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Pathways to climate adapted and healthy low income housing

Final Report

Guy Barnett, Matt Beaty, Dong Chen, Stephen McFallan, Jacqui Meyers, Minh Nguyen, Zhengen Ren, Anneliese Spinks, and Xiaoming Wang

PATHWAYS TO CLIMATE ADAPTED AND HEALTHY LOW INCOME HOUSING

CSIRO Climate Adaptation Flagship

AUTHORS

G Barnett (CSIRO Ecosystem Sciences)

R.M Beaty (CSIRO Ecosystem Sciences)

D Chen (CSIRO Ecosystem Sciences)

S McFallan (CSIRO Ecosystem Sciences)

J Meyers (CSIRO Ecosystem Sciences)

M Nguyen (CSIRO Land and Water)

Z Ren (CSIRO Ecosystem Sciences)

A Spinks (CSIRO Ecosystem Sciences)

X Wang (CSIRO Ecosystem Sciences)

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The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

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ABSTRACT

This report presents the findings from the "*Pathways to Climate Adapted and Healthy Low Income Housing"* project undertaken by the CSIRO Climate Adaptation Flagship in partnership with two organisations responsible for providing social housing in Australia.

The project was based on the premise that interactions between people, housing, and neighbourhood are dynamic and best viewed as a complex, coupled social-ecological system. Using social housing as a case study, the objectives of the project were to:

- Model vulnerability of housing and tenants to selected climate change impacts;
- Identify/evaluate engineering, behavioural and institutional adaptation options;
- Scope co-benefits of climate adaptation for human health and well-being; and
- Develop house typologies and climate analogues for national generalisations.

To implement the project, a 'housing typology' was constructed, representing the main types of low income housing found throughout Australia. Climate zones identified in the Building Code of Australia were used to determine how each housing type would perform under current and future climates, in different locations throughout Australia.

For each house type, the level of heat-related health risk to occupants was determined using the Discomfort Index (DI), calculated using a modified version of the *AccuRate* home energy rating software. House types located in climate zones with hot and humid summers were most vulnerable. In these locations, housing retrofits cannot sufficiently mitigate heat-related health risk and air-conditioning is increasingly required to maintain a safe indoor thermal environment for occupants. For example, it was estimated for a typical home with slab-on-ground, brick veneer construction, that the energy required for cooling by 2070 could grow by 75-115% in Melbourne and 95-359% in Brisbane.

Severe heat-related health risk occurs when the DI exceeds 28. The performance of each house type during the January 2009 Melbourne heatwave event was tested using *AccuRate*. The indoor DI values for all house types breached this threshold, with the 'worst case' examples of each type regularly exceeding outdoor DI, exacerbating risk.

The quality of housing, however, is just one factor that influences vulnerability. Low income households have a higher prevalence of heat-related health risk factors than the general population. In addition, it was found low income households were typically associated with urban landscapes that had the highest land surface temperatures. In other words, those most vulnerable to heat-related health impacts often live in areas where the exposure to heat will be greatest, as measured by land surface temperature.

The durability of materials commonly used in housing construction was also assessed for the impacts of climate change. Degradation processes considered, included the atmospheric corrosion of metal (both steel and zinc) and the fungal decay of timber used in both above-ground and in-ground applications. The results were then used to estimate the change in service life of housing components made from these materials. The flow-on impact of this for housing maintenance costs was estimated to be small, in the order of 5%, but will be significant at the portfolio level given pressures on budgets.

Overall, the findings of this vulnerability and adaptation assessment suggest that there are significant opportunities to reduce severe heat-related health risk within the social housing portfolio examined in this project, and for low income housing more generally. This includes through building upgrades, urban greening, and the development of 'cool places' for respite. Urban vegetation was identified as the dominant control on land surface temperatures in the outdoor environment. Upgrade of assets through changes to roof colour and installing ceiling insulation can reduce indoor temperature extremes. A range of adaptations across multiple scales are required for maximum effectiveness.

EXECUTIVE SUMMARY

This report presents the findings from the "*Pathways to Climate Adapted and Healthy Low Income Housing"* project undertaken by the CSIRO Climate Adaptation Flagship in partnership with two organisations responsible for providing social housing in Australia.

The project was based on the premise that interactions between people, housing, and neighbourhood are dynamic and best viewed as a complex, dynamic social-ecological system. Using social housing as a case study, the objectives of the project were to:

- Model vulnerability of housing and tenants to selected climate change impacts;
- Identify/evaluate engineering, behavioural and institutional adaptation options;
- Scope co-benefits of climate adaptation for human health and well-being; and
- Develop house typologies and climate analogues for national generalisations.

This project was developed with the rationale that a multi-level focus on the cross-scale interactions between housing, residents, neighbourhood, and regional climate was vital for understanding the nature of climate change vulnerability and options for adaptation.

The climate change hazards that were explored were increasing temperatures and more frequent and severe heatwaves in the context of heat-related health risks to housing occupants, and changes in radiation, humidity, and wind, in relation to material durability and service life of housing components and the implications for maintenance.

Neighbourhood and role of place

Heat vulnerability mapping was undertaken to identify spatial relationships between thermal patterns of land surface temperature and the risk factors that define sensitive populations. This analysis was conducted in four Australian cities, including Adelaide, Melbourne, Sydney and Brisbane. These cities were selected as they were the most documented in terms of research on the links between extreme heat and public health.

Low income households were defined as those with an Equivalised Total Household Income in 2006 of between $1 and $399 per week. Key risk factors for heat-related health were often twice as prevalent in low income households compared to those on medium to high incomes. Significantly, many of the risk factors were also found to coincide, for example, elderly people who are living alone and also need assistance.

Significant variations were seen in patterns of land surface temperature for each of the four cities investigated. Low income households were typically associated with parts of the city with the highest land surface temperatures. As such, those most vulnerable to heat-related health impacts were often living in areas with the highest heat exposure, as measured by land surface temperature. This pattern was consistent for all four cities investigated. Generally, cooler parts of the city had higher vegetation cover.

Thermal performance of housing

Modelling of the thermal performance and indoor environment of low income housing was undertaken using the *AccuRate* software for residential house energy rating. A key first step was the construction of a housing typology, based on the social housing dataset provided by project partners. Comprising 142,410 housing assets, this dataset represented around 35% of the households being assisted by social housing nationally and covered all major climate zones as defined within the Building Code of Australia.

Ten common house types were identified, characterising the broad range of house designs, construction processes, and materials used in low income housing. Thermal performance and indoor environment of each house type, in each climate zone, was assessed using a widely recognised measure of heat-related health risk known as the

Discomfort Index (DI), implemented as a module in the *AccuRate* software. Future climates in 2030, 2050 and 2070 were generated using the MIROC-M Global Climate Model and A1FI emission scenario. House types in climate zones with hot and humid summers were found to be most vulnerable. In these locations, house retrofits cannot mitigate the level of severe heat-related health risk (DI > 28) and air-conditioning will be increasingly required to maintain a safe indoor thermal environment. Retrofits are more effective in temperate locations, largely ameliorating climate impacts in the short term. Overall, it was estimated the energy required for cooling a typical slab-on-ground, brick veneer home could grow by 75-115% in Melbourne and 95-359% in Brisbane, by 2070.

While some house types perform better than others, most of the variation in thermal performance was due to quality rather than type of housing. If building orientation is good, than in most situations a simple building retrofit could greatly improve thermal performance. For example, using weather data from the January 2009 heatwave in Melbourne, simulations using *AccuRate* have shown that on average across the house types, a 'cheap retrofit' could reduce severe heat-related health risk (DI > 28) by 25%.

Material durability and service life

The durability of materials commonly used in housing construction was assessed for the impacts of climate change. The degradation processes considered, included the atmospheric corrosion of metal (both steel and zinc) and the fungal decay of timber used in above-ground and in-ground applications. Modelling was undertaken using climate projections from nine Global Climate Models with the A1FI emission scenario.

The analysis has revealed that on average, by 2100 in Melbourne, the rates of steel and zinc corrosion could decrease by 14% and 9% respectively, whereas in Brisbane the corrosion rates for the same metals could increase by 14%. Changes in rates of timber decay were similar, with Melbourne to experience an average decrease of 17% and 11% by 2100 for above-ground and in-ground applications, respectively. Little change was predicted in the average rate of above-ground timber decay in Brisbane over this timeframe, but in-ground timber decay could increase by an average of 14%. These results were used to estimate the change in service life of housing components made from these materials. The impact on housing maintenance costs was estimated to be small (~5%), but this may be significant for a large housing portfolio manager.

Evaluation of adaptation pathways

Information was collated on exposure, sensitivity and adaptive capacity at both building and neighbourhood scale. This was used to assess the vulnerability of 103,809 social housing assets for which full data was available. Approximately 5% were considered to be highly vulnerable, with high potential impact from climate change and low adaptive capacity. These were typically located in climate zones with hot and humid summers and will be increasingly reliant on air-conditioning. A further 4% also had high potential impact, but with high adaptive capacity, meaning there is scope to reduce heat-related health risk through adaptation. This includes urban greening to control land surface temperatures in the outdoor environment; upgrade of assets through changes to roof colour and installing ceiling insulation to reduce indoor temperature extremes; as well as various behavioural and institutional adaptation actions to maximise effectiveness.

Conclusions and next steps

The housing and neighbourhoods in which low income households live can exacerbate heat-related health risk. In most cases, there were a range of options available to help mitigate this risk. Given the social housing focus, greater understanding is required of how the results translate to other low income housing and how adaptive capacity might vary. Next steps are to further distil the findings into guidelines for climate adaptation.

1. INTRODUCTION

All new homes in Australia are required to meet minimum energy and water efficiency standards (Ambrose 2008), yet the majority of Australia's existing housing stock is 20 years of age or older (Australian Building Codes Board 2010), built with little thought for climate change or sustainability. At the same time, we suspect that disadvantaged populations are more likely to reside in this older, poorer quality housing stock, often in locations of high climate change risk, with few resources to invest in climate adaptation.

These trends, taken together, highlight equity and social justice issues for the climate adaptation of human settlements. Just as the provision of social housing has been a societal response to address social disadvantage, assuring climate change adaptation in the social housing sector and for low income households more generally, offers a major pathway for ensuring fairness in Australia's overall climate adaptation response.

This report presents the findings from the "*Pathways to Climate Adapted and Healthy Low Income Housing"* project undertaken by the CSIRO Climate Adaptation Flagship in partnership with two organisations responsible for providing social housing in Australia.

1.1 *Project objectives*

Using social housing as a case study, the objectives of this research project were to:

- Model vulnerability of housing and tenants to selected climate change impacts;
- Identify/evaluate engineering, behavioural and institutional adaptation options;
- Scope co-benefits of climate adaptation for human health and well-being; and
- Develop house typologies and climate analogues for national generalisations.

1.2 *Context and rationale*

Disadvantage tends to be geographically concentrated and endemic to a small number of locations in our cities. While there is a strong link between disadvantage and poor health, what is yet to be established is the complex interrelationship between housing, residents, and neighbourhood, and how this impacts the efficacy of climate adaptation.

Identifying the consequences of global climate change at this local scale is a challenge. This is due in part to the mismatch in the spatial scale of our understanding. With the advent of high resolution remote sensing, we now have fine-grained understanding of the built environment at the neighbourhood scale, with information on buildings, roads, vegetation, transport stops, etc. On the other hand, projections of the impact of climate change (a global phenomenon) remain limited to broad regional scale generalisations. This project was developed with the premise that a multi-level focus on the cross-scale interactions between housing, residents, neighbourhood, and regional climate is vital for understanding the nature of climate change vulnerability and options for adaptation.

The rationale for the project was to couple building level housing assessments with a broader understanding of the social-ecological neighbourhood context in which these buildings are located to determine the influence of 'place'. It was hypothesised that in some cases, the characteristics of place would exacerbate vulnerability (i.e. poor public transport, remoteness from services) yet in other situations, it may actually provide a compensatory or buffering effect (i.e. the shade benefits of vegetation). Another key innovation was the co-benefits for human health focus, where climate adaptation was seen as offering significant opportunities to not only reduce risk, but to promote human health and well-being (e.g. improved thermal comfort of housing to reduce heat illness). So the focus was not just vulnerability, but the pathways to and benefits of adaptation.

1.3 *Structure of this report*

The report has been structured according to the order in which the various research tasks were undertaken. This Section has introduced the project objectives and the context and rationale for the project. It is followed by a brief summary of the research approach, concepts and methods in Section 2. The outcomes of a review of relevant literature on heat, the built environment, and human health are presented in Section 3.

The detailed research activity undertaken is then described. This includes the spatial analysis of urban neighbourhoods and the role of place, outlined in Section 4, providing insights into how 'who you are' and 'where you live' influences heat-related health risk.

This is followed by an assessment of the impacts of climate change on the thermal performance and indoor environment of low income house types in Section 5, and changes in material durability and service life of housing components in Section 6. These separate activities are then pulled together through an integrated vulnerability and adaptation analysis – linking housing, residents, and neighbourhood – Section 7.

The report concludes with a discussion of the main project findings in Section 8 and a synthesis of gaps in knowledge and directions for future research in the final Section.

2. PROJECT DESIGN AND APPROACH

The project has been designed as 'participatory action research'. It has involved the development of partnerships with two organisations responsible for providing social housing in Australia. The aim was to foster the co-development of climate adaptation knowledge, through engagement with decision-makers responsible for social housing. The rationale being 'social housing' provides a microcosm of the types of housing and residents typical of other forms of low income housing in Australia. Further justification of the use of social housing as a case study of low income housing is provided below. The vulnerability and adaptation framework employed in the project is also introduced, as is the development of climate information and construction of the housing typology.

2.1 *Social housing as a case study*

One of the major factors often limiting the ability to undertake quantitative research on climate adaptation in the low income housing sector has been the lack of good quality data on housing assets and their occupants. In this project, we have addressed this problem through collaboration with two social housing organisations. They included the Queensland Department of Communities and a similar organisation from southern Australia that wished to remain anonymous. Collectively, this has enabled access to selected datasets on housing assets and residents, following ethics approval granted by the CSIRO Social Science Human Research Ethics Committee on 1st March 2011.

A simplified diagram showing the relationship between social housing and other low income housing types is shown in Figure 1. In this project, our definition of social housing includes 'public housing' which is generally provided by State or Territory Housing Authorities and 'community housing' which is typically provided by housing cooperatives or community organisations. Increasingly, government policies aim to direct the provision of affordable housing through growth in the community housing sector (Eardley and Flaxman 2012). There are two other forms of low income housing that can also be identified, which include private rentals and private ownership. The latter comprises both those purchasing (mortgagees) and those who own outright.

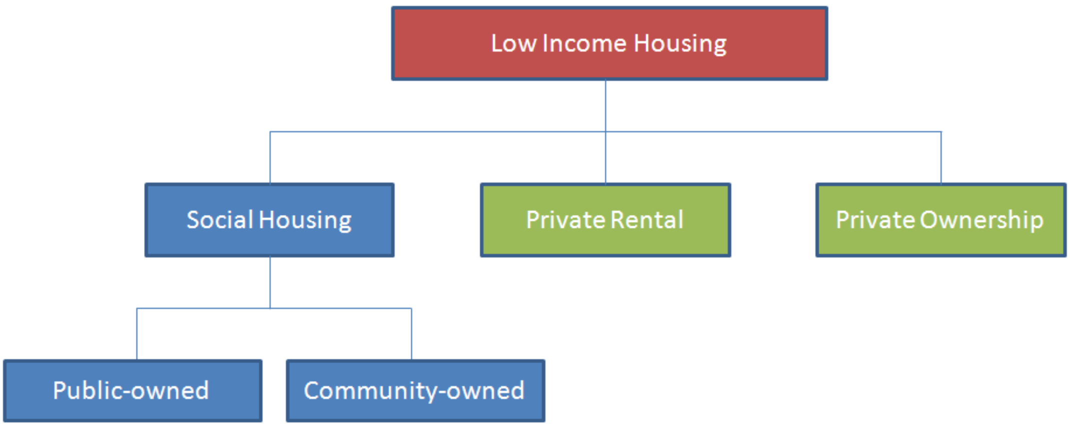


Figure 1: Relationship between social housing and other low income housing types.

The purpose of social housing has traditionally been to provide a safety valve for the private rental market and a stepping stone to home ownership for low and moderate income earners (Australian Government 2010). As such, it is usually rationed to the

most disadvantaged. To understand how the proportion of residents living in social housing compares to those in other types of low income housing, we need to first clarify our definition of low income. While there are many different definitions of low income, the choice of which to use often comes down to the type of study and context.

In this regard, there are many ways to measure income and many possible income thresholds that determine whether a household is considered to be low income or not. Studies that focus on low income in relation to housing affordability use measures such as the 30/40 rule (Yates and Gabriel 2006), residual income (Stone et al. 2011), threshold income, the ratio of housing costs to housing income (Swinburne University of Technology 2008), or changes in house prices and rental costs compared to consumer prices or incomes. Studies that focus on low income for other purposes might use measures such as the number of households below the Henderson poverty line (Melbourne Institute of Applied Economic and Social Research 2012); households in the bottom quintile of income (Australian Bureau of Statistics 2008), households with income below one-half the median household income (Wilkins et al. 2009), or those households that receive some form of welfare payment (Marshall et al. 2003).

It can also be difficult to compare households based on income alone, as households of differing size and composition will have different expenditure requirements. A dual income household without children will have very different expenditure requirements to a single parent household with several children. To standardise for households with different structures, the 'modified OECD' scale, also known as Equivalised Household Income was used (Australian Bureau of Statistics 2011). It provides a useful measure for comparing economic resources available to a standardised household, derived by calculating an equivalence factor and then dividing income by that factor (Trewin 2006). So for a lone person household, it is equal to household income. For a household of more than one person, it reflects the requirement of this household to have a higher level of income to achieve the same standard of living as the lone person household.

For this project, low income was defined as those with an Equivalised Total Household Income of between $1 and $399 per week. Households that only provided partial incomes and those that stated they earned either zero or negative dollars per week were excluded. Based on this definition, the proportion of low income households across different tenure and landlord types in Australia is presented in Figure 2.

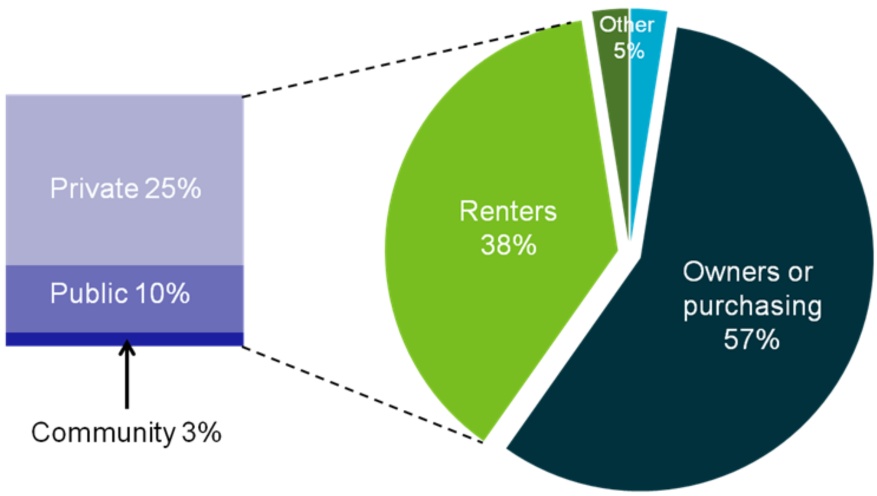


Figure 2: Proportion of low income households (Equivalised Household Income of $1 - $399/week) by tenure and landlord types across Australia (Data sourced from ABS 2006).

Thus we can see that our social housing case study, comprising public-owned and community-owned rental properties, represents 13% of all low income housing. So while it is possible to generalise based on housing asset and resident information, there will be limits to this generalisation particularly in regard to climate adaptation options due to differences in tenure and landlord types. For example, in the private rental housing sector, which comprises almost twice as many low income households as the social housing sector, matters are complicated by a 'split incentive' between the private landlords and their tenants that will often discourage action on climate change, as it is more difficult for the landlord to accrue any direct benefit from such investment. This view is supported by the work of Gabriel et al. (2010) who undertook interviews with private rental investors. They found that although private rental investors were supportive of environmental measures, they believed they would be unable to recoup the cost of such expenditure through higher rental yield. Furthermore, in an era of low vacancy rates, there would be little incentive to upgrade properties to attract tenants. For low income households who own or are purchasing their homes, there will be a different set of constraints. These issues are explored in more detail in Section 8.3.

2.2 *Vulnerability framework and concepts*

Vulnerability is a multi-dimensional concept described as resulting from the interactions of exposure to a climate hazard, the sensitivity of populations affected, and adaptive capacity to ameliorate potential impacts (Allen Consulting 2005, Smit and Wandel 2006, Preston and Stafford-Smith 2009, Brunckhorst et al. 2011, Preston et al. 2011). The relationship between vulnerability and its components is illustrated in Figure 3.

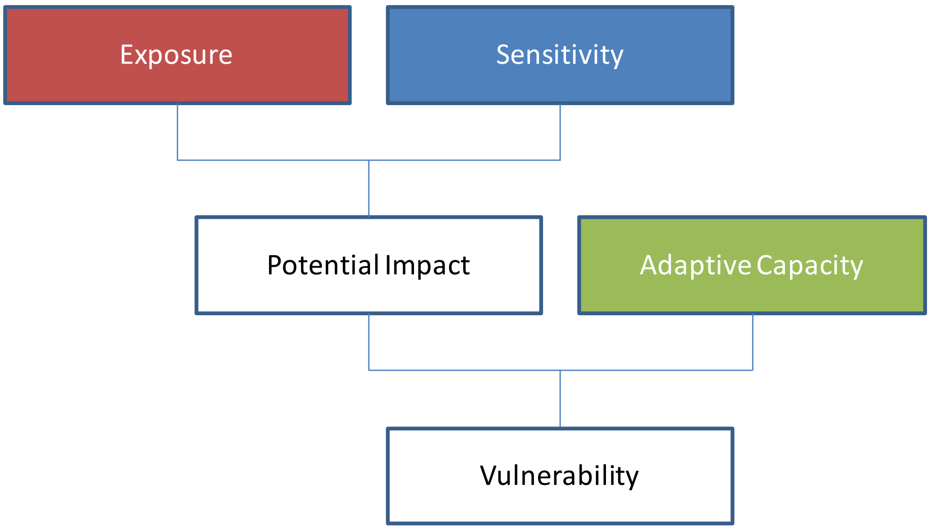


Figure 3: Key components of climate change vulnerability (after Allen Consulting 2005).

In this project, the interactions between people, housing, and neighbourhood have been viewed as a complex social-ecological system. The vulnerability of this system was framed around the climate change hazard of increasing temperatures and more frequent and severe heatwaves. Exposure was defined as the thermal performance of the housing and neighbourhood in which people live, while sensitivity is defined by the prevalence of heat-related health risk factors in the resident population. As shown in Figure 3, the combination of exposure and sensitivity will define the potential impact.

