-rise office building without roof insulation.

Table 4.1 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease between 5% and 42%.
- When cool roofs are installed in both the buildings and the city scale, overheating hours may decrease between 11% and 54%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	550 – 553	424 – 433	359 – 390
Melbourne	334 – 395	193 – 253	152 – 197
Brisbane	649 – 664	591 – 629	558 – 592
Adelaide	436 – 457	326 – 367	251 – 333
Perth	478 – 498	361 – 393	312 – 358

Table 4.1 Monthly number of hours above 26 in the five main Australian cities for a low-rise office building operating under free floating conditions.

Table 4.2 reports the number of hours below 19°C, under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

- During the operational hours, the number of hours below 19, increases between 12 and 59 hours, while during the whole period, the increase ranges between 46 and 78 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	97 – 113	377 – 424	139 – 159	450 – 494
Melbourne	217 – 230	580 – 597	276 – 285	645 – 656
Brisbane	30 – 37	158 – 229	42 – 56	221 – 294
Adelaide	215 – 272	574 – 635	261 – 317	622 – 681
Perth	98 – 112	361 – 402	138 – 158	439 – 479

Table 4.2 Monthly number of hours below 19 in the five main Australian cities for a low-rise office building operating under free floating conditions.

4.3. USING COOL ROOFS IN A HIGH-RISE OFFICE BUILDING WITHOUT ROOF INSULATION — EXISTING BUILDING, BUILDING TYPE 2

4.3.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

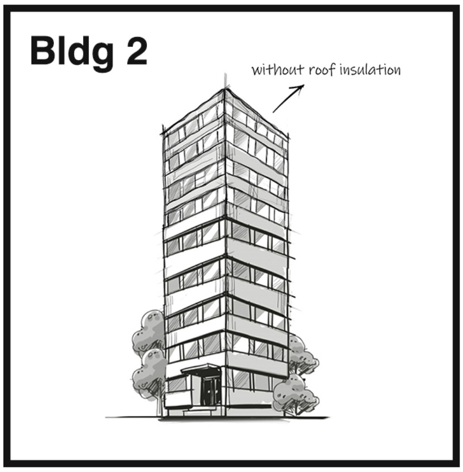


Figure 4.9 Building Type 2: Sketch of a high-rise office building without roof insulation. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A major spatial difference in cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, in Sydney, the sensible cooling load (January and February), in the eastern part of the city, Observatory Hill, is close to 13.2 kWh/m^2, while it is almost 65% higher, exceeding 21.8 kWh/m^2 in the western part of Sydney, Richmond station, Figure 4.10, presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 2, in Sydney under reference conditions.

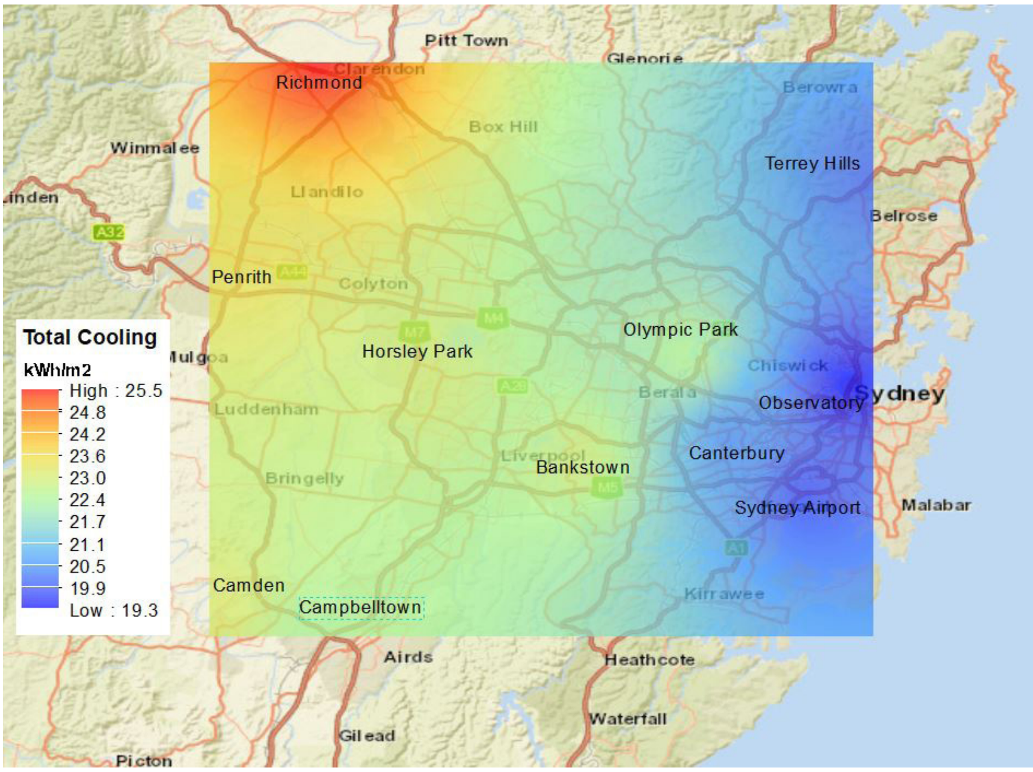


Figure 4.10 Spatial Distribution of the total sensible and latent cooling needs of high-rise office building without roof insulation in Sydney under reference conditions.

It is calculated that both building-scale (Scenario 1), and the combined building scale and urban scale application of cool roofs, can significantly reduce the cooling load of the typical high-rise office building without insulation during the summer season (Figure 4.11).

When cool roofs are installed in an individual high rise office building without roof insulation (Scenario 1), the spatially average cooling demand in the five cities decreases between 6.6% and 14.6% (Figure 4.11). When cool roofs are installed in a high-rise office building without roof insulation both at building and city scale (Scenario 2), the expected energy conservation ranges between 27% and 35.4%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

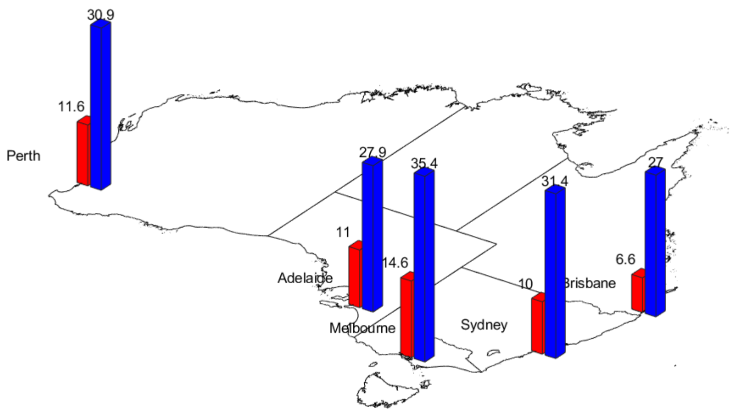


Figure 4.11 Percentage reduction of the cooling demand of a high-rise office building without roof insulation in the five main Australian cities during January and February.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it is observed that:

- The annual cooling load decreases between 7.9% and 11.7%, Figure 4.12.
- The heating penalty is very low in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

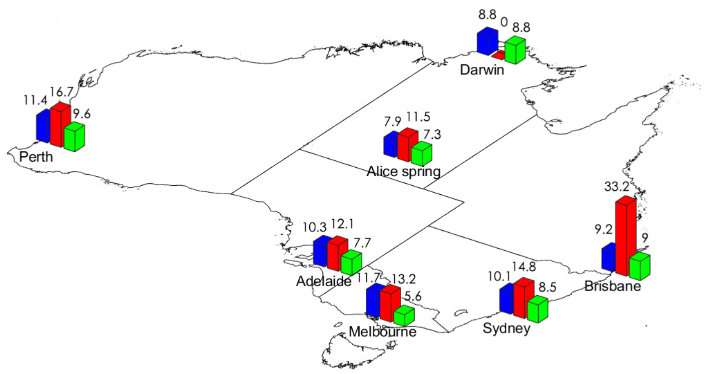


Figure 4.12 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a low-rise office building without roof insulation, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of cool roofs in an individual high rise office building without roof insulation ranges between 5.6% to 9.6%. Under free-floating conditions, cool roofs installed in high rise office buildings without roof insulation, at the Scenario 1 building scale, may reduce the peak summer ambient temperature in the five main cities, between 0.9°C and 2.3°C, Figure 4.13.

When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 1.8°C and 3.3°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.1°C and 0.6°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, as in Figure 4.13.

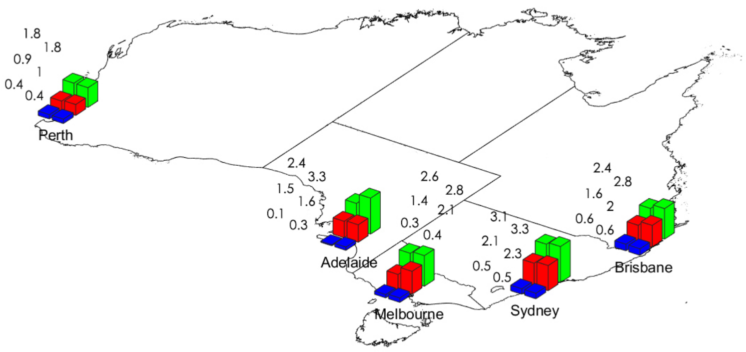


Figure 4.13 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a high-rise office building without roof insulation.

Table 4.3 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered (Scenarios 1 and 2).

- When cool roofs are installed at building scale (Scenario1), the number of overheating hours is found to decrease between 0% and 18%.
- When cool roofs are installed in both the buildings and city scale, overheating hours may decrease between 1% and 27%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	653 – 670	637 – 667	614 – 634
Melbourne	297 – 424	249 – 372	186 – 310
Brisbane	672	672	668 – 672
Adelaide	510 – 542	485 – 521	462 – 477
Perth	587 – 596	568 – 583	515 – 545

Table 4.3 Monthly number of hours above 26 in the five main Australian cities for a high-rise office building without roof insulation operating under free-floating conditions.

Table 4.4 reports the number of hours below 19°C, under the reference conditions and the first cool roof scenarios for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

- During the operational hours, the number of hours below 19 increases between 1 and 13 hours, while during the whole period, the increase ranges between 4 and 19 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	37 – 72	118 – 257	38 – 80	125 – 276
Melbourne	69 – 185	430 – 517	71 – 194	439 – 531
Brisbane	0 – 15	6 – 80	4 – 16	10 – 91
Adelaide	156 – 221	460 – 551	165 – 234	473 – 569
Perth	49 – 67	149 – 218	54 – 75	160 – 232

Table 4.4 Monthly number of hours below 19 in the five main Australian cities for a high-rise office building without roof insulation operating under free-floating conditions.

4.4. USING COOL ROOFS IN A LOW-RISE OFFICE BUILDING WITH ROOF INSULATION—NEW BUILDING, BUILDING TYPE 3

4.4.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

Figure 4.14 Building Type 3: Sketch of a low-rise office building with roof insulation — new building. Data on the characteristics of the building are given in the extended final report

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A significant spatial difference of the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city at Observatory Hill, is close to 12.4 kWh/m^2, while it is almost 64% higher, exceeding 20.3 kWh/m^2 in the Western part of Sydney, Richmond station. Figure 4.15 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 3, in Sydney under reference conditions.

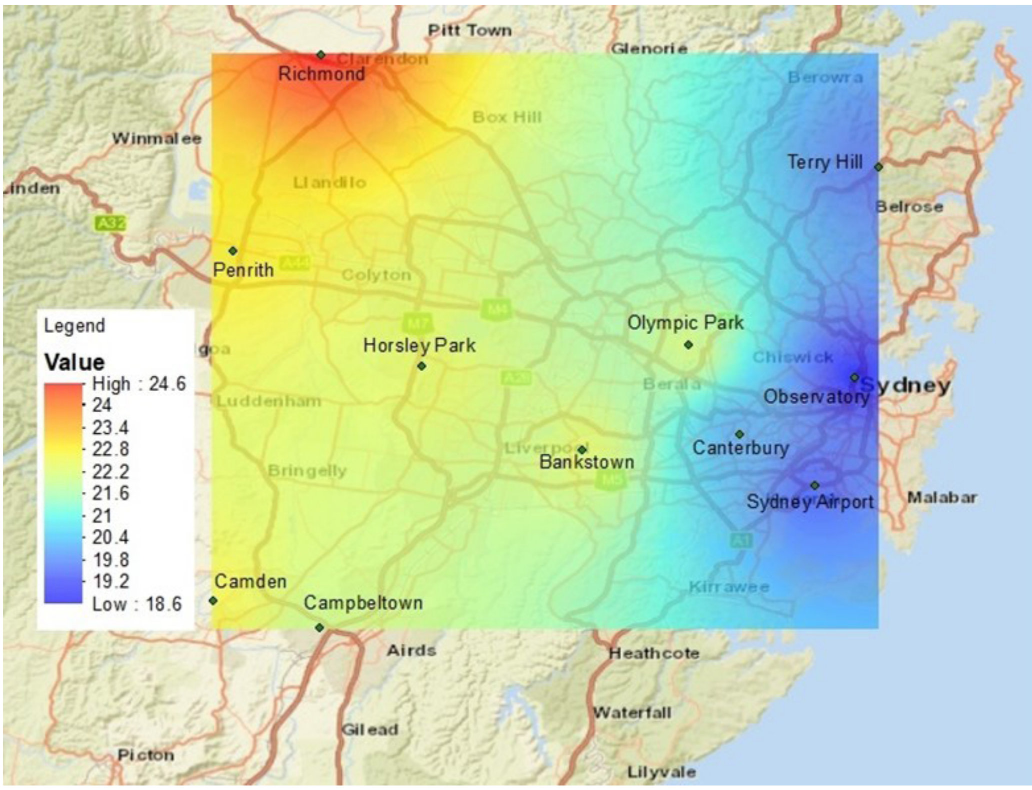


Figure 4.15 Spatial distribution of the total sensible and latent cooling needs of a low-rise office building with roof insulation — new building in Sydney under reference conditions.

It is calculated that both building-scale, Scenario 1, and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical low-rise office building with roof insulation in a new building during the summer season, Figure 4.16.

When cool roofs are installed in an individual low-rise office building with roof insulation in a new building, Scenario 1, the spatially average cooling demand in the five cities decreases between 3.9% and 7.7% as in Figure 4.16. When cool roofs are installed in a low-rise office building without roof insulation both in building and city scale, Scenario 2, the expected energy conservation ranges between 23.9% and 30.8%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

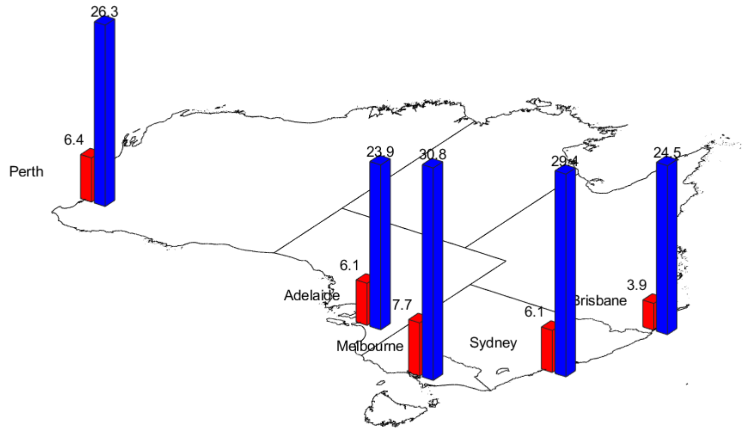


Figure 4.16 Percentage reduction of the cooling demand of a low-rise office building with roof insulation in a new building in the five main Australian cities during January and February.

For Scenario 1, when the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it is observed that:

- The annual cooling load decreases between 4.7% and 7.7% as in Figure 4.17.
- The heating penalty is substantially low in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

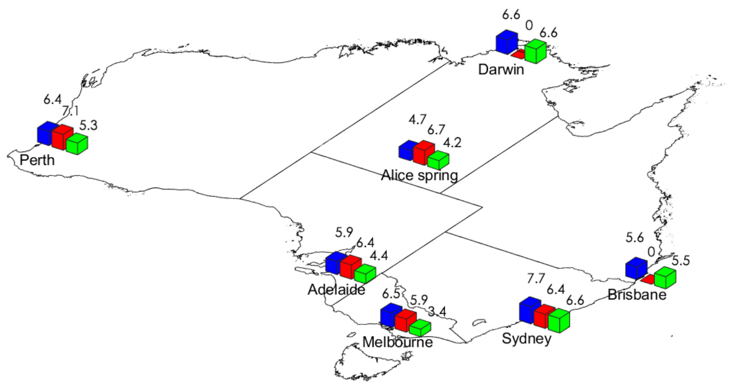


Figure 4.17 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a low-rise office building with roof insulation — new building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of cool roofs in an individual low-rise office building with roof insulation — new building ranges between 3.4% to 6.6%.

Under free floating conditions, cool roofs installed at a low-rise office building with roof insulation in a new building, at building scale (Scenario 1), may reduce the peak summer ambient temperature in the five main cities, between 0.6°C and 1.6°C, Figure 4.18. When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 1.5°C and 3.0°C.

The average maximum decrease of the peak indoor temperature during the winter period is varying between 0.3°C and 1.3°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.18.

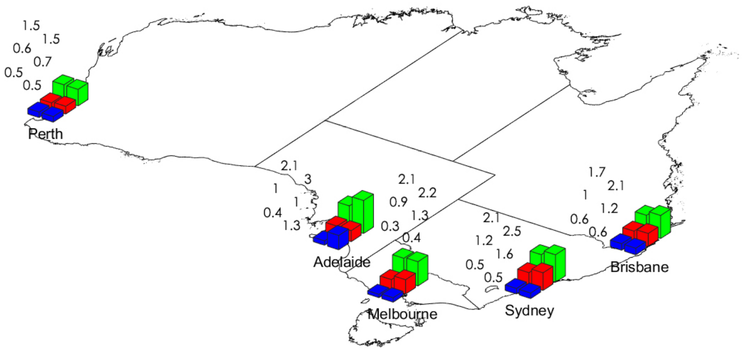


Figure 4.18 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a low-rise office building with roof insulation — new building.

Table 4.5, reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease between 0% and 12%.
- When cool roofs are installed at both the building and the city scale, overheating hours may decrease between 0% and 24%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	630 – 658	622 – 652	595 – 613
Melbourne	345 – 399	317 – 359	250 – 305
Brisbane	670 – 672	668 – 672	662 – 672
Adelaide	494 – 510	471 – 493	388 – 456
Perth	540 – 556	520 – 543	471 – 507

Table 4.5 Monthly number of hours above 26 in the five main Australian cities for a low-rise office building with roof insulation — new building operating under free-floating conditions.

Table 4.6 reports the number of hours below 19 under the reference conditions and the first cool roof scenarios for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

- During the operational hours, the number of hours below 19 increases by 3 to 42 hours, while during the whole period, the increase ranges between 3 and 98 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	41 – 4	147 – 276	45 – 116	245 – 287
Melbourne	132 – 163	415 – 492	138 – 173	432 – 509
Brisbane	45474	21 – 109	15 – 27	24 – 116
Adelaide	135 – 195	437 – 525	165 – 205	472 – 541
Perth	56 – 66	177 – 230	59 – 75	186 – 246

Table 4.6 Monthly number of hours below 19 in the five main Australian cities for a low-rise office building with roof insulation — new building operating under free-floating conditions

4.5. USING COOL ROOFS IN A HIGH-RISE OFFICE BUILDING WITH ROOF INSULATION — NEW BUILDING, BUILDING TYPE 4

4.5.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

Figure 4.19 Building Type 4: Sketch of a high-rise office building with roof insulation — new building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A distinct spatial difference in the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city, Observatory Hill, is close to 12.0 kWh/m², while it is almost 65% higher, exceeding 19.8 kWh/m² in the western part of Sydney at Richmond station. Figure 4.20 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 4, in Sydney under reference conditions.

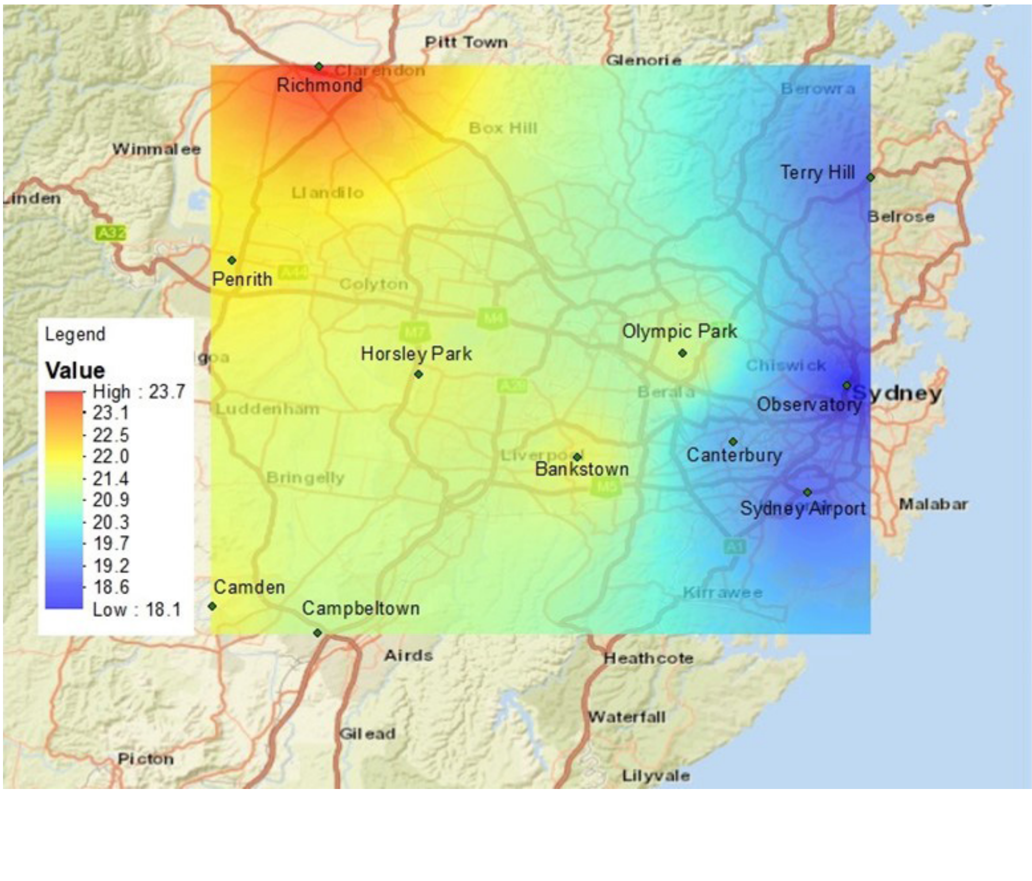


Figure 4.20 Spatial distribution of the total sensible and latent cooling needs of a high-rise office building with roof insulation — new building in Sydney under reference conditions.

It is calculated that both the Scenario 1 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 with roof insulation in a new building during the summer season, Figure 4.21.

When cool roofs are installed in a new individual high-rise office building with roof insulation as in Scenario 1, the spatially average cooling demand in the five cities decreases between 0.9% and 1.4% (Figure 4.21).

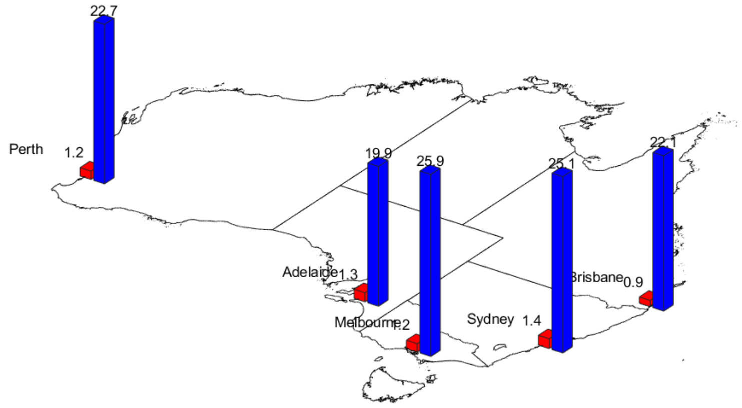


Figure 4.21 Percentage reduction of the cooling demand of a high-rise office building with roof insulation in a new building in the five main Australian cities during January and February.

When cool roofs are installed in a high-rise office building with roof insulation — new building both at building and city scale as in Scenario 2, expected energy conservation ranges between 19.9% and 25.9%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings, Scenario 1, is calculated for the five main cities and Alice Springs, Darwin and Hobart, it is seen that:

- The annual cooling load decreases by -0.3% to 1.4%, as in Figure 4.22.
- The heating penalty is substantially low in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

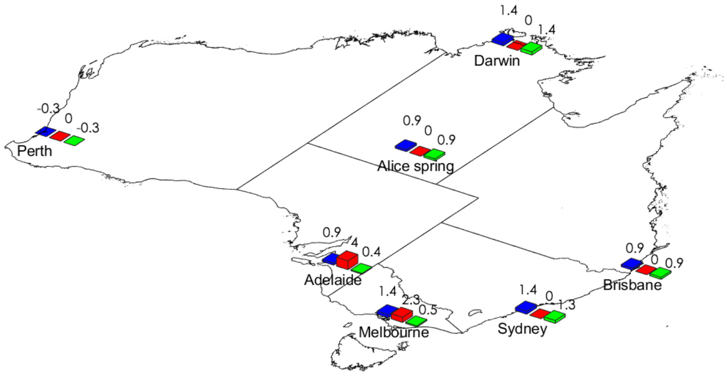


Figure 4.22 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a high-rise office building with roof insulation — new building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of a cool roof in an individual high-rise office building with roof insulation in a new building ranges between -0.3% to 1.4%.

Under free floating conditions, cool roofs installed at a high-rise office building with roof insulation in a new building, at the building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, between 0.1°C and 0.3°C , Figure 4.23.

When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 1.1°C and 2.5°C .

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.1°C and 0.2°C . However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.23.

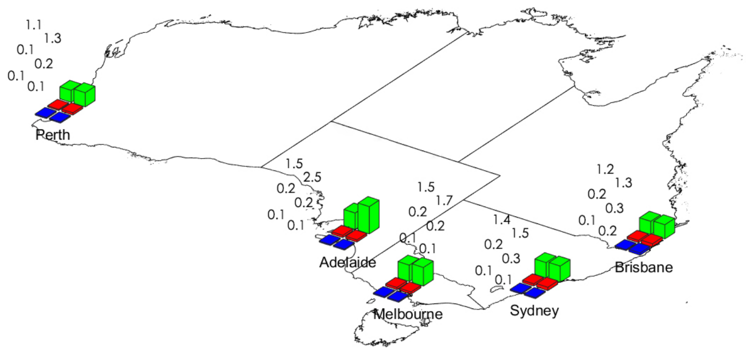


Figure 4.23 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a high-rise office building with roof insulation — new building.

Table 4.7 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease between 0% and 2%.
- When cool roofs are installed in both the buildings and the city scale, overheating hours may decrease between 0% and 22%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	661 – 672	659 – 672	634 – 657
Melbourne	382 – 427	375 – 419	286 – 353
Brisbane	672	672	672
Adelaide	529 – 560	523 – 556	436 – 511
Perth	606 – 612	600 – 609	555 – 583

Table 4.7 Monthly number of hours above 26 in the five main Australian cities for a high-rise office building with roof insulation — new building operating under free-floating conditions.

Table 4.8 reports the number of hours below 19 under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

- During operational hours, the number of hours below 19 increases between 0 and 17 hours, while during the whole period, the increase ranges between 0 and 14 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	Operational hours	Total	Operational hours	Total
Sydney	21 – 65	67 – 225	22 – 82	70 – 226
Melbourne	124 – 164	353 – 461	124 – 164	367 – 461
Brisbane	0 – 10	20821	0 – 14	21551
Adelaide	136 – 199	416 – 505	137 – 202	417 – 510
Perth	34 – 51	100 – 157	34 – 51	100 – 159

Table 4.8 Monthly number of hours below 19 in the five main Australian cities for a high-rise office building with roof insulation — new building operating under free-floating conditions.