The ability for adaptive capacity to ameliorate potential impact has been considered at both the housing and neighbourhood scales, with a focus on biophysical opportunities. For example, the opportunity to improve the performance of housing with engineering solutions, or the neighbourhood via urban greening strategies, as well as the presence of nearby cool places where public access to air-conditioning could be readily sought. More details on the methods for vulnerability and adaptation assessment used in this project are provided in Section 7.1. The purpose here is to introduce general concepts.

A growing focus in vulnerability studies are the attempts to quantify spatial patterns of exposure and sensitivity, often through indices that consider different components of vulnerability (Preston et al. 2011). This project also aims to be spatially explicit, linking bottom-up modelling of housing thermal performance, with information on heat-related health risk factors of residents, and influences of social-ecological neighbourhood and context. This is shown in Figure 4, where human health and well-being are considered the ultimate measure of the quality of the interactions between these different factors.

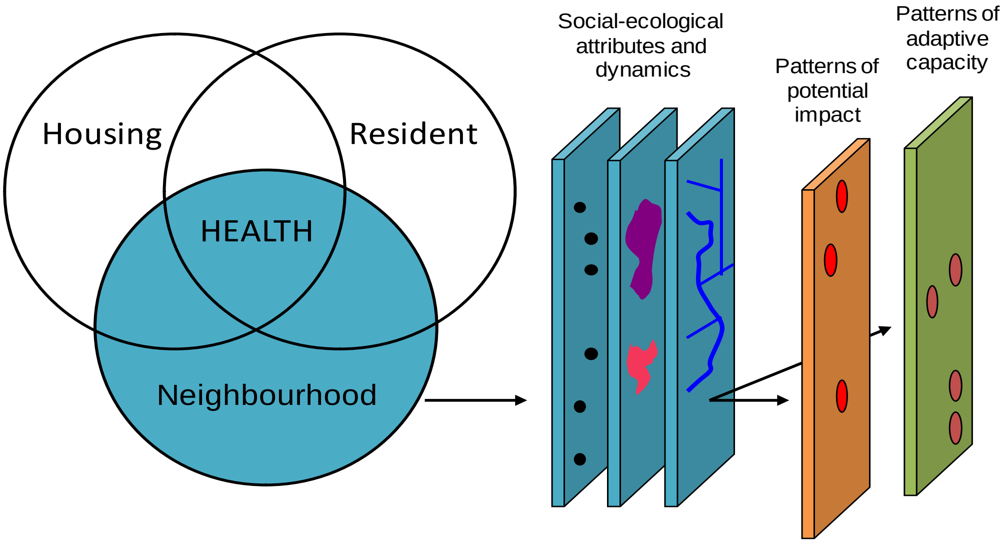


Figure 4: Contextual model of the multiple scales of analysis and how they interact to determine vulnerability and heat-related health linked through a focus on neighbourhood attributes and dynamics to determine patterns of potential impact and adaptive capacity.

There remain many challenges in representing the various determinants of vulnerability spatially, but the focus on neighbourhood and the role of 'place' in this project provides a means for achieving this. Social-ecological attributes and dynamics expressed at the neighbourhood scale can be linked with housing and resident information to provide a 'place based' focus on vulnerability, including patterns of potential impact and adaptive capacity. While the latter is often poorly understood and difficult to express spatially, a strong biophysical focus has been taken to define its component measures, grounding the notion of adaptive capacity in the physical opportunities to modify the environment. That is, housing and neighbourhood are seen as environmental determinants of human health, with adaptive capacity the ability to shape these environments to foster health.

2.3 *Current and future climate information*

The climate focus in this project was on extreme heat and changes in temperature, radiation, humidity and wind. The interest in heat was to determine the impact of rising temperatures and more frequent and severe heatwaves on the thermal comfort and

indoor environment of low income housing, and to establish in turn, what this might mean for the health and well-being of occupants. Also of interest was how changes in temperature, radiation, humidity and wind would influence the durability of common building materials (metals and timber) used in the construction of low income housing. Changes in service life and maintenance requirements of these housing components were also considered. What follows are details of how the climate information used in this project was generated and organised, informing the modelling of housing thermal performance (Section 5) and analysis of material durability and service life (Section 6).

2.3.1 Climate zones used to organise project

There are several different maps characterising Australia's climate. In this project, the climate zones developed by the Australian Building Codes Board (2009), identified in the Building Code of Australia (BCA) are adopted. Eight climate zones are recognised and these are used in the BCA to specify the minimum requirements for thermal design and energy efficiency of residential buildings, showing how these vary across Australia (Reardon and Downton 2007). This includes specifications for the building fabric (e.g. roofs, walls and floors) and insulation. The BCA climate zones are based on an earlier classification by the Australian Bureau of Meteorology (BOM) that used temperature and humidity observation data to identify six zones. The Australian Building Codes Board (ABCB) added an additional temperate zone and an alpine zone. Boundaries were also adjusted to align more closely with those of local government authorities.

The BCA climate zones have been used to organise, summarise and enable broader national generalisation of the research undertaken in this project. For example, while the project has relied heavily on data provided by our social housing partners, this data was geographically distributed across all eight of Australia's BCA climate zones. Thus to enable national generalisation of the research findings, a reference city was selected in each climate zone, for which baseline and future weather information was compiled.

It should be noted that Zone 8 (Alpine) was not included in the analysis. This was due to the low population and number of housing assets that were located in this zone and difficulties distinguishing the boundary. The BCA climate zones and reference cities used in the project are summarised in Table 1 and presented as a map in Figure 5.

Table 1: Description of the Building Code of Australia climate zones and the reference cities selected to represent them, with current and future weather data collected for each.

Climate Zone	Description	Reference City
1	High humid summer, warm winter	Townsville
2	Warm humid summer, mild winter	Brisbane
3	Hot dry summer, warm winter	Mt Isa
4	Hot dry summer, cool winter	Mildura
5	Warm temperate	Sydney
6	Mild temperate	Melbourne
7	Cool temperate	Canberra

While there are obvious limits to the ability to make generalisations based on the BCA climate zones, given the size and geography of Australia and variability of its climate. It was considered necessary to keep the project manageable. This is discussed more fully in Section 8.3, which explores the efficacy of taking results for a particular housing type in a particular location, and applying to similar housing within a BCA climate zone.

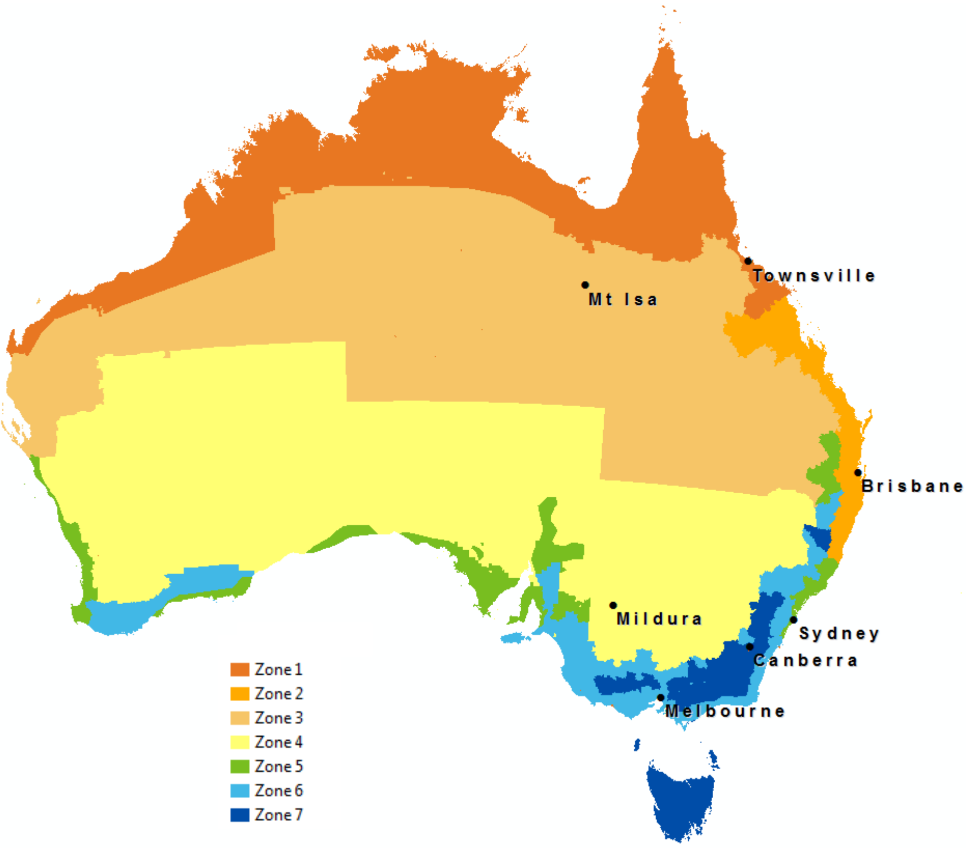


Figure 5: The climate zones used in this project (adapted from the Australian Building Codes Board 2009) and the reference cities selected to represent each climate zone.

For each reference city, weather data was acquired for a climate baseline (centred on 1990) and for projections of future climate for the periods 2030, 2050 and 2070. The methodology that was used to prepare this weather data is now described in detail.

2.3.2 Preparation of future climate information

Climate data was required for modelling of building thermal performance and indoor environment (Section 5) and the modelling of material durability and service life (Section 6). This was generated using projections of future climate derived from *OZClim*, an online climate change prediction tool developed by CSIRO specifically for Australia (Ricketts and Page 2007). While *OZClim* contains data from over 20 Global Climate Models (GCMs) used in the IPCC's AR4 Assessment (Meehl et al. 2007), only a small number of these have projections for all climate variables required in this study.

Each GCM has its different strengths and weaknesses, making it difficult to know which to use in impact assessments. Consequently, many researchers combine results from multiple GCMs to produce a single projection with a mean value and associated range of uncertainty, e.g. a warming of 1.5°C with a range of 1-2°C (Hennessy et al. 2012). This is now considered undesirable, with concerns that the internal consistency among climate variables that is preserved in individual GCMs is lost when the projections from different GCMs are combined together. For this reason and to provide for greater end-user transparency, this project has used nine individual GCMs as outlined in Table 2.

For the modelling of material durability and service life (Section 6), the projected local climate described by yearly average changes in temperature, relative humidity, rainfall, and wind speed, was required. These projections were generated using *OZClim* for

the seven reference cities outlined in Table 1, using the nine GCMs listed in Table 2, and the A1FI emission scenario. Only this emission scenario was used, as observed carbon-dioxide emissions have been tracking the high growth trajectory of the A1FI emissions scenario (Raupach et al. 2007, Le Quéré et al. 2009, Peters et al. 2012).

For the assessment of the thermal performance and indoor environment of low income housing types (Section 5), different climate projection information was required. This particular modelling was undertaken using the *AccuRate* software tool developed by CSIRO (Delsante 2005). *AccuRate* requires data on ambient air temperature, solar irradiance, air humidity and wind speed, which needs to be prepared in the form of a Typical Meteorological Year (TMY) weather file to support the building simulations.

Table 2: Description of the Global Climate Models (GCMs) that were used in this project.

Models	Developers
CCCMA	Canadian Centre for Climate Modelling and Analysis, Canada
CNRM	National de Researches Meteorologiques, France
CSIRO-Mk3.5	Commonwealth Scientific and Industrial Research Organisation, Australia
GISS-AOM	National Aeronautics and Space Administration, Goddard Institute for Space Studies, USA
GISS-EH	Goddard Institute for Space Studies, National Aeronautics and Space Administration, USA
IAP-FGOALS	National Key laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, China
IPSL-CM4	Institute Pierre Simon Laplace, France
MIROC-M	Centre for Climate System Research, National Institute for Environmental Studies, and Frontier Research Centre for Global Change, Japan
MRI-GCM232	Meteorological Research Institute, Japan

Given the complexity of the *AccuRate* modelling and number of different climate zones, housing types, and building adaptation options to be considered, it was only feasible to consider one GCM. The decision as to which of the nine GCM's in Table 2 represents the 'most likely' climate future was informed by the findings from (Perkins et al. 2007). These authors undertook an empirical evaluation of how well commonly used GCMs in Australia were able to replicate features of the current climate. They used weather observation data from the Australian Bureau of Meteorology for this purpose and concluded that MIROC-M was the most 'skilful' model on average across Australia.

To confirm the suitability of the MIROC-M model, the approach developed by Whetton (2012) for classifying climate change projection information into a small number of representative climate futures, was also applied. With a key focus on temperature, the projections for 2050 using the A1FI emission scenario for the nine GCMs listed in Table 2 were classified, confirming significant model agreement with the majority indicating a hotter (+1.5°C to 3.0°C) climate for most areas of Australia. Consistently represented in this majority was the MIROC-M model, which coupled with the findings of Perkins et al. (2007), justified selection of this GCM to represent the 'most likely' climate future. Thus, projections of future climate were generated using *OZClim* for 2030, 2050 and 2070 for each of the reference cities (Table 1), again using the A1FI emission scenario.

2.3.3 Construction of future TMY weather files

Typical Meteorological Year (TMY) weather data is commonly used in building energy simulations (Chen et al. 2012). It is weather data that is compiled for a specific location usually from historical records. It provides a year of weather data that represents the range of climate variability, with annual averages consistent with long term averages.

As discussed earlier, TMY weather files provide the climate input for the *AccuRate* software. TMY weather files were sourced to provide a baseline climate (centred on 1990) for each reference city in Table 1. Future TMY weather files were created for these same locations for the periods 2030, 2050 and 2070, using a morphing approach developed by Belcher et al. (2005) that combines an existing TMY weather file based on historical observations with climate change projection information. It requires the hourly weather data that is contained in the baseline TMY weather file, which is then adjusted using projections of mean monthly climate change. It is an approach that has been employed in several recent Australian studies that have used building simulations to investigate the impact of climate change on the energy requirements of residential buildings (Wang et al. 2010a, Wang et al. 2011, Ren et al. 2011, Chen et al. 2012).

For this project, the climate projection information was generated as described earlier, using *OZClim*, for 2030, 2050 and 2070 for each of the reference cities (Table 1), using the MIROC-M GCM and the A1FI emission scenario. The 'morphing approach' that was applied is summarised in Equations (1) – (4) describing how future hourly ambient temperature, relative humidity, solar irradiance, and wind speed data were calculated,

$$T = T_o + \Delta T_m + \alpha_{tm}(T_0 - \langle T_0 \rangle)_m \quad (1)$$

where $\alpha_{tm} = (\Delta TMAX_m - \Delta TMIN_m)/(\langle T_{0\,max} \rangle_m - \langle T_{0\,min} \rangle_m)$; T_0 and T are the TMY weather (baseline climate) and predicted future weather hourly dry-bulb ambient air temperature (°C) respectively; $\langle T_0 \rangle_m$, $\langle T_{0\,max} \rangle_m$, and $\langle T_{0\,min} \rangle_m$ are monthly means of ambient dry-bulb, daily maximum, and daily minimum temperatures respectively from the TMY weather data; ΔT_m, $\Delta TMAX_m$, and $\Delta TMIN_m$ are predicted changes in ambient dry-bulb, daily maximum, and daily minimum temperatures (°C) due to climate change.

$$RH = RH_0 + \Delta RH_m \quad (2)$$

In this case, RH_0 and RH are the TMY weather hourly relative humidity and the predicted future weather hourly relative humidity (%) respectively; and ΔRH_m is the predicted change in the monthly mean of relative humidity (%) with climate change.

$$I = \left(1 + \alpha_{m,I}\right) I_0 \quad (3)$$

For estimating solar irradiance, I_0 and I are the TMY weather hourly solar irradiance and predicted future weather hourly solar irradiance (W/m^2) respectively; and $\alpha_{m,I}$ is the percentage change in the monthly mean solar irradiance (%) with climate change.

$$V = \left(1 + \alpha_{m,v}\right) V_0 \quad (4)$$

Wind speed was calculated using V_0 and V, which are the TMY weather hourly wind speed and the predicted future weather hourly wind speed (m/s) respectively; $\alpha_{m,v}$ is the predicted percentage change in the monthly mean value of solar irradiance (%).

2.4 *Social housing dataset and typology*

Social housing assets are primarily made available to low income occupants and thus the rationale applied in this project was that a social housing case study would serve as a suitable 'microcosm' of low income housing and provide a means of making broader generalisations to other low income housing types. What follows is a description of the social housing dataset that was constructed, and how this has been used to develop a housing typology for the purpose of generalisation to other low income housing types.

2.4.1 Description of social housing dataset

To determine how climate change might impact the thermal performance and indoor environment of low income housing in Australia, a social housing dataset was built using specific housing asset information provided by our project partners – two social housing organisations responsible for a large share of Australia's social housing stock.

The social housing dataset was comprised of 142,410 housing assets, covering all of Australia's major climate zones as identified by the Building Code of Australia climate zone map (Figure 5). The age distribution of this housing stock is presented in Figure 6, where it can be seen that 58% of this stock was constructed prior to the introduction of the Building Code of Australia (BCA) in 1988. Consequently, it can be assumed this stock was built with little thought for climate change and broader sustainability issues.

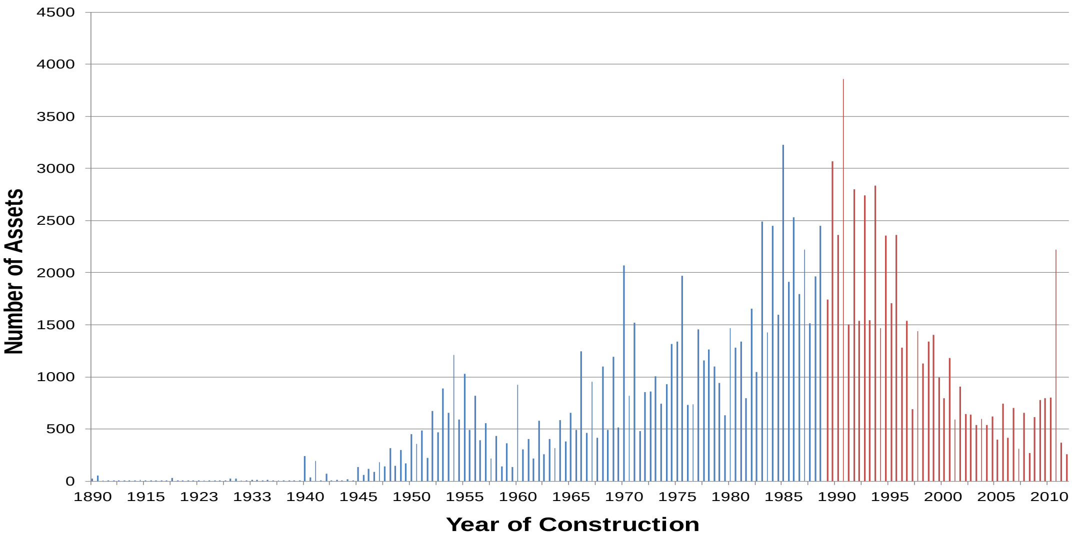


Figure 6: Age distribution of housing stock contained within the social housing dataset.

The large majority of assets contained with the social housing dataset had either one, two or three bedrooms, and were almost evenly split between single detached housing and a range of other house types, including medium density through to low-rise and high-rise apartments. Other information in the social housing dataset included details of the geographic location of the asset, construction materials used for wall and roof cladding, through to the type of subfloor construction i.e. slab-on-ground or raised.

2.4.2 Construction of housing typology

The aim of the housing typology was to classify the 142,410 housing assets comprising our social housing dataset, into a sufficient number of core housing types to represent the main range of house designs and construction materials that are used in low income housing. In developing the typology, emphasis was placed on the factors thought to have the most influence on thermal performance and indoor environment.

Another prime consideration was the need to keep the typology as simple as possible, so the number of permutations to be modelled remained manageable. For instance X housing types, by Y climate scenarios, by Z adaptation options, soon adds up into a significant number of computationally intensive model runs and analytical complexity.

In addition to keeping the typology simple, another key consideration was the ability to generalise the findings from our social housing dataset to low income housing using available national housing stock data. The National Exposure Information System (NEXIS) developed by Geoscience Australia (Nadimpalli et al. 2007) for disaster management was identified as the most suitable dataset for this purpose, importantly providing spatially explicit information on age distributions and construction materials.

Looking at this data, it can be seen that the variation in Australia's housing types and compositions are not particularly high, especially for housing constructed in the last 30 years. This is because recent designs and construction approaches have become more generic throughout Australia (Amitrano et al. 2007). Nonetheless, there are distinct regional variations in the older properties within our social housing dataset, including Queenslanders in the north, through to row and terrace houses in the south. Our typology has tried to capture these distinct regional variations as far as possible.

While a number of mathematical approaches to classify the social housing dataset were trialled including self organising maps, classification trees and cluster analysis, the approach ultimately used was pragmatic, recognising minimal data was available for classification, particularly when generalising results to wider housing populations. For example, the data available within the public release of NEXIS limited our main classification parameters to the type and period of construction and material used for wall cladding and roofing. The final typology classification is presented in Table 3, with ten housing types identified, capturing 76% of assets in our social housing dataset.

Table 3: Description of the classification used to represent low income housing types.

Code	Type	Subfloor	External Wall	Year Built	Bedrooms	Count	Percent
A1	House	Slab on ground	Brick/block veneer	Pre-2005	3 or 4	18648	17.1%
B1	House	low-set raised	Brick/block veneer	Pre-2005	3 or 4	6589	6.1%
B2	House	low-set raised	Fibro/Weatherboard	Pre-2005	3 or 4	2393	2.2%
C1	House	High-set raised	Brick/block veneer	Pre-2005	3 or 4	2417	2.2%
C2	House	High-set raised	Fibro/Weatherboard	Pre-2005	3 or 4	10101	9.3%
D1	House	Slab on ground	Brick/block veneer	Post-2005	3 or 4	506	0.5%
E1	Flat	Low-rise	Concrete/brick/block	Anytime	1	29200	26.8%
F1	Flat	Low-rise	Concrete/brick/block	Anytime	2 or 3	32002	29.4%
G1	Flat	High-rise	Concrete/brick/block	Anytime	1	1946	1.8%
H1	Flat	High-rise	Concrete/brick/block	Anytime	2 or 3	5076	4.7%
Total						108878	100%

For each housing type, hard copy floor plans and details were acquired from our two social housing partners and used to identify a representative example of each housing type (Table 4). These examples and their floor plans were used to construct the digital data files needed for input into *AccuRate* modelling of thermal performance (Section 5).

Table 4: Summary of housing types including floor plan details and an indicative photo.