4.6. USING COOL ROOFS IN A LOW-RISE SHOPPING MALL CENTRE — NEW BUILDING, BUILDING TYPE 5

4.6.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

Figure 4.24 Building Type 5: Sketch of a low-rise shopping mall — new building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A significant spatial difference in cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, in Sydney, the sensible cooling load in January and February, in the eastern part of the city at Observatory Hill, is close to 52.3 kWh/m^2, while it is almost 28% higher, exceeding 67.0 kWh/m^2 in the western part of Sydney at Richmond station. Figure 4.25 presents the spatial distribution of the sum of sensible and latent cooling loads for Building Type 5, in Sydney under reference conditions.

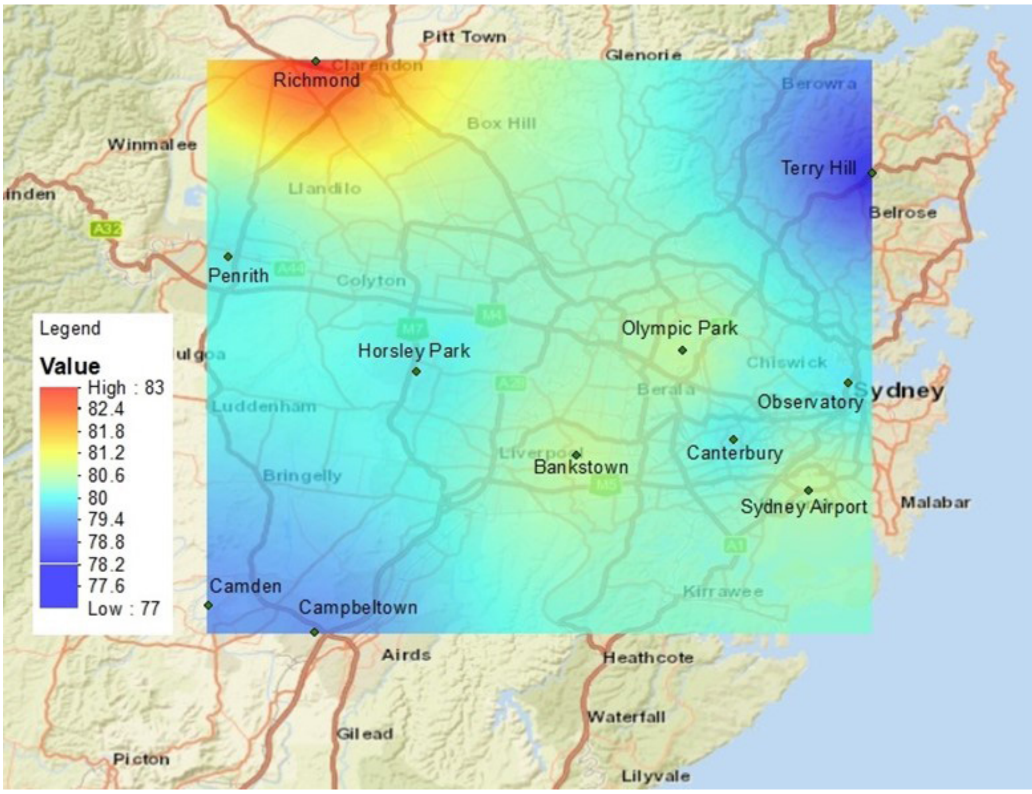


Figure 4.25 Spatial Distribution of the total sensible and latent cooling needs of a low-rise shopping mall centre — new building in Sydney under reference conditions.

It is calculated that at both building scale, Scenario 1, and combined building scale and urban scale application, cool roofs can significantly reduce the cooling load on a new typical low-rise shopping mall during the summer season, Figure 4.26.

When cool roofs are installed in a new individual low-rise shopping mall, Scenario 1, the spatially average cooling demand in the five cities decreases between 1.6% and 3.6%, Figure 4.26.

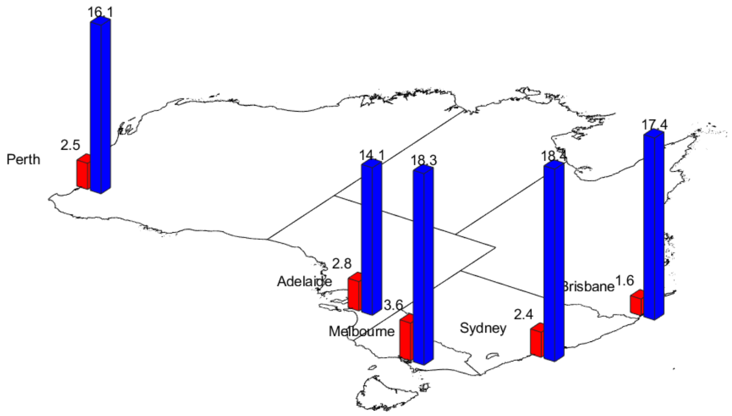


Figure 4.26 Percentage reduction of the cooling demand of a low-rise shopping mall centre — new building in the five main Australian cities during January and February.

When cool roofs are installed in a low-rise shopping mall centre - new building, both at building and city scale (Scenario 2) expected energy conservation ranges between 14.1% and 18.4%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings, Scenario 1 is calculated for the five main cities plus Alice Springs, Darwin and Hobart, it is observed that:

- The annual cooling load decreases between 2.3% and 3.8%, Figure 4.27.
- The heating penalty is substantially low in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

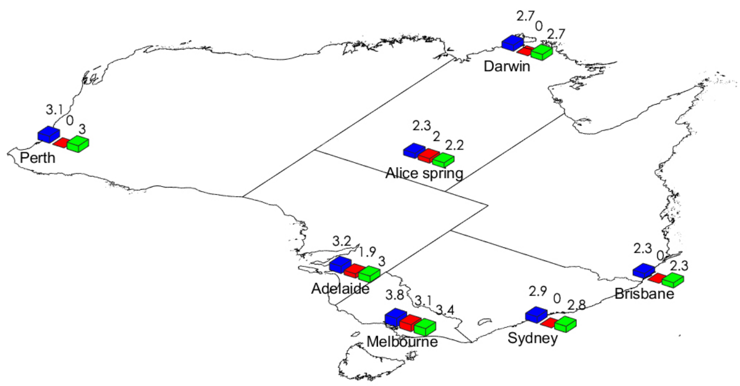


Figure 4.27 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a low-rise shopping mall centre — new building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of cool roofs in an individual low-rise shopping mall centre range between 2.2% to 3.4%.

Under free floating conditions, cool roofs installed at a low-rise shopping mall - new building, at the building scale (Scenario 1) may reduce the peak summer ambient temperature in the five main cities by between 0.4°C and 0.8°C as in Figure 4.28.

When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 1.3°C and 2.9°C. The average maximum decrease of the peak indoor temperature during the winter period varies between 0.2°C and 0.4°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort as in Figure 4.28.

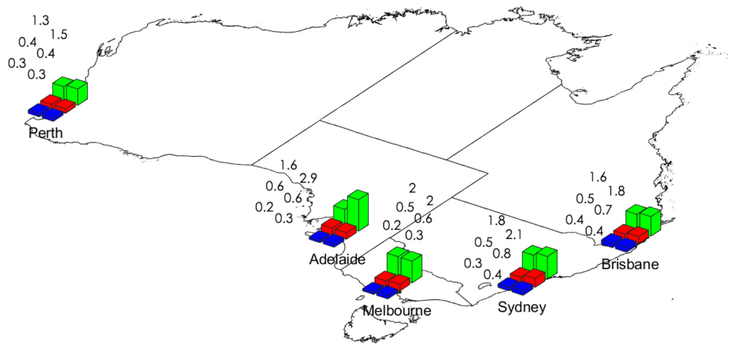


Figure 4.28 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a low-rise shopping mall centre — new building.

Table 4.9 reports the number of hours with an indoor temperature higher than 26°C under the reference conditions and also when cool roofs are considered (Scenarios 1 and 2).

- When cool roofs are installed at the building scale (Scenario1), the number of overheating hours is found to decrease by 0% and 3%.
- When cool roofs are installed in both the buildings and at the city scale, overheating hours may decrease by 1% and 11%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	641 – 669	639 – 668	611 – 619
Melbourne	430 – 455	418 – 444	382 – 408
Brisbane	672	671 – 672	666 – 672
Adelaide	520 – 533	518 – 530	467 – 506
Perth	594 – 595	586 – 593	551 – 564

Table 4.9 Monthly number of hours above 26 in the five main Australian cities for a low-rise shopping mall centre — new building operating under free-floating conditions.

Table 4.10 reports the number of hours below 19°C, under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

— During operational hours, the number of hours below 19 increases between 0 and 3 hours, while during the whole period, the increase ranges between 1 and 6 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	18 – 51	131 – 253	18 – 51	134 – 257
Melbourne	32 – 65	283 – 355	34 – 68	287 – 361
Brisbane	15 – 31	43 – 116	17 – 31	44 – 121
Adelaide	64 – 79	345 – 388	65 – 81	348 – 392
Perth	28 – 38	172 – 217	29 – 40	176 – 221

Table 4.10 Monthly number of hours below 19 in the five main Australian cities for a low-rise shopping mall centre — new building operating under free-floating conditions

4.7. USING COOL ROOFS IN A MID-RISE SHOPPING MALL CENTRE — NEW BUILDING, BUILDING TYPE 6

4.7.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

Figure 4.29 Building Type 6: Sketch of a mid-rise shopping mall centre — new building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A distinct spatial difference in the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city, Observatory Hill is close to 51.3 kWh/m^2, while it is almost 28% higher, exceeding 65.8 kWh/m^2 in the western part of Sydney at Richmond station. Figure 4.30 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 6, in Sydney under reference conditions.

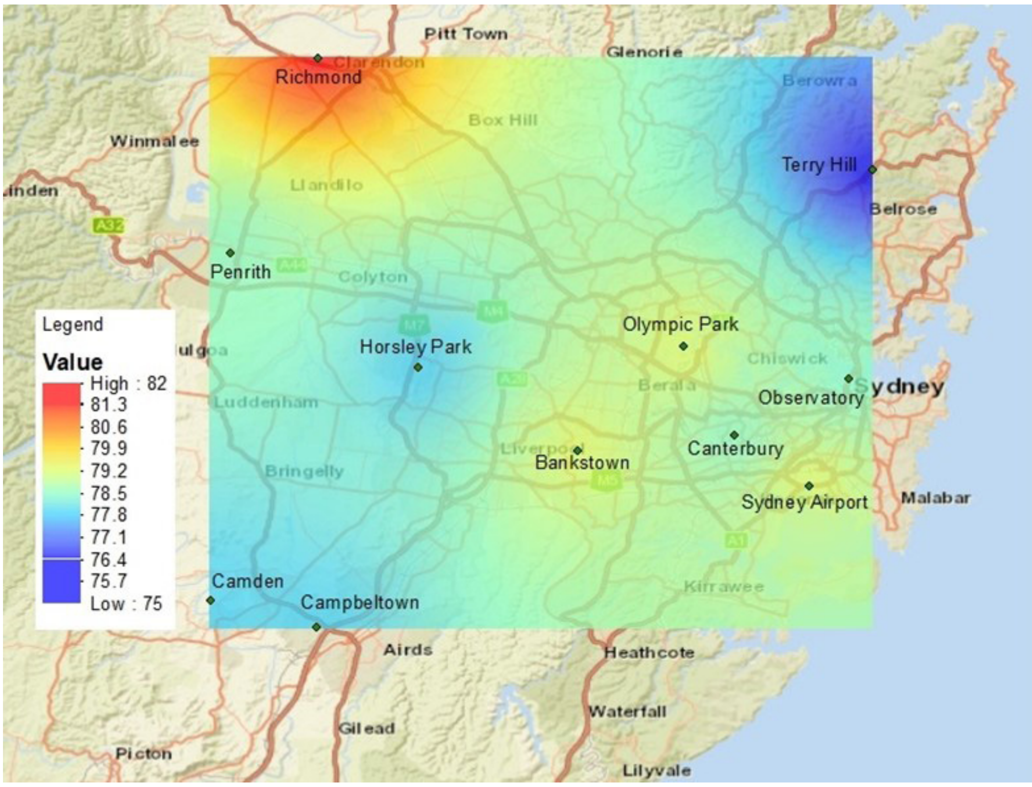


Figure 4.30 Spatial Distribution of the total sensible and latent cooling needs of a mid-rise shopping mall centre — new building in Sydney under reference conditions.

It is calculated that both building-scale (Scenario 1), and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical mid-rise shopping mall centre as a new building during the summer season (Figure 4.31).

When cool roofs are installed in an individual mid-rise shopping mall centre as a new building (Scenario 1), the spatially average cooling demand in the five cities decreases between 0.8% and 1.8%, see Figure 4.31.

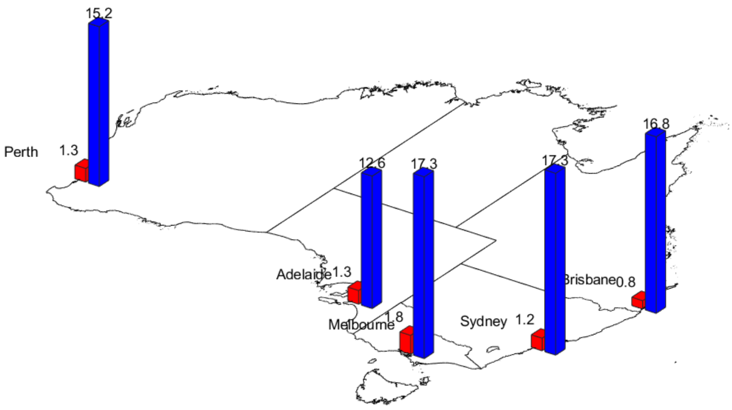


Figure 4.31 Percentage reduction of the cooling demand of a mid-rise shopping mall centre as a new building in the five main Australian cities during January and February.

When cool roofs are installed in a mid-rise shopping mall centre as a new building both in building and city scale (Scenario 2), the expected energy conservation ranges between 12.6% and 17.3%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings in Scenario 1 is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it is observed that:

- The annual cooling load decreases between 1.1% and 1.8% (Figure 4.32).
- The heating penalty is very low in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

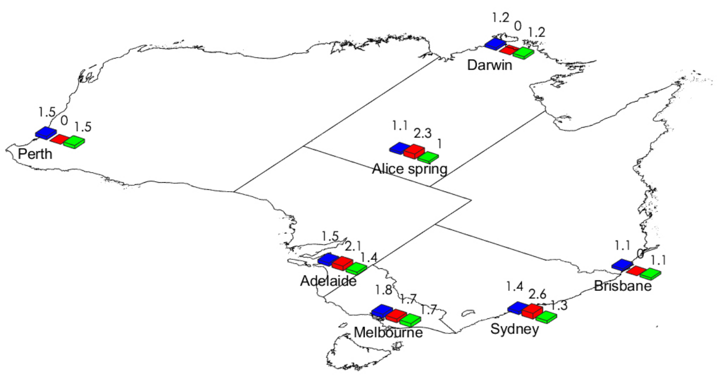


Figure 4.32 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a mid-rise shopping mall centre — new building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of cool roofs in an individual mid-rise shopping mall centre as a new building ranges between 1.1% to 1.7%.

Under free floating conditions, cool roofs installed at the mid-rise shopping mall centre, at the building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, between 0.2°C and 0.6°C, Figure 4.33. When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 1.1°C and 2.7°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.1°C and 0.2°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.33.

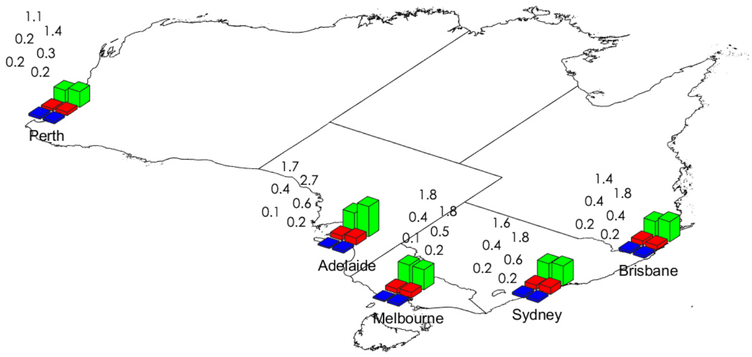


Figure 4.33 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a mid-rise shopping mall centre — new building.

Table 4.11 reports the calculated number of hours with indoor temperature higher than 26°C , under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale (Scenario1), the number of overheating hours is found to decrease by 0% and 1%.
- When cool roofs are installed at both the building and the city scale, overheating hours may decrease between 0% and 12%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	662 – 670	661 – 670	638 – 668
Melbourne	455 – 479	451 – 473	398 – 425
Brisbane	672	672	672
Adelaide	543 – 552	542 – 549	493 – 532
Perth	618 – 623	616 – 623	586 – 592

Table 4.11 Monthly number of hours above 26 in the five main Australian cities for a mid-rise shopping mall centre — new building operating under free-floating conditions.

Table 4.12 reports the number of hours below 19 under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

— During the operational hours, the number of hours below 19 increases by 0 and 2 hours, while during the whole period, the increase ranges between 0 and 3 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	14 – 50	89 – 219	14 – 50	89 – 219
Melbourne	26 – 63	244 – 331	27 – 64	247 – 334
Brisbane	45870	15 – 87	46266	16 – 89
Adelaide	62 – 81	325 – 369	63 – 82	327 – 372
Perth	23 – 32	132 – 181	23 – 34	132 – 183

Table 4.12 Monthly number of hours below 19 in the five main Australian cities for a mid-rise shopping mall centre — new building operating under free-floating conditions.

4.8. USING COOL ROOFS IN A HIGH-RISE SHOPPING MALL CENTRE — NEW BUILDING, BUILDING TYPE 7

4.8.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

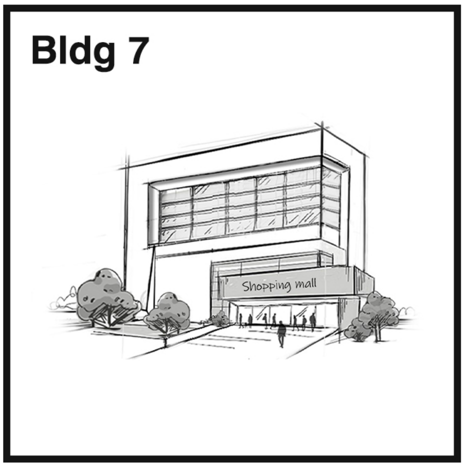


Figure 4.34 Building Type 7: Sketch of a high-rise shopping mall centre — new building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A sizable spatial difference in cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city at Observatory Hill is close to 50.9 kWh/m², while it is almost 28% higher, exceeding 65.4 kWh/m², in the Western part of Sydney at Richmond station. Figure 4.35 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 7, in Sydney under reference conditions.

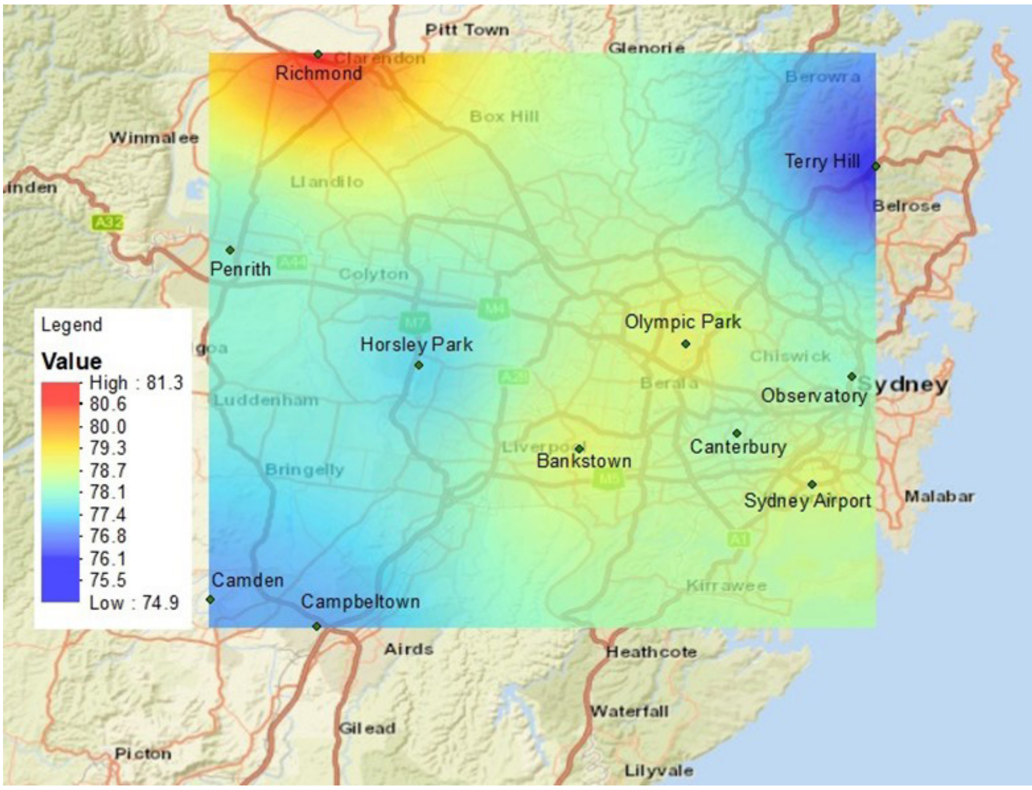


Figure 4.35 Spatial distribution of the total sensible and latent cooling needs of a high-rise shopping mall centre — new building in Sydney under reference conditions.

It is calculated that both building-scale, Scenario 1, and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical high-rise shopping mall centre-new building during the summer season, Figure 4.36.

When cool roofs are installed in an individual high-rise shopping mall centre as a new building (Scenario 1), the spatially average cooling demand in the five cities decreases between 0.5% and 1.2% as in Figure 4.36.

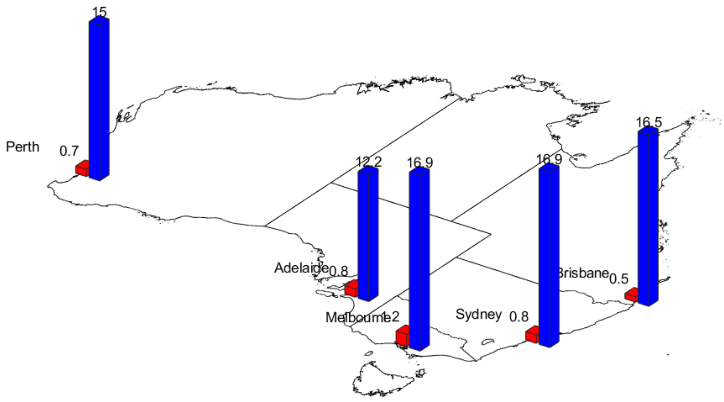


Figure 4.36 Percentage reduction of the cooling demand of a high-rise shopping mall centre — new building in the five main Australian cities during January and February.

When cool roofs are installed in a high-rise shopping mall centre new building — both at building and city scale, Scenario 2, the expected energy conservation ranges between 12.2% and 16.9%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings (Scenario 1) is calculated for the five main cities and Alice Springs, Darwin and Hobart, it is observed that:

- The annual cooling load decreases between 0.7% and 1.2%, Figure 4.37.
- The heating penalty is very low in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

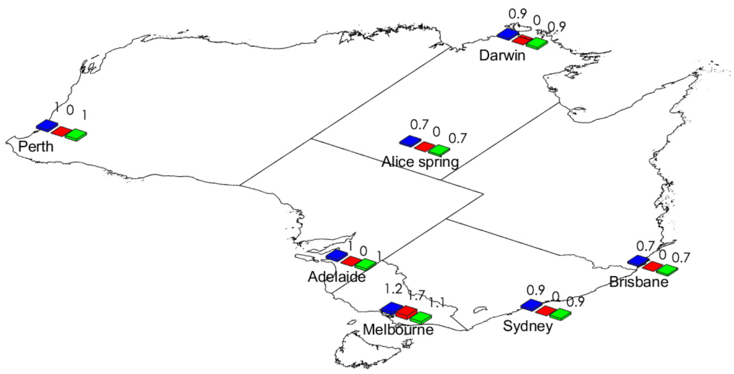


Figure 4.37 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a high-rise shopping mall centre — new building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of a cool roof in an individual high-rise shopping mall centre — as a new building, ranges between 0.7% to 1.1%.

Under free floating conditions, cool roofs installed at the high-rise shopping mall centre at the building scale (Scenario 1), may reduce the peak summer ambient temperature in the five main cities, between 0.2°C and 0.5°C (Figure 4.38). When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 1.1°C and 2.7°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.1°C and 0.2°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.38.

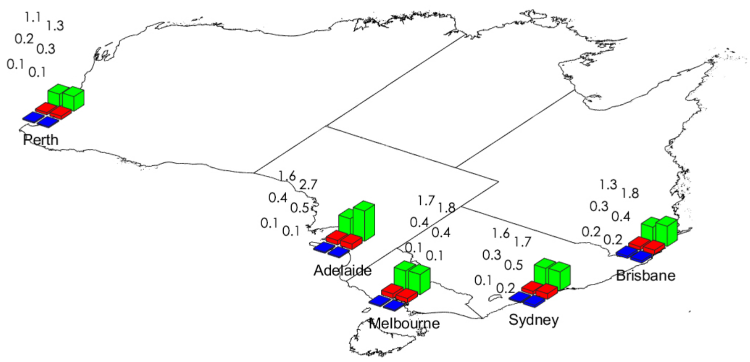


Figure 4.38 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a high-rise shopping mall centre as a new building shopping.

Table 4.13 reports the calculated number of hours with an indoor temperature higher than 26°C under the reference conditions and also when cool roofs are considered under Scenarios 1 and 2.

- When cool roofs are installed at building scale, Scenario1, the number of overheating hours is found to remain almost unchanged.
- When cool roofs are installed in both the buildings and the city scale, overheating hours may decrease between 0% and 12%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	665 – 672	665 – 672	642 – 669
Melbourne	460 – 482	459 – 482	404 – 431
Brisbane	672	672	672
Adelaide	548 – 556	547 – 555	498 – 536
Perth	625 – 627	625	594 – 603

Table 4.13 Monthly number of hours above 26 in the five main Australian cities for a high-rise shopping mall centre — new building operating under free-floating conditions.

Table 4.14 reports the number of hours below 19°C, under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

- During operational hours, the number of hours below 19°C, increases between 0 and 4 hours, while during the whole period, the increase ranges between 0 and 9 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	13 – 50	79 – 208	13 – 50	79 – 208
Melbourne	26 – 63	236 – 325	26 – 64	236 – 326
Brisbane	5 – 25	9 – 83	5 – 25	9 – 84
Adelaide	62 – 81	316 – 365	62 – 85	318 – 370
Perth	19 – 31	117 – 165	20 – 35	118 – 174

Table 4.14 Monthly number of hours below 19 in the five main Australian cities for a high-rise shopping mall centre — new building operating under free-floating conditions.

4.9. USING COOL ROOFS IN A LOW-RISE APARTMENT BUILDING — NEW BUILDING, BUILDING TYPE 8

4.9.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

Figure 4.39 Building Type 8: Sketch of a low-rise apartment building new building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A major spatial difference in cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city, Observatory Hill is close to 7.6 kWh/m^2, while it is almost 83% higher, exceeding 13.9 kWh/m^2 in the western part of Sydney at Richmond station. Figure 4.40 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 8, in Sydney under reference conditions.

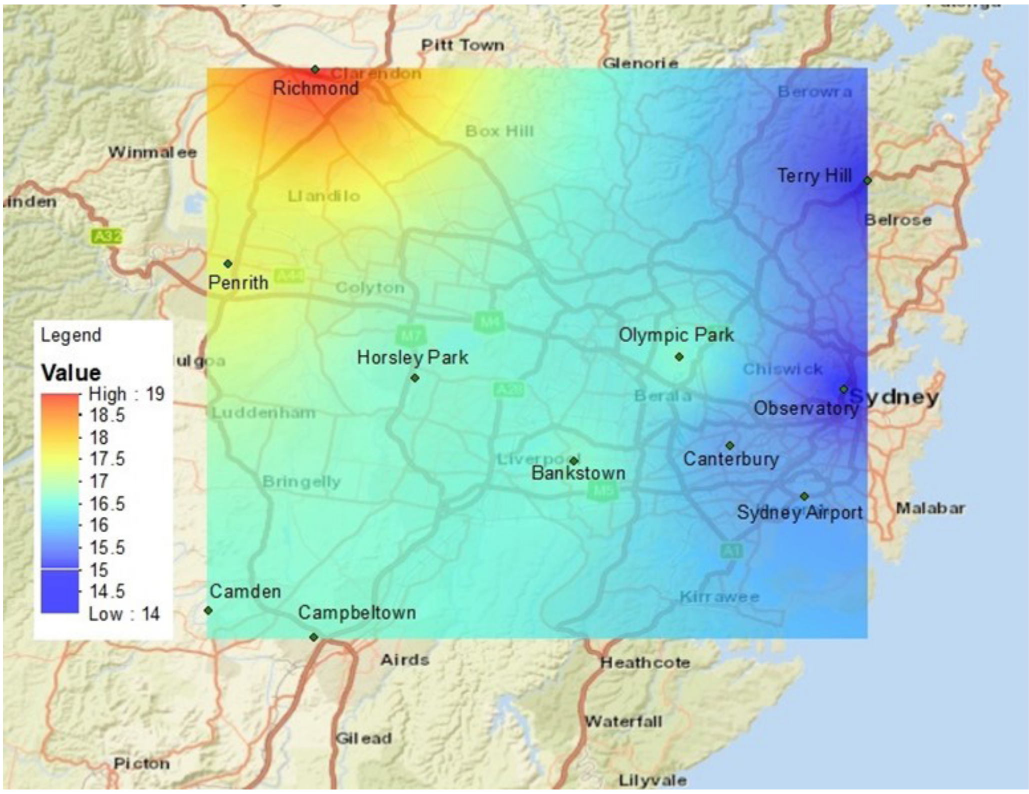


Figure 4.40 Spatial distribution of the total sensible and latent cooling needs of a low-rise apartment building — new building in Sydney under reference conditions.

It is calculated that both building-scale, Scenario 1, and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical low-rise new apartment building during the summer season, Figure 4.41.

When cool roofs are installed in an individual low-rise apartment building — new building (Scenario 1), the spatially average cooling demand in the five cities decreases between 5.3% and 14.9%, Figure 4.41.

When cool roofs are installed in a new low-rise apartment building at both building and city scale (Scenario 2), the expected energy conservation ranges between 31.0% and 44.7%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

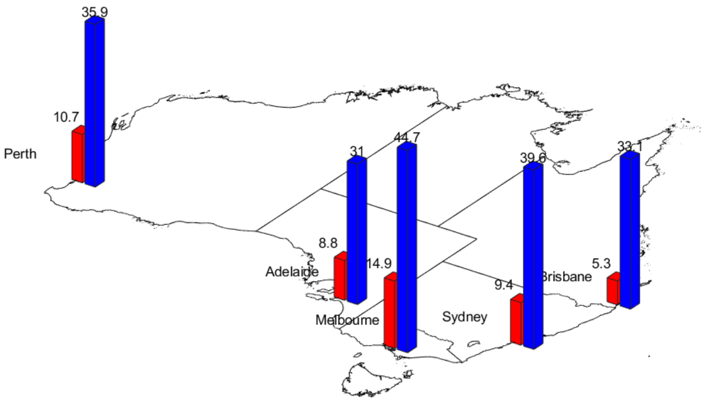


Figure 4.41 Percentage reduction of the cooling demand of a low-rise apartment building — new building in the five main Australian cities during January and February.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings (Scenario 1), is calculated for the five main cities and Alice Springs, Darwin and Hobart, it is seen that:

- The annual cooling load decreases between 5.3% and 10.6% as in Figure 4.42.
- The heating penalty is very low in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

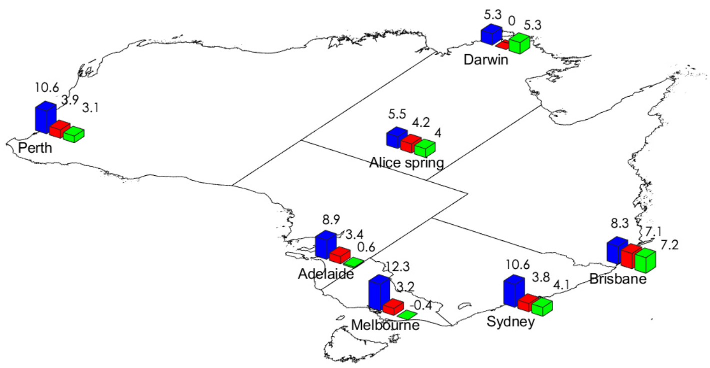


Figure 4.42 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a low-rise apartment building — new building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of cool roofs in an individual low-rise apartment building-new building ranges between -0.4% to 7.2%.

Under free floating conditions, cool roofs installed at a low-rise apartment building — new building — at the building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, by 0.5°C and 1.0°C, Figure 4.43.

When cool roofs are installed at both the building and urban scale, the expected average indoor temperature drop increases and ranges between 1.2°C and 2.7°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.2°C and 0.4°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of indoor temperature does not affect indoor thermal comfort, as in Figure 4.43.

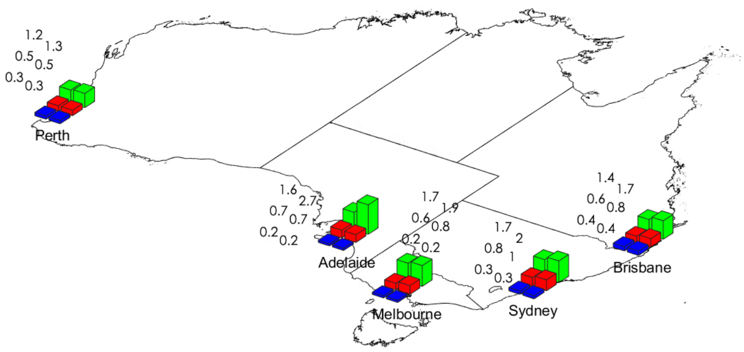


Figure 4.43 Average maximum drop of indoor temperature during summer, scenarios 1 and 2 and winter period for a low-rise apartment building — new building.

Table 4.15 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered (Scenarios 1 and 2).

- When cool roofs are installed at building scale, Scenario 1, the number of overheating hours is found to decrease between 0% and 16%.
- When cool roofs are installed in both the buildings and the city scale, overheating hours may decrease between 4% and 35%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	440 – 529	411 – 507	341 – 421
Melbourne	135 – 212	114 – 191	64 – 138
Brisbane	635 – 656	624 – 651	581 – 614
Adelaide	556 – 593	555 – 593	532 – 536
Perth	328 – 408	289 – 388	210 – 328

Table 4.15 Monthly number of hours above 26 in the five main Australian cities for a low-rise apartment building — new building operating under free-floating conditions.

Table 4.16 reports the number of hours below 19 under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

— The relative increase of the number of hours below 19 increases between 2 and 23 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	Operational hours	Total	Operational hours	Total
Sydney	N/A	428 – 549	N/A	438 – 566
Melbourne	N/A	729 – 731	N/A	735 – 737
Brisbane	N/A	120 – 240	N/A	129 – 248
Adelaide	N/A	316 – 365	N/A	318 – 370
Perth	N/A	442 – 524	N/A	465 – 540

Table 4.16 Monthly number of hours below 19 in the five main Australian cities for a low-rise apartment building — new building operating under free-floating conditions.

4.10. USING COOL ROOFS IN A MID-RISE APARTMENT BUILDING — NEW BUILDING, BUILDING TYPE 9

4.10.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

Figure 4.44 Building Type 9: Sketch of a mid-rise apartment building — new building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A distinct spatial difference in the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city at Observatory Hill is close to 7.5 kWh/m^2, while it is almost 81% higher, exceeding 13.6 kWh/m^2, in the western part of Sydney at Richmond station. Figure 4.45 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 9, in Sydney under reference conditions.

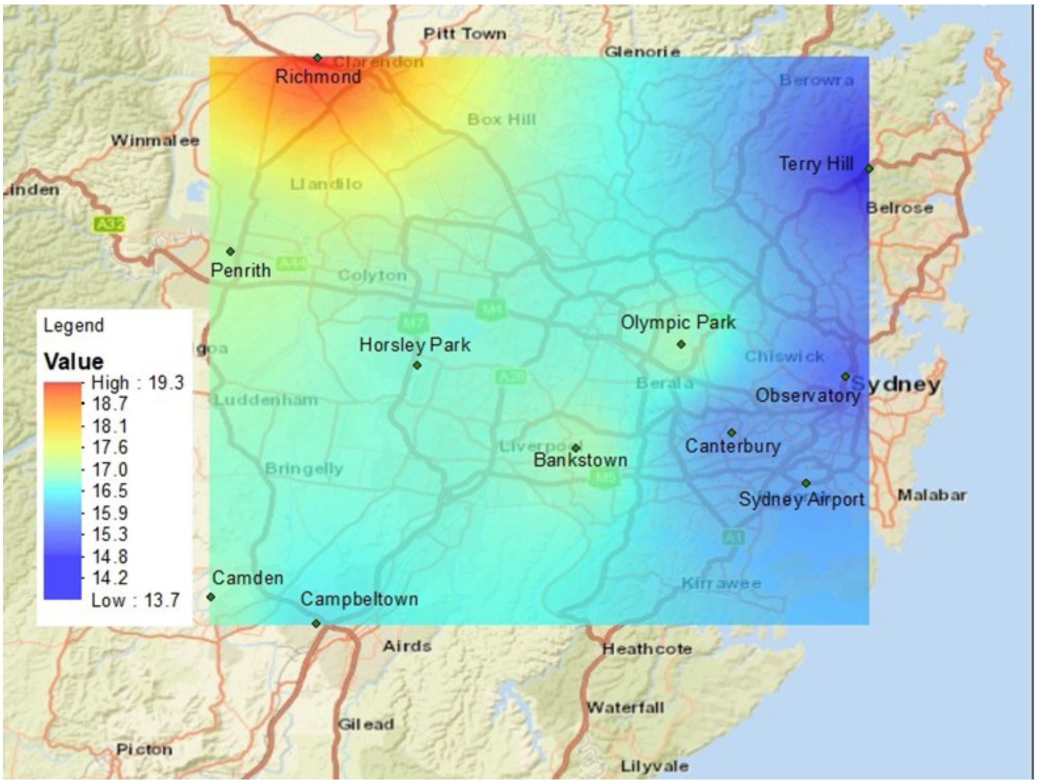


Figure 4.45 Spatial Distribution of the total sensible and latent cooling needs of mid-rise apartment building — new building in Sydney under reference conditions.

It is calculated that both building-scale, Scenario 1, and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical mid-rise apartment building — new building, during the summer season, as in Figure 4.46.

When cool roofs are installed in an individual mid-rise apartment building-new building, Scenario 1, the spatially average cooling demand in the five cities decreases between 3.1% and 11.4%, Figure 4.46.

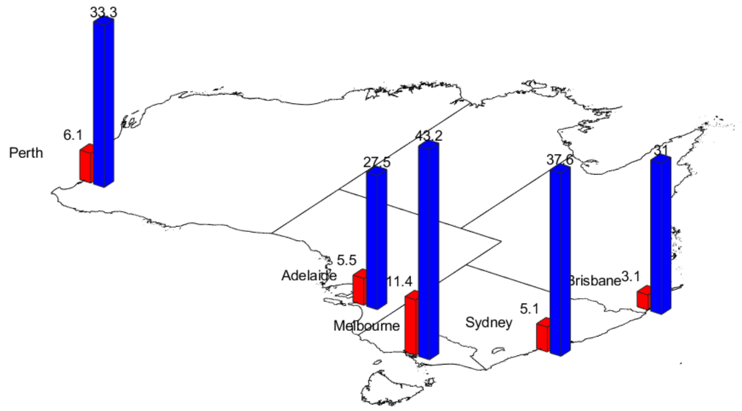


Figure 4.46 Percentage reduction of the cooling demand of a mid-rise apartment building — new building in the five main Australian cities during January and February.

When cool roofs are installed in a mid-rise apartment building-new building both in building and city scale, Scenario 2, the expected energy conservation ranges between 31.0% and 43.2%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings, Scenario 1, is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it is observed that:

- The annual cooling load decreases between 3.3% and 9.2%, Figure 4.47.
- The heating penalty is substantially lower in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

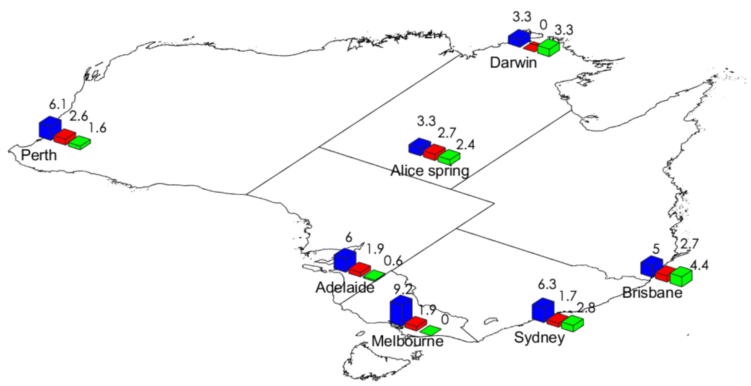


Figure 4.47 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a mid-rise apartment building — new building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of a cool roof in an individual mid-rise apartment building — new building ranges between 0% to 4.4%.

Under free floating conditions, cool roofs installed at a mid-rise apartment building, at the building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, between 0.3°C and 0.6°C, Figure 4.48.

When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 1.1°C and 2.5°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.1°C and 0.2°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.48.

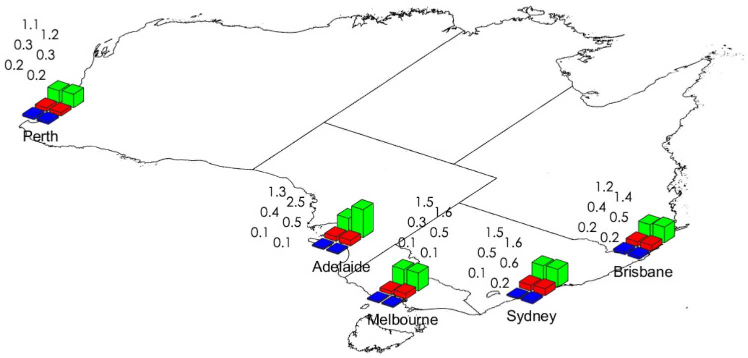


Figure 4.48 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a mid-rise apartment building — new building.

Table 4.17 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease by 0% to 14%.
- When cool roofs are installed in both the buildings and the city scale, overheating hours may decrease between 5% and 37%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	450 – 556	433 – 540	371 – 444
Melbourne	125 – 210	108 – 197	64 – 133
Brisbane	639 – 664	637 – 660	598 – 631
Adelaide	328 – 421	311 – 409	219 – 355
Perth	329 – 412	304 – 403	219 – 346

Table 4.17 Monthly number of hours above 26 in the five main Australian cities for a mid-rise apartment building — new building operating under free-floating conditions.

Table 4.18 reports the number of hours below 19 under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

— The number of hours below 19 increases between 0 and 14 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	Operational hours	Total	Operational hours	Total
Sydney	N/A	431 – 558	N/A	431 – 572
Melbourne	N/A	736 – 738	N/A	737 – 741
Brisbane	N/A	108 – 236	N/A	112 – 242
Adelaide	N/A	714 – 732	N/A	718 – 732
Perth	N/A	449 – 532	N/A	459 – 546

Table 4.18 Monthly number of hours below 19 in the five main Australian cities for a mid-rise apartment building — new building operating under free-floating conditions.

4.11. USING COOL ROOFS IN A HIGH-RISE APARTMENT BUILDING — NEW BUILDING, BUILDING TYPE 10

4.11.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

Figure 4.49 Building Type 10: Sketch of a high-rise apartment building — new building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A distinct spatial difference in the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city, Observatory Hill, is close to 7.3 kWh/m^2, while it is almost 84% higher, exceeding 13.4 kWh/m^2 in the western part of Sydney at Richmond station. Figure 4.50 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 10, in Sydney under reference conditions.

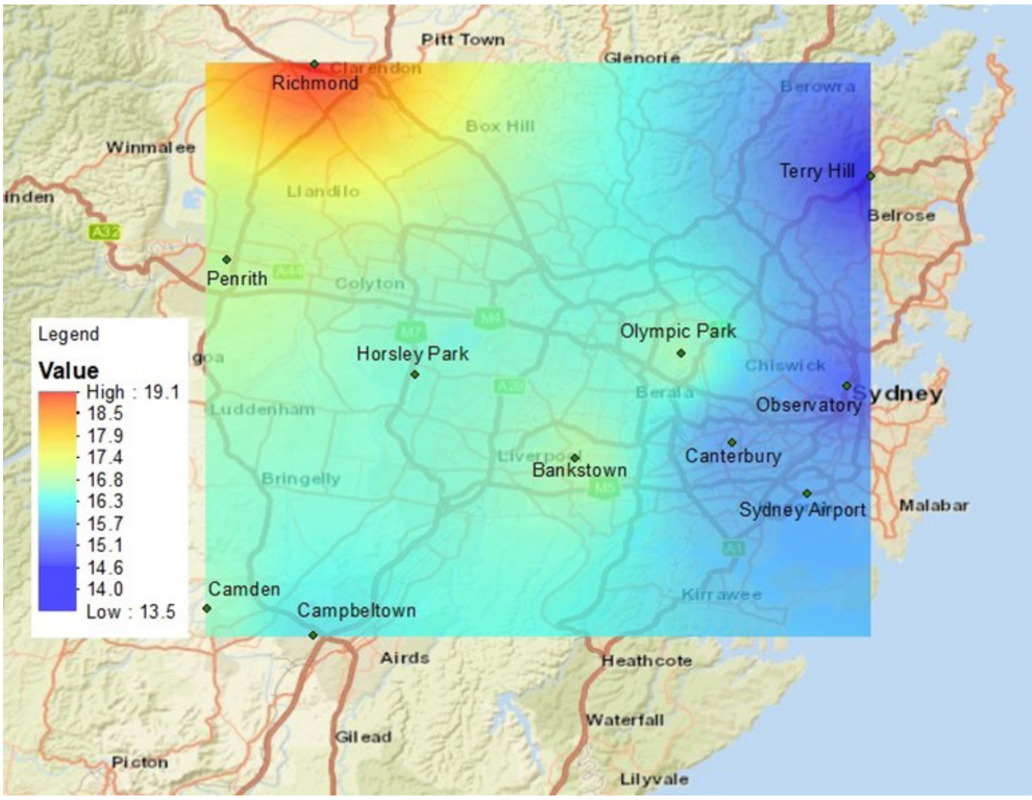


Figure 4.50 Spatial Distribution of the total sensible and latent cooling needs of a high-rise apartment building — new building in Sydney under reference conditions.

It is calculated that both building-scale, Scenario 1, and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical high-rise apartment building — new building during the summer season (see Figure 4.51).

When cool roofs are installed in an individual high-rise apartment building-new building, Scenario 1, the spatially average cooling demand in the five cities decreases between 1.9% and 4.9% (Figure 4.51).

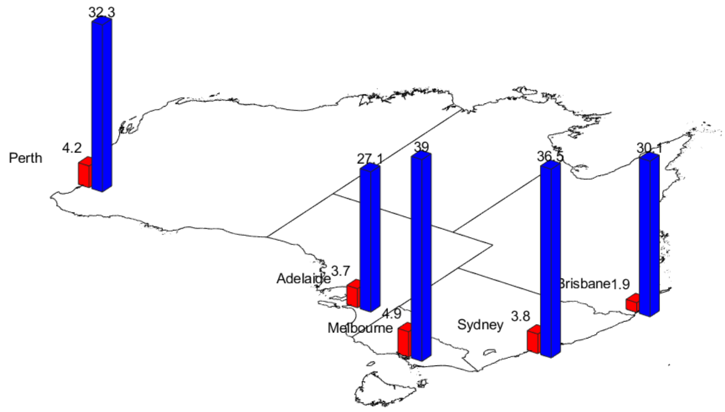


Figure 4.51 Percentage reduction of the cooling demand of high-rise apartment building without roof insulation in the five main Australian cities during January and February.

When cool roofs are installed in a low-rise office building without roof insulation both in building and city scale, Scenario 2, the expected energy conservation ranges between 30.1% and 39.0%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it is seen that:

- The annual cooling load decreases between 1.9% and 5.5%, Figure 4.52.
- The heating penalty is markedly low in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

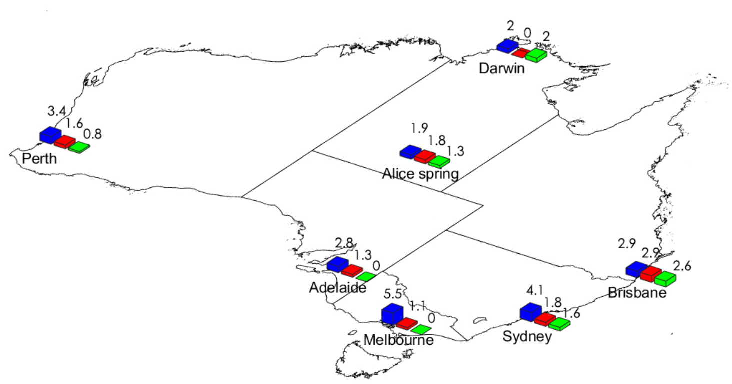


Figure 4.52 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a high-rise apartment building — new building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of cool roofs in an individual high-rise apartment building — new building ranges between 0% to 2.6%.

Under free floating conditions, cool roofs installed at a high-rise apartment building — new building, at the building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, between 0.2°C and 0.4°C, Figure 4.53.

When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 1.1°C and 2.4°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.1°C and 0.2°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.53.

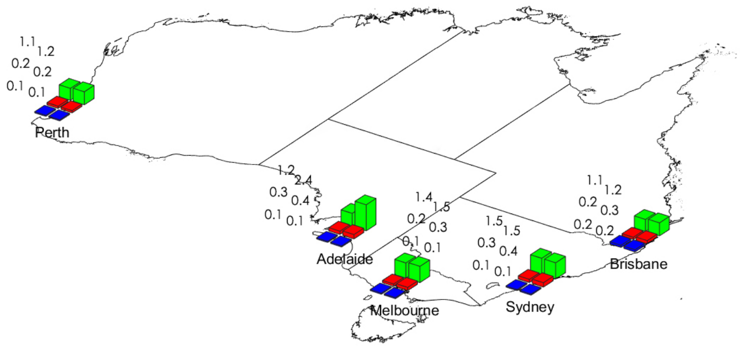


Figure 4.53 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a high-rise apartment building — new building.

Table 4.19, reports the calculated number of hours with indoor temperature higher than 26°C , under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease between 0% and 7%.
- When cool roofs are installed in both the buildings and at city scale, overheating hours may decrease between 4% and 36%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	480 – 568	464 – 556	377 – 464
Melbourne	114 – 205	106 – 198	63 – 132
Brisbane	642 – 665	640 – 664	606 – 637
Adelaide	245 – 349	241 – 343	150 – 295
Perth	327 – 412	314 – 408	216 – 350

Table 4.19 Monthly number of hours above 26 in the five main Australian cities for a high-rise apartment building — new building operating under free-floating conditions.

Table 4.20 reports the number of hours below 19 under the reference conditions and the first cool roof scenarios for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

- The number of hours below 19 increases between 0 and 10 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	N/A	429 – 566	N/A	436 – 576
Melbourne	N/A	737 – 743	N/A	738 – 743
Brisbane	N/A	102 – 234	N/A	107 – 238
Adelaide	N/A	721 – 732	N/A	721 – 732
Perth	N/A	456 – 540	N/A	465 – 550

Table 4.20 Monthly number of hours below 19 in the five main Australian cities for a high-rise apartment building — new building operating under free-floating conditions.

4.12. USING COOL ROOFS IN A STAND-ALONE HOUSE — EXISTING BUILDING, BUILDING TYPE 11

4.12.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

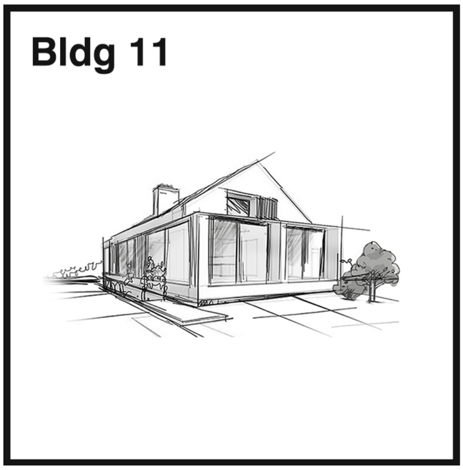


Figure 4.54 Building Type 11: Sketch of a stand-alone house — existing building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference and the two cool roofs scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of the local climatic conditions on the cooling load of buildings and reveal the spatial distribution of the cooling needs. The full set of the simulated data and results are given in the extended final report.

A distinct spatial difference in the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city, Observatory Hill is close to 9.2 kWh/m^2, while it is almost 64% higher, exceeding 15.1 kWh/m^2 in the western part of Sydney at Richmond station. Figure 4.55 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 11 in Sydney under reference conditions.

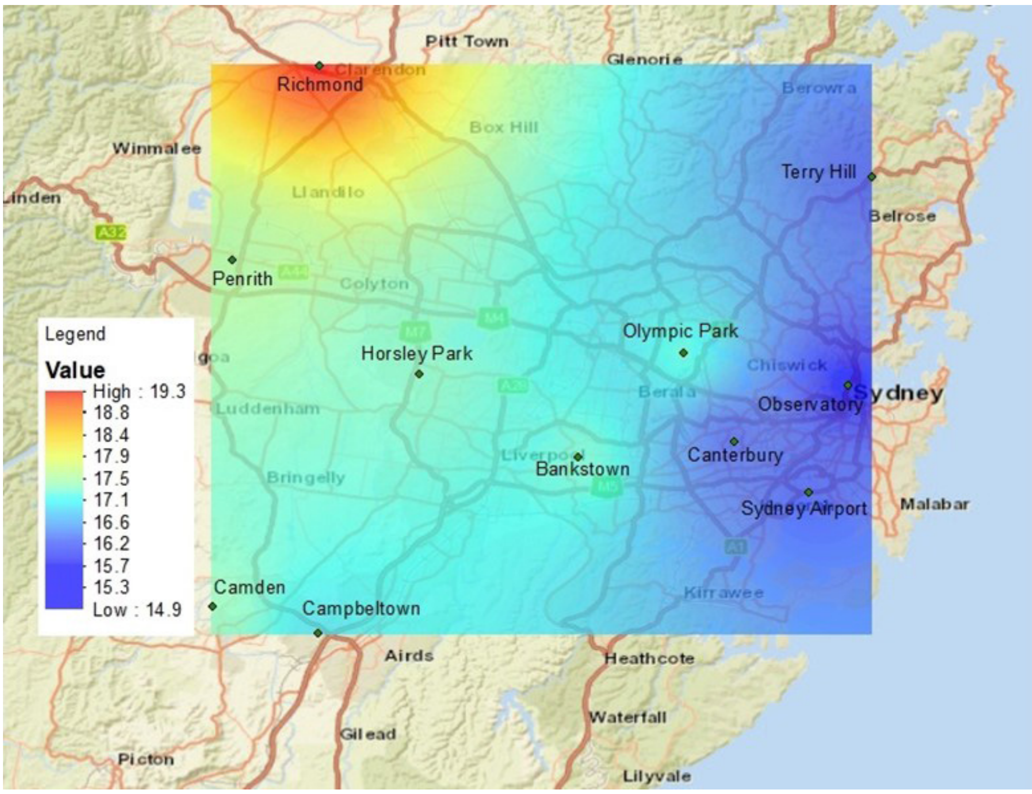


Figure 4.55 Spatial Distribution of the total sensible and latent cooling needs of a stand-alone house — existing building in Sydney under reference conditions.