House Type A1
Slab on ground, brick veneer (older)

House Type B1
Low-set subfloor, brick veneer

House Type B2
Low-set subfloor, fibro/weatherboard

House Type C1
High-set subfloor, brick veneer

House Type C2

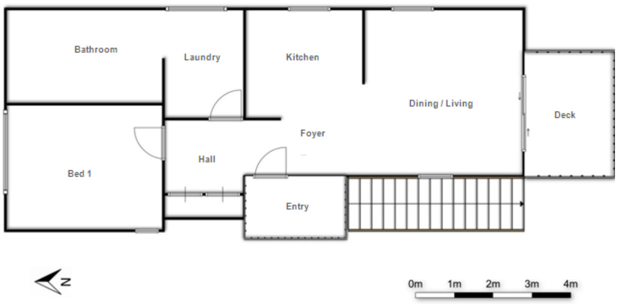
High-set subfloor, fibro/weatherboard

House Type D1

Slab-on-ground, brick veneer (current)

Type E1

Low-rise flat, 1 bedroom

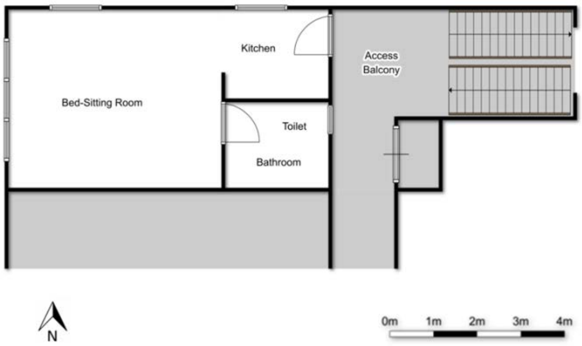


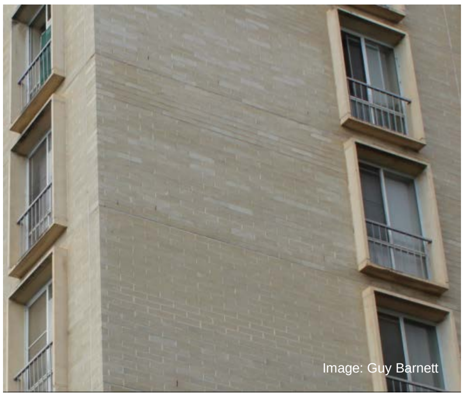
House Type F1

Low rise flat, 2-3 bedroom

House Type G1

High rise flat, 1 bedroom





House Type H1

High rise flat, 2-3 bedroom

3. EXTREME HEAT AND HUMAN HEALTH

Optimal human health and physiological functioning relies on the body maintaining an internal temperature of around 37 degrees Celsius (Parsons 2003). During periods of excess ambient heat, the body responds through various cooling processes including sweat production, increased cardiac output and the redirection of blood flow to the skin to promote heat loss through radiation and conduction. These mechanisms may be compromised in vulnerable individuals, however, meaning that the body's temperature may rise to dangerous levels which in turn may lead to serious illness or even death.

Following on from unprecedented death tolls during heatwave events in several parts of Europe (Katsouyanni et al. 1988, Hemon and Jougla 2004, Kosatsky 2005), the United States (Klinenberg 2002, Luber and McGeehin 2008) and Australia (Nitschke et al. 2007, Vaneckova et al. 2010, Tong et al. 2010) during the past two decades, increasing attention has now been focussed on the effects of excess heat on human health. This shift in public awareness has coincided with predictions of increasing global temperatures due to climate change (IPCC 2007), suggesting adverse effects of heat on health will become an even more significant public health burden in the future.

In particular, it has been predicted that both mortality and morbidity due to high ambient temperatures will increase not only as a direct result of climate change (Bambrick et al. 2008) but also as a result of changing population susceptibility over coming decades. Most notably, population aging and increased prevalence of chronic health conditions such as cardiovascular and renal diseases will lead to higher human sensitivity to the adverse effects of extreme temperatures. However, the potential remains for this increase in sensitivity to be offset by climate adaptation measures which aim to lower the impact of climate factors (Hajat et al. 2010). The purpose of this section of the report is to summarise the key scientific literature which has examined the effects of extreme hot temperatures on human health. These findings are outlined as follows.

3.1 *Measuring exposure to extreme heat*

Air temperature is the most commonly used measure of exposure to extreme heat. In most studies, ambient temperature is determined from regional weather stations and the assumption is made that all individuals within the population are exposed to the same temperatures (Martiello and Giacchi 2010). The maximum temperature is most often used for exposure measurement although some studies have suggested that minimum temperatures may be a better indicator of human thermal stress, particularly as they are a good indicator of high night time temperatures that do not allow the relief of cooling (Martiello and Giacchi 2010). Other measures of exposure to extreme heat include various thermal comfort indices which typically combine temperature with humidity to account for added discomfort and the physiological effects of humidity.

Evidence suggests that the period of time to which the human body is exposed to heat is important for health outcomes. Heat waves are episodes of several days duration with extreme high temperatures that exceed norms for the geographic location and season. Heat waves can be characterised by a number of dimensions which in turn affect the potential health impacts of the event (Anderson and Bell 2010). These include intensity of temperatures reached, their duration, and timing in the season.

The epidemiologic literature includes a large number of studies that have investigated the health impacts of heatwave events. The exact definition of a heatwave, however, varies significantly between studies. This is well documented in the literature and will not be specifically addressed here, suffice to say there has been little consideration of how buildings – the places in which people live and work – mediate heat exposure.

3.2 *Quantifying the impact on human health*

The current understanding of human vulnerability to extreme heat is largely based on epidemiological studies of mortality (Brown and Walker 2008), however there are a number of other health impact measures which could potentially be used to quantify the impact of heat on health. These include health service use (e.g. hospital admissions, emergency department presentations, ambulance call-outs), days of disability caused by extreme heat exposure, duration of healthy life lost and economic costs incurred including days of lost productivity, direct health care costs, estimated inherent value of good health and public health costs (Bambrick et al. 2008). However, the literature currently contains very few estimates of these other measures, other than the studies which have quantified increases in use of health service during extreme hot weather.

A number of studies have reported an increase in health services use during hot days. For example, hot weather has coincided with increases in emergency department visits (Josseran et al. 2010), hospital admissions (Knowlton et al. 2009, Khalaj et al. 2010); ambulance call-outs (Nitschke et al. 2007) and emergency 911 calls (Hartz et al. 2011). Some studies showed increased health service demand by specific sub-populations such as the elderly (Josseran et al. 2010, Kovats et al. 2004) or very young (Kovats et al. 2004) or for specific disease categories only including respiratory and renal disease and disorders of dehydration and electrolyte imbalance (Michelozzi et al. 2009). Two Australian studies examining emergency hospital admissions and ambulance call outs observed increases in morbidity due to heat-related injuries (Khalaj et al. 2010) and assault related injuries (Nitschke et al. 2007) during observed hot weather events.

Although administrative data is convenient and relatively accessible, one limitation is that studies relying on this data are only able to report and analyse effects of extreme heat on broad disease groupings that correspond to the International Classification of Disease categories e.g. cardiovascular disease, respiratory illness, etc. (Hajat et al. 2010). Other measures of morbidity reported in the literature have included the subjective reporting of health deterioration and self-reporting of objective morbidity (e.g. dizzy spells, hospitalisation, falling) during periods of hot weather (Larrieu et al. 2008).

A large number of epidemiologic studies, mainly using either episodic or continuous time series analysis, have demonstrated an association between episodes of extreme hot temperatures and excess mortality (e.g. Anderson and Bell 2010, Hertel et al. 2009, Kovats et al. 2004). The effect estimates of excess all-cause mortality due to higher than normal temperatures range from 0 to 11% (Kovats et al. 2004). The differences in findings across studies are likely due to variation in the extreme heat event being studied. Estimates for disease specific mortality increases can be higher, with reports of increases of blood circulation mortalities by 30% (Choi et al. 2005).

3.3 *Socio-demographic and individual factors*

There are a range of socio-demographic and individual risk factors for health impacts during hot weather. The main factors that researchers have investigated include age, gender, pre-existing medical conditions, physical disability, mental illness, and various socio-economic factors. These are now critiqued to establish the weight of evidence.

3.3.1 Age and gender

Older age is the most consistent predictor of adverse health outcomes due to extreme heat (e.g. Borrell et al. 2006, Vaneckova et al. 2010, Conti et al. 2005, Loughnan et al. 2010, Ma et al. 2012), while several studies have also highlighted the vulnerability of children that are aged five years and below (Khalaj et al. 2010, Kovats et al. 2004).

Excess deaths due to extreme heat are typically observed among populations aged 65 years onwards (Vaneckova et al. 2010, Choi et al. 2005) with the risk continuing to rise with advancing age (Heudorf and Meyer 2005, Ramlow and Kuller 1990). There are

several mechanisms that potentially explain why older people suffer the greatest heat-related health burdens including the deterioration of physiological functioning due to aging that affect key adaptive processes such as the ability to sweat and regulate cardiac output during warmer weather. Additionally, older people are more likely to suffer from chronic diseases that contribute to heat vulnerability, and are also more likely to be taking various forms of medication that may further exacerbate the risk.

Epidemiological studies have either reported no differences between genders in terms of increased morbidity and mortality risk (Foroni et al. 2007, Ma et al. 2012, O'Neill et al. 2003) or that the effects are more pronounced among women (Kysely and Kriz 2008, Borrell et al. 2006, Larrieu et al. 2008, Ramlow and Kuller 1990, Stafoggia et al. 2006, Yu et al. 2010). The mechanism by which females may be more affected than males in hot weather are not completely understood, however this may be due to the physiological differences between men and women (e.g. fewer sweat glands in women) or because women are often over-represented in older age groups, which tend to be the most at risk of severe heat-related health outcomes (Brown and Walker 2008).

3.3.2 Pre-existing medical conditions

Pre-existing medical conditions have repeatedly been found to increase the mortality and morbidity risks of extreme heat (Larrieu et al. 2008, Khalaj et al. 2010), most likely due to compromised physiological functioning and frailty associated with physical illness (Foroni et al. 2007). A meta-analysis of six case-control studies found that cardiovascular disease and pulmonary illness were both associated with increased mortality risk due to hot weather (Bouchama et al. 2007). An Australian study reported an increase in emergency hospital admissions on extremely hot days among those with underlying diseases of the nervous, circulatory, respiratory and cardiovascular systems as well as among individuals with neoplasms and renal disease (Khalaj et al. 2010).

3.3.3 Physical disability and mental illness

Increased mortality risk due to heatwaves and extreme hot temperatures has been associated with confinement to bed and being unable to care for oneself (Bouchama et al. 2007, Kilbourne et al. 1982), lack of mobility (Vandentorren et al. 2006), cognitive impairment and low scores on the Activity of Daily Living Scale (Foroni et al. 2007).

Mental illness has been demonstrated to be a strong predictor for both increased mortality (Bouchama et al. 2007, Kaiser et al. 2001, Naughton et al. 2002), hospital admission (Khalaj et al. 2010) and both subjectively and objectively experienced morbidity (Larrieu et al. 2008) during extreme hot weather. Analysis of six case control studies investigating the risk of increased mortality reported psychiatric illness as the strongest risk factor of all pre-existing medical conditions (Bouchama et al. 2007).

There is some evidence that non-compliance with psychiatric medication may be a factor in mortality (Kaiser et al. 2001) and that psychiatric illness is disproportionately high among younger individuals who die during extreme heat (Naughton et al. 2002).

3.3.4 Socio-economic disadvantage

The contribution of social disadvantage and deprivation towards poor health outcomes has been well established. The role of socioeconomic status (SES) in determining health outcomes during extreme hot weather has also been extensively investigated (e.g. Kaiser et al. 2001, Loughnan et al. 2010, Naughton et al. 2002, Yu et al. 2010) but with mixed findings regarding the risk conferred by disadvantage. This is most likely due to the variety of ways in which SES is defined and measured across different studies, and the different health outcomes under investigation. For instance, a study in Australia using an area measure of SES based on census data reported no effect of socioeconomic status on heat-related mortality in northern Sydney (Vaneckova et al. 2010). Meanwhile, another Australian study using an area based measure of SES did

find a relationship between lower SES and hospital admission for acute myocardial infarction (Loughnan et al. 2010), while a study following the Chicago heatwave found increased mortality of individuals earning less than $10,000 (Naughton et al. 2002).

The link between lower SES and greater heat-related morbidity may be explained by the finding that lower socioeconomic and ethnic minority groups have been found to live in neighbourhoods with greater exposure to heat stress (Harlan et al. 2006).

Education is a commonly used indicator of SES and a number of studies have explored how education level affects health outcomes during hot weather. As with several other indicators of SES and social disadvantage, the evidence for a relationship between education and poor health outcomes is rather mixed, with some studies reporting a significant increase in heat-related mortality or morbidity among individuals with less education (Borrell et al. 2006, O'Neill et al. 2003, Larrieu et al. 2008) while several others reported no significant effect of SES (Foroni et al. 2007, Ma et al. 2012).

3.4 *Behavioural decisions and physical actions*

In the previous section, demographic and individual factors were introduced. What follows is a review of the role of behavioural decisions and the actions one can take. This includes recreational drug and pharmaceutical use, decisions around the type of clothing and style of dressing, through to the use of cooling devices in the home, and adaptation behaviours such as seeking out cool places and environments for respite.

3.4.1 Recreational drug and pharmaceutical use

Alcohol is known to have a diuretic effect and standard public health advice during hot weather alerts is to limit alcohol consumption (Hajat et al. 2010). Yet there are few studies that have reported alcohol use to be a risk factor for adverse health outcomes during extreme hot weather. An early study reported alcoholism to be a risk factor for heatstroke during a heatwave in Missouri in 1980 (Kilbourne et al. 1982). There were no studies that could be found on the risk conferred by tobacco use during hot weather.

Pharmaceutical use has often been associated with increased risk of mortality and morbidity due to extreme heat (Barbieri et al. 2006, Bouchama et al. 2007, Kaiser et al. 2001, Kilbourne et al. 1982, Martin-Latry et al. 2007, Foroni et al. 2007) however the mechanisms underlying the relationship are still not well understood and it is often difficult to discern the relative contributions of medication use and the underlying disease which is being treated (Hajat et al. 2010). In general, classes of medication that are considered to confer the highest risk during extreme hot weather include various diuretics, psychotropic medications, anticholinergics and neuroleptics.

Possible causal mechanisms include dehydration through diuretic effects which in turn lead to a reduction in the clearance of toxins, decreased heart rate and contractility, electrolyte imbalance caused by laxative effects or vomiting and diarrhoea leading to electrolyte imbalance, reduction in sweat production, as well as interference with thermoregulation, vasoconstriction and reduction in judgement and alertness.

3.4.2 Type of clothing and dressing style

The style of dressing, such as dressing in lighter, cooler clothing has been found to be protective against both mortality and morbidity during heatwaves (Larrieu et al. 2008, Vandentorren et al. 2006). The studies reporting this protective effect, however, were European and it was not clear whether the relationship between dressing style and risk posed during hot weather can be generalised to the Australian context and population.

3.4.3 Use of cooling devices in the home

The availability and use of air-conditioning in the home has been found to be strongly protective against heat-related mortality in a number of case-control studies undertaken

(Bouchama et al. 2007, Kaiser et al. 2001, Kilbourne et al. 1982, Naughton et al. 2002, Vandentorren et al. 2006) while taking cool baths and showers (Naughton et al. 2002) and using fans (Bouchama et al. 2007) may also help reduce the risk of mortality.

Air-conditioning use has also been shown to reduce heat-related morbidity through reduction in health services use. A time series analysis conducted in Israel which used electricity consumption as a proxy measure for air-conditioning use, estimated that air-conditioning use attenuated the affect of extreme temperatures on emergency department visits by approximately 4% for every 1000 Megawatt hours consumed (Novikov et al. 2011). Ownership and use of air-conditioning was protective against hospital admission during hot weather in California after controlling for potential confounding factors i.e. household income and socioeconomics (Ostro et al. 2010).

A recent Australian study by Farbotko and Waitt (2011) concluded that residential air-conditioning is a potentially maladaptive technology for reducing the risk of heat stress in low income households. They argue that while it has the potential to provide relief during hot weather, it comes with a double burden in the form of increased electricity usage and the risk that it won't be available when it is needed the most due to power outages, which are also associated with extreme heat. While for these reasons it may be the intervention of last resort, air-conditioning is likely to represent the only solution in energy inefficient homes or for highly vulnerable people. For example, with regard to the latter, Summers et al. (2012) advise that Australian households that contain people with Multiple Sclerosis, where heat frequently exacerbates their symptoms, will spend between 4 and 12 times more on keeping cool than the average Australian household.

3.4.4 *Seeking cool places and environments*

Behaviour such as seeking cooler environments such as air-conditioned locations during hot weather and leaving the home at least once daily have been found to be protective against mortality during extreme hot weather (Bouchama et al. 2007, Kaiser et al. 2001, Kilbourne et al. 1982, Naughton et al. 2002). This is a common strategy recommended in heatwave plans (Ebi and Burton 2008), but there appears to be little analysis of how viable this option is in regard to the distribution and access to cool places within a location. In the study by Farbotko and Waitt (2011) introduced earlier on residential air-conditioning, they suggest an improved focus on public cool places is needed to reduce the vulnerability of low income households to extreme hot weather.

While cool places are traditionally thought of as publicly accessible buildings such as libraries, community centres, shopping centres, where air-conditioning is likely to be available, a broader definition could be considered that includes the cooling services offered by nature including shade and shelter from vegetation or the presence of water. This is explored further in Section 3.5 which has a focus on environment and housing.

3.4.5 *Social isolation and living alone*

Living alone has been shown to be a strong risk factor for mortality during extreme hot weather (Bouchama et al. 2007, Kaiser et al. 2001, Naughton et al. 2002, Stafoggia et al. 2006). However, there is limited evidence that social isolation in general leads to greater health risks. A study of the risk factors for mortality in the Chicago heatwave did not find having friends or relatives nearby was protective (Naughton et al. 2002).

3.5 *Urban environment and housing factors*

This final section of the literature review focuses more specifically on the environmental determinants of heat-related health risk, where environment is defined as both indoor environment and outdoor environment. The former referring to the physical features of the residential home and the latter, physical characteristics of the urban neighbourhood including shade and shelter benefits of vegetation, as well as other physical attributes.

3.5.1 Physical features of the home

While there have been a number of studies that have examined the role of housing interventions to improve health (Thomson et al. 2009), much of the work in relation to thermal efficiency has been undertaken in Europe, the USA and New Zealand with an emphasis on the impact of cold weather (Howden-Chapman and Chapman 2012).

Of the studies that have looked at hot weather, a case-control study conducted in France found a greater risk of dying during a heatwave event among those living in homes without insulation and with bedrooms right beneath the roof (Vandentorren et al. 2006). Another study found greater risk of non-fatal heat stroke amongst those living above the ground floor within multi-storey dwellings (Kilbourne et al. 1982). No studies have reported on the association between features typical of Australian housing and the risk of adverse health effects during hot weather. This is a major research gap.

3.5.2 Vegetation shade and shelter around home

When planted around buildings, trees provide shade, protection from winds and modify the ambient conditions around individual buildings making conditions more comfortable for people (Akbari 2002). Direct shade on buildings affects energy use and thermal comfort by reducing solar heat gain through windows, walls, and roofs. Trees and shrubs planted around buildings reduce radiant heat gain and unwanted glare and will add moisture to the air through evapotranspiration. It has been shown that air is more humid and up to 5ºC cooler in the shade of trees in summer than in areas where there are no trees (Taha et al. 1988, Parker 1989, Fisher 2007, Souch and Souch 1993).

The amount trees influence energy use and comfort levels depends on the general climate, the building type, and the size, type and position of the trees (Heisler 1986). Various studies estimate that properly sited trees can save between 10% and 50% of annual energy use in conventional houses, compared with the same houses in the open (Yu and Hien 2006, Akbari and Konopacki 2005, Simpson and McPherson 1996).

There is some evidence that the presence of vegetation and shade trees in the vicinity of the home may create a cooling effect that significantly impacts upon health related outcomes (Kilbourne et al. 1982, Vandentorren et al. 2006). Results of simulation modelling undertaken for neighbourhoods in Phoenix, USA found sparse vegetation and lack of open spaces correlated with higher temperatures and scores on a human thermal comfort index (Harlan et al. 2006). An Australian study however, investigating the geospatial effects of urban heat on mortality found the proportion of vegetation did not contribute significantly to heat-related deaths in Sydney (Vaneckova et al. 2010).

3.5.3 Geographical region and characteristics

Several recent studies have used spatial analysis to map heat exposure and the geography of vulnerable populations (Reid et al. 2009, Vescovi et al. 2005) while others have extended this approach to specific heat-related health outcomes (Uejio et al. 2011). Approaches such as these are beginning to provide insights into how heat risk factors are socially and spatially distributed. There is moderate evidence that characteristics of 'place' may affect the relationship between hot weather and health.

An Australian study found individuals living within 5-20 km to the West and South-west of the Sydney CBD were more vulnerable to heat-related mortality, although this relationship remained significant only for the South-west in multivariate analysis (Vaneckova et al. 2010). Similarly, a study of excess mortality during a heatwave in Pennsylvania found excess mortality was twice as high in the city of Pittsburgh compared to surrounding country areas. The authors speculated this may have been due to socioeconomic differences (residential areas outside the city were more affluent) and also a possible cooling effect of less densely urbanised areas (Ramlow and Kuller 1990). In contrast, an Italian study did not find a relationship between rural / urban

residential locality and heat-related mortality (Foroni et al. 2007). Another US study concluded that although absolute increases in mortality were greatest in urban areas, relative increases are actually greater in rural and suburban locations although none of the differences were found to be statistically significant (Sheridan and Dolney 2003).

3.6 *Evaluation of potential interventions*

Broad, population level protection measures against heat-related morbidity and mortality have been introduced across North America, Europe, Australia and parts of Asia. These measures consist mainly of heat alert systems, coupled with public health awareness campaigns to inform individuals and communities on how best to protect themselves during hot weather. The advice that is most commonly provided includes:

- avoiding alcohol,
- wearing light clothing,
- drinking fluids regularly,
- seeking air-conditioned locations,
- staying indoors (particularly during hottest part of the day),
- wearing a hat,
- avoiding or reducing physical activity,
- protecting one-self from sun,
- knowing the symptoms of heat-related illness and how to respond,
- checking in on vulnerable people,
- not leaving children in closed cars, and
- taking frequent baths or showers.

However, the evidence base to support some of the advice that is issued remains unclear and it is possible that some erroneous information is issued to the general population (Hajat et al. 2010). Good evidence exists for the protective effect of increasing fluids, spending time in air-conditioned locations if susceptible, and reduction of normal activity levels. In contrast, the following advice is not currently supported by evidence, which includes avoiding fans due to dehydration effects, avoiding alcohol consumption (especially low alcohol beverages) and avoiding caffeine.

Population surveys have reported varying degrees of awareness and protective behaviour among individuals about the health risks of extreme heat and ways in which to potentially reduce vulnerability. For example, the majority of patients with chronic cardiac and pulmonary diseases participating in a Canadian longitudinal cohort study perceived themselves as vulnerable to extreme heat and reported the adoption of recommended protective measures such as spending time in air-conditioning, reducing activity and drinking extra fluids during extreme hot weather (Kosatsky et al. 2009). However 25% stated that they would refuse to spend a night in an air-conditioned shelter during a prolonged heatwave. As noted earlier, there is also evidence from a study in Australia, that even if air-conditioning is available to low income households, it may not be used due to concerns over the cost of electricity (Farbotko and Waitt 2011).