It is calculated that at both building-scale, Scenario 1, and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical stand-alone house (existing building) during the summer season, Figure 4.56.

When cool roofs are installed in an individual stand-alone house — existing building, Scenario 1, the spatially average cooling demand in the five cities decreases between 17.9% and 66.3%, Figure 4.56. When cool roofs are installed in a stand-alone house without roof insulation both at building and city scale, Scenario 2, the expected energy conservation ranges between 41.5% and 70.0%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

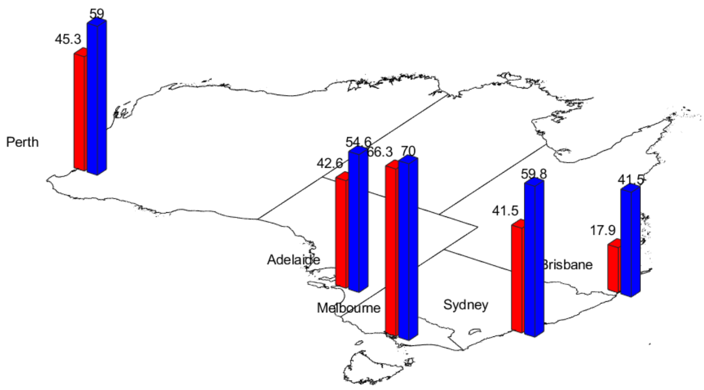


Figure 4.56 Percentage reduction of the cooling demand of a stand-alone house — existing building in the five main Australian cities during January and February.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings, Scenario 1, is calculated for the five main cities and Alice Springs, Darwin, and Hobart, is the results obtained indicate that:

- The annual cooling load decreases between 22.5% and 52.8%, Figure 4.57.
- The heating penalty is markedly low in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

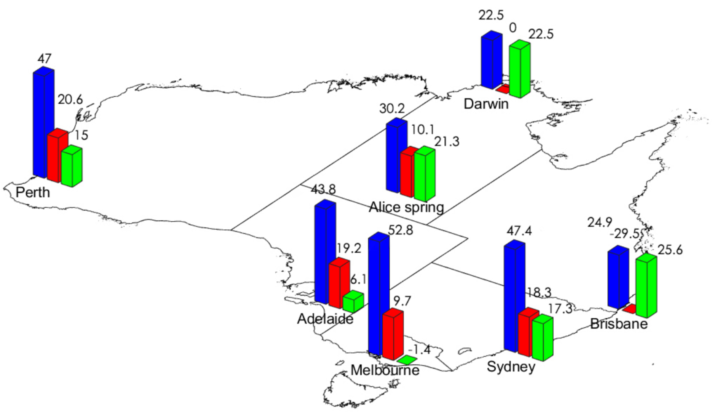


Figure 4.57 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a stand-alone house — existing building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of a cool roof on an individual stand-alone house — existing building, ranges between -1.4% to 25.6%.

Under free floating conditions, cool roofs installed at a stand-alone house at the building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, between 2.4°C and 5.1°C as in Figure 4.58. When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 3.1°C and 6.1°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 1.2°C and 1.9°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.58.

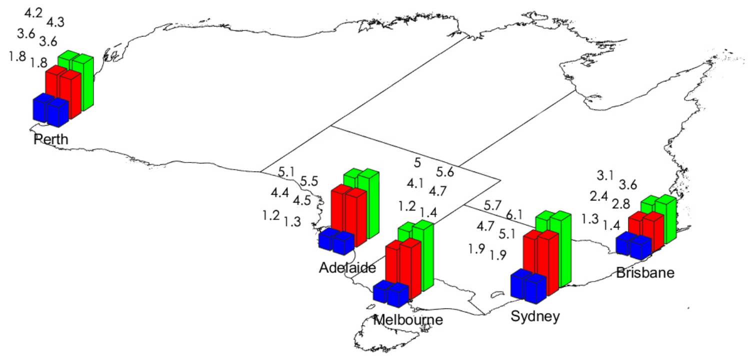


Figure 4.58 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a stand-alone house — existing building.

Table 4.21 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease between 8% and 68%.
- When cool roofs are installed in both the buildings and at city scale, overheating hours may decrease between 5% and 52%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	397 – 431	273 – 342	213 – 287
Melbourne	192 – 250	96 – 151	62 – 121
Brisbane	573 – 592	530 – 565	463 – 490
Adelaide	297 – 354	185 – 282	136 – 248
Perth	332 – 371	226 – 300	170 – 268

Table 4.21 Monthly number of hours above 26 in the five main Australian cities for a stand-alone house — existing building operating under free-floating conditions.

Table 4.21 reports the number of hours below 19 under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

— The number of hours below 19 increases between 11 and 80 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	N/A	504 – 563	N/A	578 – 621
Melbourne	N/A	708 – 717	N/A	735 – 743
Brisbane	N/A	235 – 330	N/A	270 – 360
Adelaide	N/A	691 – 721	N/A	720 – 732
Perth	N/A	496 – 532	N/A	576 – 607

Table 4.22 Monthly number of hours below 19 in the five main Australian cities for a stand-alone house — existing building operating under free-floating conditions.

4.13. USING COOL ROOFS IN A TYPICAL SCHOOL BUILDING — EXISTING BUILDING, BUILDING TYPE 12

4.13.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

Figure 4.59 Building Type 12: Sketch of a typical school building — existing building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A distinct spatial difference of the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city at Observatory Hill, is close to 14.5 kWh/m², while it is almost 82% higher, exceeding 26.4 kWh/m² in the western part of Sydney at Richmond station. Figure 4.60 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 12 in Sydney under reference conditions.

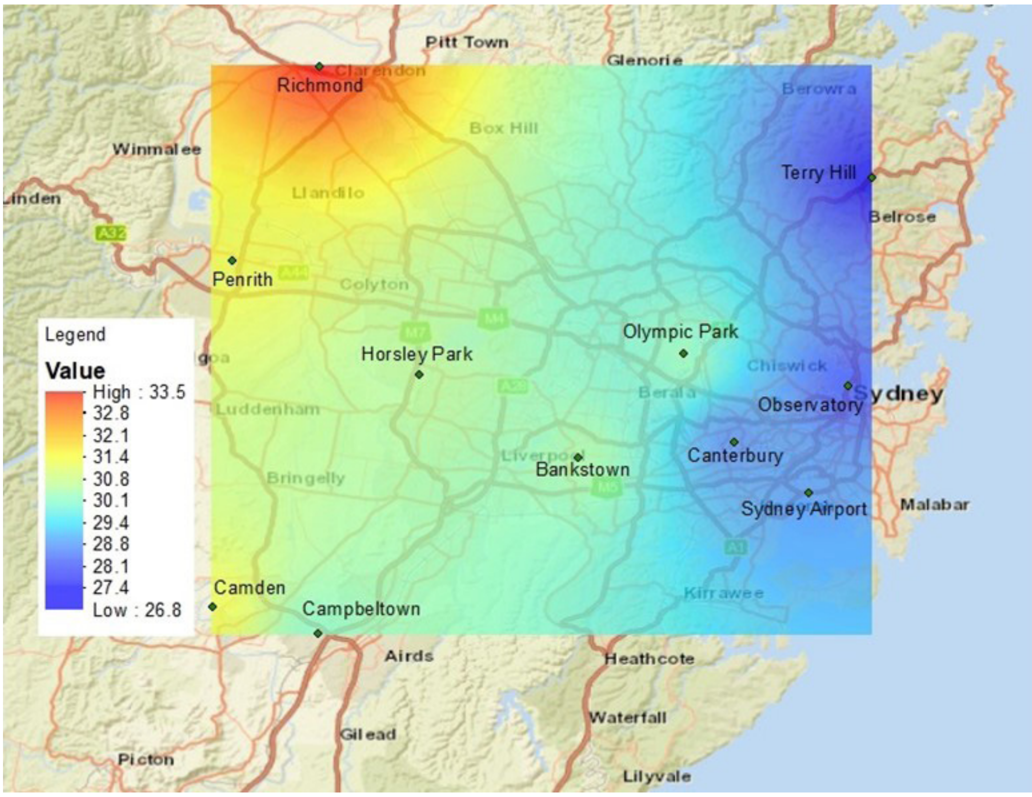


Figure 4.60 Spatial Distribution of the total sensible and latent cooling needs of low-rise office building without roof insulation in Sydney under reference conditions.

It is calculated that both building-scale, Scenario 1, and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical school existing building during the summer season, Figure 4.61.

When cool roofs are installed in an individual existing school building, Scenario 1, the spatially average cooling demand in the five cities decreases between 3.5% and 4.5%, Figure 4.61.

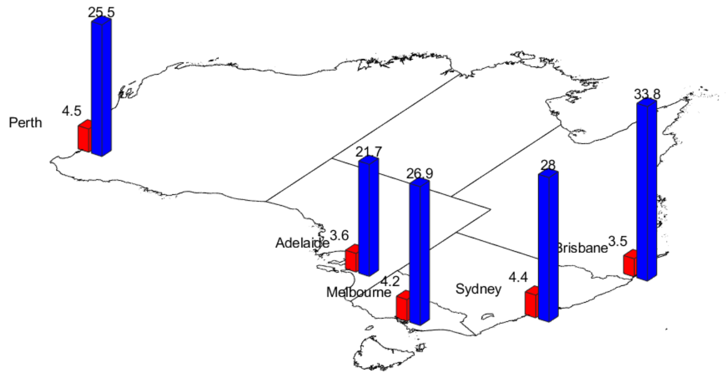


Figure 4.61 Percentage reduction of the cooling demand of a typical school building — existing building in the five main Australian cities during January and February.

When cool roofs are installed in a typical school building — existing building both at building and city scale, Scenario 2, the expected energy conservation ranges between 21.7% and 33.8%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings, Scenario 1, is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it is observed that:

- The annual cooling load decreases between 2.6% and 4.8%, Figure 4.62.
- The heating penalty is substantially lower in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

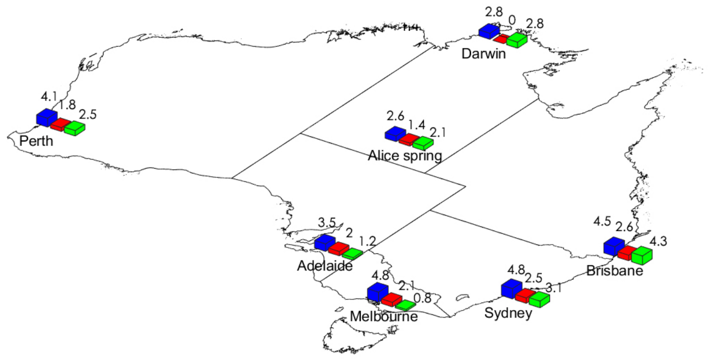


Figure 4.62 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a typical school building — existing building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of a cool roof in an existing individual typical school building ranges between 0.8% to 4.3%.

Under free floating conditions, cool roofs installed at a typical school building, at the building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, between 0.2°C and 1.0°C, Figure 4.63. When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 1.2°C and 2.6°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.1°C and 0.2°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.63.

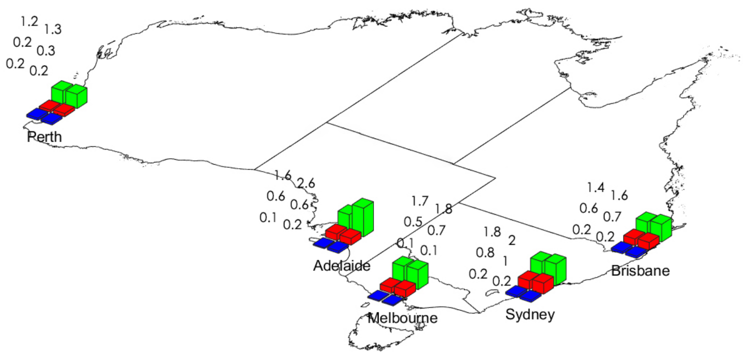


Figure 4.63 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a typical school building — existing building.

Table 4.23 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease between 1% and 9%.
- When cool roofs are installed at both building and city scale, overheating hours may decrease between 1% and 23%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	486 – 533	471 – 508	368 – 446
Melbourne	159 – 226	154 – 211	120 – 173
Brisbane	623 – 650	616 – 645	569 – 607
Adelaide	285 – 371	275 – 358	200 – 316
Perth	345 – 409	325 – 402	251 – 347

Table 4.23 Monthly number of hours above 26 in the five main Australian cities for a typical school building — existing building operating under free-floating conditions.

Table 4.24 reports the number of hours below 19 under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

- During the operational hours, the number of hours below 19 increases between 2 and 6 hours, while over the whole period, the increase ranges between 4 and 14 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	84 – 106	383 – 481	86 – 111	389 – 495
Melbourne	186 – 206	664 – 684	190 – 210	672 – 680
Brisbane	35 – 50	156 – 248	37 – 52	165 – 253
Adelaide	257 – 313	642 – 707	262 – 316	647 – 712
Perth	142 – 155	421 – 463	147 – 161	427 – 472

Table 4.24 Monthly number of hours below 19 in the five main Australian cities for a typical school building — existing building operating under free-floating conditions

4.14. USING COOL ROOFS IN A LOW-RISE OFFICE BUILDING WITH ROOF INSULATION — EXISTING BUILDING, BUILDING TYPE 13

4.14.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

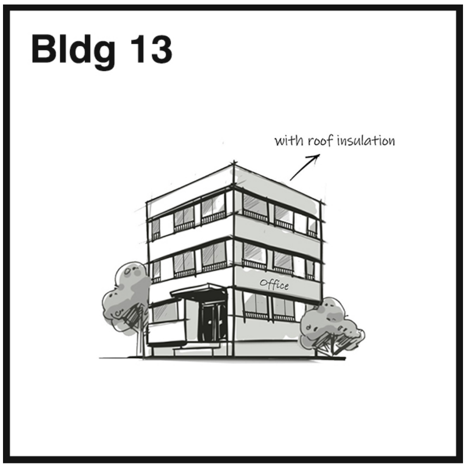


Figure 4.64 Building Type 13: Sketch of a low-rise office building with roof insulation — existing building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A distinct spatial difference of the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city at Observatory Hill, is close to 15.2 kWh/m², while it is almost 61% higher, exceeding 24.4 kWh/m² in the western part of Sydney at Richmond station. Figure 4.65 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 13, in Sydney under reference conditions.

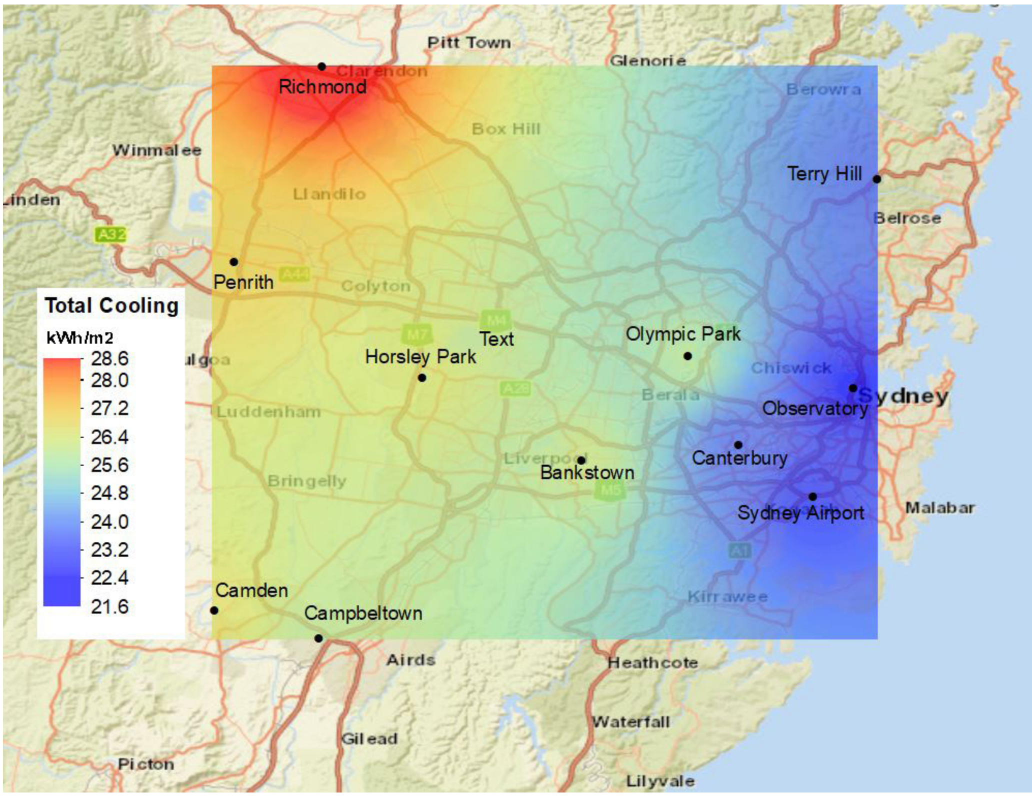


Figure 4.65 Spatial Distribution of the total sensible and latent cooling needs of a low-rise office building with roof insulation —existing building in Sydney under reference conditions.

It is calculated that both building scale, Scenario 1, and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical low-rise office building with roof insulation in an existing building during the summer season (see Figure 4.66).

When cool roofs are installed in an individual low-rise office building with roof insulation — existing building — Scenario 1, the spatially average cooling demand in the five cities decreases between 17.3% and 31.4%, Figure 4.66.

When cool roofs are installed in a low-rise office building with roof insulation in an existing building both at building and city scale, Scenario 2, the expected energy conservation ranges between 35% and 48.4%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

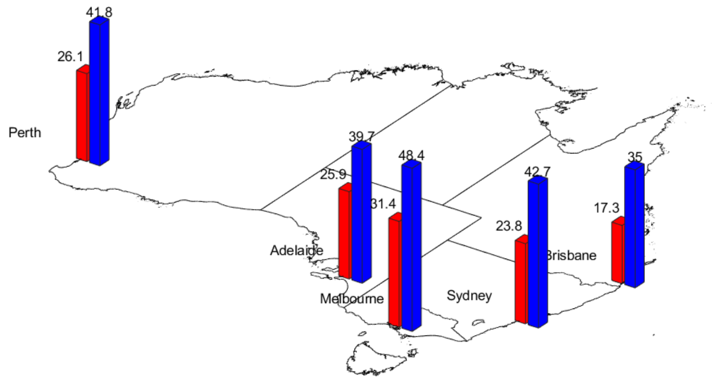


Figure 4.66 Percentage reduction of the cooling demand of a low-rise office building with roof insulation — existing building in the five main Australian cities during January and February.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings, Scenario 1, is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it is seen that:

- The annual cooling load decreases between 20.1% and 26.5%, Figure 4.67.
- The heating penalty is substantially lower in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

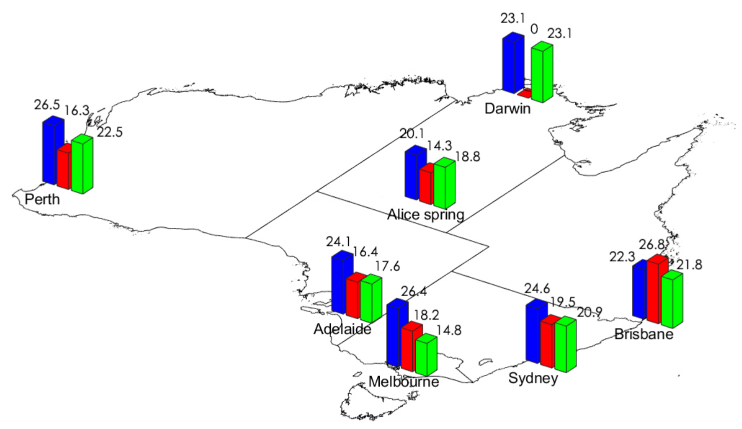


Figure 4.67 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a low-rise office building with roof insulation — existing building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of a cool roof in an individual low-rise office building with roof insulation (existing building) ranges between 14.8% to 23.1%.

Under free floating conditions, cool roofs installed at a low-rise existing office building with roof insulation at the building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, between 2.6°C and 6.1°C, Figure 4.68. When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 3.5°C and 6.8°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.9°C and 2.0°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.68.

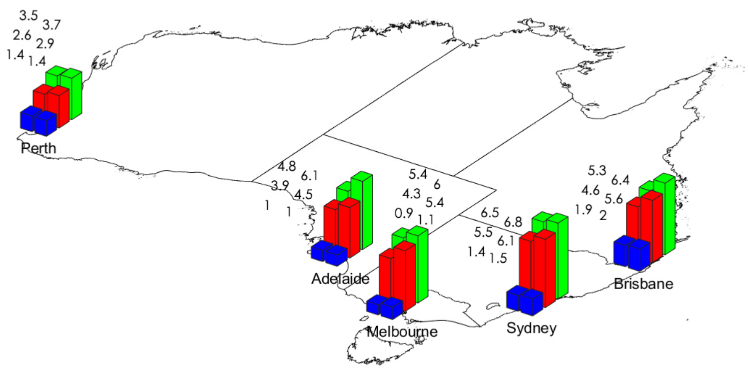


Figure 4.68 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a low-rise office building with roof insulation in an existing building.

Table 4.25 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease between 1% and 23%.
- When cool roofs are installed at both building and the city scale, overheating hours may decrease by 2% and 39%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	604 – 606	544 – 519	472 – 473
Melbourne	340 – 393	236 – 276	185 – 240
Brisbane	664 – 672	644 – 666	617 – 657
Adelaide	459 – 493	373 – 428	308 – 385
Perth	517 – 534	445 – 468	387 – 429

Table 4.25 Monthly number of hours above 26 in the five main Australian cities for a low-rise office building with roof insulation — existing building operating under free-floating conditions.

Table 4.26 reports the number of hours below 19 under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

- During the operational hours, the number of hours below 19 increases between 2 and 35 hours, while during the whole period, the increase ranges between 34 and 50 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	74 – 95	284 – 363	89 – 114	329 – 407
Melbourne	179 – 200	520 – 558	200 – 229	556 – 595
Brisbane	18 – 29	85 – 173	26 – 31	119 – 207
Adelaide	176 – 239	516 – 595	210 – 274	560 – 636
Perth	83 – 95	273 – 336	98 – 112	323 – 374

Table 4.26 Monthly number of hours below 19 in the five main Australian cities for a low-rise office building with roof insulation — existing building operating under free-floating conditions.

4.15. USING COOL ROOFS IN A HIGH-RISE OFFICE BUILDING WITH ROOF INSULATION — EXISTING BUILDING, BUILDING TYPE 14

4.15.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

Figure 4.69 Building Type 14: Sketch of a high-rise office building with roof insulation — existing building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A distinct spatial difference of the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city, Observatory Hill, is close to 12.5 kWh/m^2, while it is almost 65% higher, exceeding 20.6 kWh/m^2 in the western part of Sydney at Richmond station. Figure 4.70 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 14, in Sydney under reference conditions.

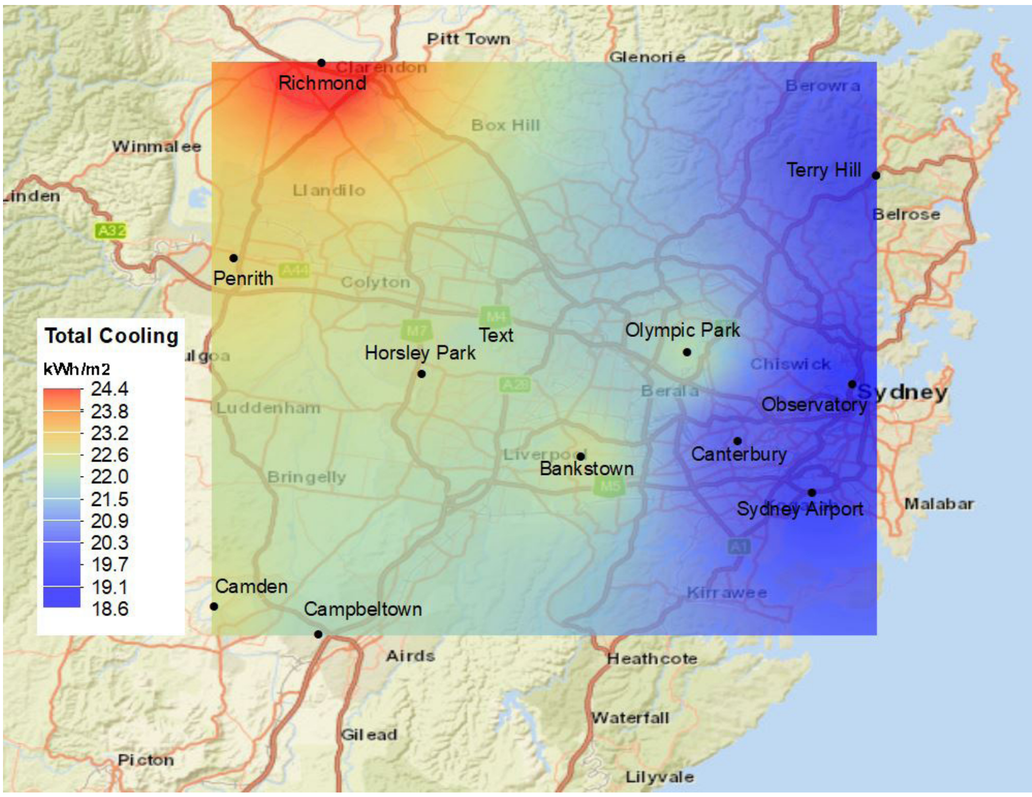


Figure 4.70 Spatial Distribution of the total sensible and latent cooling needs of high-rise office building with roof insulation — existing building in Sydney under reference conditions.

It is calculated that both building-scale, Scenario 1, and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical high-rise office building with roof insulation in an existing building during the summer season, Figure 4.71.

When cool roofs are installed in an individual high-rise office building with roof insulation — existing building, Scenario 1, the spatially average cooling demand in the five cities decreases between 3.3 and 7.4%, Figure 4.71.

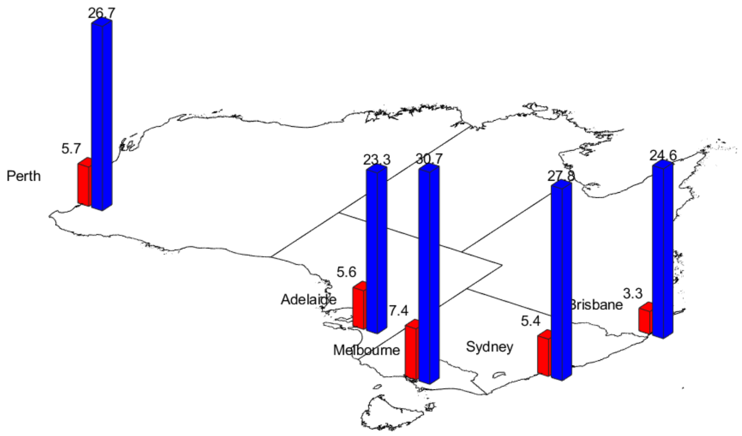


Figure 4.71 Percentage reduction of the cooling demand of a high-rise office building with roof insulation — existing building in the five main Australian cities during January and February

When cool roofs are installed in a high-rise office building with roof insulation in an existing building, both at building and city scale, Scenario 2, the expected energy conservation ranges between 23.3% and 30.7%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings, Scenario 1, is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it is observed that:

- The annual cooling load decreases between 4.1% and 5.6% (Figure 4.72).
- The heating penalty is substantially low in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

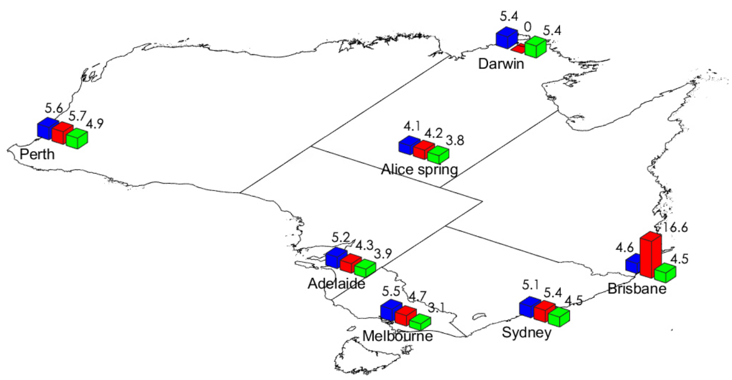


Figure 4.72 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a high-rise office building with roof insulation —existing building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of a cool roof in an individual existing high-rise office building with roof insulation ranges between 3.1% to 5.4%.

Under free floating conditions, cool roofs installed at a high-rise office building with roof insulation at building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, between 0.5°C and 1.3°C, Figure 4.73. When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 1.3°C and 2.9°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.2°C and 0.4°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.73.

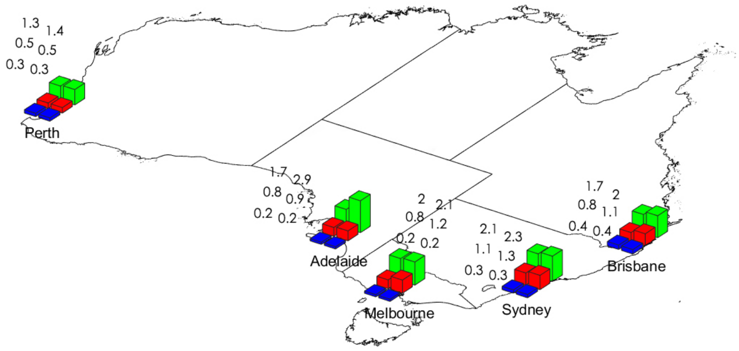


Figure 4.73 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a high-rise office building with roof insulation — existing building.

Table 4.27 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease between 0% and 9%.
- When cool roofs are installed in both the buildings and the city scale, overheating hours may decrease between 0% and 27%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	657 – 670	653 – 670	625 – 650
Melbourne	375 – 424	341 – 395	262 – 332
Brisbane	672	672	672
Adelaide	518 – 552	501 – 541	412 – 495
Perth	592 – 604	587 – 596	534 – 567

Table 4.27 Monthly number of hours above 26 in the five main Australian cities for a high-rise office building with roof insulation — existing building operating under free-floating conditions.

Table 4.28 reports the number of hours below 19 under the reference conditions and the first cool roof scenarios for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

- During the operational hours, the number of hours below 19 increases between 1 and 6 hours, while during the whole period, the increase ranges between 2 and 13 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	26 – 69	88 – 241	27 – 75	93 – 249
Melbourne	137 – 175	398 – 488	140 – 179	405 – 501
Brisbane	1 – 14	3 – 71	2 – 19	5 – 75
Adelaide	143 – 212	435 – 531	146 – 216	442 – 540
Perth	40 – 58	121 – 187	44 – 59	131 – 194

Table 4.28 Monthly number of hours below 19 in the five main Australian cities for a high-rise office building with roof insulation — existing building operating under free-floating conditions.

4.16. USING COOL ROOFS IN A LOW-RISE SHOPPING MALL CENTRE — EXISTING BUILDING, BUILDING TYPE 15

4.16.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

Figure 4.74 Building Type 15: Sketch of a low-rise shopping mall centre — existing building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A distinct spatial difference of the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city at Observatory Hill, is close to 54.9 kWh/m², while it is almost 30% higher, exceeding 71.6 kWh/m² in the western part of Sydney at Richmond station. Figure 4.75 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 15, in Sydney under reference conditions.

It is calculated that both building-scale, Scenario 1, and combined building scale and urban scale application of cool roofs, can significantly reduce the cooling load of the typical low-rise shopping mall centre — existing building during the summer season, Figure 4.75.

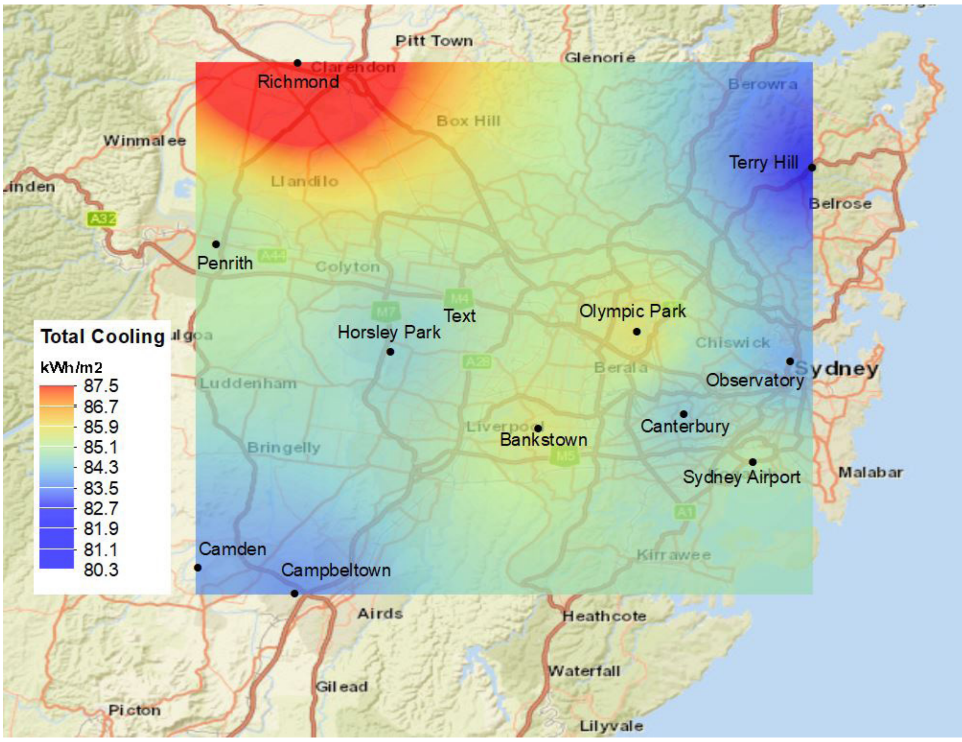


Figure 4.75 Spatial Distribution of the total sensible and latent cooling needs of low-rise shopping mall centre — existing building in Sydney under reference conditions.

When cool roofs are installed in an existing individual low-rise shopping mall centre-, Scenario 1, the spatially average cooling demand in the five cities decreases between 7.8% and 15.9%, Figure 4.76.

When cool roofs are installed in a low-rise shopping mall centre-existing building both in building and city scale, Scenario 2, the expected energy conservation ranges between 22.1% and 29.1%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

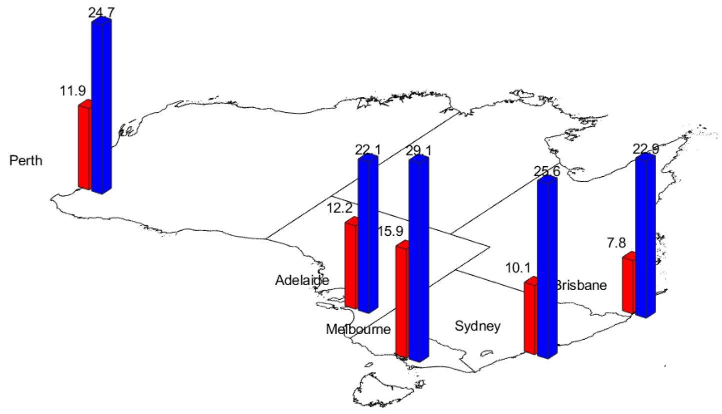


Figure 4.76 Percentage reduction of the cooling demand of a low-rise shopping mall centre — existing building in the five main Australian cities during January and February.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings, Scenario 1, is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it is seen that:

- The annual cooling load decreases between 9.9% and 15.8% (Figure 4.76).
- The heating penalty is substantially lower in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of building.

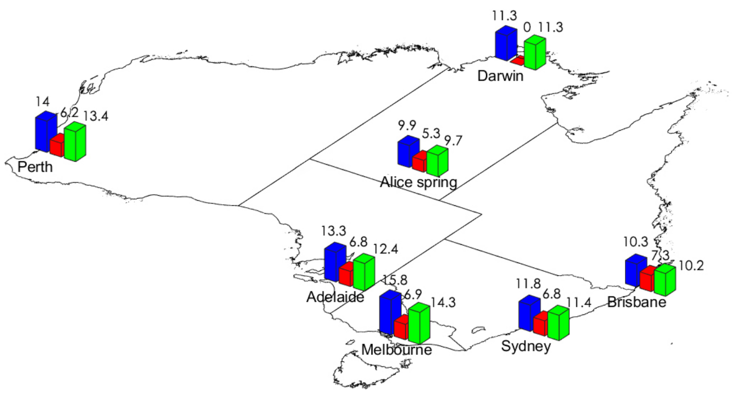


Figure 4.77 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a low-rise shopping mall centre — existing building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of a cool roof in an individual low-rise shopping mall centre-existing building ranges between 9.7% to 14.3%.

Under free floating conditions, cool roofs installed at a low-rise shopping mall centre (existing building), at the building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, between 1.8°C and 3.0°C, Figure 4.78. When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 2.6°C and 4.2°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.5°C and 1.2°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort as in Figure 4.78.

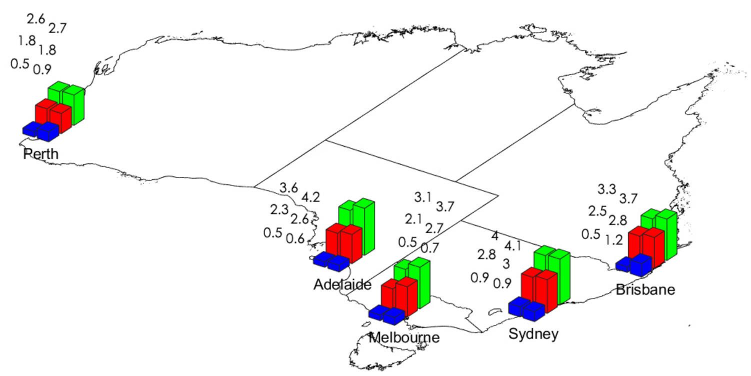


Figure 4.78 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a low-rise shopping mall centre — existing building.

Table 4.29 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease between 0% and 9%.
- When cool roofs are installed in both the building and city scale, overheating hours may decrease between 0% and 17%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	624 – 658	604 – 650	570 – 595
Melbourne	401 – 436	378 – 401	333 – 364
Brisbane	664 – 672	662 – 672	648 – 672
Adelaide	498 – 513	478 – 496	424 – 467
Perth	557 – 558	539 – 545	501 – 511

Table 4.29 Monthly number of hours above 26 in the five main Australian cities for a low-rise shopping mall centre — existing building operating under free-floating conditions.

Table 4.30 reports the number of hours below 19 under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

- During the operational hours, the number of hours below 19 increases between 2 and 6 hours, while during the whole period, the increase ranges between 5 and 14 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	32 – 60	208 – 293	34 – 62	217 – 302
Melbourne	48 – 84	350 – 407	54 – 86	364 – 412
Brisbane	20 – 42	79 – 171	25 – 45	91 – 182
Adelaide	84 – 112	392 – 452	86 – 116	398 – 457
Perth	43 – 50	223 – 272	46 – 54	232 – 282

Table 4.30 Monthly number of hours below 19 in the five main Australian cities for a low-rise shopping mall centre — existing building operating under free-floating conditions.

4.17. USING COOL ROOFS IN A HIGH-RISE SHOPPING MALL — EXISTING BUILDING, BUILDING TYPE 16

4.17.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

Figure 4.79 Building Type 16: Sketch of a high-rise shopping mall — existing building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A distinct spatial difference of the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city at Observatory Hill, is close to 51.5 kWh/m², while it is almost 30% higher, exceeding 66.8 kWh/m² in the western part of Sydney at Richmond station. Figure 4.80 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 16, in Sydney under reference conditions.

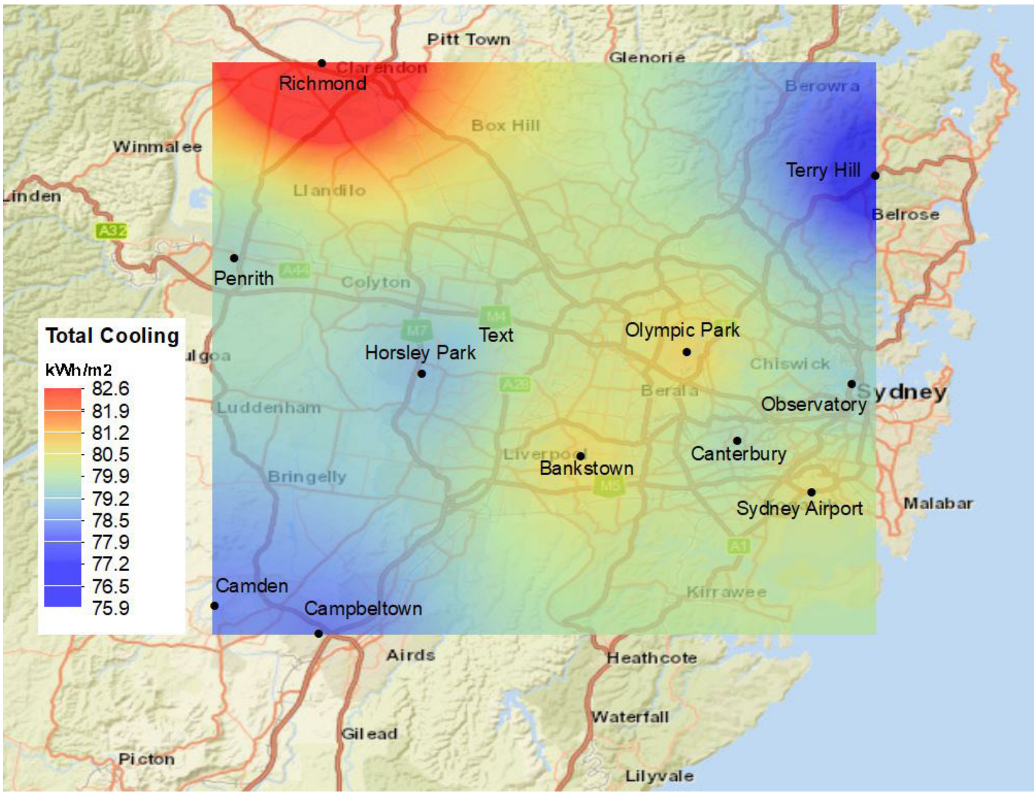


Figure 4.80 Spatial Distribution of the total sensible and latent cooling needs of high-rise shopping mall — existing building in Sydney under reference conditions.

It is calculated that both building-scale, Scenario 1, and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical high-rise shopping centre as an existing building during the summer season, Figure 4.81.

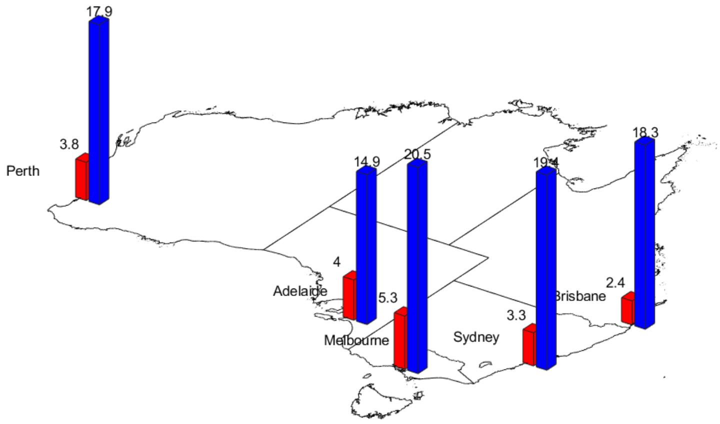


Figure 4.81 Percentage reduction of the cooling demand of a high-rise shopping mall — existing building in the five main Australian cities during January and February.

When cool roofs are installed in an individual high-rise shopping mall as an existing building, Scenario 1, the spatially average cooling demand in the five cities decreases between 2.4% and 5.3%, Figure 4.82. When cool roofs are installed in an existing high-rise shopping mall both at building and city scale, Scenario 2, the expected energy conservation ranges between 14.9% and 20.5%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings, Scenario 1, is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it can be seen that:

- The annual cooling load decreases between 3.1% and 4.9% (Figure 4.82).
- The heating penalty is substantially lower in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of buildings.

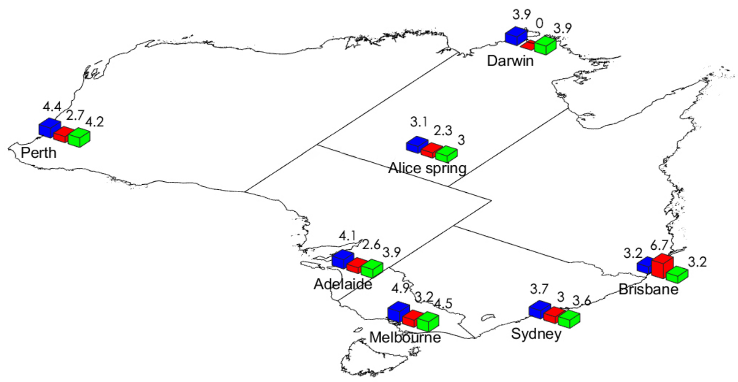


Figure 4.82 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a high-rise shopping mall centre — existing building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of a cool roof in an individual high-rise shopping mall centre-existing building ranges between 3.2% to 4.5%.

Under free floating conditions, cool roofs installed at an existing high-rise shopping mall (at the building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, between 0.6°C and 1.1°C, Figure 4.83. When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 1.3°C and 3°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.2°C and 0.4°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.83.

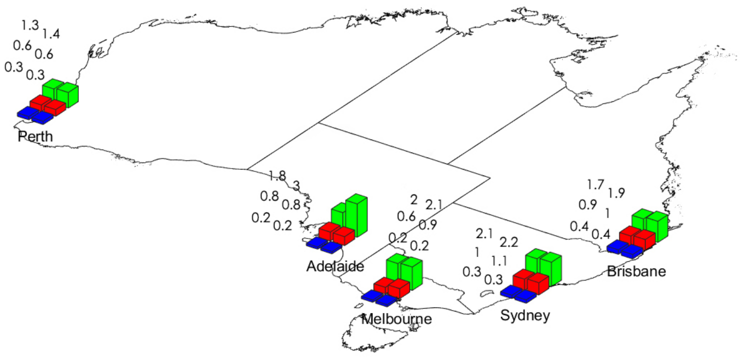


Figure 4.83 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a high-rise shopping mall centre — existing building.

Table 4.31 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease between 0% and 2%.
- When cool roofs are installed in both the building and the city scale, overheating hours may decrease between 0% and 14%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	660 – 670	655 – 670	634 – 666
Melbourne	448 – 474	440 – 465	383 – 416
Brisbane	672	672	672
Adelaide	538 – 546	538 – 541	485 – 525
Perth	615 – 618	612 – 615	577 – 588

Table 4.31 Monthly number of hours above 26 in the five main Australian cities for a high-rise shopping mall — existing building operating under free-floating conditions.

Table 4.32 reports the number of hours below 19 under the reference conditions and building implemented cool roofs scenario for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

— During the operational hours, the number of hours below 19 increases between 0 and 2 hours, while during the whole period, the increase ranges between 1 and 9 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	**Operational hours**	**Total**	**Operational hours**	**Total**
Sydney	16 – 53	97 – 233	16 – 54	99 – 237
Melbourne	36 – 71	269 – 349	38 – 72	275 – 354
Brisbane	9 – 29	19 – 95	11 – 30	20 – 97
Adelaide	70 – 104	340 – 404	71 – 104	342 – 405
Perth	28 – 39	144 – 196	29 – 39	153 – 199

Table 4.32 Monthly number of hours below 19 in the five main Australian cities for a high-rise shopping mall — existing building operating under free-floating conditions

4.18. USING COOL ROOFS IN A STAND-ALONE HOUSE — NEW BUILDING, BUILDING TYPE 17

4.18.1. ENERGY IMPACT OF COOL ROOFS DURING THE SUMMER PERIOD

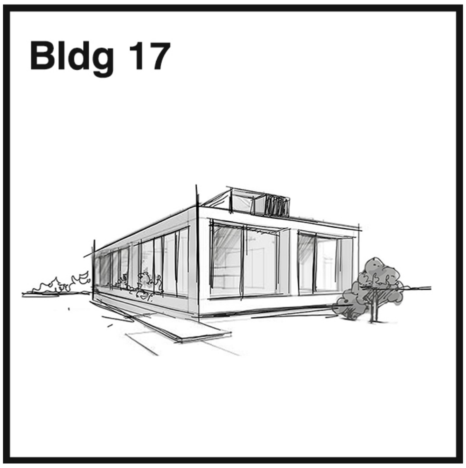


Figure 4.84 Building Type 17: Sketch of a stand-alone house — new building. Data on the characteristics of the building are given in the extended final report.

Using the mesoscale simulated climatic data for January and February, the cooling load of each of the 17 buildings is calculated for the reference building and the two cool roof scenarios mentioned above. Simulations are performed for a high number of local climatic stations in each city to estimate the impact of local climatic conditions on the cooling load of the buildings and reveal the spatial distribution of cooling needs. The full set of simulated data and results are given in the extended final report.

A distinct spatial difference of the cooling demand is calculated for most of the cities because of the intensive urban overheating and heat island effect. For example, In Sydney, the sensible cooling load, (January and February), in the eastern part of the city at Observatory Hill, is close to 7.5 kWh/m^2, while it is almost 63% higher, exceeding 12.2 kWh/m^2 in the western part of Sydney, Richmond station. Figure 4.85 presents the spatial distribution of the sum of sensible and latent cooling load for Building Type 17, in Sydney under reference conditions.

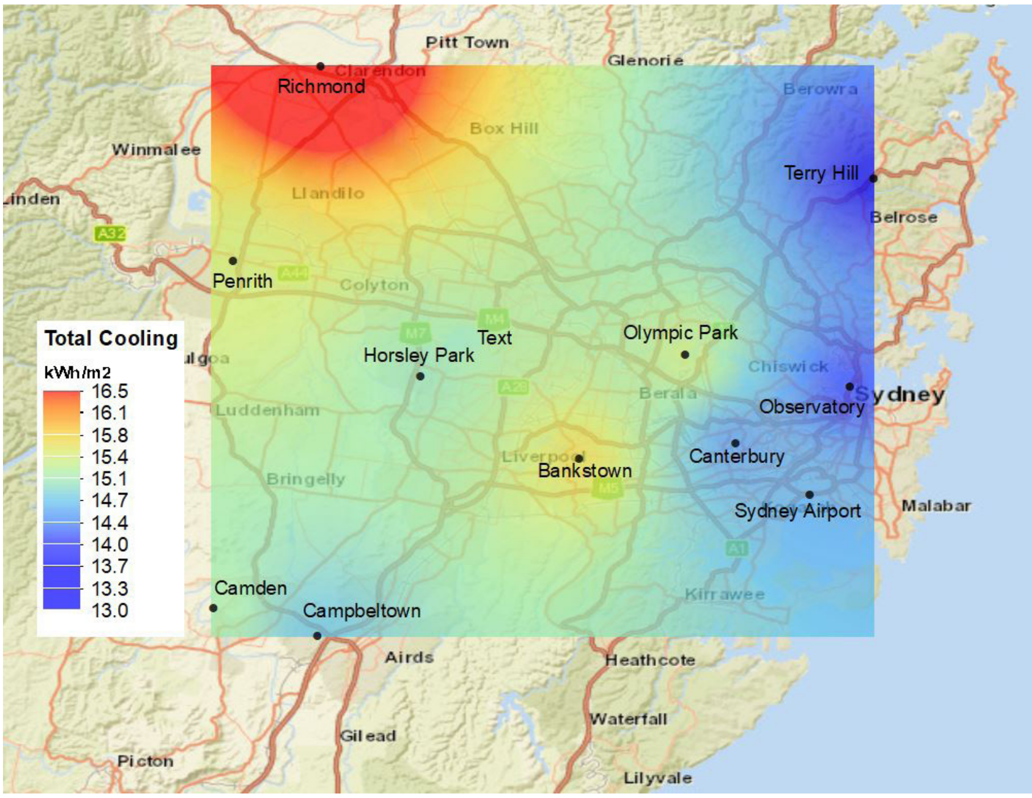


Figure 4.85 Spatial Distribution of the total sensible and latent cooling needs of a stand-alone house — new building in Sydney under reference conditions.

It is calculated that both building-scale, Scenario 1, and combined building scale and urban scale application of cool roofs can significantly reduce the cooling load of the typical stand-alone house as a new building during the summer season, Figure 4.86.

When cool roofs are installed in an individual stand-alone house, Scenario 1, the spatially average cooling demand in the five cities decreases between 18.1% and 41.4%, Figure 4.86.

When cool roofs are installed in a stand-alone house — new building both in building and city scale, Scenario 2, the expected energy conservation ranges between 41.5% and 61.4%. The detailed results for all stations, cities and scenarios can be found in the extended final report.

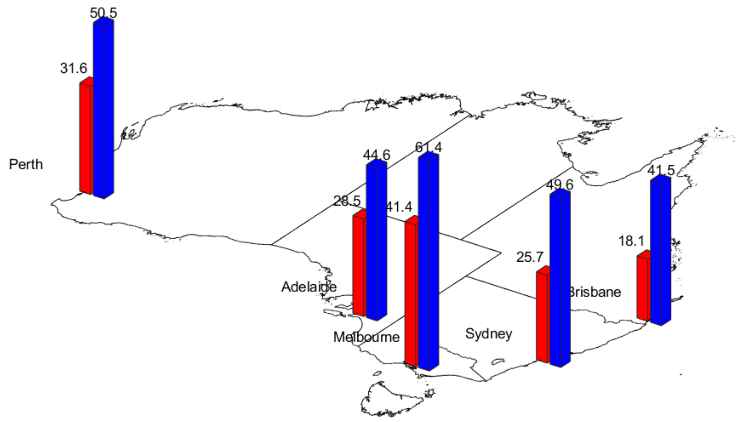


Figure 4.86 Percentage reduction of the cooling demand of a stand-alone house — new building in the five main Australian cities during January and February.

When the annual cooling load as well as the annual heating penalty induced by the installation of cool roofs in individual buildings, Scenario 1, is calculated for the five main cities and Alice Springs, Darwin, and Hobart, it is observed that:

- The annual cooling load decreases between 18.4% and 37.1%, Figure 4.87.
- The heating penalty is substantially lower in all cities except Hobart, where the use of cool roofs is not highly recommended for this type of buildings.

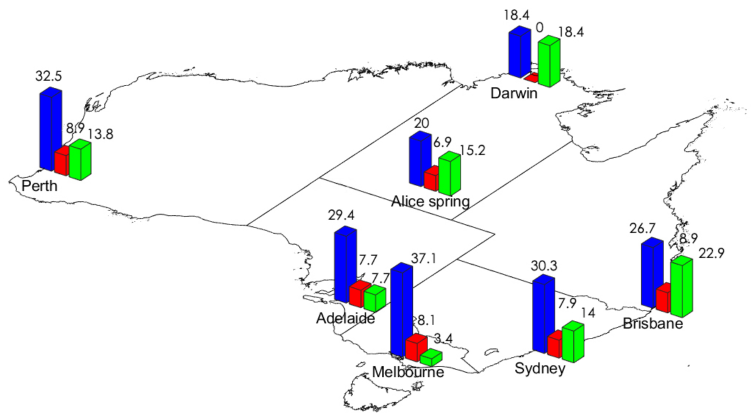


Figure 4.87 Annual increase of the heat demand and decrease of the cooling energy in the main Australian cities when cool roofs are installed at a stand-alone house — new building, at the building scale, Scenario 1.

Considering that the efficiency of the heating and cooling system is equal to one, then the net annual energy benefits arising from the installation of a cool roof in an individual stand-alone house-new building ranges between 3.4% to 22.9%.

Under free floating conditions, cool roofs installed at a stand-alone house-new building, at the building scale, Scenario 1, may reduce the peak summer ambient temperature in the five main cities, between 2.0°C and 2.9°C, Figure 4.88.