A successful work-based intervention in Abu Dhabi, United Arab Emirates showed that issuing advice to construction workers in how to avoid heat-related illness reduced cases by 50 – 79.5% (Joubert et al. 2011). The intervention was multi-faceted and involved a multi-media awareness campaign targeting 465 companies employing heat exposed workers (mostly in the construction industry). Specific advice provided to the

workers included drinking fluids, increasing salt intake, taking regular breaks, ensuring plenty of sleep at night and informing supervisors if unwell. While the results of this intervention are promising, the evaluation involved only two of the targeted companies.

There have been no empirical evaluations of environmentally based interventions to reduce heat-related morbidity. Simulation modelling of urban mitigation strategies in Phoenix, Arizona concluded that a combination of heat reducing strategies (increasing emissivity, proportion of vegetated areas, thermal conductivity and albedo of the urban environment) would lead to a 48% reduction in heat-related emergency calls (Silva et al. 2010). Increasing albedo was predicted to be the single most effective strategy.

While not specifically considering health outcomes, Bowler et al. (2010) conducted a comprehensive review to evaluate the available evidence on whether urban greening strategies, such as tree planting or green roofs, affects the air temperature of urban areas. These authors concluded based on meta-analysis of data from different studies that, on average, an urban park could be 1ºC cooler than surrounding built up areas. They acknowledge that shade from trees is important for lowering temperatures, but that unshaded green areas such as irrigated grass can also be cooler, highlighting the role of evaporative cooling. Of note however, the cooling benefit of vegetation appears to be quite localised, diminishing rapidly beyond the boundary of the vegetated area.

As noted by Coutts et al. (2012), vegetation is regularly cited as a way to lower urban temperatures, but what is often overlooked is the role of water in driving the processes that provide these 'cooling' services. Recent studies undertaken by Gober et al. (2010) and Jenerette et al. (2011) provide estimates of the water resources that are required to manipulate urban heat island effects in Phoenix, USA. Similar research is needed in Australia, given the issue of water security facing many of our towns and cities, and the impact of associated water restrictions on vegetation health. Thus, Coutts et al. (2012) argue for an increased role for Water Sensitive Urban Design as a means of retaining more water in the urban landscape to support processes that provide cooling services.

4. NEIGHBOURHOOD AND ROLE OF PLACE

In this section of the report, heat vulnerability mapping is undertaken to identify spatial relationships between thermal patterns of land surface temperature and the risk factors that define sensitive populations. This analysis was conducted in four Australian cities, including Adelaide, Melbourne, Sydney and Brisbane. These cities were selected as they are the most documented in terms of research on the links between extreme heat and public health. The questions that the research aimed to address are as follows:

- How does the thermal geography of a city vary in relation to built environment?
- Are heat sensitive populations located in the most vulnerable parts of the city?

The boundaries of our four case study cities were defined by the Australian Bureau of Statistics (ABS) Urban Centre boundaries. The Census Collection District (CCD) was used as the focal scale of analysis, as this is the finest spatial resolution for which population census data are available – representing on average about 225 dwellings.

4.1 *Remote sensing of land surface temperatures*

Strong spatial variations in temperature have been recorded across many urban areas (Voogt and Oke 2003, Harlan et al. 2006, Weng 2009, Buyantuyev and Wu 2010). Remotely sensed thermal infrared (TIR) data can be used to characterise the thermal landscape in relatively high spatial detail (Weng 2009, Quattrochi and Luvall 1999, Weng et al. 2004). Although remotely sensed TIR data are used to derive land surface temperatures (LST) rather than air temperatures, there is a direct relationship between LST and ambient temperature. Fundamentally, LST modifies air temperature in the lower layer of the atmosphere dampening or exacerbating high air temperatures (Voogt and Oke 1997). However, the strength of this relationship varies depending on the geographical location and atmospheric conditions (Rigo et al. 2006, Qin et al. 2001, French et al. 2003, Kawashima et al. 2000, Coll et al. 2010, Srivastava et al. 2009).

LST can also have a major influence on the internal temperature of a building (Voogt and Oke 1997) particularly in relation to building height (Smargiassi et al. 2008) and for dwellings without air-conditioning (Kestens et al. 2011). Thus, surface temperatures derived from satellite images provide an effective local measure of heat exposure that can be used to link the exposure of housing occupants to high temperatures and public health concerns over heat-related health risks (Kestens et al. 2011, Voogt and Oke 1997). This issue is explored further in Section 5, where we undertake bottom-up modelling of building thermal performance to provide a temporal dimension and understanding of how building thermal performance changes with climate change.

Satellite imagery was selected for cloud free periods of extreme heat. Heat wave events were identified for our four cities in two ways. Those identified as natural disasters by Emergency Management Australia and also using weather observation data from the Australian Bureau of Meteorology to identify days where temperatures exceeded a maximum temperature threshold of 32°C. We then compared the temporal distribution of extreme heat events with the availability of archival Landsat imagery held by Geoscience Australia. Given the satellite return period (16 days) and variability in temporal distribution of heatwave events, there was a relatively low likelihood of an image being available for any one heatwave event. Because of this, we looked for matches for the period 2001-2011. This resulted in identification of four to six events for each city. Of these, only 2 to 3 images per city were sufficiently cloud free to be used in analysis. Imagery for these events was obtained from Geoscience Australia.

The Landsat thermal infrared (TIR) images were processed to remove minor cloud and converted from a digital at-sensor number to surface temperatures using a calibration procedure based on sensor characteristics (e.g. Landsat Mission reference). A set of

corrections for atmospheric effects and differences in land surface emissivity were then applied (Sun et al. 2010) using the mono-window algorithm approach developed by Qin et al. (2001) with emissivity correction based on Van de Griend and Owe (1993). The resultant maps of land surface temperatures created are illustrated in Figure 7 below.

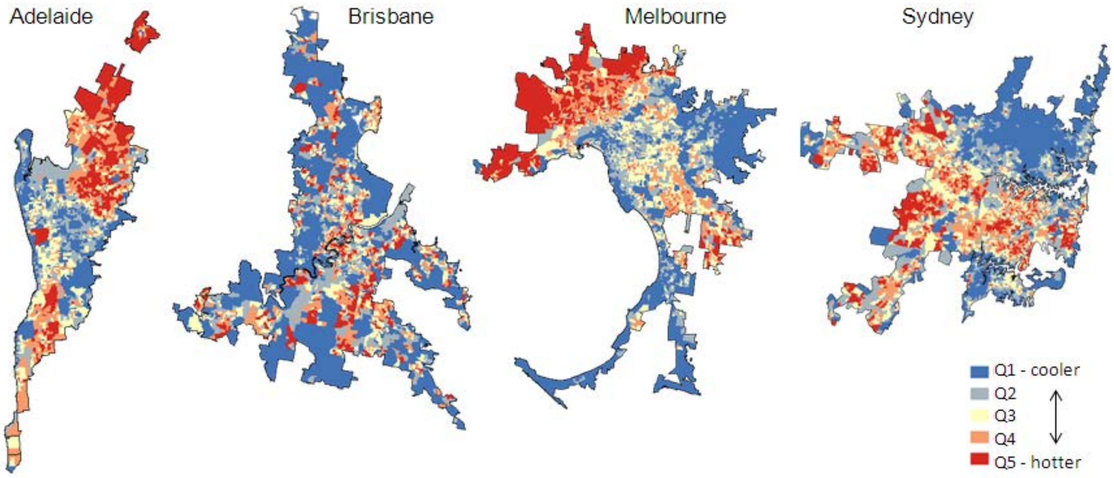


Figure 7: Land surface temperature maps for Adelaide, Brisbane, Melbourne and Sydney, presented as quintiles based on mean values for each Census Collection District (CCD).

Significant variations can be seen in patterns of LST for each city. Adelaide has high LSTs predominantly in the northern and southern parts of the city while the central portion of the city, from the coast to the ranges is cooler. Brisbane has relative high LSTs throughout the city but the highest land surface temperatures occur in the central portion of the city, with cooler temperatures in the outer parts of the city. Melbourne has complex patterns of LST with higher temperatures in the northwest and south central parts of the city and lower temperatures in the north central and southern parts of the city. In Sydney, LSTs are highest in the western parts of the city, while the northern and south-eastern parts are relatively cooler. Explanations for these patterns are now discussed as the role of landscape and environmental drivers are considered.

4.2 *Other measures of landscape and built environment*

As discussed in Section 3.5, the type and amount of vegetation in a given area can have a significant influence on cooling through the provision of shade and shelter. In this project, we used the Normalized Difference Vegetation Index (NDVI) as a measure of vegetation density and vigour. Using Landsat data, NDVI was derived as a ratio of land surface reflectance in the near infrared (NIR) and red visible (RED) wavelengths,

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \tag{5}$$

NDVI values range from -1 to +1 with higher values typically indicating more dense and vigorous vegetation and low values indicating low vegetation and, in urban areas, high impervious surface cover. Patterns of NDVI for the four cities are shown in Figure 8.

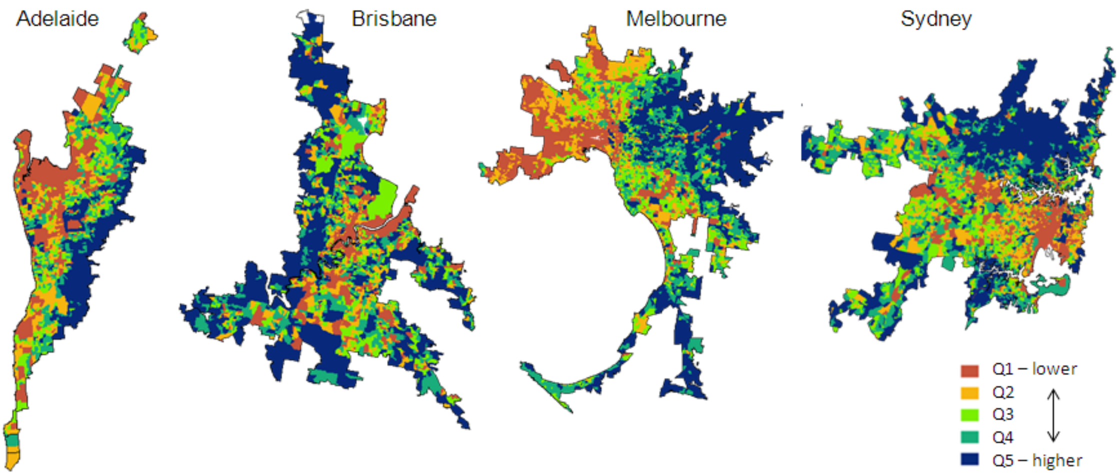


Figure 8: Vegetation maps (using NDVI) for Adelaide, Brisbane, Melbourne and Sydney, presented as quintiles based on mean values for each Census Collection District (CCD).

In most cases, NDVI shows a similar but opposite trend to that described for LST. In other words, the cooler parts of the city identified in Figure 7 are generally the places with high vegetation (i.e. NDVI values). However, it was also considered important to examine the influence of other measures of landscape and built environment. This is because elevation, distance to the coast, and the angle at which solar radiation strikes the land surface can all influence surface temperatures. In Australia, north facing slopes may be warmer than south facing slopes due to different amounts of incident solar radiation. We used ArcGIS 10 to derive measures of elevation, aspect, and slope from high resolution data from the Shuttle Radar Topography Mission (SRTM). This allowed the influence of topography on land surface temperatures to be assessed. It also allowed the control of topographic variation in analyses of the influence of other factors, such as NDVI. Topographic data was also used to develop a solar radiation index to coincide with the time when each image was acquired. As the four cities were all coastal, distance to coast was estimated to account for the influence of sea breezes.

The composition and structure of the built environment also has an important influence on land surface temperature patterns (Weng 2009). Previous research in this area has focussed on the proportion of built up land and building (Bottyan and Unger 2003), street canyon geometry (Eliasson 1996), land use and land cover (Dousset and Gourmelon 2003), and vegetation (Weng et al. 2004). To assess the contribution of components of urban form to LST and heat exposure, metrics were derived for land cover, composition and configuration. Configuration metrics were developed using the 2006 Australian Bureau of Statistics Mesh Block data and included the net residential density (number of dwellings per unit area of residential land use), gross residential density (number of dwellings per total land area in a CCD) and average residential block size. The proportion of single detached dwellings for each CCD was derived from the 2006 Australian Census of Population and Housing (Australian Bureau of Statistics 2006). The total length of roads in a CCD was derived from PSMA data.

4.3 *Overlaying known heat-related health risk factors*

Low income households have been defined in this project as those with an Equivalised Total Household Income in 2006 of between $1 and $399 per week. The proportion of all households that fall into this category as reported in the 2006 Census of Population and Housing are Adelaide 28%, Brisbane 22%, Sydney 23% and Melbourne 24%. The distribution of low income households in the four cities is now presented in Figure 9.

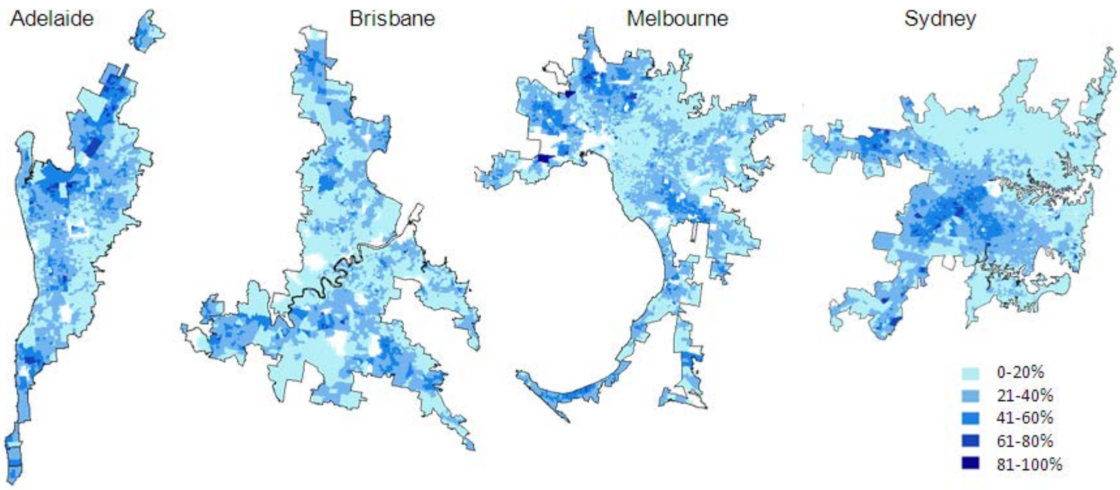


Figure 9: Low income households (equivalised income of $1-399/week) as a percentage of total households in each CCD for cities of Adelaide, Brisbane, Melbourne and Sydney.

Based on the results of the literature review presented earlier (Section 3), a number of individual, behavioural and socio-demographic risk factors were selected as measures of the sensitivity of low income households to heat exposure. These risk factors were matched to appropriate variables found in the 2006 Census of Population and Housing (Australian Bureau of Statistics 2006). The variables selected were summarised at CCD level and are listed in Table 5 along with the risk factors they are representing.

Table 5: Risk factors and component variables used to define the sensitivity of low income households to extreme heat. All data sourced from the Census (ABS 2006).

Risk factor	Census variable
Low income	% weekly income < AUD 400
Age	% low income population 0-4 years old
	% low income population 65 years or older
Education	% low income population year 10 or less
Occupation	% low income population unemployed
	% low income population works outside
Social isolation	% low income population not proficient in English
	% low income population living alone
Disability	% low income population requiring assistance
Neighbourhood stability	% low income population changed households

The evidence supporting these risk factors has been outlined in Section 3, but what follows now is a brief justification of the variables used to represent these risk factors.

With regard to age, there is substantial evidence supporting the increased risk posed to the young and the elderly. In this study, the proportion of people in each CCD who were living in low income households and aged either 65 years and older or less than five years, were used to represent this risk factor. Education is a commonly used indicator of SES and a number of studies have investigated how education level affects health outcomes during hot weather. The measure used here, was proportion of adults from low income households in each CCD, with a maximum of year 10 level schooling.

Employment status and the type of work that people do can influence vulnerability to heat. This was represented by the proportion of adults in each CCD who are living in low income households and are unemployed. Certain occupations that require outdoor or factory work may also increase the risk of suffering from heat stress (Kjellstrom and

Weaver 2009). The proportion of the population who works outside was used as a measure of day time heat exposure. This variable captures the proportion of the population who live in low income households and undertake mostly outside work.

Social isolation has been identified as a heat-related health risk factor. One form of social isolation is people who live alone, which was expressed in this study as the proportion of low income households where a person lives alone. Other aspects of social isolation can involve people who are linguistically isolated, where they may not receive weather warnings or advice or have difficulty in seeking assistance. This was represented by the proportion of people who feel they are not proficient at English.

Physical or mental disability is another important heat-related health risk factor and has been described in significant detail in Section 3. The variable that was used in this study was the number of people with a profound or severe disability. It measures the proportion of people who need help or assistance in one or more core activity areas of self-care, mobility and communication, due to a long-term health condition (lasting six months or more), a disability (lasting six months or more), or old age (Trewin 2006).

Looking at the key risk factors and the variables used to represent them, it can be seen in Figure 10 using data for Melbourne, that risk factors for heat-related health are not distributed evenly within the population. This is true for many other cities as well. Of note, is many of the key risk factors are twice as prevalent in low income households compared to those on medium to high incomes. Significantly, many risk factors also co-vary, for example, with elderly people who also live alone and need assistance.

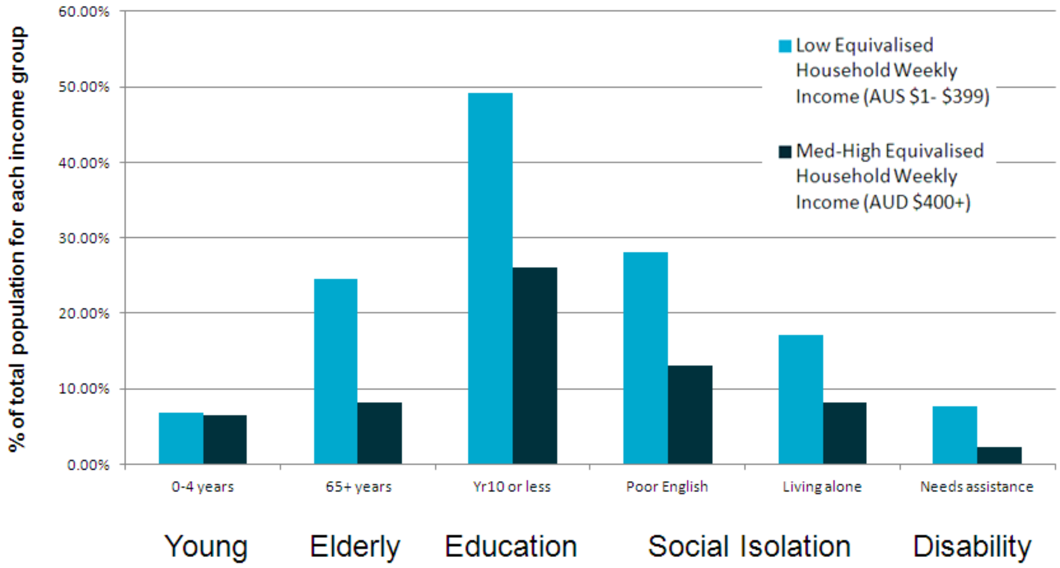


Figure 10: Heat-related health risk factors in Melbourne (Data sourced from ABS 2006).

4.4 *Statistical analyses and spatial relationships*

Two main types of analysis were performed using the datasets developed for each of the four case study cities. The first involved modelling LST as a function of a set of topographic and built environmental variables using spatial regression. The second examined spatial relationships between LST and heat-related health risk factors and utilised bivariate local indicators of spatial association (LISA) methods. The steps involved in undertaking these analyses and results generated are now summarised.

4.4.1 Heat exposure and the built environment

Ordinary least squares (OLS) and spatial regression analyses were undertaken to identify relationships between LST and measures of landscape and built environment. Correlations were explored and dependent and independent variables tested for spatial autocorrelation using the global Moran's I statistic. This revealed significant ($p < 0.05$) spatial autocorrelation in each dataset. Spatial autocorrelation often occurs in spatial datasets and violates the independence assumption of many statistical techniques, including ordinary least squares (OLS) regression, unless it can be accounted for by independent variables. To address this problem, a spatial error model was developed to predict LST using the open source *GeoDa* software (Anselin et al. 2006). Spatial error models provide a means for accounting for spatial dependence in independent variables and regression errors by adding a term to the traditional OLS model that describes the spatial autocorrelation structure of a given dataset. This results in more robust coefficient estimates by reducing the bias introduced by spatial autocorrelation.

As shown in Table 6, there were some common patterns amongst the four cities with regard to LST and the landscape and built environment variables. NDVI was the most important factor explaining variation in LST, with LST being negatively related to NDVI. Overall, high temperatures were associated with low NDVI values. Topographic and built environment factors were also important but varied by city. For example, elevation was an important factor in Adelaide, Brisbane and Sydney but not for Melbourne. While distance from the coast was an important variable for all cities with higher temperatures associated with inland locations, and solar radiation was important for all cities except Brisbane. Gross residential density was an important factor in Adelaide, Melbourne and Sydney, but not Brisbane. Block size was important for all cities, but Adelaide.

Table 6: Results from the spatial error model describing relationship between variables and LST (bold values are significant at the 0.01 level; italicized values are not significant).

Variable	ADE Coefficient	BNE Coefficient	MEL Coefficient	SYD Coefficient
CONSTANT	**14.728**	**49.034**	*36.042*	**24.289**
NDVI	**-9.452**	**-26.242**	**-21.682**	**-21.65**
log Elevation	**-0.754**	**0.431**	*-0.041*	**0.877**
log Distance to coast	**2.513**	**0.577**	**1.779**	**1.137**
Solar radiation	**1.604**	*0.011*	**0.282**	**0.915**
log Net residential density	*0.023*	*0.15*	*-0.081*	**0.616**
log Gross residential density	**0.393**	*0.13*	**0.361**	**0.422**
Road length	*0*	**0.034**	*0.007*	**0.014**
log Average block size	*-0.067*	**-1.554**	**0.085**	**-0.471**
Single detached housing	**0.005**	**-0.004**	*-0.001*	*0.001*
LAMBDA	0.883	0.808	0.899	0.863
Pseudo r-squared	0.85	0.82	0.92	0.89
AIC	6440	7876	18246	16814
AIC change from OLS	-1972	-1412	-5266	-4345
Log likelihood (LL)	-3210	-3928	-9113	-9397
LL change from OLS	986	706	2633	1172

In summary, heat exposure in each of the cities showed significant spatial variability and was related to the underlying structure of the built environment. Each city has large areas where land surfaces temperatures are higher than other parts of the city and these areas correspond mainly with areas of low vegetation cover. There are also more localised 'cool spots' associated with features such as parks and river courses. These findings are consistent with other studies that show the importance of vegetation and other built environment factors in determining land surface temperatures (Weng 2009, Bottyan and Unger 2003, Eliasson 1996, Dousset and Gourmelon 2003).