When cool roofs are installed at both the building and urban scale the expected average indoor temperature drop increases and ranges between 2.7°C and 4°C.

The average maximum decrease of the peak indoor temperature during the winter period varies between 0.7°C and 1.5°C. However, high values of the peak indoor temperature during the winter period are calculated only in cooling dominated climates and when ambient temperature was much higher than 19°C. In this case, no heating is needed, and the decrease of the indoor temperature does not affect indoor thermal comfort, Figure 4.88.

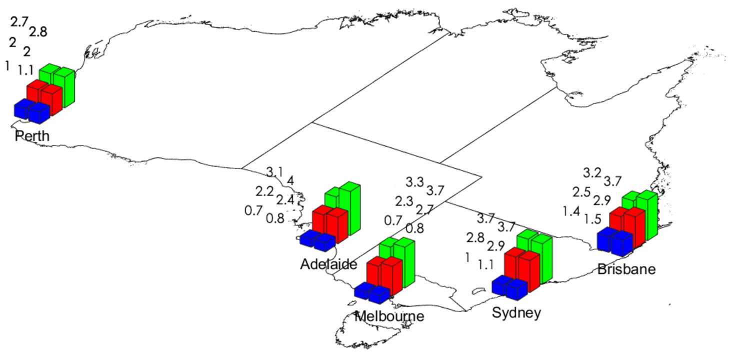


Figure 4.88 Average maximum drop of the indoor temperature during summer, scenarios 1 and 2 and winter period for a stand-alone house — new building.

Table 4.33 reports the calculated number of hours with indoor temperature higher than 26°C, under the reference conditions and also when cool roofs are considered, Scenarios 1 and 2.

- When cool roofs are installed at the building scale, Scenario1, the number of overheating hours is found to decrease between 1% and 40%.
- When cool roofs are installed in both the buildings and the city scale, overheating hours may decrease between 8% and 47%.

Number of hours above 26 in a typical summer month			
City	**Reference**	**Scenario 1**	**Scenario 2**
Sydney	422 – 456	339 – 415	352 – 356
Melbourne	171 – 230	107 – 161	64 – 129
Brisbane	558 – 618	552 – 583	485 – 566
Adelaide	284 – 356	203 – 300	139 – 264
Perth	330 – 376	256 – 327	192 – 288

Table 4.33 Monthly number of hours above 26 in the five main Australian cities for a stand-alone house — new building operating under free-floating conditions.

Table 4.34 reports the number of hours below 19 under the reference conditions and the first cool roof scenarios for a typical winter month. Data are given for both the operational hours of the building as well as for the whole period.

- The number of hours below 19 increases between 9 and 49 hours.

Number of hours below 19°C in a typical winter month				
	Reference		Scenario 1	
City	Operational hours	Total	Operational hours	Total
Sydney	N/A	429 – 523	N/A	478 – 562
Melbourne	N/A	702 – 704	N/A	720 – 728
Brisbane	N/A	189 – 296	N/A	234 – 333
Adelaide	N/A	680 – 718	N/A	703 – 727
Perth	N/A	446 – 486	N/A	487 – 535

Table 4.34 Monthly number of hours below 19 in the five main Australian cities for a stand-alone house — new building operating under free-floating conditions.

4.19. IMPACT OF COOL ROOFS ON THE PEAK ELECTRICITY DEMAND DURING SUMMER

4.19.1. CONTEXT

Extensive use of air conditioning increases peak electricity demand and obliges utilities to build additional power plants that may operate for a limited time (see Figure 4.89). Cool roofs contribute considerably to decrease the cooling demand of buildings and lower peak electricity demand in cities.

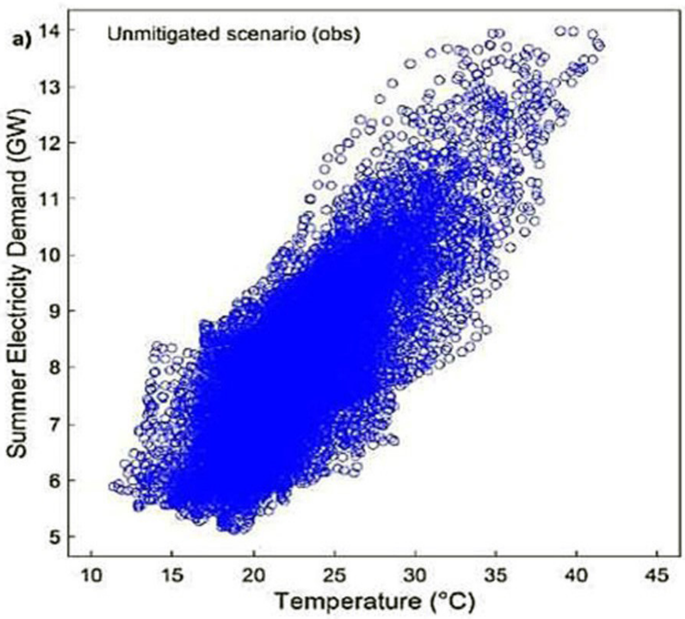


Figure 4.89 Electricity demand versus ambient temperature in Sydney.

The study investigated the magnitude of the peak electricity reduction caused by the installation of cool roofs in buildings and cities during the summer period, for the cities of Adelaide, Brisbane and Sydney and for two stations in each city presenting the higher and lower ambient temperature in each city.

Using building simulation techniques, the hourly sensible cooling demand was estimated for the defined 17 types of buildings under the reference conditions as well as considering that cool roofs are implemented at both building and city scale, Scenario 2. The ratio of the hourly sensible cooling demand for each building when cool roofs are used, against the corresponding cooling demand under the reference conditions has been calculated for a complete summer month. The calculations use climatic data as inputs to the mesoscale simulations.

The overall analysis demonstrated in a clear way the potential of cool roofs to decrease peak electricity demand during the summer period.

4.19.2. RESULTS – CONCLUSIONS

- In low-rise buildings without roof insulation or with a low level of insulation, the application of cool roofs in both individual buildings and across the whole urban area can significantly reduce the peak electricity demand load. For instance, In Brisbane, the average median daily ratio of cooling load in a cool roof with the modified urban temperature scenario (Scenario 2) in relation to the reference scenario is estimated to be 0.64 – 0.65 and 0.72 – 0.76 for a low-rise office building without roof insulation — existing building (b01) and low-rise office building with roof insulation — existing building (b13), respectively. A better performance is calculated for Sydney where the corresponding ratios are 0.47 and 0.61, and Adelaide, 0.28 – 0.48 and 0.56 – 0.6. Thus, for this type of building, cool roofs contribute to a striking decrease in peak electricity demand during the whole summer period, as in Figure 4.90.
- A strong correlation of the peak electricity savings with the ambient temperature is observed. The higher the ambient temperature the lower the peak electricity savings. Thus, the highest benefits are calculated for Adelaide, then Sydney and Brisbane.
- The reduction of the peak electricity demand at 14:00 hrs, is also very significant. Figure 4.91 shows the variation of the calculated ratios for Adelaide, Brisbane and Sydney, at 14:00 hrs for a low rise office building without insulation. For Adelaide, the peak electricity savings may range between 10 – 70%, for Sydney 10 – 60% and for Brisbane, 10 – 20%.
- Peak electricity reduction is found to be important for most of the high rise buildings as shown in Figure 4.90. The magnitude of the reduction ranges between 10 – 50 % mainly in Adelaide and Sydney

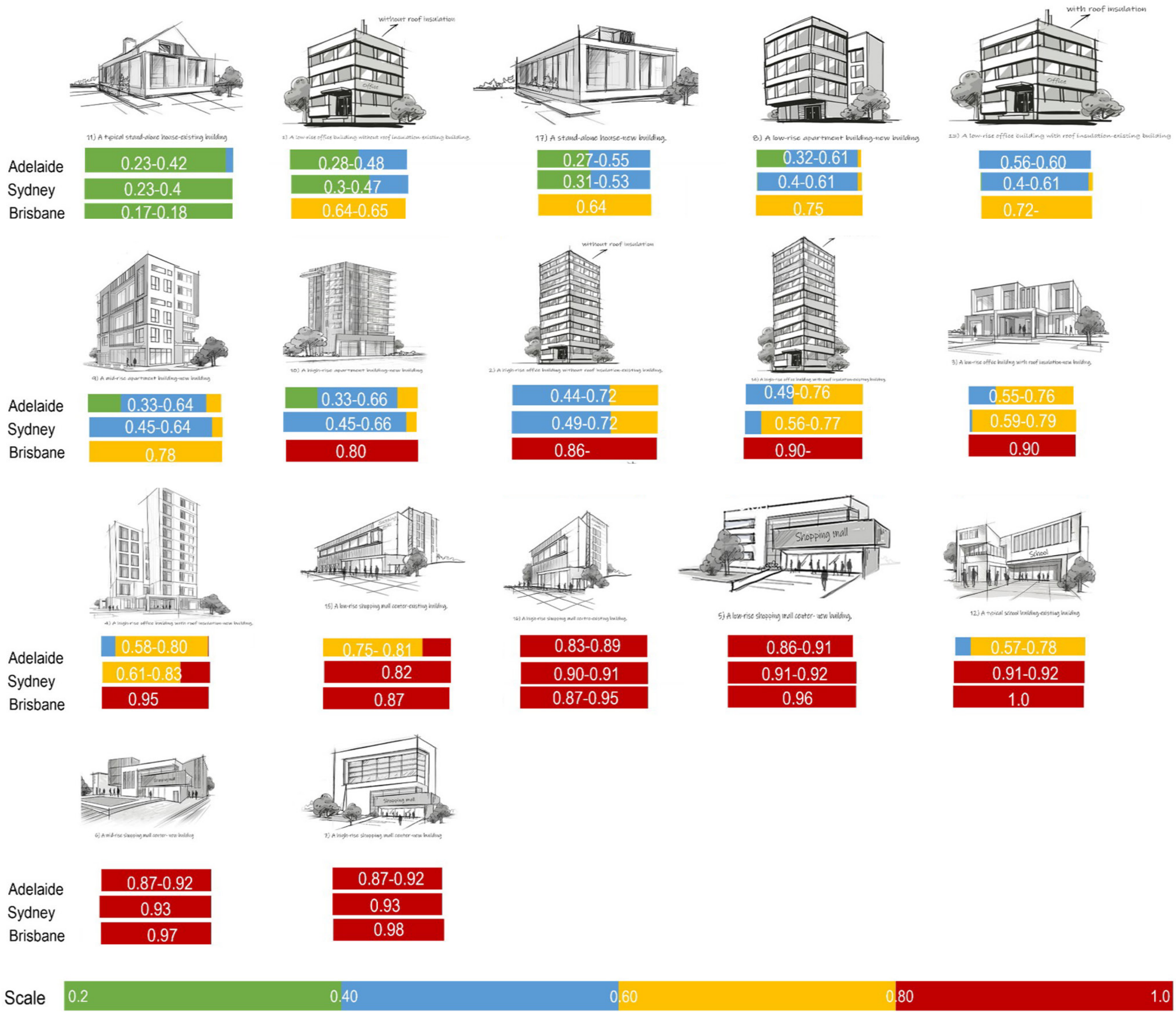


Figure 4.90 Ratio of the daily median sensible cooling load when cool roofs are used at the building and city scale, against the corresponding cooling demand under the reference conditions, for the 17 types of buildings in Adelaide, Brisbane, and Sydney.

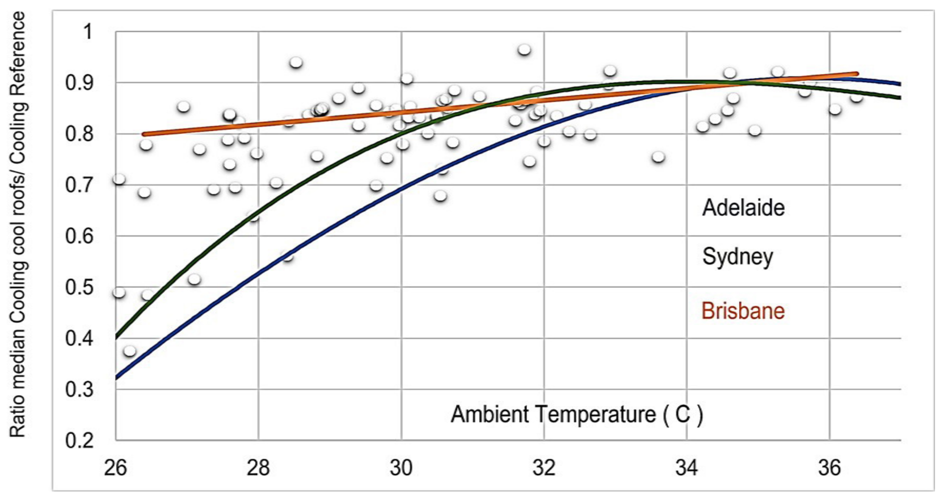


Figure 4.91 Ratio of the electricity demand for sensible cooling at 14:00 pm when cool roofs are installed at the building and city scale against the corresponding reference load, for Adelaide, Brisbane, and Sydney.

4.20. ASSESSMENT OF THE INCREASE OF THE EFFICIENCY OF AIR CONDITIONING SYSTEMS INDUCED BY COOL ROOFS

4.20.1. CONTEXT

The energy efficiency ratio (EER) of an air conditioning (AC) system is a ratio of useful cooling provided to work or energy required and is highly dependent on ambient air temperature. Cool roofs can reduce the cooling loads of buildings due to their impact on solar heat gain and local urban climate. The application of cool roofs can also increase the EER of AC systems, resulting in an extra cooling load saving (Gracik et al., 2015).

We evaluated the impact of cool roofs on the EER of AC systems and the corresponding cooling load savings. The cooling load saving from modified EER is in addition to the primary cooling load savings from lower heat gain and improved urban climate resulting from the installation of cool roofs in individual buildings and in the whole urban area.

The study was performed for residential and commercial AC systems, including split and Variable air volume (VAV) systems, and is performed for the warmer and cooler parts of Sydney, Brisbane and Adelaide. The study evaluated the impact of cool roofs on the EER of six different AC systems and the corresponding cooling load savings in 17 types of buildings in two summer months of January and February.

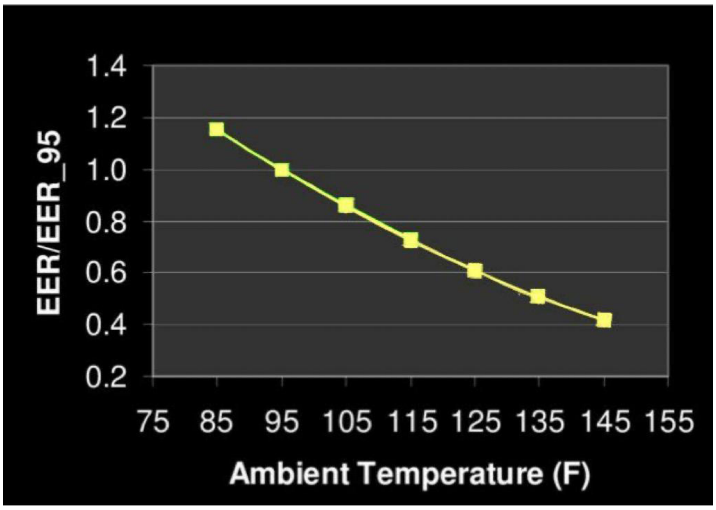


Figure 4.92 Decrease of the EER of AC as a function of the ambient temperature (Rice, 2005).

The median ratio of hourly cooling loads for cool roofs with a modified urban temperature scenario (scenario 2) to reference scenario and its correlation with ambient air temperature for each day was then computed to gain a better understanding of the cooling load reduction potential of cool roofs on different days with different ambient temperatures. The temperature data used in this study is the ambient temperature of the reference scenario at 14:00 hrs. Next, the EER (t) for the reference and cool roof with the modified urban temperature scenario (scenario 2) was computed using the hourly ambient temperatures for different AC residential and commercial systems, including split and VAV systems. The equations used for the calculation of EER (t) for different AC systems are given in the extended report.

Finally, the two-months cooling loads savings resulting from the application of cool roofs in individual buildings (scenario 1) and the cool roof with the modified urban temperature scenario (scenario 2) was compared with the corresponding two-month cooling load savings from the modified EER for different AC systems for all building types.

4.20.2. RESULTS

The EER of the six different AC systems under the reference scenario and the cool roof with modified urban temperature scenario (Scenario 2) is computed (Figure 4.93). The estimations illustrate a noticeable improvement in the EER of all cooling systems due to lower temperatures from the cool roof and modified urban temperature, Scenario 2, compared to the reference scenario.

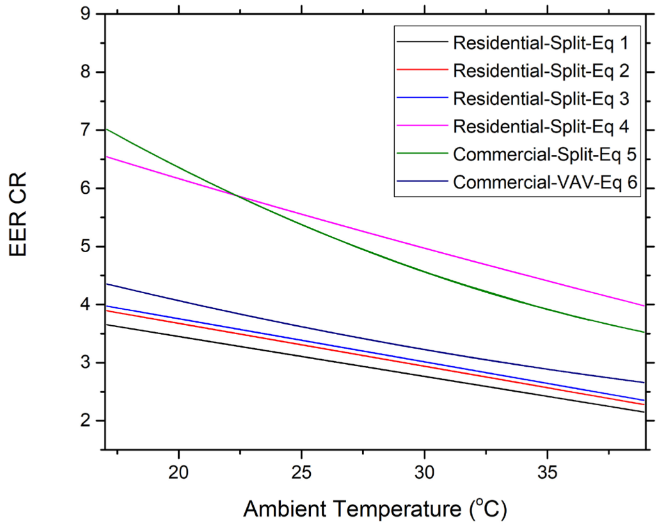


Figure 4.93 Variation of the EER of the AC systems considered as a function of the ambient temperature.

The main conclusions are:

- The application of cool roofs in both individual buildings and at the whole urban area is predicted to improve the hourly EER of the six selected AC systems by 0.12 – 0.32 in Sydney and 0.11 – 0.35 in Brisbane.
- In low-rise buildings with low levels of insulation, the cooling load savings from a modified EER is noticeable. For instance, the cooling load savings with a modified EER is estimated to range between 1.25 and 2.32 kWh/m^2 for existing low-rise office buildings without roof insulation at Richmond station in Sydney and between 1.9 and 3.7 kWh/m^2 in Brisbane. The corresponding cooling load saving by application of cool roofs in individual buildings (scenario 1) and the application of cool roofs in both individual buildings and across the whole urban area (scenario 2) for the same building, is predicted to be 13.2 and 14.9 kWh/m^2, in Sydney, respectively and 14.7 and 16.0 kWh/m^2 in Brisbane, respectively.
- In high-rise buildings with a high level of insulation, the cooling load savings from the modified EER is significant. For instance, the two-month cooling load savings is estimated to range between 1.4 and 2.7 kWh/m^2 for a new high-rise office building with roof insulation in Sydney at Richmond station and 1.7 and 3.2 kWh/m^2 in Brisbane. The corresponding cooling load saving resulting from the application of cool roofs to an individual building (scenario 1) and the application of cool roofs in both individual buildings and over the urban area as a whole (scenario 2) for the same building in Sydney is predicted to be 0.4 and 2.4 kWh/m^2, respectively and between 0.3 and 1.5 kWh/m^2 in Brisbane, respectively. [2]
- In commercial buildings, the cooling load savings from modified EER is quite significant. They are estimated to range between 5.4 and 10.4 kWh/m^2 for a new high-rise shopping mall centre in Sydney, 5.3 and 10.5 kWh/m^2 in Brisbane and 4.6 and 8.9 kWh/m^2 in Adelaide. The corresponding cooling load saving from the application of cool roofs in the individual building (scenario 1) versus the application of cool roofs in both individual buildings and at the whole urban area (scenario 2) for the same building in Sydney is predicted to be 0.7 and 3.7 kWh/m^2, respectively. The saving for Brisbane is predicted to be 0.6 and 3.2 kWh/m^2 respectively and 0.6 and 4.3 kWh/m^2 in Adelaide, respectively.

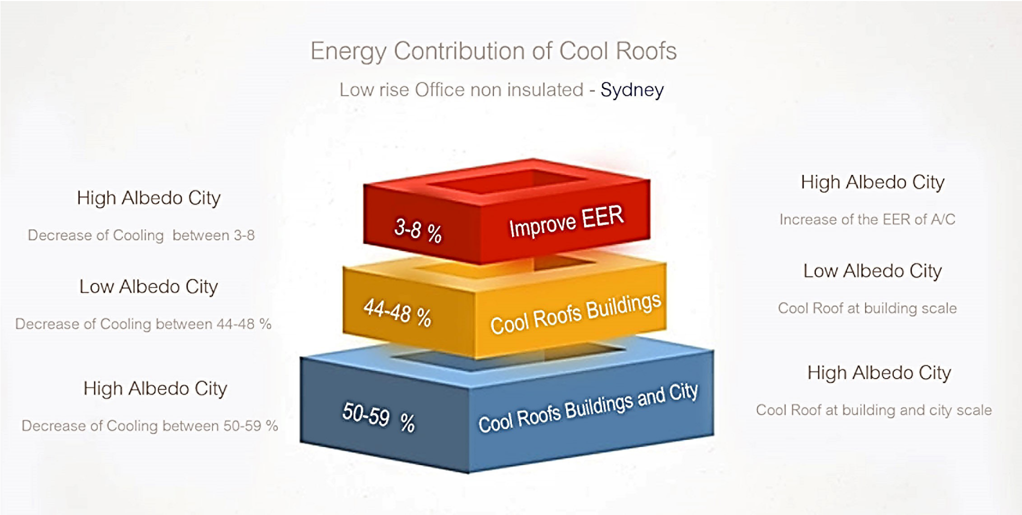


Figure 4.94 Energy contribution of cool roofs for a low rise non-insulated building in Sydney.
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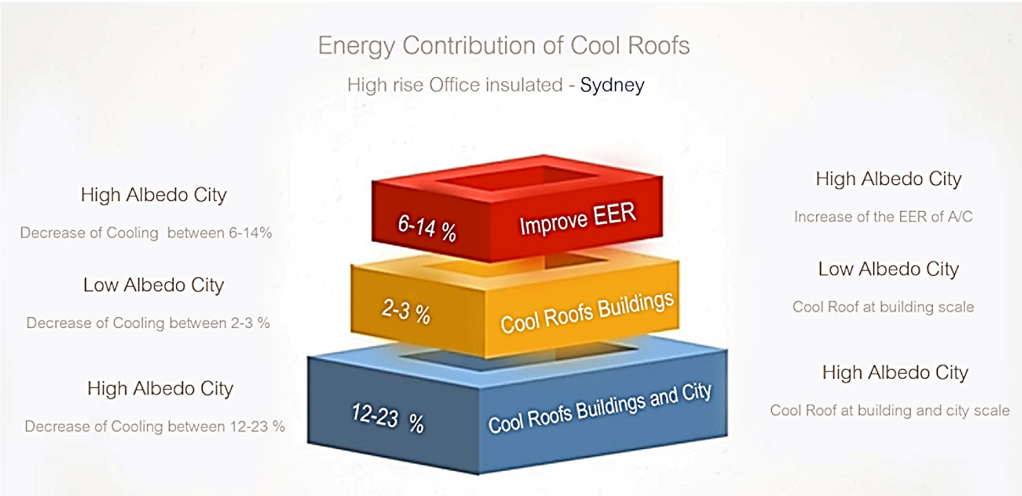

Figure 4.95 Energy contribution of cool roofs for a high rise well insulated building in Sydney.
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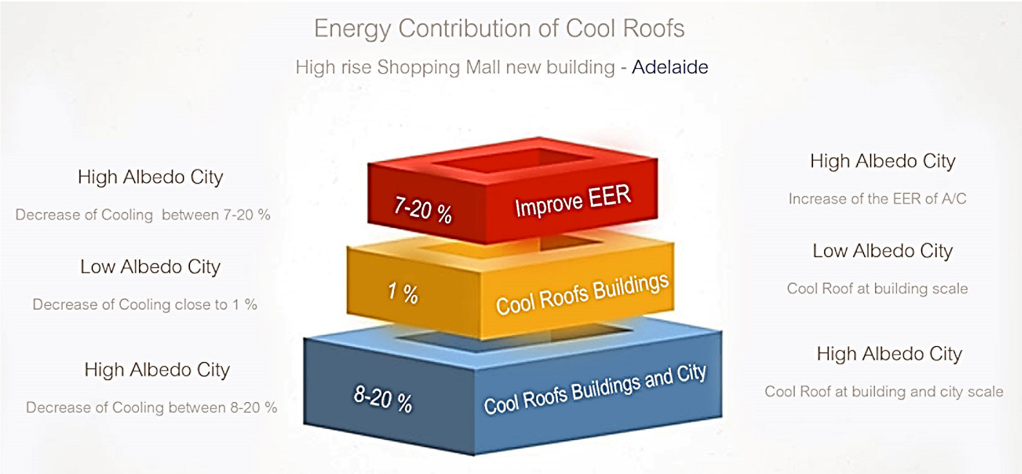

Figure 4.96 Energy contribution of cool roofs for a new shopping mall in Adelaide.
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4.21. ECONOMIC FEASIBILITY OF COOL ROOFS

4.21.1. CONTEXT

The economic feasibility of the cool roofs has been analysed for all capital cities using four economic indices:

- Net present value
  - Internal rate of return method
  - Life cycle cost analysis (LCA)
  - Depreciated payback period method
- The analysis has been performed for
  - All capital cities
  - Two stations, warmer and cooler per city
  - Two cool roof systems,
    1. A metal roof with cool characteristics is installed on top of the existing roof, presenting a higher cost and life expectancy
    2. A cool coating is applied on the existing roof, presenting a considerably lower cost than the cool metal roofs
  - 17 types of buildings as previously described
  - Low and high electricity cost scenarios. The cost of electricity varied considerably between the states.

Energy performance features	Observatory	Richmond
Energy consumption prior cool roof (MWh)	66.4	86.0
Energy consumption after cool roof (MWh)	40.1	54.0
Energy savings (MWh)	26.3	31.9
Energy savings (%)	39.61%	37.14%
Area (m^2)	2.400	2.400
Roof costs - Metal roof (AU$/$m^2$)	38.0	38.0
Roof costs - Coating (AU$/$m^2$)	22.75	22.75
Life expectancy - Metal roof (years)	28.5	28.5
Life expectancy - Coating (years)	22.5	22.5
HVACs Coefficient of Performance (COP)	2.5	2.5
Existing roof's renovation costs (AU$/$m^2$)	15.0	15.0

Table 4.35 Representative Inputs used for the economic feasibility analysis. Data are for Sydney and Building 1.

All the detailed inputs are listed in the final report.

Given the differences in the economic approach that form the background of the four methods which have been applied, the results of the analysis can be understood through the following two points:

a. Since the implementation of cool roofs techniques is not a revenue-generating investment but one that reduces the operational expenses of the buildings' function, it is not always possible to achieve positive net present values or internal rates of return. These two indices can only be used in a comparative sense and not in an absolute way, i.e. the solution with the biggest value is better, even if the value is a negative one.
b. Similarly, it is not always possible to achieve a meaningful payback period since the investment in the building's roof has to be implemented anyway, either as a conventional roof or as a cool one.

The determining factor is, therefore, the life cycle cost, in the sense that the solution that ensures its minimization is the most suitable one. As we are examining retrofitting, the life cycle cost of the "do nothing" scenario does not consider the construction cost but is only considering the incremental cost of the two variations of the cool roof. Consequently, life cycle cost is used as the base for the assessment.

4.21.2. RESULTS AND CONCLUSIONS

With respect to a comparative assessment of the 17 buildings considered, some conclusions are deduced with a generic validity:

- The feasibility of roof refurbishment in low-rise buildings is much more apparent than in high-rise ones due to the much higher participation of the roof in the overall exposed surface of the building.
- In exactly the same way, roofs without thermal insulation, and consequently with high energy requirements, present bigger energy savings potential.

In the case of uninsulated, low-rise roofs the impact of cool roofs is maximized.

- With respect to the 17 buildings considered, it does not come as a surprise that low-rise buildings, without thermal insulation of the roof and with high energy requirements are presenting the biggest energy savings potential and consequently the most attractive economic results.
- For such buildings, the life cycle cost can be reduced by as much as 82%. In such favourable cases, the payback period can be as low as two years.
- But even for the least favourable cases, those of high-rise buildings, with insulated roofs (like for example B01, BO5 and B17) and for lower electricity prices, the life cycle cost of coating the cool roof can be reduced compared to the "do nothing" conventional roof, which is more than enough to justify the cool coating's application, despite comparatively longer payback periods.
- The impact of weather conditions is important, since the feasibility is directly linked to energy requirements for each specific building.
- Finally, the impact of electricity prices is paramount, and it gets more important the higher the energy requirements are: it leads to drastically higher life cycle cost for the do nothing' solution, and consequently to shortened payback periods for the application of cool roofs of both types examined.

This last point should act as a reminder, of how expensive being long-sighted can be. The dramatic increase in international electricity prices in 2021, and the prevailing volatility in the energy markets, can only underline that cost-effective energy conservation measures pay off, especially when implemented on time and not after having been hit by an energy crisis.

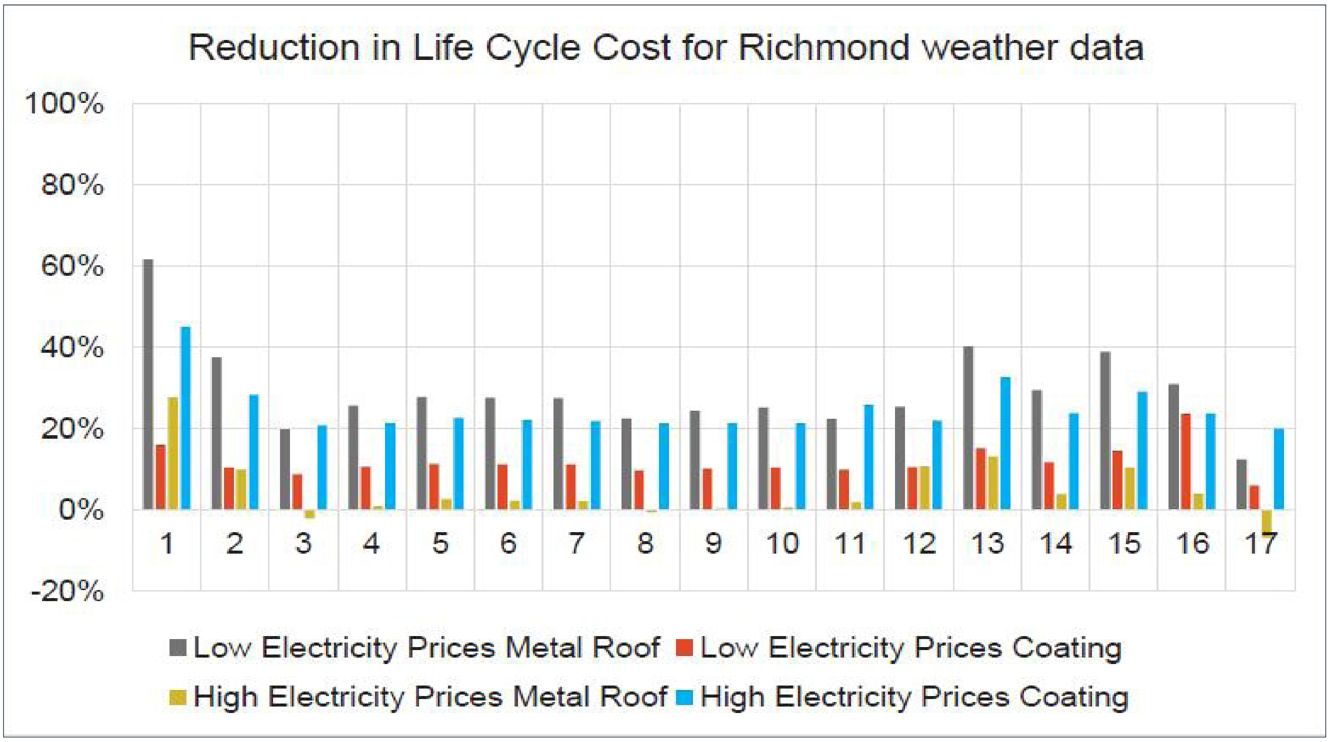


Figure 4.97 Reduction in LCC for Richmond weather conditions in Sydney for all buildings and scenarios.

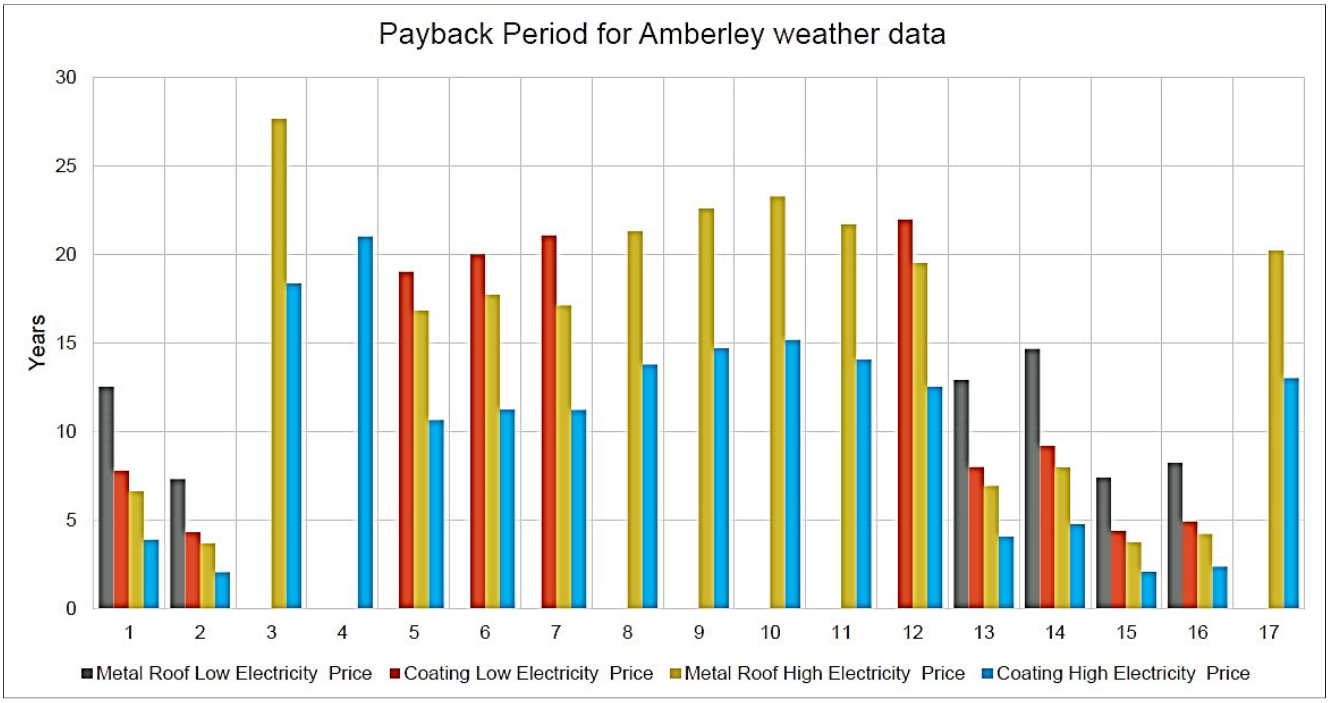


Figure 4.98 Payback period for the buildings for Amberley weather conditions, Brisbane.

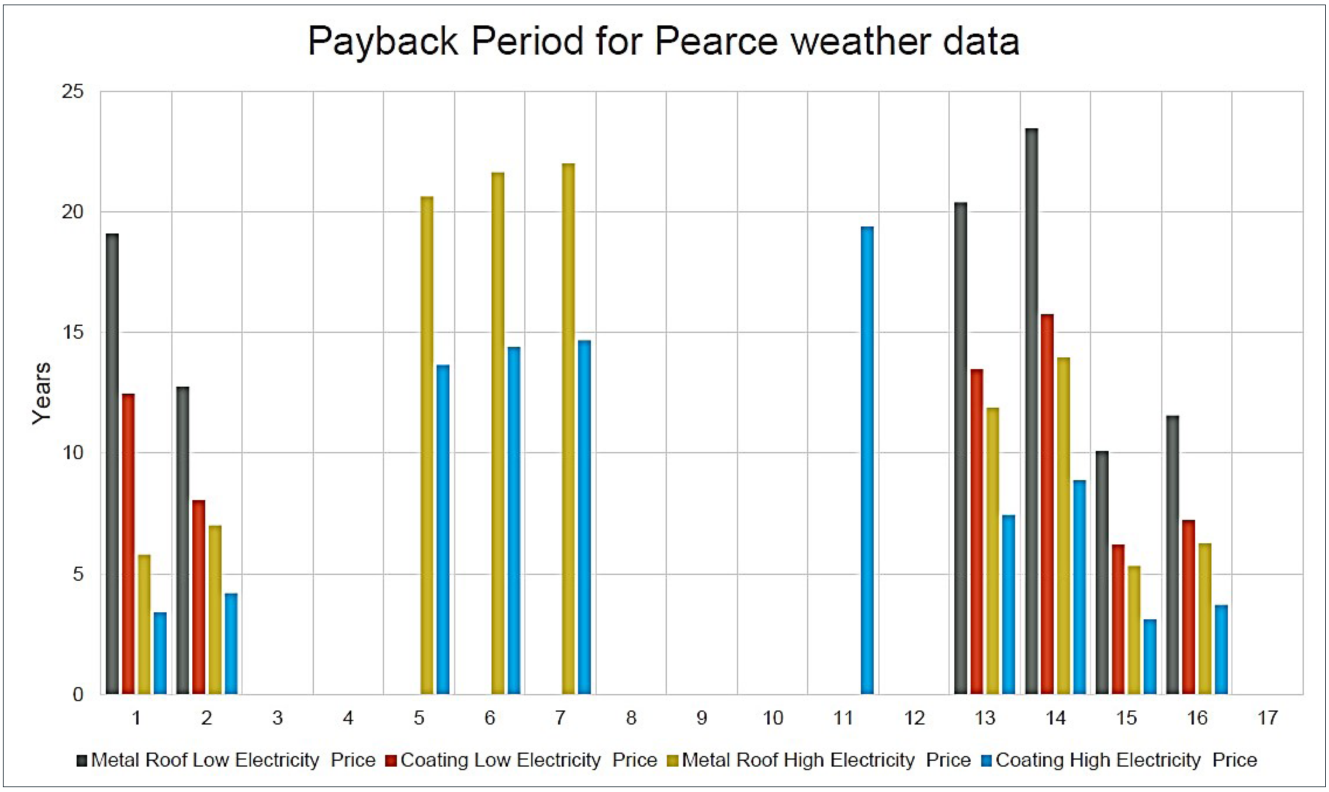
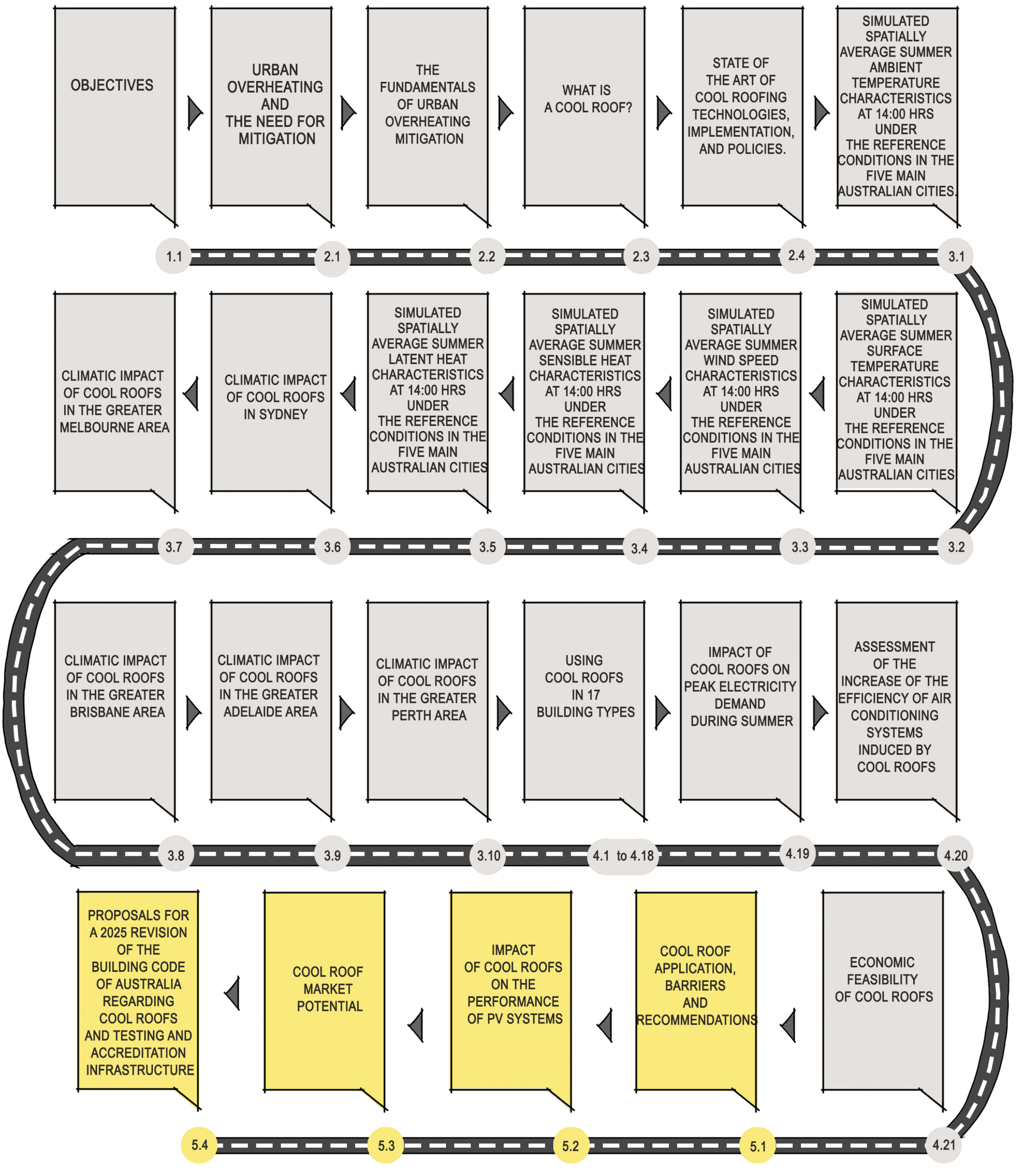


Figure 4.99 Payback period for the buildings for Pearce weather conditions, Perth.

5. BARRIERS, IMPLEMENTATION
BENEFITS, DRAWBACKS AND RECOMMENDATIONS



5.1. COOL ROOF APPLICATION: BARRIERS AND RECOMMENDATIONS

To identify the barriers in the application of cool roofs in Australia and collect recommendations to address these barriers, a survey was created to gather the perspectives of Australian cool roof stakeholders. Five categories of potential barriers were pre-identified for attendees to select from (Figure 5.1). Additional barriers shared by the stakeholders, as well as the proposed recommendations to overcome the barriers, were collected.

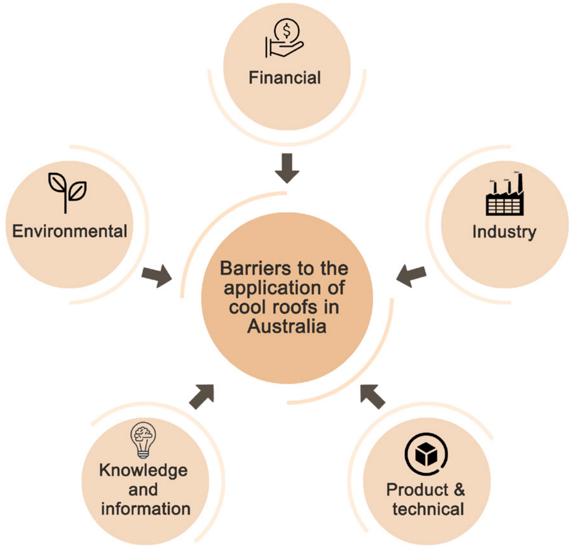


Figure 5.1 Barriers to the application of cool roof in Australia.

The Australian Cool Roof industry has and still is suffering from a lack of awareness, legislation, policy, and standards. Major barriers in the Australian cool roof industry have been identified by the stakeholders and their recommendations to overcome the barriers have also been summarised. Key barriers and recommendations are illustrated in Figure 5.2 and are summarized as follows:

1. There is no government incentive or support for developers or builders to utilise/apply the heat reflective coating technology to their structures. The introduction and increase of financial support like incentives, subsidies and rebate systems from federal and state levels are strongly advocated.
2. Due to the lack of supportive policy and standardised accreditation for cool roof products, proven and tested cool roofs are not getting the credibility and recognition they deserve. All products should be tested or provide authoritative academic research information set against a well-defined standard to be recommended by government authorities and be the subject of financial assistance in their purchase and installation. The stakeholders have expressed urgency and indispensability of the introduction of such policies and legislation, as well as modifying the current building code to accommodate heat mitigation techniques like cool roofs.
3. The focus on further development and commercialisation of cool roof technologies and advancements in cost reduction and efficiency improvement is recommended. There should be a minimum requirement of durability, reflectance, emittance, spread rate and other key parameters.
4. Inadequate communication among various industries and between industry and the public are hindering progress. Stakeholders believe that better information sharing and improving the public's awareness of cool roofs' benefits are both essential.
5. White or light-coloured cool roofs can be aesthetically unacceptable. The suitability of cool roofs is further hindered by possible glare and limited applicability under certain climatic conditions. Stakeholders highlighted that the glare issue only exists under specific circumstances and proposed that it should be clarified by professionals to eliminate unnecessary concern by the public.

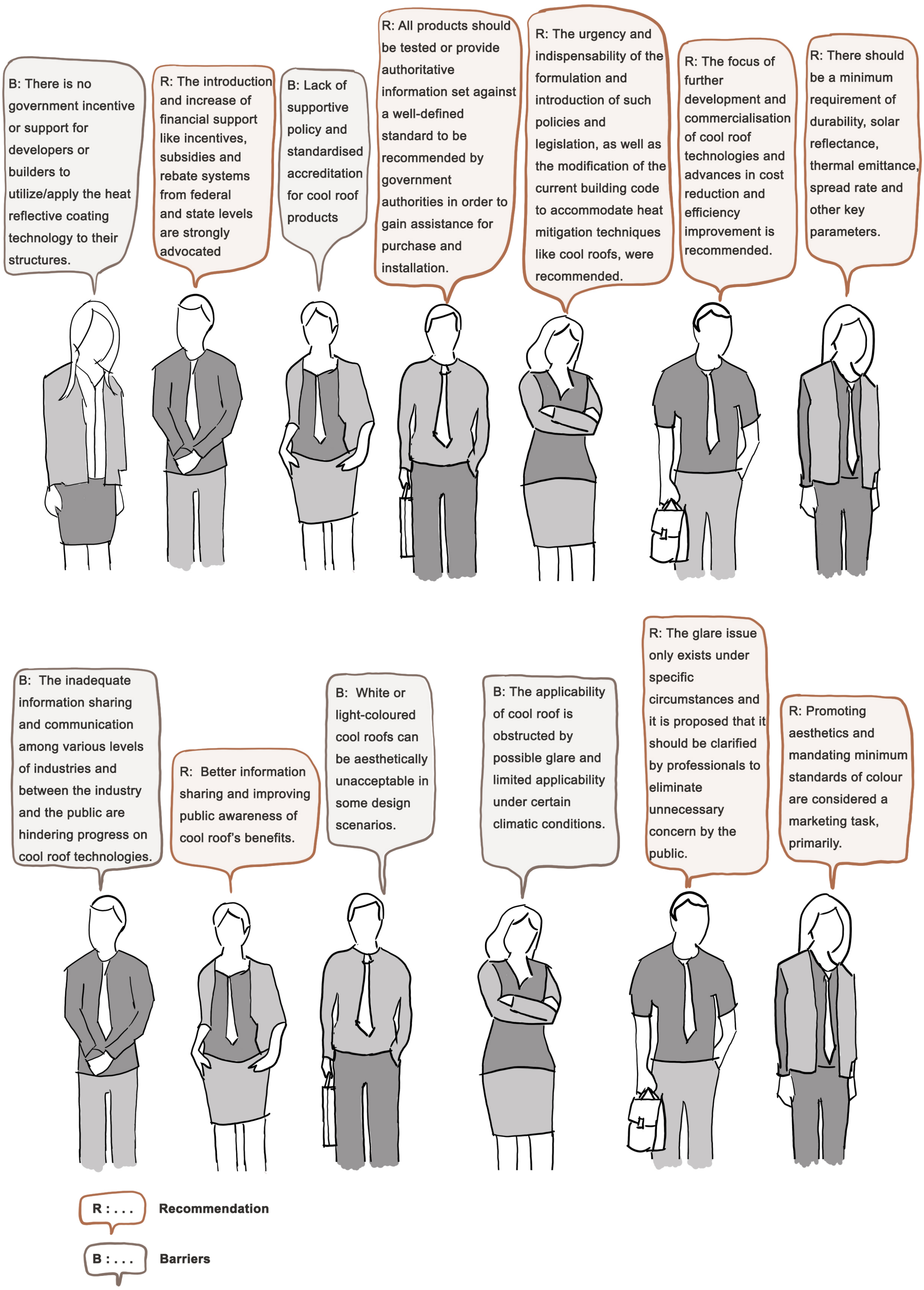


Figure 5.2 Cool roof application: barriers and recommendations.

5.2. IMPACT OF COOL ROOFS ON THE PERFORMANCE OF PV SYSTEMS

This section of the report reviews previous research concerning the effectiveness of the cool roof application on solar PV efficiency. Specifically, the purposes of this section are:

1. To review the benefit of using cool roof technology when implemented at different scales.
2. To outline the key findings of the integrated roof by highlighting a set of interrelated attributes and their impacts on the outdoor and indoor thermal environments, based on a review of the existing research literature.
3. To identify the most accurate method of measuring, examining and simulating PV panel efficiency.
4. To classify effective criteria for the performance of PV systems and cool roof technologies.

5.2.1. DATA SOURCES AND STUDY ELIGIBILITY CRITERIA

Data sources for the literature review included Scopus, Web of Science and Google Scholar. The snowballing technique was also used on full texts that met the inclusion criteria. Study eligibility criteria included studies on "cool roof" OR "reflective roof "+ "PV" OR "solar panel" OR "photovoltaic", focusing on the building or construction sector, in English and without time limitation.

Collectively, the following conclusions have been drawn:

- The efficiency of solar PV integrated with cool roof application depends on a number of criteria, such as microclimatic conditions, local development context, building context, cool roof design and PV panel configurations (Figure 5.3). Roof albedo was mentioned as the most important factor impacting on the efficiency of both cool roofs and PV panels. The inferences of the study are summarised in the following way:
  - » For every increase in roof albedo by 0.1:
    a. The annual energy yield of PV increases by 0.71% – 1.36%.
    b. Cool roof performance increases by 14%.
    c. The roof surface temperature decreases by 3.1°C – 5.2°C. A decrease by 1°C in the roof surface temperature increases PV system efficiency by 0.2% – 0.9%.

However, these relationships depend greatly on several factors, including panel efficiency assumptions, albedo of the reference scenario, location of PV-cool roofs, type of building, and the scale of our atmospheric model (mesoscale or microscale).

Roof albedo was mentioned as the most important factor impacting on the efficiency of both cool roofs and PV panels.

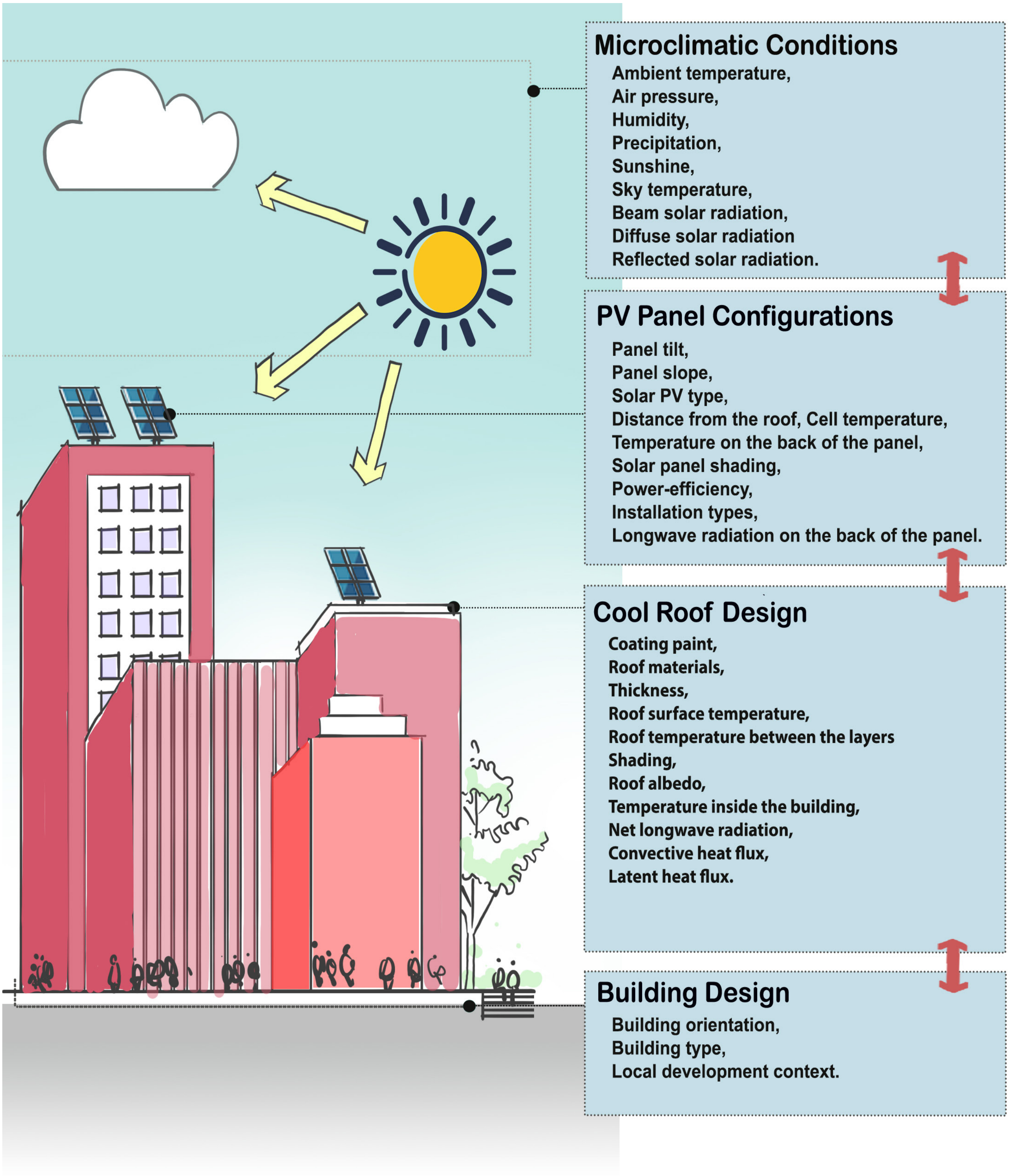


Figure 5.3 Criteria for evaluating the effectiveness of solar PV applications integrated with cool roof application.