4.4.2 Heat exposure and heat-related health risk

The spatial relationships between LST and heat-related health risk were assessed using global bivariate Moran's I and the local indicator of spatial association (LISA) analysis using *GeoDa* software (Anselin et al. 2006). The bivariate version of Moran's I can be used to determine the direction and strength of the spatial relationship between two variables thus providing a measure of the overall clustering in the dataset. The global relationship may not be representative of local conditions (Anselin 1995) so bivariate LISA was used to provide information about the location and types of spatial correlation. To do this, bivariate LISA measures the correlation between a variable at a specific location and the weighted average of another variable in the neighbourhood, in this case, the neighbouring CCDs. Statistical significance for Moran's I and LISA values were determined by comparing the observed distribution of the data with a randomly generated distribution based on 999 random permutations (Anselin 1995).

The results of this analysis are presented in Figure 11 and Figure 12, showing the distribution of significant clusters and the type of relationship they represent. In this study, two clusters were identified: firstly, areas with a high heat-related health risk and high LST (High-High), and secondly, areas with a high heat-related health risk and a low LST (High-Low). High-High clusters are places where heat-related health risk in low income households is associated with higher land surface temperatures, while High-Low clusters show places where heat-related health risk is high, but LST is low. These locations are where the built environment is cooler, buffering heat exposure.

Each of the four cities had similar patterns with regard to the distribution of low income populations. Overall, these populations are spatially concentrated in specific parts of the city with two main patterns: low income areas in older parts of the city and low income areas in outer urban growth areas. Specific heat-related health risk factors were found to be concentrated in these areas and tended to co-vary. For example, the proportion of the low income population 65 years and older and living alone tended to occur in the same neighbourhoods. There were differences in the spatial distribution of some heat-related health risk factors, due to differences in the social and demographic profiles of different neighbourhoods. For example, high concentrations of low income households comprising residents 65 years and older did not generally overlap with high concentrations of 0-4 year olds. The former tend to be concentrated in the older parts of the city, whereas the latter were predominantly concentrated in new growth areas.

A key finding is that low income households are concentrated in the parts of the urban landscape with the highest land surface temperatures. In other words, the people most vulnerable to heat-related health impacts are living in the areas with the highest heat exposure, as measured by land surface temperature. This pattern was strong and consistent among all four cities investigated. Similarly, each of the heat-related health risk factors for low income populations were found to be significantly correlated to land surface temperatures in these areas. In contrast, there were some examples of low income populations associated with lower land surface temperatures and these were typically in areas with higher levels of vegetation (Figure 8). This was not common, however, with household income shown in several studies to be related to vegetation and also land surface temperature (Jenerette et al. 2007, Buyantuyev and Wu 2010).

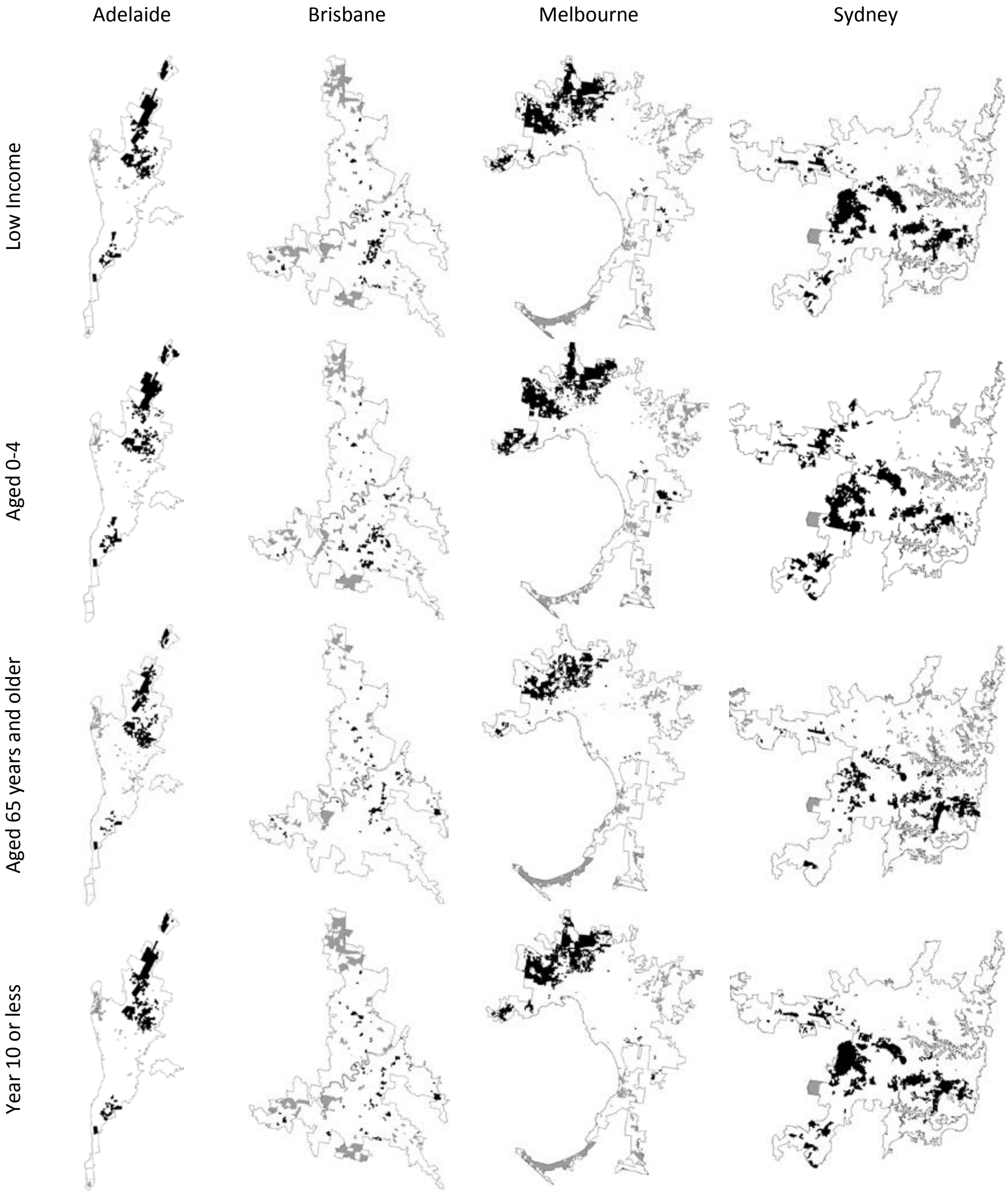


Figure 11: Results of bivariate LISA showing the spatial relationship between income, age, education and LST for the cities where black is High-High and grey High-Low.

The findings of this study are in general agreement with this international research showing concentrations of low income households in hot areas, with little vegetation. In each city the hottest areas with high proportions of low income residents were located in two basic settings: older inner suburbs with high residential densities and high amounts of impervious surfaces, and newer outer suburbs with lower residential

densities but larger houses and low amounts of vegetation. These patterns reflect the common development history of Australian cities including social stratification of older neighbourhoods and new housing development typically occurring on the urban fringe.

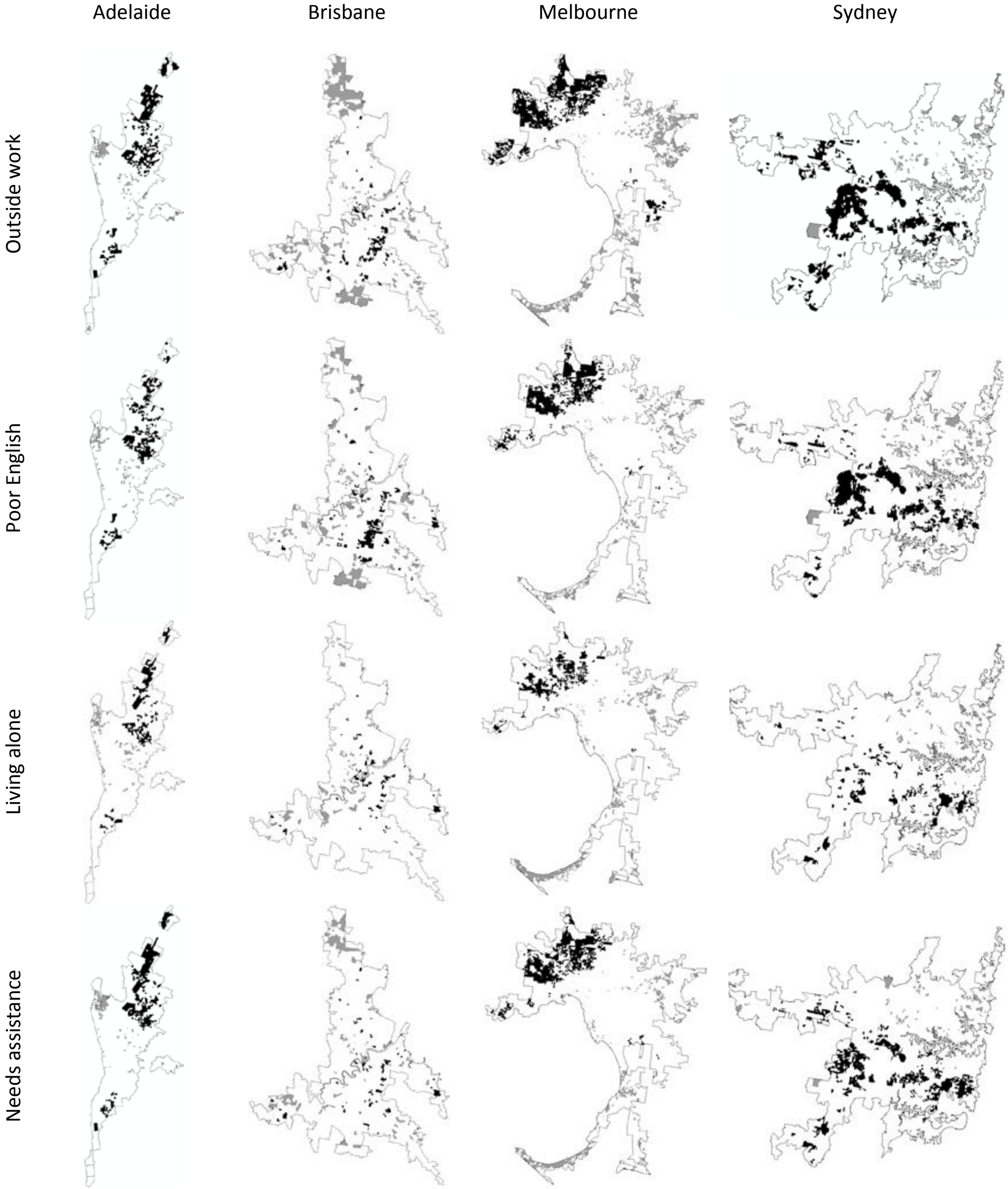


Figure 12: Results of bivariate LISA showing the spatial relationship between social isolation, employment, disability and LST where black is High-High and grey High-Low.

5. MODELLING OF HOUSING PERFORMANCE

This sections sets out the methods that were used to assess the performance of low income housing types with regard to thermal comfort and indoor environment. The software tool *AccuRate* was used and adapted for this purpose. *AccuRate* is a tool developed by CSIRO to support residential house energy rating in Australia (Delsante 2005). It calculates the energy requirements of residential buildings taking into account local climate, building design, orientation, and the construction materials that make up the building fabric. *AccuRate* has been used in several recent Australian studies to explore the impact of climate change on residential building performance for several cities across Australia (Wang et al. 2010a, Wang et al. 2011, Ren et al. 2011, Chen et al. 2012). This previous research activity largely focussed on energy consumption for space heating and cooling and how this might be impacted by climate change. This work has been extended in this project to consider thermal performance of low income housing types in the context of heat stress and occupant discomfort. This involved the modification of *AccuRate* to enable calculation of the Discomfort Index (Thom 1959), a widely used measure of heat-related health risk (Epstein and Moran 2006). What now follows is a description of this modelling activity and summary of the research findings.

5.1 *Methods to calculate thermal discomfort*

Many indices have been developed to estimate thermal comfort and environmental heat stress. Epstein and Moran (2006) undertook a review of 40 such indices. Some are highly sophisticated, requiring the calculation of environmental, physiological, and behavioural factors (e.g. temperature, humidity, air speed, solar radiation, metabolic rate, age, physical activity, and clothing). This level of detail may be important when assessing if the indoor thermal performance of a building meets certain standards for thermal comfort, such as those which have been defined by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). However, as noted by Vaneckova et al. (2011), simpler indices requiring only basic environmental factors are generally all that is used in epidemiological and health studies. The most common of these are the Wet Bulb Globe Temperature and the Discomfort Index, both of which have been in regular use for over 40 years (Epstein and Moran 2006). In this study, we adopted the Discomfort Index based on its 'ease of use' and physiological significance.

To implement this index, the non-star-rating module of *AccuRate* was employed. This module enables the simulation of building thermal performance for multiple zones in a building (e.g. bedroom, living area, bathroom, etc.). Importantly, it was run in natural ventilation (unconditioned) mode, as there was limited data available on the presence of mechanical cooling, such as fans and air-conditioning in our social housing dataset. What this means, is the impact of cooling devices on indoor thermal environment are not considered in this analysis. Nonetheless, Farbotko and Waitt (2011) suggest that even where air-conditioners are present in low income households, they are often left switched off because of concerns over increasing electricity costs. So presence of an air-conditioner in a low income household is no guarantee it will be used when needed.

The output that is generated by *AccuRate* is predictions of hourly temperature and airflows within and between building zones over a period of one year. Temperature alone was not deemed sufficient for understanding the relationship between indoor environment and human health, so a new module for *AccuRate* was developed to estimate the wet-bulb temperature (^{0}C) and the dry-bulb temperature (^{0}C) for each zone within the dwelling. These estimates were then used to calculate a common index of environmental heat load known as the Discomfort Index (DI), as follows

$$DI = 0.5Tw + 0.5Ta \quad (6)$$

Where the terms Tw and Ta are wet-bulb and dry-bulb temperatures (^{0}C), respectively. The DI is expressed as an hourly value over a period of one year, as determined by the baseline and future TMY files described in Section 2.3. The DI value represents the environmental heat load and associated heat-related health risk. Based on studies of diverse populations in a range of climates, four classes of risk are identified (Table 7).

Table 7: Discomfort Index and heat-related health risk (after Epstein and Moran 2006).

DI Value	Thermal sensation
< 22	No heat stress is encountered
22-24	Most people feel a mild sensation of heat
24-28	Heat load is moderately heavy, people feel very hot
>28	Heat load is severe, people at increased risk of heat illness

The threshold DI value of 28 has been used in this study to define heat-related health risk. This is a level at which it becomes increasingly difficult to maintain a safe core body temperature. The human body is designed to maintain a core body temperature of 37°C (Kjellstrom 2009). When the core body temperature reaches 38°C, there is a diminished capacity for physical work (Kerslake 1972), mental activity is impaired (Ramsey 1995), and accident risk increases (Ramsey et al. 1983). When the core body temperature reaches 39°C, there is potential for heat exhaustion and heat stroke, while above 40.6°C the situation becomes life threatening (Leithead and Lind 1964).

5.2 *Sensitivity analysis of adaptation options*

With the method for estimating DI implemented in *AccuRate*, the next step was to explore how heat-related health risk might change with different climate adaptation options implemented at the building scale. A range of potential options were identified through literature review and the experience of the modelling team. These included changing roof materials and colour, increasing the level of ceiling insulation, reducing air leaks and infiltration, exploring the influence of building orientation and solar access, through to various glazing and window shading options. For the purpose of testing the efficacy of these options, *AccuRate* was used to estimate the DI values for selected housing types, using the baseline climate, for each of the seven reference cities. This enabled an assessment of the efficacy of each option, which was used to inform the construction of building adaptation scenarios for exploration in latter research steps.

It should be noted that all *AccuRate* simulations in this study were carried out based on various assumptions on the quality of the building construction, properties of materials, and the behaviour of building occupants. These assumptions were all consistent with the Protocol for House Energy Rating Software developed by the Australian Building Codes Board (2006). In reality, building construction quality and occupant behaviours can all vary significantly and may differ from the assumptions used in *AccuRate*. For example, it is difficult to know if a building has been correctly insulated without the use of thermal imaging. For this reason, our simulations are regarded as estimates only.

5.2.1 Roof materials and colour

A large body of research on the Urban Heat Island (UHI) effect has identified the role of albedo in moderating urban temperatures (Silva et al. 2010). With regard to roofs, this has led to the identification of ‘cool roofs’ as a key climate adaptation strategy (Akbari

et al. 2001). The way this works, is that solar energy from the sun strikes a rooftop, and while most is reflected back into the sky, some is absorbed as heat in the roof. Dark coloured roofing materials absorb large amounts of heat, making them warm in the sun which then heats the building. Light coloured roofs on the other hand, stay cooler in the sun and therefore transmit less heat into the building. Silva et al (2010) concluded from an evaluation of heat reducing strategies in the USA, that increasing albedo was the single most effective strategy to reduce heat-related health impacts. To evaluate the effectiveness of this strategy we used *AccuRate* to model the influence of change in roof colour from 'dark' to 'light' on House Type A1, as shown in Figure 13. For dark roofs the value for solar absorptivity was set at 0.85, and for light roofs 0.30.

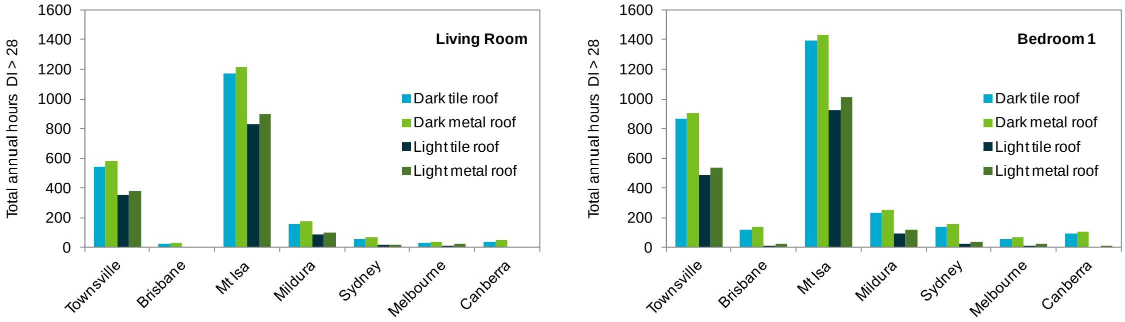


Figure 13: Impact of roof colour (dark vs light) and materials on thermal performance of the Living Room and Bedroom 1 zones in House Type A1 for the reference climate year.

For all reference cities, changing roof colour from dark to light had a significant impact on reducing the total annual hours of severe heat-related health risk to occupants (DI > 28). For example, severe heat-related health risk in the Living Room of House Type A1 was reduced by a maximum of 95% in Canberra (40 to 2 hours) and minimum of 29% in Mt Isa (1172 to 830 hours). Testing of other house types confirmed similar results. The results were consistent for different roofing materials, suggesting tile roofs perform slightly better than metal roofs, but that roof colour is more important than roof material in reducing thermal risk to occupants. This highlights the importance of albedo in urban climate adaptation and the emphasis placed on cool roofs (Akbari et al. 2001).

5.2.2 Increasing ceiling insulation

The installation of ceiling Insulation within a dwelling reduces transfer of heat between the indoor and outdoor environment, thus helping maintain stable indoor temperatures. This is important for human health and well-being, as both fluctuations and extremes in temperature can have serious impacts on human health and well-being, as outlined in Section 3 of this report. The Building Code of Australia (BCA) sets minimum standards for the level of insulation in new housing construction, measured using R-values, which varies according to the climate zone in which the dwelling is to be built (see Figure 5). Materials with a higher R-value provide a higher insulation (McGee and Mosher 2008).

AccuRate was used to examine the impact of different levels of ceiling insulation on the thermal performance and indoor environment of each housing type. Holding all other variables constant, Figure 14 demonstrates the results for House Type C1 showing a significant benefit in moving from a situation of no ceiling insulation to R1.5. Of note is the diminishing return (i.e. benefit) as the R-value of the insulation is further increased.

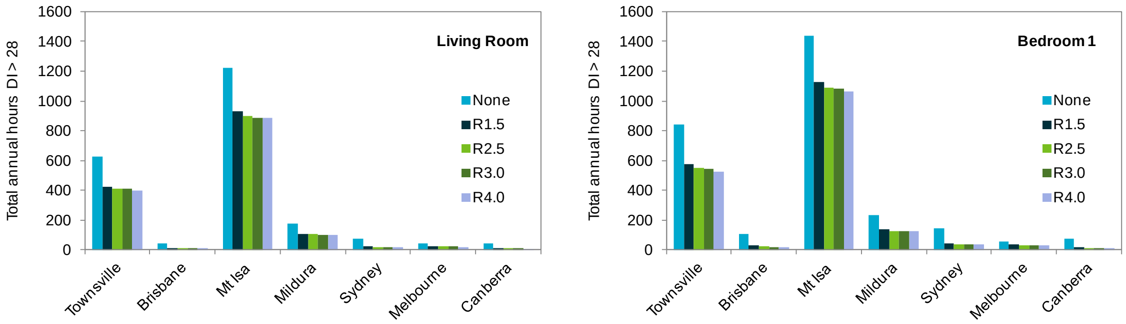


Figure 14: Impact of level of ceiling insulation (R-values) on the thermal performance of the Living Room and Bedroom 1 zones in House Type C1 for the reference climate year.

Ceiling insulation proved an important strategy in all reference cities for reducing the total annual hours of severe heat-related health risk to occupants (DI > 28). Looking at the results for the Living Room presented in Figure 14, moving from having no ceiling insulation to R1.5 in House Type C1 reduced the heat-related health risk to occupants by up to 78% in Canberra (46 to 10 hours) and a minimum of 24% in Mt Isa (1221 to 929 hours). Slight improvements were also gained by increasing R-values further.

5.2.3 Reducing air leaks and infiltration

Air infiltration refers to the amount of air that leaks in and out of a dwelling. It is caused by cracks and openings in the dwelling, such as around doors and window frames. It is usually addressed through weatherproofing techniques, which often involve caulking to fill gaps and the use of weatherstrips to reduce drafts. Weatherproofing is a simple and cost-effective way to reduce heating and cooling costs and improve thermal comfort.

An assessment of the effectiveness of weatherproofing strategies in reducing the total annual hours of severe heat-related health risk to occupants (DI > 28) was done using *AccuRate*. Holding all other variables constant for House Type C1, modelling of the impact of low, medium and high weatherproofing was undertaken. The results are presented in Figure 15. For all reference cities, weatherproofing had little influence on reducing the level of severe thermal risk to occupants. This is not to say that it is not important, but rather when it comes to extreme temperatures and heatwave conditions there are many other engineering adaptation strategies that will be far more effective.