- PV systems have significant impacts on urban elements such as air temperature, the provision of shade and building energy consumption.
- Integration of solar PV with cool roofs helps reduce peak electricity demand, and PV in tandem with cool roofs is able to generate more electricity than PV - green roofs. Green roofs can raise annual PV energy yield by 1.8%, and cool roofs with their higher albedo can raise it by 3.4%.
- Although PV with a lower tilt angle have a higher performance during summer, and systems with a higher tilt angle have a higher performance during the winter season, the compensation of the cool roof paint can actually change the optimum position of the tilt angle of PV panels.
- The higher albedo of the cool roofs can decrease roof surface temperature. It can have positive or negative impacts on PV efficiency and solar thermal systems. It depends on microclimatic conditions, the local development context, the building context, cool roof design and PV panel configurations.
- The performance of PV technology in an urban context can be improved by: 1) designing panels that can more effectively reject heat that does not turn into electricity, 2) installing high reflective coating for PV panels which one might call "cool photovoltaics", 3) installing PV panels with some distance off the roof to provide air gaps and ventilation, 4) developing hybrid PVT collectors with various mass flow rates due to their ability to increase outlet temperature, output voltage and output power as well as to decrease panel surface temperature and environmental pollution and 5) developing BIPV roofing systems due to their indirect shading impact and ability to produce electricity, especially with decreasing PV costs.

Overall, the existing literature suggests that the future improvement of PV - cool roofs could generate more electricity and decrease air temperature due to the significant reduction of excess heat release to the surrounding environment. The improvement could also result in a significant reduction of carbon emissions, reducing climate change on a larger scale. Hence, further research and government intervention options need to consider the specific microclimatic conditions, local development context, building context, cool roof design, and solar PV configurations when developing PV — cool roofs.

The future improvement of PV — cool roofs could also result in a significant reduction of carbon emissions, reducing climate change on a larger scale.

5.3. COOL ROOF MARKET POTENTIAL

Cool roofs are currently emerging as one of the most important strategies to lower the temperature of buildings, improve indoor comfort and safety, reduce energy bills through decreasing air conditioning needs, and battle urban heat islands. Despite these benefits, people still want to know: "How much does a cool roof installation cost?".

Cool roofs, either retrofit or full roof replacement, do not necessarily cost more than conventional roofs, particularly if retrofitting old roofs. Price will vary wildly, depending on the material used and the design of the building. This section of the report is primarily intended to estimate the approximate installation cost of cool roofs in Australian states and then estimate the level of related job creation in order to encourage the development of policies, programs, and markets to deliver cool roofs across Australia.

5.3.1. COOL ROOF INSTALLATION COST IN AUSTRALIA

The standard cost of the cool roof material in Australian dollars (AUD) per square meter and for 14 products was presented in Chapter 2, in the section, "Cool roof market report". The results showed that the average cost of the cool roof material is AUD$13/m^2. The highest price identified was AUD$32.5/m^2, while the lowest was AUD$2.5/m^2.

This section of the report estimates the minimum and maximum cost of cool roofs in eight Australian states. This estimate was applied to total roof area in 2020 and annual new roof area added between 2015 and 2016 (Figure 5.4). Overall, the results show that:

- The total minimum and maximum potential cost of cool roof installation for **all roofs** in Australia in 2020 is AUD$6.9b (USD$4.9b) and AUD$89.2b (USD$64.2b), respectively.
- The cost breakdown of building types installing cool roofs is 84% residential, 9% commercial, and 7% industrial (as at 2020).
- The estimated minimum annual cost of installing cool roofs for **new roofs** is AUD$168m (USD$121m), and the maximum is AUD$2.2b (USD$1.6b).

Cool roofs are currently emerging as one of the most important strategies to lower the temperature of buildings, improve indoor comfort and safety, reduce energy bills through decreasing air conditioning needs, and battle urban heat islands.

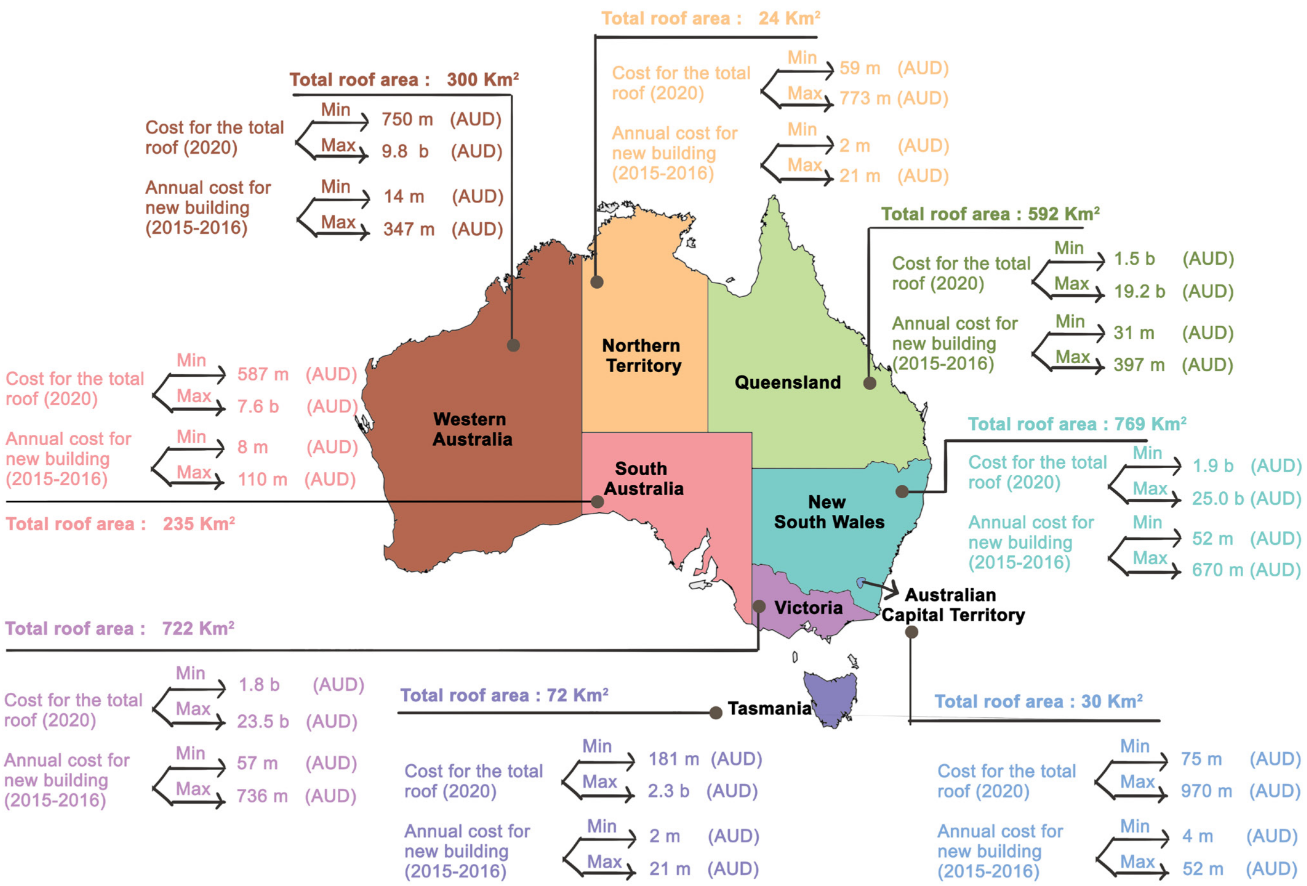


Figure 5.4 Estimated minimum and maximum cost of cool roofs in eight Australian states.

5.3.2. ECONOMIC POTENTIAL OF COOL ROOF APPLICATION

In this section, the potential number of direct jobs, indirect jobs and induced jobs created by cool roof application in Australia, were calculated by using the following considerations:

- Number of direct jobs considering 5.3 jobs per million of AUD (7 jobs per million of USD).
- Number of indirect jobs considering 3.6 jobs per million of AUD (4.9 jobs per million of USD).
- Number of induced jobs considering 8.7 jobs per million of AUD (11.8 jobs per million of USD).

Figure 5.5 presents the potential number of jobs created using cool roofs for the **total roof area in 2020** as well as average annual job creation for a new roof area installed between 2015 and 2016. Overall, results show that:

- Applying a cool roof strategy for total roofs in 2020 could provide between:
  - 34,576 to 449,490 direct jobs
  - 1,008 to 13,105 indirect jobs, and
  - 58,285 to 757,711 induced jobs.
- Annually, the application of cool roofs can provide, on average:
  - 5,940 direct jobs
  - 173 indirect jobs, and
  - 10,013 induced jobs.

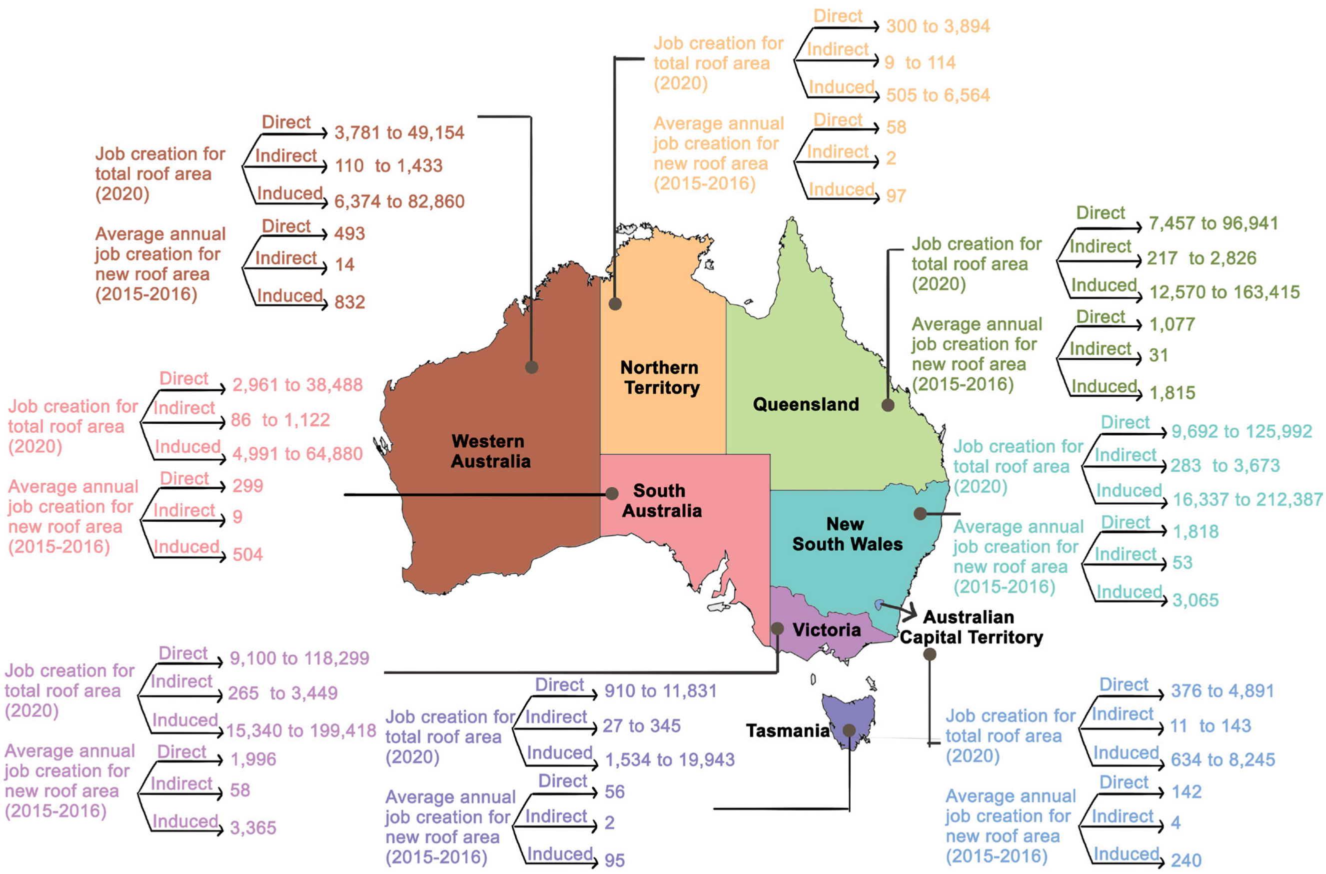


Figure 5.5 Job creation potential of cool roof application in Australia.

5.4. PROPOSALS FOR THE 2025 REVISION OF THE BUILDING CODE OF AUSTRALIA AND TESTING AND ACCREDITATION INFRASTRUCTURE

ONE-PAGE EXECUTIVE SUMMARY

Highlights

- The NCC sets a maximum solar absorbance of 0.45 for non-residential buildings.
- No separate limit for flat and pitched roofs and no limit for residential buildings.
- The provision could be circumvented with a performance solution, overlooking environmental impacts.
- No measurement procedures in the NCC or Australian Standards (only ISO, ASTM, or CEN).
- We advance proposals for the NCC2025 revision.
- We present proposals to establish a testing and accreditation infrastructure in Australia.

Summary of Policy Recommendations

- Recommendations for the NCC2025 revision:
  - Proposal 1. Use the Solar Reflectance Index (SRI) instead of solar absorptance.
  - Proposal 2. Add a performance requirement on mitigation of urban overheating in Section J or an entirely new section.
  - Proposal 3. Limits to SRI for all buildings, including residential.
  - Proposal 4. Limits apply to retrofits.
  - Proposal 5. Limits cannot be set back (or lowered) by local governments.
  - Proposal 6. Different SRI for pitched and sloped roofs.
  - Proposal 7. Explicit indication of standard test and calculation methods.
  - Proposal 8. Standard test methods and calculation procedures part of the NCC.
  - Proposal 9. Interim unaged and aged values for SRI limits.
  - Proposal 10. Mould and condensation risk reduction.
- Goals of a testing and accreditation infrastructure:
  - Protect and support the consumer and the cool roofs industry from unfair competition.
  - Enforce compliance with the National Construction Code and simplify its verification.
  - Be unequivocal and repeatable, and support-decision making and dispute resolution.
- Pillars of the testing and accreditation infrastructure:
  - Pillar 1 — Industry-led association governing the testing and accreditation infrastructure.
  - Pillar 2 — Accreditation of testing laboratories.
  - Pillar 3 — Factory Production Control.
  - Pillar 4 — Support of product development.
  - Pillar 5 — Test methods delivering repeatable and reproducible results.
  - Pillar 6 — Performance over time: measured aged SRI, SR, and TE after 3 years of natural exposure.
  - Pillar 7 — Public database of rated products.
  - Pillar 8 — Product labelling by the Australian Cool Roofing Council.

Keywords: solar reflectance; thermal emittance; solar reflectance index; testing; building code; standard; laboratory.

5.4.1. INTRODUCTION AND CURRENT SITUATION

Here, we provide an overview of the current regulatory framework in Australia related to the solar absorbance of roofing and advance proposals for the 2025 revision of the National Construction Code (NCC), including the concepts for establishing a testing and accreditation infrastructure that would serve the implementation of cool roofs and enable the verification of compliance.

Currently (NCC2019 & NCC2022), solar reflective roofs are included in the Building Code of Australia only as a Deemed to Satisfy provision for non-residential buildings Class 3 and from Class 5 to 9 (NCC Vol 1 J1.3b). The prescription does not apply to apartment buildings or houses. For non-residential buildings, the maximum solar absorbance is set to 0.45 for rooftops of buildings in Australian climate zones 1 to 7 (i.e., all excluding alpine areas). In some situations, the prescription is modified in South Australia, indicating a maximum solar absorbance of 0.40.

Aspects currently not addressed. Several elements are not covered in the 2019 and 2022 editions of the National Construction Code and should therefore be addressed:

- There is no solar absorbance threshold for residential buildings, i.e., the majority of rooftops.
- A Performance Solution could circumvent the prescription on maximum solar absorbance.
- There is no indication of a threshold for thermal emittance.
- There is no differentiation between low sloped and pitched roofs, usually treated separately.
- There is no indication of standard test and calculation methods, which hinders comparison of products.
- Ageing is not considered, but reflectance losses due to weathering and soiling can be significant.

5.4.2. PROPOSALS IN PREPARATION FOR THE NCC2025 REVISION

Proposal 1: Use the Solar Reflectance Index instead of solar absorptance. The Solar Reflectance Index (SRI) is a parameter that combines in one number, both solar reflectance (SR) and thermal emittance (TE), which the NCC currently overlooks. The SRI for any roof is linearly interpolated, considering the surface temperature it would have in standard summer conditions, scaled between a comparison white (SRI = 100 for SR = 0.80 and TE = 0.90) and a comparison black roof (SRI = 0 for SR = 0.05, TE = 0.90). The advantage is having a single parameter defining the performance.

Also, it is possible to define an “equivalent SRI” for green roofing — or any other present or future technology providing a heat sink — thus mitigating urban overheating. Low solar reflectance and low surface temperature exist in green roofs, because of evapotranspiration, for example.

Proposal 2: Add a performance requirement for mitigation of urban overheating in Section J or an entirely new section. The prescriptions for the SRI should not be simple Deemed to Satisfy Provisions, as they can be avoided by implementing a Performance Solution, for example a solar absorptive roof with hyper-insulation, saving energy at building level but overheating the built environment. An urban overheating section would introduce performance-based requirements that would apply to any roofing type, also covering green roofing or more advanced technologies, and averting continuous revisions and patches.

Proposal 3: Limits to SRI for all buildings, including residential. The thresholds on the SRI should be applied to all building classes, especially including residential buildings that have the largest cumulative roof area in Australian cities (2,744 km^2).

Proposal 4: Limits apply to retrofits, including reroofing or substantial maintenance. Exemptions for architectural heritage buildings should be included in the National Construction Code.

Proposal 5: Limits cannot be lowered by local governments. Councils cannot reduce SRI requirements for new developments, with the exception of exemptions for architectural heritage. Near infrared-reflective options having the same colour as heritage materials should be considered when possible, i.e., when aesthetics should be preserved but there is no requirement to maintain the original materiality.

Proposal 6: Different SRI for pitched and sloped roofs. There should be a separate statement for the SRI limits for pitched and low-sloped (or flat) roofs, as common in international codes.

Proposal 7: Explicit indication of standard test and calculation methods. The standard test methods and calculation procedures should be explicitly referenced in line and not simply in schedule 4 of NCC Vol 1. The procedure employed to compute solar reflectance should be unambiguous, otherwise, product comparison would be impossible. The solar irradiance distribution for air mass 1 global horizontal (AM1GH) as in ASTM E903, is recommended.

Proposal 8. Standard test methods and calculation procedures part of the NCC. Whenever possible, the NCC should include the formulas (not protected by copyright), measurement principles and description, minimising information behind a paywall.

Proposal 9. Interim unaged and aged values for SRI limits. There should be a requirement to reveal the aged performance of roofing products upon testing, which can be set once Australia's accreditation framework is implemented. Therefore, there would be a need for a staged approach with interim values, giving the industry sufficient time to adapt and implement all changes to achieve the targets. The thresholds suggested below apply to climate zones from 1 to 7. Aged values must be used in building energy simulations (e.g., for NatHERS or any simulation performed as verification following JV2 JV3).

Stage 1. NCC 2025 — Minimum unaged values

Roof	SRI	Solar Reflectance	Thermal emittance
Flat or low-sloped (≤ 2:12)	75	0.65	0.75
Pitched (> 2:12)	18	0.25	0.75

Stage 2. NCC2028 (or NCC2031) — Minimum aged values (after 3 years of natural exposure)

Roof	SRI	Solar Reflectance	Thermal emittance
Flat or low-sloped (≤ 2:12)	57	0.53	0.75
Pitched (> 2:12)	18	0.25	0.75

Stage 3. NCC2031 (or NCC2034) — Minimum aged values (after 3 years of natural exposure)

Roof	SRI	Solar Reflectance	Thermal emittance
Flat or low-sloped (≤ 2:12)	76	0.65	0.80
Pitched (> 2:12)	21	0.25	0.80

All products are to be rated by the future Australian Cool Roofing Council which is to be established. All products can be rated, but compliance can be met only for products above the thresholds set in the NCC.

Exceptions to the SRI thresholds are to be considered for anti-slip portions of rooftops (e.g., walkways) or less than 10% of the roof surface. After consultation with the industry, a mandate to cover mechanical rooms with roof sheeting and coat HVAC ducting with high SRI materials (which would reduce HVAC overheating) is to be considered after NCC2028.

Proposal 10: Mould and condensation risk reduction. To minimise the risk of mould and condensation with high albedo roofing, Section F part F6 should require a general assessment by the manufacturer with recommended solutions assessed experimentally, after inspection of existing buildings, and with numerical heat and moisture transport simulations as indicated in FV6. ASHRAE 160 and EN 15026 should be referred to explicitly and extensive consultation with the industry is advised.

5.4.3. INCENTIVES

The precise value for the incentives should be defined by a cost-benefit analysis, modelling all direct and indirect costs. Based on international best practice, here we propose incentives applying to:

- Reroofing existing buildings
- New constructions where the minimum SRI value is exceeded.
    - Level 1, when the minimum SRI is exceeded by 20%;
    - Level 2, only for low-sloped roofs with aged SRI exceeding 100, thus supporting super-cool roofs that retain high albedo over time.

The analysis of incentives adopted overseas highlighted that the most straightforward incentives are:

- Tax deductions: A fraction or the whole energy efficiency investment can be deducted from income tax, often over several years.
- Discounted financing rates (e.g., set by the RBA).

The following strategic recommendations are provided regarding the features of the incentives scheme:

- *Easy to understand and use by the consumer*, without the need for an accountant in the early decision-making stages.
- *Modular*. The following strategic recommendations are provided regarding the features of the incentives scheme:
- *Include an immediate contribution*. The incentives should work towards overcoming the initial investment (e.g., by providing support towards a deposit for a loan for energy efficiency interventions) or costs associated with decision making. An example of an immediate contribution might be a voucher contributing to the initial costs of an energy assessment of the property (e.g., limited to residential buildings) and assistance in the process.

5.4.4. PROPOSAL FOR A TESTING AND ACCREDITATION INFRASTRUCTURE IN AUSTRALIA

A testing and accreditation infrastructure should achieve several goals:

- *Protect and support the consumer.*
- *Protect and support the cool roofs industry* from untested products or unfair competition.
- *Enforce compliance with the National Construction Code and simplify its verification.* A single reference for testing and accreditation eliminates any ambiguity in the type of acceptable certificate.
- *Be unequivocal, repeatable, and support decision-making and dispute resolution:* Have a clear reference for compliance checks in dispute resolution, especially for public procurement.

The pillars discussed hereafter should inspire the testing and accreditation infrastructure.

Pillar 1: An industry-led association governing the testing and accreditation infrastructure. With voluntary participation, an industry-led organization with the interim name, the Australian Cool Roofing Council (ACRC), should be established. Participants in the ACRC would include government, universities, research institutions, and accredited laboratories, with leadership provided by industry. Industry leadership ensures that the ACRC adopts consensual documents regularly referred to by industry and that the industry has constant input into ensuring the success of the ACRC.

Pillar 2: Accreditation of testing laboratories. Testing laboratories are accredited with the ACRC according to ISO 17025. Testing laboratories must be independent institutions, and they should participate in an interlaboratory round-robin exercise every five years. The accredited laboratories should use traceable reference samples for reflectance emissivity measurements, established in collaboration with metrology institutes (e.g., National Measurement Institute).

Pillar 3: Factory Production Control. Independent testing can be conducted with accredited laboratories, anonymously acquiring products on the market and performing tests.

Pillar 4: Support of Product Development. The testing procedures must be designed to support continuous product development, deliver improved performance to Australian consumers, and enable the Australian industry to enhance its competitiveness, domestically and overseas.

Pillar 5: Test methods delivering repeatable and reproducible results. The test methods should deliver unequivocal, repeatable, and reproducible results. For this reason, it is also recommended to specify the reference air mass that is less likely to produce differences in results with different test methods. The calculation of solar reflectance using AM1GH as in ASTM E903 is advised.

Pillar 6: Performance over Time. Solar reflectance and thermal emittance (and the resulting computed SRI) should be assessed before and after natural exposure at representative sites. This pillar should include three parts:

- Natural exposure
- Feedback from practice
- Interim testing.

Natural exposure. Data from natural exposure programs performed overseas must not be accepted for the Australian market. The testing procedure must include natural exposure for no less than three years at accredited exposure sites where samples are measured and degradation recorded (Figure 5.6 and 5.7). The detailed protocols for a natural exposure must be defined by the future Australian Cool Roofing Council also in consideration of the experience of the US CRRC and ECRC, as the international standards for natural exposure (i.e., ISO 2810 and ASTM G7) provide relatively lose guidelines. It is recommended to establish three national exposure sites across Australia, located in the following climate zones (CZ):

- Zones 1 and 2, such as Brisbane, Cairns, or Darwin (CZ1 high humidity summer, warm winter; CZ2 warm humid summer, mild winter)
- Zones 5 and 6, such as Inner West or Western Sydney (CZ5 warm temperate; CZ6 mild temperate)
- Zones 3 and 4, such as Alice Springs, Dubbo, or other inland areas (CZ3 hot dry summer, warm winter; CZ4 hot dry summer, cool winter).

Figure 5.6 Examples of racks for natural exposure of building envelope materials. A rack used for an experimental campaign at Politecnico di Milano, Italy (left) and a rack used at one of the exposure farms of the European Cool Roofing Council, at Universitá di Modena e Reggio Emilia, Italy (right, courtesy Prof Alberto Muscio). Different rack designs are used. Key features include avoiding cross-contamination of samples and the ability to achieve the desired tilt with reasonable accuracy. At defined time intervals (typically after 3, 6, 12, 18, 24, and 36 months of natural ageing) the samples are retrieved and measured in the laboratory.

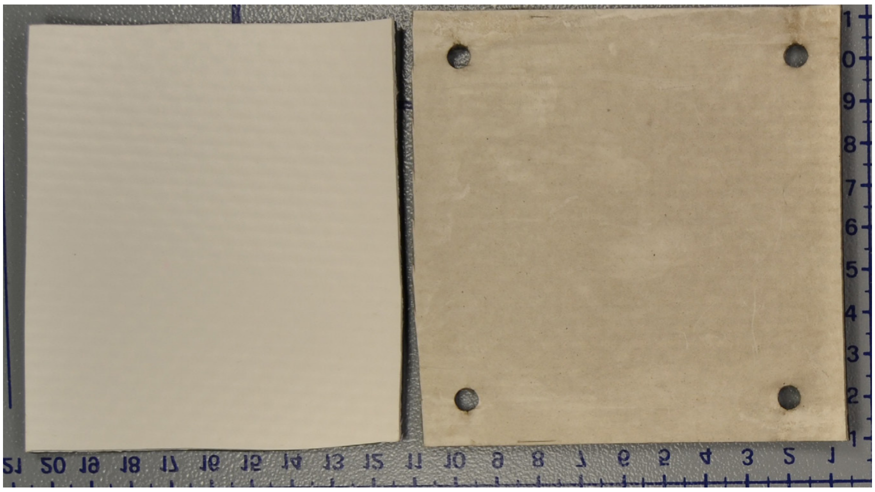


Figure 5.7 A white roofing membrane before and after three years of natural exposure in Milan, Italy.

Feedback from practice with annual inspections. At least one measurement per product per year should be performed on-site by an independently accredited tester/inspector, randomly selected by the ACRC for the annual inspection. The scheme of annual inspections should be designed with the aim of funnelling information to the manufacturers to improve products and quality of installation, and not with a merely punitive purpose.

Rapid rating — interim testing with laboratory exposure. Before natural exposure is completed and results are available, interim aged results could be achieved:

- With early results from the natural exposure (advised), such as 18 months, which for most products provide a value close to the long-term (3-year) reflectance loss; or
- With a laboratory exposure practice as described in ASTM D7897, which was originally developed to mimic weathering and soiling at three CRRC sites in the US. The laboratory exposure protocol would need to be tuned to mimic Australian exposure conditions after the Australian natural exposure program is established (Figure 5.8).

Figure 5.8 Examples of different weathering chambers for laboratory exposure to UV radiation and variations in temperature and humidity, and rain.

Pillar 7: Public database. Measured values should be publicly accessible through a national database maintained on the website of the future Australian Cool Roofing Council. The database should contain:

- Time zero (unaged) solar reflectance, thermal emittance, and SRI
- Interim values (with rapid rating or early results from natural exposure, indicating the method)
- Aged values for each site and three-site average.

Pillar 8: ACRC labelling. The ACRC should label products, and the certificate should be traceable. The label should include a QR code with a reference to the complete testing report and all metadata about the testing conditions and validity of the certificate.

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