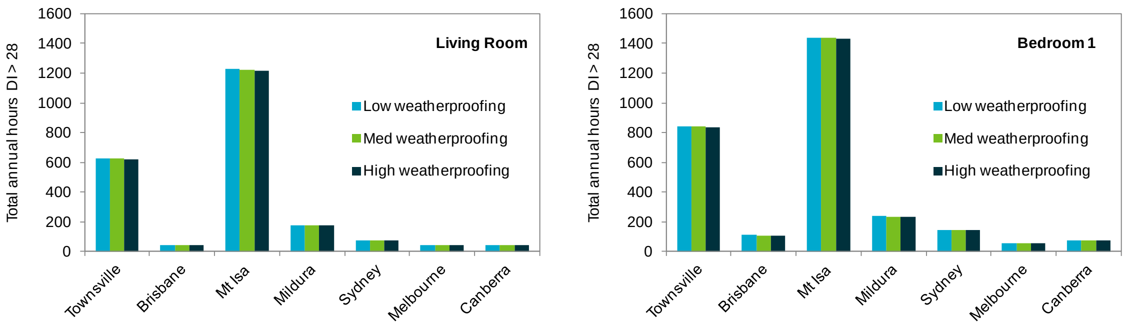


Figure 15: Impact of weatherproofing to reduce air infiltration on thermal performance of the Living Room and Bedroom 1 zones in House Type C1 for the reference climate year.

From a human health and well-being perspective, either uncontrolled or excessive air infiltration has been linked to increased risk of damp and mould which can impact the

health and comfort of occupants (Howden-Chapman and Chapman 2012). An added benefit of weatherproofing is it also helps residents reduce heating and cooling costs.

5.2.4 Building orientation and solar aspect

The design and solar orientation of a building (whether it predominantly faces north, east, south or west) will determine solar access, and consequently influence heating and cooling requirements and the need for artificial light. The influence of orientation on thermal performance has again been investigated using the DI value in *AccuRate*.

The results are presented in Figure 16. House Type A1 was used in this example as it is based on a concrete slab and brick veneer construction, and thus has higher thermal mass than other housing types. Holding all variables constant, the house was rotated and thermal comfort tested for north, east, south, and west orientations, respectively.

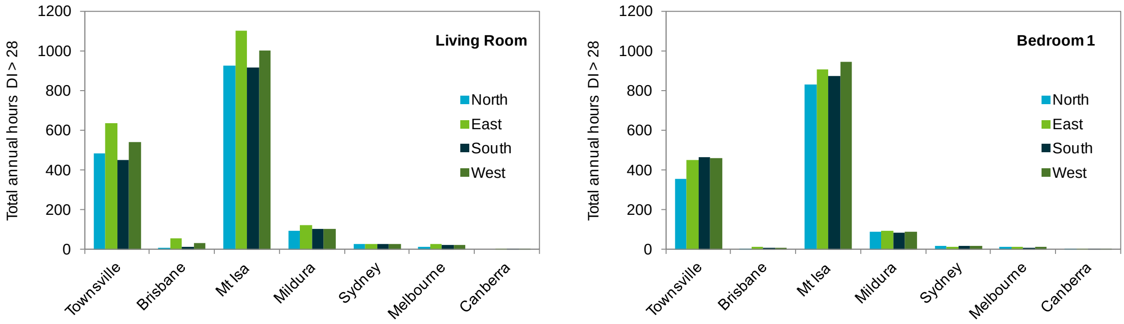


Figure 16: Impact of building orientation and solar aspect on the thermal performance of the Living Room and Bedroom 1 zones in House Type A1 for the reference climate year.

The results show that orientation is important, with north-south orientations generally performing better than east-west orientations. It should be noted, however, that the *AccuRate* analysis is performed on each zone in the dwelling. Consequently, it must be remembered that the results will not only be influenced by the orientation of the dwelling, but also the location within the dwelling of the zone that is being assessed. This is why in Figure 16 the results for the Living Room are different to Bedroom 1.

Nonetheless, looking closely at Figure 16 we can see changing the orientation from east to north, can significantly reduce the level of severe heat-related health risk to occupants (DI > 28). For example for the Living Room in Brisbane, this change results in an 83% reduction in the total annual hours of DI > 28, with a further 10% difference between thermal exposure in the Living Room and Bedroom 1 given the same north orientation. Orientation is important in hot locations as well (Mt Isa, Townsville, and Mildura), with a 20% reduction possible, but clearly other adaptation is also required.

5.2.5 Windows, shading and other options

Other engineering adaptation options have also been explored, including the impact of window shading, installation of double glazing, and further insulation options including floor and wall insulation. As before, *AccuRate* was used to test these options, using House Type C1 and keeping other variables constant. The results are shown in Figure 17, which includes the results for ceiling insulation previously presented in Figure 14, to enable comparison with the various engineering adaptation options described above.

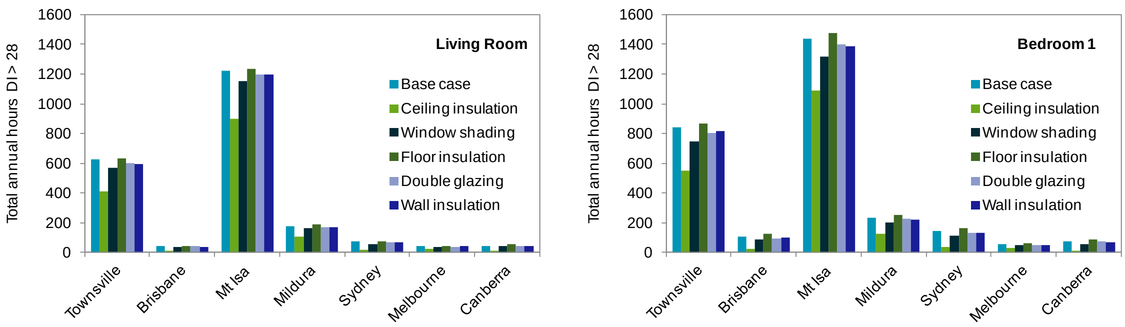


Figure 17: Impact of various engineering adaptation options on the thermal performance of the Living Room and Bedroom 1 zones in House Type C1 for reference climate year.

What Figure 17 shows is ceiling insulation has the most impact on improving thermal comfort, with window shading proving the next best, followed by double glazing, then wall insulation and floor insulation. Comparing each option in isolation enables the specific contribution of each, and potential role in climate adaptation, to be identified. Not included in Figure 17, is the influence of roof colour and solar orientation, which as shown previously, has a major impact on reducing thermal discomfort and health risk.

5.3 *Climate change impacts on thermal discomfort*

Based on the sensitivity analysis outlined in the previous section, the assessment of changes in thermal discomfort with climate change have been undertaken using four scenarios for each housing type. These include a ‘worst case’, a ‘base case’, a ‘cheap retrofit’, and ‘expensive retrofit’. The scenarios were developed using combinations of adaptation options and various assumptions, which are described further in Table 8.

Table 8: Assumptions of four adaptation scenarios used to test the thermal performance (heat-related health risk) of each housing type and the impact of likely climate change.

Scenario	Description
Worst Case	Assumes the housing type has an east orientation, dark coloured roof, and no ceiling insulation. This scenario aims to represent the worst possible performance to be expected from each housing type. For the high rise flats (G1 and H1) the worst case scenario assumes the flat is located on the top floor of the building with poor orientation.
Base Case	Assumes the housing type has a north orientation and light coloured roof, but no ceiling insulation. It provides a baseline performance against which the following retrofit scenarios are then assessed. For the high rise flats (G1 and H1) the base case scenario assumes the flat is in a mid floor location in the building, with better orientation.
Cheap Retrofit	Builds on previous base case scenario with the addition of R2.5 ceiling insulation, high weatherproofing to reduce air infiltration, and shading of windows with 60% shade cloth. It aims to represent the ‘biggest bang for buck’ from investment in building level adaptation.
Expensive Retrofit	Builds on previous cheap retrofit scenario, with inclusion of double glazing and improved window frames, as well carpet and vinyl floor coverings, if required, providing R1 insulation. It aims to represent the maximum benefit that can be gained by building level adaptation.

As we are using the 10 housing types that were identified in Section 2.4 to represent the 142,410 housing assets in our social housing portfolio, the purpose of the scenarios was to capture the range of thermal performance one might expect within each of the housing types, given differences in building orientation, roof colour, level of insulation, window shading, and so on, that are present in assets in the social housing portfolio. The scenarios thus enable exploration of the minimum and maximum performance that might be achieved, and the efficacy of different climate adaptation options, defined by cheap and expensive retrofits. The latter assumes cost is no barrier to asset upgrade.

For the purpose of testing building performance and the efficacy of climate adaptation options, *AccuRate* was used to estimate the total annual hours of DI > 28, indicating severe heat-related health risk to occupants. This was undertaken for each housing type (n=10), under each adaptation scenario (n=4), for each of the seven reference cities (n=7), using a reference climate and three future climates (n=4), resulting in a total of 1120 model runs within *AccuRate*. The results are summarised in Figure 18.

Comparing the differences across BCA climate zones, the cities of Mt Isa, Townsville, and Mildura have shown for all house types under all adaptation scenarios, that there are periods of severe heat-related health risk (DI > 28). This is particularly true for the 'worst case' scenario of each housing type. Cheap and expensive retrofits reduce the level of severe heat-related health risk, but cannot totally mitigate the impact in these locations with either high humid (Townsville) or hot summers (Mt Isa and Mildura).

For the other reference cities of Brisbane (warm humid summer) as well as Sydney, Melbourne and Canberra (more temperate climates), there were large differences between 'worst case' and 'base case' for all house types. It appears that severe heat-related health risk (DI > 28) is able to be mitigated in most situations in these locations through the cheap or expensive retrofit option. This holds true particularly in the short term (2030) and to a lesser extent the medium term (2050). What these results show is that in these locations building adaptation can go a long way towards improving the thermal performance of most low income housing types. It also suggests, particularly with the 'cheap retrofit' that building adaptation can buy time. In many instances, this 'cheap retrofit' would take the housing asset through to the end of asset life (assuming that this might be 50 years of age) and largely mitigate the health risk to occupants.

With regard to differences between the housing types, there are several key points. Firstly, when looking at the 'worst case' scenario, FI and to a lesser extent H1, which represent two bedroom flats in low rise and high rise buildings respectively, they don't perform as well as the other housing types. This is because 'worst case' assumes a top floor location with dark coloured roof and no ceiling insulation. It also reflects the importance of orientation, as the flats represented by F1 and H1 contain significant window area with little shading (Section 2.4). Performance improves significantly with the 'base case' which highlights that flats are particular sensitivity to orientation and roof colour. In the case of H1, the 'base case' also sees a shift from top floor to mid floor location in a high rise building, which is more representative of majority of flats.

Overall, Type D1 representing a slab on ground brick veneer construction built to current standard (5 Star), is consistently the best performing housing type across the climate zones. In Canberra and Melbourne, the severe heat-related health risk (DI > 28) is completely mitigated by the 'cheap retrofit' out to the year 2070, which would be considered the end of life for most existing House Type D1 assets. In Sydney, Mildura and Brisbane, severe heat-related health risk (DI > 28) can be substantially mitigated by cheap retrofits out to 2050, but then increases in 2070, particularly in Brisbane. In Townsville and Mt Isa, the House Type DI performs better than other house types, but climate change impacts cannot be mitigated. In these locations, air-conditioning is required both now and will be increasingly required into the future to reduce the level of severe heat-related health risk to the occupants living in these hot and humid locations.

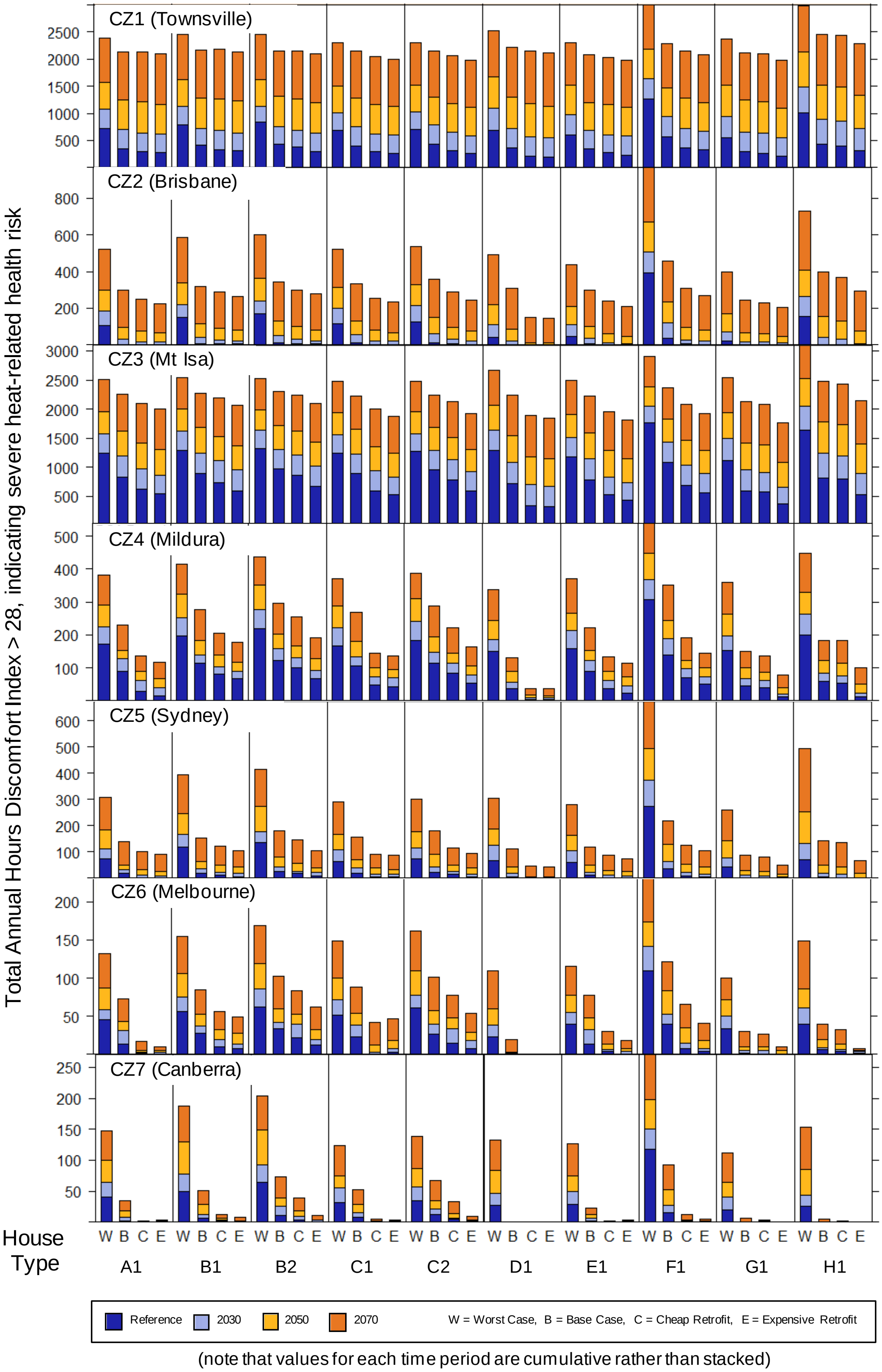


Figure 18: Summary of total annual hours discomfort index exceeds the threshold of 28 for each housing type, within each reference city, for the reference and future climates.

Slab on ground, brick veneer construction (A1 and D1) consistently perform well, but this difference compared to other housing types is more pronounced in cooler locations such as Melbourne and Canberra. In Sydney and Brisbane, there is somewhat less of a difference, with similar performance from raised construction (B1, B2, C1, and C2). This is particularly true for Brisbane, where C1 and C2 are built for natural ventilation.

While there are differences between the house types, across climate zones, what appears to be more important is the quality of the house type, rather than the type itself. In other words, there is often greater variation in the performance between 'worst case' and 'expensive retrofit' within a house type, than there is between the different house types. This is not always true, but does suggest the significant role for climate adaptation engineering. It highlights the need to address the 'worst case' scenarios in each house type first, as the best way to improve performance. Also of note, was that in many climate zones, low rise and high rise flats perform just as well as many of the houses, with the notable exception of the 'worst case' scenario. This is encouraging given focus on urban consolidation and higher density living in many Australian cities.

5.4 *Thermal discomfort and January 2009 heatwave*

While the focus so far has been to understand the thermal performance of the housing types under current and future climates, as represented by TMY weather files (see Section 2.3), there was also interest in testing how each house type performs during an extreme heatwave event. For this purpose, one year of weather data covering the January 2009 heatwave in Melbourne was obtained from the Australian Bureau of Meteorology and prepared as a TMY weather file for use by *AccuRate*. This heatwave was of unprecedented intensity and duration, comprising three consecutive days of temperatures above 43°C. It resulted in an estimated 374 excess deaths (Victorian Government 2009), significant power outages for 500,000 residents, and the buckling of railway lines and disruption to train services (Queensland University of Technology 2010). As such, it represents one of the most severe recent heatwaves in Australia.

For each housing type and for each of the adaptation scenarios (i.e. worst case, base case, cheap retrofit, and expensive retrofit), the values for the Discomfort Index (DI) were calculated using *AccuRate* on an hourly basis. The results for the five day period covering 27 to 31 January 2009 (120 hours) are shown in Figure 19. Remembering that severe heat-related health risk occurs when the DI value exceeds 28, it can be seen that this threshold was breached in every house type that was simulated. On average across the house types the 'worst case' scenario resulted in severe heat-related health risk for 30% of the duration of the five day heatwave. This could be reduced to 17% and 13% with the cheap retrofit and expensive retrofit, respectively.

Also of note in Figure 19, is that indoor DI values for the 'worst case' for each house type commonly exceed the outdoor DI Values. What this means is poor performing house types can amplify the heat-related health risk (DI > 28), with indoor DI values often higher than that which would be experienced outside. There are also temporal lags that can be observed in Figure 19. These typically occur after the peak in outdoor DI is observed (often in the late evening), and is particularly prevalent in house types characterised by high thermal mass, which are slower to shed indoor DI values than the outdoor environment. Conversely, they are also slower to heat up in the first place.

This has important implications for behavioural adaptation, whereby House Types A1 and D1 and the low rise and high rise flats (E1, F1, G1 and H1) will be protective for heat-related health risk early in a heatwave event. However, during prolonged events they will begin to retain heat due to their thermal mass, and without air-conditioning, there will be periods where occupants may be better to seek shade and shelter outside or retreat to 'cool places' with air-conditioning, while their home sheds any stored heat.

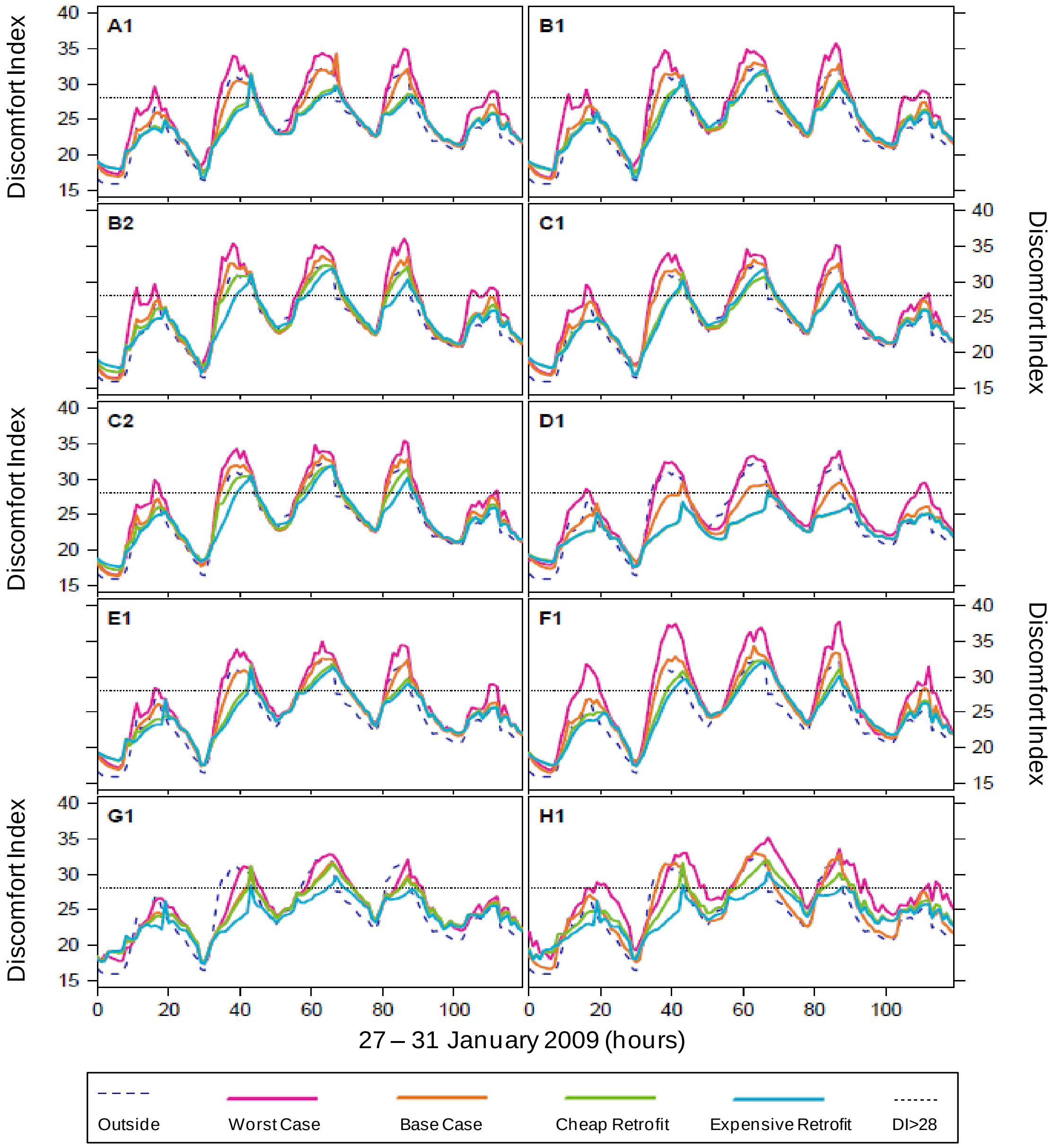


Figure 19: Outdoor and indoor Discomfort Index (DI) values for each house type, showing simulated performance during the 2009 heatwave event in Melbourne.

Some house types do perform better than others, however, with House Type D1 the best at flattening out the peaks. In fact with the 'cheap retrofit', this house type only exceeded the threshold for severe heat-related health risk for 1 out of the 120 hour duration of the heatwave. This is shown in Figure 20, where the next best performing house types were the 'expensive retrofits' for the high rise flats (G1 and H1) with 6 hours over the threshold, and older slab-on-ground brick veneer construction (A1), which had 10 hours of DI in excess of 28. So the take home messages are that adaptation of buildings can help to reduce the level of severe heat-related health risk (DI > 28) during heatwaves. The current standard slab-on-ground brick veneer house clearly performs the best, but significant improvements can be made to the older slab-on-ground homes and to high rise apartments (G1 and H1) to reduce heat exposure. For example, on average across all ten house types, a 'cheap retrofit' could reduce severe heat-related health risk (DI > 28) as measured in the 'base case', by 25%.

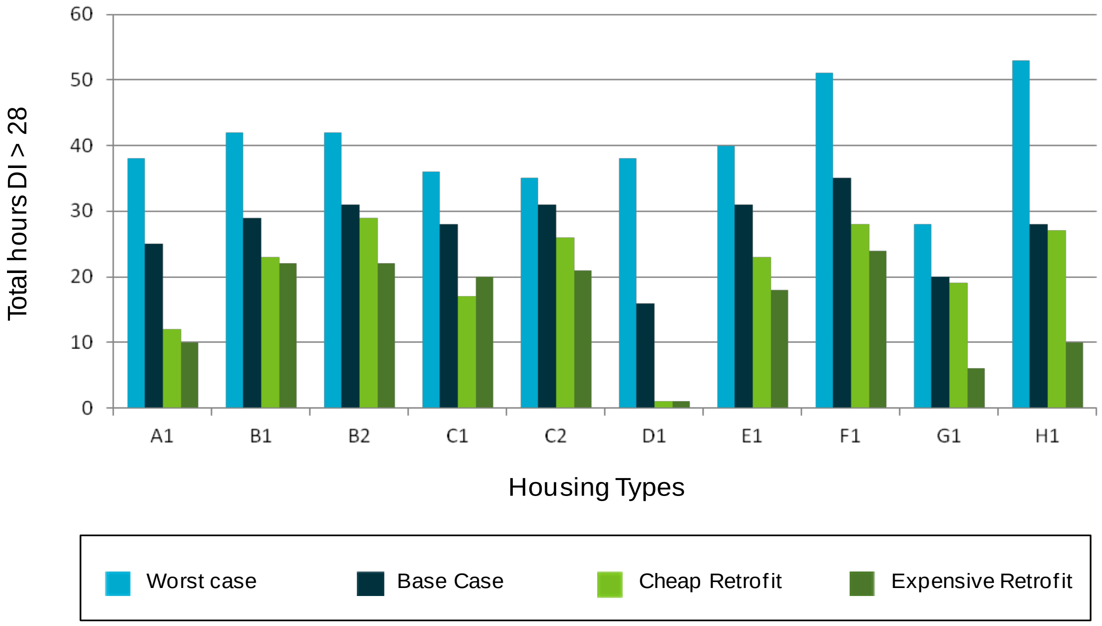


Figure 20: Outdoor and indoor Discomfort Index (DI) values for each house type, showing simulated performance during the 2009 heatwave event in Melbourne.

5.5 *Changes in cooling/heating energy requirement*

The primary focus in this project has been to assess the thermal performance and indoor environment of low income housing types. The residential house energy rating software *AccuRate* was used for this purpose. As such, it has also been possible to calculate the annual total heating and cooling energy requirement (MJ/m^2). As this was not the main focus of the project, it has not been done for every house type, but rather one house (A1) and one flat (E1). The results are shown in Table 9, where they have been generated for each adaptation scenario for each of the seven reference cities.

It should be noted here, *AccuRate* calculates the annual heating and cooling energy requirements to maintain comfortable indoor environment with assumptions about the quality of construction, properties of materials, and occupant behaviour set according to the Protocol for House Energy Rating Software (ABCB 2006). Actual consumption of energy for heating and cooling will depend on the quality and efficiency of appliances used. Furthermore, factors such as the quality of building construction and operational behaviour of occupants can vary widely and may differ from the assumptions used in *AccuRate*. So the results presented in Table 9 should be regarded as estimates only.

Comparing the percentage change in heating and cooling energy requirement between the reference cities in 1990 and 2070, the overall trend is for a reduction in the energy required for heating and an increase in energy required for cooling. The magnitude of these changes varies from city to city and by the type of building adaptation scenario that is considered. For example, focusing on House Type A1 with a 'cheap retrofit' for the locations of Melbourne and Brisbane, it is estimated that by 2070 there will be a reduction in the energy required for heating (42% and 75%, respectively), whereas the energy required for cooling will increase significantly (101% and 333%, respectively).

Of note in Table 9, is that the percentage change in energy requirement by 2070 is often smaller in the 'worst case' scenario than the 'expensive retrofit'. This must be taken into context. For example, the cooling energy required by House Type A1 in Brisbane increases by 359% by 2070 in the 'expensive retrofit', yet in absolute terms the energy that is required (MJ/m2) is almost three times less than the 'worst case'.

Table 9: Annual heating and cooling energy requirements for House Types A1 and E1, for each adaptation scenario, in each city for 1990 and future climates 2030, 2050, 2070.

City	Scenario	Energy	1990		2030		2050		2070		% Δ by 2070	
		(MJ/m2)	A1	E1	A1	E1	A1	E1	A1	E1	A1	E1
Melbourne	Worst Case	Heating	733	784	643	692	555	603	459	503	-37%	-36%
		Cooling	220	171	262	212	317	250	385	311	75%	82%
	Base Case	Heating	866	885	763	784	660	684	547	573	-37%	-35%
		Cooling	110	104	135	126	164	152	208	192	88%	85%
	Cheap Retrofit	Heating	424	443	365	388	307	335	244	275	-42%	-38%
		Cooling	52	51	65	64	84	79	106	101	103%	97%
	Expensive Retrofit	Heating	405	412	350	362	296	313	237	259	-41%	-37%
		Cooling	39	42	48	54	63	67	83	84	115%	103%
Sydney	Worst Case	Heating	234	249	181	192	135	143	90	95	-62%	-62%
		Cooling	389	213	460	273	557	354	693	477	78%	123%
	Base Case	Heating	288	301	219	231	160	171	103	112	-64%	-63%
		Cooling	103	77	143	111	201	166	291	249	182%	222%
	Cheap Retrofit	Heating	99	131	69	96	45	66	25	38	-75%	-71%
		Cooling	44	39	65	59	99	88	156	144	254%	271%
	Expensive Retrofit	Heating	100	126	69	93	45	65	24	38	-76%	-70%
		Cooling	33	33	49	50	78	80	127	127	289%	289%
Brisbane	Worst Case	Heating	174	175	135	135	100	101	67	67	-61%	-62%
		Cooling	406	170	502	243	617	344	791	512	95%	202%
	Base Case	Heating	194	201	149	153	109	112	71	72	-63%	-64%
		Cooling	116	76	196	126	290	203	422	317	263%	319%
	Cheap Retrofit	Heating	62	83	43	59	28	39	16	22	-75%	-74%
		Cooling	59	44	98	74	162	127	255	208	333%	372%
	Expensive Retrofit	Heating	61	82	43	59	28	39	15	22	-76%	-73%
		Cooling	46	37	78	62	128	111	212	184	359%	393%
Townsville	Worst Case	Heating	17	17	10	10	5	5	2	2	-87%	-86%
		Cooling	954	517	1144	696	1360	904	1675	1232	76%	139%
	Base Case	Heating	18	20	11	12	6	7	2	3	-88%	-87%
		Cooling	401	317	567	461	762	638	1051	904	162%	185%
	Cheap Retrofit	Heating	2	4	1	2	0	1	0	0	-95%	-95%
		Cooling	237	193	348	292	476	409	663	578	179%	200%
	Expensive Retrofit	Heating	2	5	1	2	0	1	0	0	-95%	-96%
		Cooling	194	172	290	262	406	365	569	522	193%	203%
Canberra	Worst Case	Heating	977	1031	875	927	775	824	662	706	-32%	-32%
		Cooling	329	245	385	290	448	344	537	417	63%	70%
	Base Case	Heating	1191	1202	1069	1082	949	963	810	826	-32%	-31%
		Cooling	121	83	150	112	188	142	245	189	102%	128%
	Cheap Retrofit	Heating	604	629	533	563	463	498	385	423	-36%	-33%
		Cooling	42	30	56	43	75	60	105	83	151%	176%
	Expensive Retrofit	Heating	577	589	511	527	446	467	372	398	-36%	-32%
		Cooling	26	21	38	32	54	46	79	67	200%	215%
Mildura	Worst Case	Heating	524	585	462	516	402	447	335	372	-36%	-36%
		Cooling	519	393	589	443	671	505	780	593	50%	51%
	Base Case	Heating	624	665	546	585	470	507	387	420	-38%	-37%
		Cooling	262	239	304	275	354	321	425	390	62%	63%
	Cheap Retrofit	Heating	285	330	242	288	202	246	158	199	-44%	-40%
		Cooling	118	112	142	132	171	155	213	196	80%	75%
	Expensive Retrofit	Heating	280	315	239	275	200	236	157	193	-44%	-39%
		Cooling	90	89	110	105	133	129	167	165	86%	86%
Mt Isa	Worst Case	Heating	74	80	55	60	38	42	23	25	-69%	-68%
		Cooling	1447	1129	1607	1275	1783	1442	2016	1662	39%	47%
	Base Case	Heating	81	94	59	70	41	49	23	29	-71%	-70%
		Cooling	806	691	947	824	1103	978	1309	1180	62%	71%
	Cheap Retrofit	Heating	22	37	14	25	8	16	4	8	-81%	-79%
		Cooling	400	334	487	410	587	502	718	632	80%	89%
	Expensive Retrofit	Heating	21	37	13	26	8	17	4	8	-82%	-78%
		Cooling	313	281	390	350	480	431	599	549	91%	96%

Figure 21 illustrates the daily heating and cooling energy requirements for House Type A1 in Melbourne and Brisbane. The benefits of the 'cheap retrofit' for reducing heating and cooling energy consumption over a 12 month period can be inferred. Of interest, are the differences between Melbourne and Brisbane. This is due to the established relationship between temperature and energy requirement (Howden and Crimp 2001).

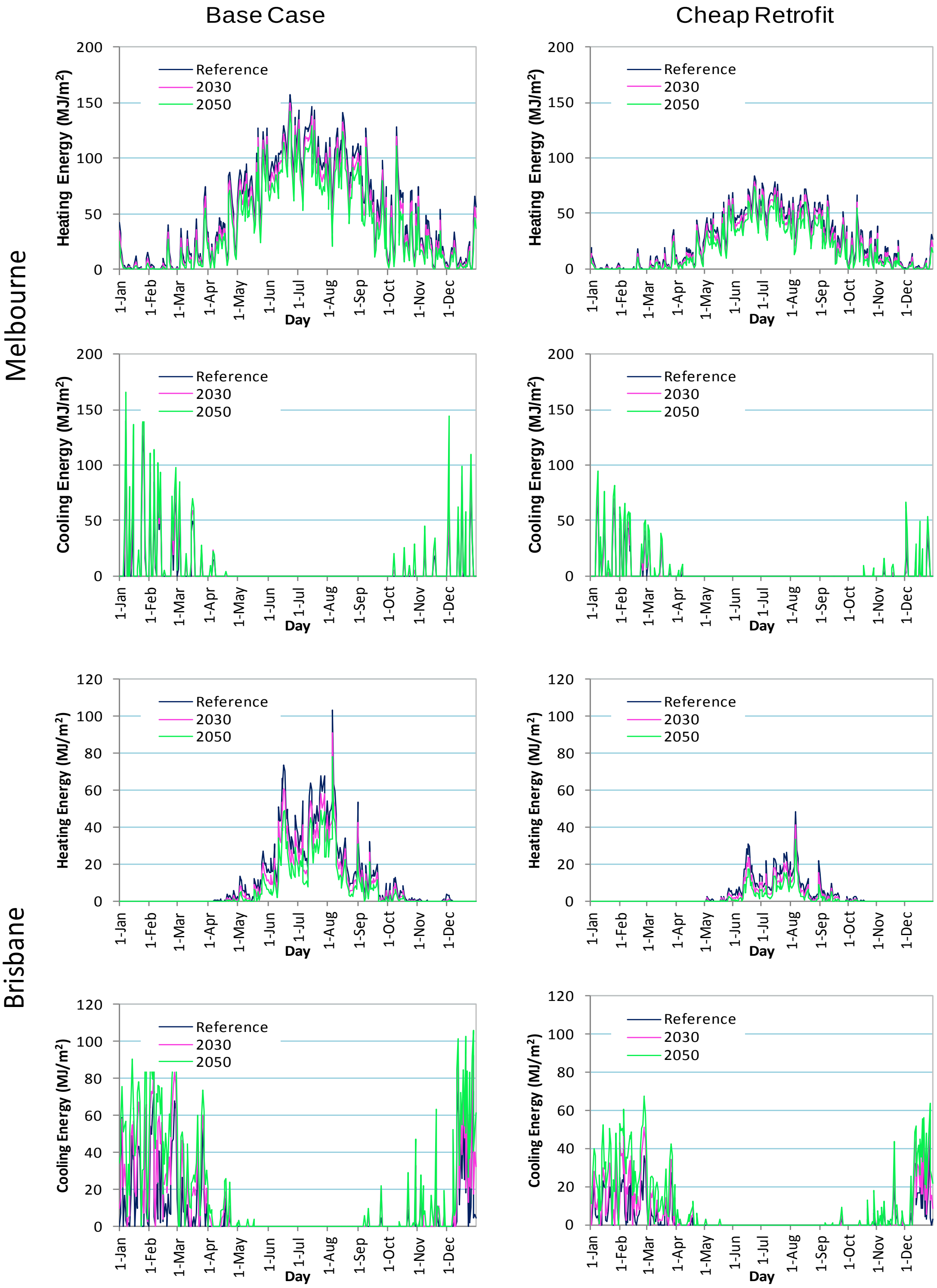


Figure 21: Daily H/C energy requirement for House Type A1 in Melbourne and Brisbane, comparing Base Case and Cheap Retrofit for the reference climate, 2030, and also 2050.

6. MATERIAL DURABILITY AND SERVICE LIFE

This section presents the methods used to perform a quantitative assessment of the impacts of climate change on the durability of materials commonly used in housing construction. The types of materials and degradation processes considered, included the atmospheric corrosion of metal (both steel and zinc) and the fungal decay of timber used in both above-ground and in-ground applications. The results were then used to estimate the change in service life of housing components made from these materials.

While there has been recent work on the impacts of climate change on deterioration of concrete (Wang et al. 2011, Wang et al. 2010b), it was not deemed appropriate to include concrete in this study given the complexities of the deterioration process. While increases in atmospheric CO_2 will increase the carbonisation of concrete, the deterioration process is also governed by structural damage resulting from movement. This leads to the formation of cracks which contribute to deterioration. Consequently, the application of this work on concrete deterioration to specific housing components was deemed premature without more detailed understanding of the current state and condition of concrete components used in housing, which requires a separate study.

It should be noted that the purpose of the modelling that will now be described was not to inform engineering applications, but rather to provide an estimate of the impact of climate change on the cost profiles for housing maintenance, for each of the housing types. The sources of uncertainty in this modelling are acknowledged as appropriate. Recent work undertaken by Nguyen et al. (2013) suggests there is considerably more uncertainty associated with modelling the material degradation process, than in the climate change models used to develop projections of future degradation rates. We have used accepted degradation models to undertake this work and are confident in the estimates generated of the impacts of climate change on housing maintenance.

6.1 *Atmospheric corrosion of metal*

Research into atmospheric corrosion of metal is an active field. Various studies have been conducted to determine the influence of weather and other environmental factors on the rate of corrosion over time (Benarie and Lipfert 1986, Feliu and Morcillo 1993b, Feliu and Morcillo 1993a, de la Fuente et al. 2007, de la Fuente et al. 2011). Based on this research, the long term atmospheric corrosion of metal is adequately described by,

$$c_{atm} = c_0 t^n \quad (7)$$

where c_{atm} is the atmospheric corrosion depth (in μm) after t years in service; while c_0 (μm/yr) is the estimated corrosion rate during the first year of service; and n is a power factor less than 1.0 based on knowledge of how corrosion depth progresses with time.

6.1.1 Methods to estimate corrosion rates in Australia

To implement this atmospheric corrosion model, Nguyen et al. (2011) have developed a model to estimate the corrosion rate c_0 for Australian weather conditions. It has been developed for steel surfaces and the zinc coating commonly used to protect steel from corrosion. The model assumes the process of corrosion will progress successively, i.e. acting first to corrode the zinc coating and then the steel substrate. Based on the work of Nguyen et al. (2011), the atmospheric corrosion rate that might be expected during the first year of service for metal components in Australia, can be estimated as follows,

$$c_{0,z} = 0.025 t_{wet}^{0.6} S_{air}^{0.5} + 0.006 t_{wet}^{0.2} P_{air} \quad (8)$$

$$c_{0,s} = 0.5t_{wet}^{0.8}S_{air}^{0.5} + 0.1t_{wet}^{0.5}P_{air} \quad (9)$$

where $c_{0,z}$ and $c_{0,s}$ are corrosion rates (μm/yr) for zinc and steel, respectively; t_{wet} is the time of surface wetness per year; S_{air} is airborne salinity in mg/m^2/day; while P_{air} is the level of airborne pollution expressed as SO_x in μg/m3. Several input parameters are required to estimate the terms t_{wet}, S_{air}, and P_{air} and are summarised briefly as,

- Factors related to coastal shelter and configuration;
- Climate variables required to calculate time of wetness;
- Coastal exposure and wave energy generating airborne salt;
- Local shelter and protection of the metal surface from rain; and
- Distance to nearest industry and source of atmospheric pollution.

For brevity in this report, readers are referred to Nguyen et al. (2011) for further details on these input parameters and how they are used to estimate terms t_{wet}, S_{air}, and P_{air}.

The models developed by Nguyen et al. (2011) for estimating corrosions rates have been calibrated using available scientific information, including the Australian Standard AS 4312 (Standards Australia 2008) and through field testing in Australia (King et al. 1982, King et al. 1999, King and Carberry 1992) and South East Asia (Cole 2000).

6.1.2 Extension of methods to incorporate climate change

This project extends the work of Nguyen et al. (2011) and provides one of the first attempts to quantify the impacts of climate change on atmospheric corrosion. It has involved critical review of the potential impact of climate change on the key weather and environmental inputs specified in the models described by Equation (8) and (9).

Several areas of potential impact were identified. Among these were the effect of increasing CO_2 concentrations on zinc corrosion, with lab experiments by Chung et al. (2000) indicating that increases in relative humidity and CO_2 can act to increase the corrosion resistance of zinc and therefore reduce the corrosion rate. Further research and validation under field conditions are required, however, to confirm this effect and its relative importance. Similarly, there is a well-known beneficial effect of rain in washing out the atmospheric corrosive pollutants that have settled on metal surfaces, and thus reducing the corrosion rate (Corrosion Doctor 2011). This effect has been factored into the modelling by Nguyen et al. (2011), where they assign a factor of 2 for the airborne salinity depositing on metal surfaces sheltered from rain compared to those surfaces exposed to rain. Yet to establish how this ‘washing-out’ process might change with climate change is no simple task, as the projected increases in rainfall intensity under climate change are likely to be cancelled out by reductions in the frequency of rainfall.

In addition to the above, the review revealed three other potential impacts that were deemed important and could more readily be incorporated into the modelling process. These included the effect of changes in wind speed on airborne salinity; the effect of changes in temperature on corrosion rates; and effect of changes in relative humidity on time of wetness. The methods used to estimate these impacts are now described.

Effects of changes in wind speed on airborne salinity

Airborne salinity in the form of aerosols is generated primarily from the action of surf and ocean waves, which are governed by wind and fetch characteristics for a specific location. A relationship of volumetric airborne salinity $S_{air,vol}$ (μg/m3) with mean wind speed U (m/s) was given by McKay et al. (1994) based on measurements as follows

$$ln(S_{air,vol}) = 0.23\,U + 3.05 \tag{10}$$

Cole et al. (1999, 2004) subsequently used this relationship to develop a geographic information system (GIS) to predict airborne salinity based on wind and fetch data for various locations across Australia. This was a catalyst for development of CSIRO's Corrosion Mapping System (CSIRO 2007, CSIRO 2002). Nguyen et al. (2011) used this system to classify the Australian coastline into five broad coastal hazard zones and identify factors for wave-generated airborne salt to be included in the modelling.

The relationship between $S_{air,vol}$, the volumetric airborne salinity, and S_{air}, the airborne salinity term based on measurement of deposits on a salt candle, can be expressed as,

$$S_{air} = n\,S_{air,vol}\,U\,A_s \tag{11}$$

where n is the deposition efficiency factor*;* A_s is the area of the salt candle surface the salinity aerosol impacts on. Using equations (10) and (11) the climate change factor is,

$$c_{Sair} = \frac{S_{air,projected}}{S_{air\ 1990}} = \frac{\sum_{m=1\ldots12} U_{projected,m}\ exp\ (0.23\ U_{projected,m})}{\sum_{m=1\ldots12} U_{1990,m}\ exp\ (0.23\ U_{1990,m})} \tag{12}$$

where $U_{1990,m}$ represents the mean wind speed of month m of the reference year 1990; $U_{projected,m}$ is the projected mean wind speed of month m of the projected year under climate change; $S_{air,projected}$ is the projected airborne salinity due to climate change; and $S_{air\ 1990}$ is the reference airborne salinity at the reference year 1990. The monthly mean for wind speeds was used to incorporate the effect of seasonal changes of wind speed on airborne salinity. This is consistent with Nguyen et al. (2011), but assumes that the relative change in wind speed will be consistent across all the wind directions.

Effects of changes in temperature on corrosion rate

Atmospheric corrosion is an electro-chemical process. In theory the corrosion rate will be dependent on ambient temperature. This dependency follows the Arrhenius law,

$$c_0 = \alpha e^{-\frac{E_a}{RK}} \tag{13}$$

where c_0 is the corrosion rate; α is a frequency factor; K is the absolute (degrees Kelvin); E_a is the activation energy; and R is the Boltzmann gas constant (R = 8.31 $JK^{-1}mol^{-1}$). Atmospheric corrosion is a complex discontinuous electro-chemical process that is subject to highly variable ambient conditions. For example, corrosion only occurs when there is a moisture layer formed on the metal surface. For Australian conditions, Cole and Paterson (2010) demonstrated that metal surfaces go through a daily wetting cycle. At night, as ambient relative humidity increases and temperature decreases, a moisture layer forms and corrosion reactions are facilitated. At sunrise, however, the reverse occurs whereby temperature increases and relative humidity decreases, resulting in evaporation of the moisture layer and corrosion is then halted.

With such a complex wetting and drying regime, effects of temperature on atmospheric corrosion are very hard to predict. Cole and Paterson (2010) suggest that for practical purposes, '*an increase of 2 Kelvin (from 293 Kelvin to 295 Kelvin) will promote a 0.6% change in corrosion rate'*. Fitting this assumption to equation (13), and taking 1990 as the reference year, a climate change factor due to temperature change, is defined as:

$$c_{temp} = \frac{c_{0,T_{projected}}}{c_{0,T_{1990}}} = e^{260\left(\frac{1}{T_{1990}} - \frac{1}{T_{projected}}\right)} \quad (14)$$

where T_{1990} is the absolute yearly average temperature at the reference year 1990, while $T_{projected}$ is the projected absolute yearly average temperature due to climate change; $c_{0,T_{1990}}$ and $c_{0,T_{projected}}$ are corrosion rates at T_{1990} and $T_{projected}$, respectively. While changes in temperature are expected to have only a minor effect on corrosion rates, the temperature effect predicted by Equation (14) is simple to evaluate and was left in the assessment to facilitate better understanding of this climate change impact.

Effects of changes in relative humidity on time of wetness

For most regions of Australia, climate change projections are indicating increases in temperature and decreases in relative humidity, although there are some exceptions. Because the minimum daily temperature for most Australian cities rarely gets below 0°C, changes in relative humidity are the primary determinant of changes in the time of wetness. As this regime of surface wetting and drying can happen on a daily cycle, the weather data required to evaluate the effect of time of wetness needs to be sub-daily.

It was not possible within the timeframes available for this project to estimate change in time of wetness parameter t_{wet} from climate change projection data. Consequently, it was derived using indirect methods which involved analysis of historical weather data for the seven cities explored in this project, each representing a different BCA climate zone. This historical analysis has revealed these parameters can be related as follows,

$$t_{wet} = a \times RH + b \quad (15)$$

Where parameters a and b are given in Table 10. Using Equation (15), a climate change factor for time of surface wetness due to change in humidity is defined as,

$$C_{twet} = \frac{t_{wet,projected}}{t_{wet,1990}} = \frac{a \times RH_{projected} + b}{a \times RH_{1990} + b} \quad (16)$$

where RH_{1990} is the relative humidity at the reference year 1990; $RH_{projected}$ is the projected relative humidity due to climate change; and $t_{wet,1990}$ and $t_{wet,projected}$ are the times of surface wetness for the reference year 1990 and under climate change.

Table 10: Coefficients for linear relationship between t_{wet} and RH for the reference cities.

City	Length of historical records (yrs)	A	B
Townsville	67	0.0256	-1.4967
Brisbane	58	0.0197	-1.0315
Mt Isa	26	0.025	-0.5
Mildura	67	0.0256	-0.85
Sydney	57	0.0205	-1.0924
Melbourne	37	0.0183	-0.9127
Canberra	60	0.0205	-1.0924

Projecting atmospheric corrosion rates with climate change

The projected corrosion rate under climate change $c_{0,projected}$ can be estimated from the base corrosion rate c_0, which can be taken from the reference year 1990 as follows,

$$c_{0,projected} = C_{rate,metal}\, c_0 \quad (17)$$

Where $C_{rate,metal}$ is defined as the climate change factor for the corrosion rate of the metal considered. Using the corrosion rate Equations (8) and (9), the impact of climate change on the corrosion of zinc and steel can be derived using the following methods,

$$C_{rate,zinc} = C_{temp}\, C_{twet}^{0.6}\, C_{Sair}^{0.5} \quad (18)$$

$$C_{rate,steel} = C_{temp}\, C_{twet}^{0.8}\, C_{Sair}^{0.5} \quad (19)$$

The climate change factors presented here indicate increases in the corrosion rates when being greater than 1.0, and decreases in corrosion rate when they are smaller than 1.0. The difference between the factors and 1.0 gives the percentage of the change caused by climate change in comparison with the reference year of 1990.

In Equation (18) and (19), the effects of climate change parameters on corrosion rates are considered separately by three climate change factors. Changes in temperature affect the rate of electro-chemical reaction of the corrosion process, changes in relative humidity affect the time of wetness, and changes in wind speed affect the airborne salinity. This disaggregation is an advantage where the main individual effects can be explored separately and thus can be readily applicable to other corrosion models when needed. However, this is taken with an assumption that interactions between these parameters in the corrosion process are negligible. This assumption can be justified by the fact that the changes in these parameters are small. Temperature changes are less than 6ºC, relative humidity changes are less than 10%, and wind speed changes are less than 2 m/s, which are within the range of weather variability that the corrosion model developed by Nguyen et al. (2011) was designed for and is thus acceptable.

6.1.3 Impacts of climate change on atmospheric corrosion

Using equations (17) to (19), a quantitative assessment of climate change impacts on the atmospheric corrosion rate has been undertaken for the reference cities used to represent each of the BCA climate zones in the project. The results are summarised in Table 11. The values presented are the minimum, maximum, and ensemble mean, from the nine GCMs used in the analysis. Also included are results from the MIROC-M model which was considered by Perkins et al. (2007) to be the most 'skilful' model on average at representing observed climate across Australia. All results are presented as percentage change, which is the percentage increase (when positive) or decrease (when negative) of the corrosion rate compared to that of the reference 1990 climate.

The results suggest that those cities in temperate climates (i.e. Melbourne, Sydney, and Canberra) will have decreasing corrosion rates for both steel and zinc in the future. On average by 2100, corrosion of steel and zinc is estimated to reduce respectively by 14% and 9% in Melbourne, 7% and 5% in Sydney, and 14% and 10% in Canberra. This is due largely to the climate projections used in this work which predict reductions in average RH and to a lesser extent wind speed, which both influence C_{twet} and C_{Sair}.

Table 11: Percentage changes relative to 1990 climate in corrosion rates for steel and zinc calculated using 9 GCMs and A1FI scenario, for each of the seven reference cities.

City	Factor	Value	2030	2050	2070	2100
Melbourne	$C_{rate,steel}$	Min	-10%	-19%	-31%	-46%
		Max	3%	6%	10%	12%
		Mean	-4%	-7%	-11%	-14%
		MIROC	-2%	-4%	-6%	-8%
	$C_{rate,zinc}$	Min	-7%	-15%	-24%	-36%
		Max	5%	10%	15%	22%
		Mean	-3%	-5%	-7%	-9%
		MIROC	-2%	-4%	-6%	-9%
Sydney	$C_{rate,steel}$	Min	-7%	-13%	-22%	-31%
		Max	1%	3%	6%	10%
		Mean	-2%	-4%	-6%	-7%
		MIROC	-1%	-1%	-2%	-3%
	$C_{rate,zinc}$	Min	-5%	-10%	-16%	-24%
		Max	2%	4%	8%	13%
		Mean	-2%	-3%	-4%	-5%
		MIROC	-1%	-2%	-4%	-5%
Brisbane	$C_{rate,steel}$	Min	-2%	-4%	-7%	-10%
		Max	6%	14%	24%	39%
		Mean	2%	4%	8%	14%
		MIROC	4%	8%	14%	20%
	$C_{rate,zinc}$	Min	-1%	-2%	-4%	-5%
		Max	6%	14%	24%	37%
		Mean	2%	4%	8%	14%
		MIROC	3%	6%	11%	16%
Townsville	$C_{rate,steel}$	Min	-3%	-7%	-11%	-16%
		Max	4%	8%	13%	20%
		Mean	1%	2%	4%	6%
		MIROC	4%	8%	13%	20%
	$C_{rate,zinc}$	Min	-2%	-5%	-8%	-12%
		Max	4%	8%	13%	19%
		Mean	1%	3%	4%	7%
		MIROC	3%	7%	11%	17%
Canberra	$C_{rate,steel}$	Min	-8%	-17%	-28%	-42%
		Max	-1%	-1%	-2%	-1%
		Mean	-4%	-7%	-10%	-14%
		MIROC	-1%	-2%	-3%	-5%
	$C_{rate,zinc}$	Min	-6%	-13%	-22%	-33%
		Max	0%	0%	0%	1%
		Mean	-3%	-5%	-8%	-10%
		MIROC	-2%	-3%	-5%	-7%
Mildura	$C_{rate,steel}$	Min	-9%	-18%	-29%	-41%
		Max	-1%	-1%	-2%	-2%
		Mean	-4%	-7%	-11%	-16%
		MIROC	-1%	-2%	-3%	-4%
	$C_{rate,zinc}$	Min	-8%	-15%	-25%	-35%
		Max	0%	1%	2%	4%
		Mean	-3%	-5%	-8%	-11%
		MIROC	-1%	-3%	-4%	-6%
Mt Isa	$C_{rate,steel}$	Min	-12%	-24%	-40%	-60%
		Max	6%	13%	22%	32%
		Mean	-2%	-4%	-7%	-10%
		MIROC	6%	13%	22%	32%
	$C_{rate,zinc}$	Min	-9%	-19%	-32%	-49%
		Max	5%	10%	17%	25%
		Mean	-2%	-3%	-5%	-7%
		MIROC	5%	10%	17%	25%

On the other hand, cities in humid climates (i.e. Brisbane and Townsville) are expected to have increasing corrosion rates under climate change, where average wind speed is projected to increase and appears to be the dominant factor. All nine GCMs provide consistent projections of increasing wind speed, which influences C_{Sair} in both cities.

The highest increases of $C_{rate,steel}$ and $C_{rate,zinc}$ are found in Brisbane, as presented in Table 11. For example, in 2100 under A1FI scenario, the change in $C_{rate,steel}$ is 14% on average, but can be up to 39% when using a specific GCM. The results are similar for $C_{rate,zinc}$ with an average change of 14% and maximum of 37%, in comparison to 1990.

Most of the increase in corrosion rates in Brisbane and Townsville are due to increases in projected wind speed, which lead to higher concentrations of airborne salinity. The reductions in Sydney, Melbourne and other temperate cities are due to projected drier conditions with lower humidity, leading to lower time of wetness on the metal surface.

6.2 *Fungal decay of above-ground timber*

Timber is commonly used in a range of above-ground housing applications including timber frames, decking, fencing, and so on. Depending on the application, the timber component may or may not be exposed to the weather. What follows is a description of the modelling approach used to estimate how the rate of fungal decay of timber might change with climate change, and the results generated through this analysis.

6.2.1 Methods to estimate fungal decay rate and depth

This section summarises the developed prediction model for above-ground timber under attack of decay fungi. The data used for model development and the technical details of the model are described more fully in Wang et al. (2008). It is based on the assumption that progress of decay depth with time t for above-ground timber elements follows an idealised bilinear relationship characterised by a decay lag (years), and a decay rate, r (mm/year). Thus for a given decay lag and decay rate, the decay depth that can be expected after t years of installation, d_t (mm), can be expressed as follows,

$$d_t = \begin{cases} 0, & if\ t \le lag \\ (t - lag)r & if\ t > lag \end{cases} \quad (20)$$

Decay rate r is assumed to be the product of multipliers that take into account the different influences of material, construction, and environmental factors as follows,

$$r = k_{wood} k_{climate} k_p k_t k_w k_n k_g \quad (21)$$

where k_{wood} is a wood parameter; $k_{climate}$ is a climate parameter; $k_p$is a painting parameter; k_t is a thickness parameter; k_w is a width parameter; k_n is a fastener parameter; and k_g is an assembly parameter. The climate parameter is defined by,

$$k_{climate} = 0.03 t_{rain}^{0.5} \quad (22)$$

in which t_{rain} is the time of rain in one year (hrs/year). The wood parameter depends on the durability class of timber (Nguyen et al. 2008b) and the type of wood, as follows,

$$k_{wood} = \begin{cases} 0.50, & for\ Class\ 1 \\ 0.62, & for\ Class\ 2 \\ 1.14, & for\ Class\ 3 \\ 2.20, & for\ Class\ 4 \\ 6.52, & for\ sapwood \end{cases} \quad (23)$$

The methods for deriving the remaining parameters in Equation (23), which include k_p, k_t, k_w, k_n, k_g are not outlined here, but described in detail by Nguyen et al. (2008).

6.2.2 Extension of methods to incorporate climate change

Climate change will affect the rate of above-ground timber decay through changes in yearly average time of rain, t_{rain} (hrs/year). The method developed to determine the impact of climate change on above-ground decay, $C_{rate,AG}$, can thus be described as,

$$C_{rate,AG} = \frac{r_{projected}}{r_{1990}} = \frac{k_{climate,projected}}{k_{climate,1990}} = \frac{t^{0.5}_{rain,projected}}{t^{0.5}_{rain,1990}} \quad (24)$$

where the subscript $_{projected}$ means at a future year under climate change, and the subscript $_{1990}$ means at year 1990 as the reference year. As climate change science only provides trends of changes in key climate parameters, the projection of detailed sub-daily data records of rainfall for estimating the time of rain, t_{rain} (hrs/year), are not available. An approach is therefore proposed herein to estimate the projected time of rain for a specific location in Australia. Using the historical sub-daily (hourly) data of rainfall for each of our reference cities, the time of rainfall every year is determined. A linear correlation was found between the time of rain and yearly average RH for each of the seven cities. Assuming that these relationships hold true for the projected future climates, the projected time of rain, $t_{rain,projected}$ (hrs/year), can be estimated from projected yearly average relative humidity, $RH_{projected}$, using the following equation,

$$t_{rain,projected} = a \times RH_{projected} + b \quad (25)$$

where a and b are linear coefficients presented earlier in Table 10 for our seven cities.

6.2.3 Impacts of climate change on above-ground timber

Using Equations (24) and (25), a quantitative assessment of climate change impacts on the above-ground decay rate is undertaken for the seven reference cities. The climate change factor $C_{rate,AG}$ was estimated for the period 1990 to 2100 using the climate projections from nine GCMs. Table 12 lists the climate change factor $C_{rate,AG}$ at years 2030, 2050, 2070 and 2100 under the A1FI emission scenario. The values presented are the minimum, maximum, ensemble mean, and results from the MIROC-M model. All results are presented as percentage change, which is the percentage increase (when positive) or decrease (when negative), compared to the 1990 climate.

In summary, it was found that on average above-ground timber decay would decrease slightly by about 1% in Brisbane and 3% in Townsville by 2100. In the more temperate cities of Sydney, Canberra and Melbourne, above-ground timber decay is expected to decrease on average by 6%, 14% and 17% respectively, over the same time period. As with corrosion of metals, reductions in above-ground timber decay rates in Sydney, Canberra and Melbourne are due to the projected drier conditions with lower humidity.

Table 12: Percentage changes relative to 1990 climate in above-ground timber decay calculated using 9 GCMs and the A1FI scenario, for each of the seven reference cities.

City	Factor	Value	2030	2050	2070	2100
Melbourne	$C_{rate,AG}$	Min	-8%	-18%	-31%	-51%
		Max	0%	0%	0%	1%
		Mean	-3%	-7%	-12%	-17%
		MIROC	0%	0%	0%	1%
Sydney	$C_{rate,AG}$	Min	-5%	-11%	-19%	-29%
		Max	2%	3%	6%	8%
		Mean	-1%	-3%	-4%	-6%
		MIROC	2%	3%	6%	8%
Brisbane	$C_{rate,AG}$	Min	-3%	-7%	-12%	-18%
		Max	3%	7%	11%	15%
		Mean	0%	0%	-1%	-1%
		MIROC	3%	7%	11%	15%
Townsville	$C_{rate,AG}$	Min	-4%	-8%	-13%	-19%
		Max	2%	3%	6%	8%
		Mean	-1%	-1%	-2%	-3%
		MIROC	2%	4%	6%	8%
Canberra	$C_{rate,AG}$	Min	-8%	-16%	-28%	-46%
		Max	2%	4%	7%	10%
		Mean	-3%	-6%	-9%	-14%
		MIROC	2%	4%	7%	10%
Mildura	$C_{rate,AG}$	Min	-8%	-17%	-31%	-50%
		Max	1%	3%	4%	6%
		Mean	-4%	-8%	-13%	-19%
		MIROC	1%	3%	4%	6%
Mt Isa	$C_{rate,AG}$	Min	-11%	-24%	-44%	-95%
		Max	5%	9%	15%	21%
		Mean	-3%	-5%	-9%	-13%
		MIROC	5%	9%	15%	21%

6.3 *Fungal decay of in-ground timber*

This section summarises the prediction model for timber in-ground under attack of decay fungi. In-ground timber refers to timber that is in contact with soil, such as the buried part of house stumps, posts, timber retaining walls, and so on. The modelling approach relies on the same basic assumption as described for above-ground timber, where the decay depth after t years of installation, d_t (mm), is a function of the decay lag (years) and the decay rate, r (mm/year), as was outlined earlier in Equation (20).

6.3.1 Methods to estimate in-ground fungal decay

Calculating decay rate of in-ground timber is done the same way as for above-ground using Equation (21), where the decay rate r is assumed to be the product of multipliers that take into account the effects of material, construction, and environmental factors. Where the approach then differs is in the methods for estimation of wood parameter k_{wood} and climate parameter $k_{climate}$. The climate parameter should be derived as,

$$k_{climate} = f(R_{mean})^{0.3}\, g(T_{mean})^{0.2} \quad (26)$$

in which,

$$f\left(R_{mean}\right)=\begin{cases}0 & \text{if } R_{mean}\le 250 \text{ mm or } N_{dm}>6,\\ f_0(R_{mean})\left(1-\dfrac{N_{\mathrm{dm}}}{6}\right) & \text{if } R_{mean}>250 \text{ mm and } 0\le N_{dm}\le 6\end{cases} \tag{27}$$

$$g\left(T_{mean}\right)=\begin{cases}0 & \text{if } T_{mean}\le 5^{\circ}\text{C},\\ -1+0.2T_{mean} & \text{if } 5<T_{mean}\le 20^{\circ}\text{C},\\ -25+1.4T_{mean} & \text{if } T_{mean}>20^{\circ}\text{C}.\end{cases} \tag{28}$$

where R_{mean} is the yearly average rainfall (mm); T_{mean} is yearly average temperature (C); and N_{dm} is the average number of dry months, only estimated for some dry areas in Northern Territory. For most Australian cities, $N_{dm} < 6$ and $R_{mean} > 250$ therefore,

$$f_0(R_{mean}) = 10\left[1 - e^{-0.001(R_{mean}-250)}\right] \tag{29}$$

The wood parameter k_{wood} depends on the type of wood, and the durability class of the timber species, and should be derived for the in-ground timber model as now outlined,

For heartwood:

$$k_{wood,heart} = \begin{cases}0.23 & for\ Class\ 1;\\ 0.48 & for\ Class\ 2;\\ 0.76 & for\ Class\ 3;\\ 1.36 & for\ Class\ 4;\end{cases} \tag{30}$$

For sapwood:

$$k_{wood,sap} = \begin{cases}2.72 & for\ hardwood\\ 5.44 & for\ softwood\end{cases} \tag{31}$$

For corewood:

$$k_{wood,core} = 2k_{wood,heart} \tag{32}$$

The durability class of timber species that are commonly used throughout Australia are specified in AS 5604-2005 and are also further described in Nguyen et al. (2008).

Decay rate for treated wood posts

It is assumed that in a treated timber log, the sapwood is the only type of wood treated with preservative, whilst the heartwood remains untreated. To facilitate computation, the retention of a preservative is converted into a Chromated Copper Arsenate (CCA) equivalent. For creosote, C_{creosote} (%kg/kg), its CCA equivalent, $C_{\mathrm{CCA\text{-}equiv}}$ (%kg/kg) is,

$$C_{CCA-equiv} = \begin{cases}0.07C_{creosote} & for\ softwood\\ 0.01C_{creosote} & for\ hardwood\end{cases} \tag{33}$$

If preservative retention is given in the unit kg/m^3 instead, the conversion between %kg/kg and kg/m^3 may be done by using the approach detailed by (Gardner 2001).

6.3.2 Extension of methods to incorporate climate change

The decay lag and the decay rate are correlated, thus given a particular decay rate *r* determined as described in the previous subsection, the decay lag (years) is given by,

$$lag = 5.5r^{-0.95} \tag{34}$$

The decay rate can be rewritten as,

$$r = k_w f\left(R\right)^{0.3} g\left(T\right)^{0.2} \tag{35}$$

For most Australian cities, N_{dm} < 6 and R_{mean} > 250 therefore,

$$f\left(R_{mean}\right) = 10\left(1 - e^{0.001\left(R_{mean} - 250\right)}\right) \tag{36}$$

$$g\left(T_{mean}\right) = \begin{cases} 0 & \text{if } T_{mean} \leq 5^{\circ}\text{C}, \\ -1 + 0.2T_{mean} & \text{if } 5 < T_{mean} \leq 20^{\circ}\text{C}, \\ -25 + 1.4T_{mean} & \text{if } T_{mean} > 20^{\circ}\text{C}. \end{cases} \tag{37}$$

Climate change will therefore affect the decay rate through changes in yearly average rainfall R_{mean}, and yearly average temperature T_{mean}. A climate change factor for the rate of fungal decay attack on in-ground timber, $C_{rate,IG}$, can be calculated as follows,

$$C_{rate,IG} = \frac{r_{projected}}{r_{1990}} = \left[\frac{f(R_{projected})}{f(R_{1990})}\right]^{0.3} \times \left[\frac{g(T_{projected})}{g(T_{1990})}\right]^{0.2}$$

$$= \left[\frac{1 - e^{-(R_{projected} - 250)/1000}}{1 - e^{-(R_{1990} - 250)/1000}}\right]^{0.3} \times \begin{cases} 0, & if\ T \leq 5°C \\ \left[\frac{-1 + 0.2T_{projected}}{-1 + 0.2T_{1990}}\right]^{0.2}, & if\ 5 < T \leq 20°C \\ \left[\frac{-25 + 1.4T_{projected}}{-25 + 1.4T_{1990}}\right]^{0.2}, & if\ T > 20°C \end{cases} \tag{38}$$

where $r_{projected}$ and r_{1990} are the decay rate projected under climate change and the decay rate at year 1990 as the reference year, respectively; $R_{projected}$ and R_{1990} are the mean rainfall projected and at year 1990, respectively; $T_{projected}$ and T_{1990} are the mean temperature projected and at year 1990, respectively. The climate change factor for in-ground timber decay, $C_{rate,IG,}$ is thus dependent on temperature and rainfall projections.

6.3.3 Impacts of climate change on in-ground timber

Using Equations (35) to (38), a quantitative assessment of climate change impacts on the decay rate is made for the seven reference cities, using nine GCMs and emission scenario A1FI. The climate change factor $C_{rate,IG}$ was calculated for the period 1990 to 2100. Table 13 lists the ranges of change and the averages of the climate change factor $C_{rate,IG}$ at years 2030, 2050, and 2070. The four values in each result cell are the minimum, the maximum, the ensemble mean, and the results from MIROC-M model.

All values are percentage change, which indicates an increase (when positive) or a decrease (when negative) of the decay rate compared to the reference year 1990.

Table 13: Percentage changes relative to 1990 climate in decay of in-ground timber calculated using 9 GCMs and A1FI scenario, for each of the seven reference cities.

City	Factor	Value	2030	2050	2070	2100
Melbourne	$C_{rate,IG}$	Min	-4%	-10%	-21%	-61%
		Max	2%	5%	8%	11%
		Mean	-1%	-2%	-4%	-11%
		MIROC	1%	2%	3%	5%
Sydney	$C_{rate,IG}$	Min	-1%	-2%	1%	4%
		Max	2%	5%	11%	22%
		Mean	1%	2%	6%	13%
		MIROC	2%	5%	7%	18%
Brisbane	$C_{rate,IG}$	Min	3%	5%	3%	-6%
		Max	7%	13%	20%	26%
		Mean	5%	9%	12%	14%
		MIROC	6%	12%	19%	25%
Townsville	$C_{rate,IG}$	Min	-2%	-6%	-16%	-49%
		Max	3%	6%	10%	13%
		Mean	1%	2%	2%	-2%
		MIROC	3%	6%	10%	13%
Canberra	$C_{rate,IG}$	Min	-1%	-2%	-6%	-12%
		Max	3%	6%	10%	14%
		Mean	1%	2%	2%	1%
		MIROC	3%	5%	8%	12%
Mildura	$C_{rate,IG}$	Min	-100%	-100%	-100%	-100%
		Max	28%	48%	78%	112%
		Mean	-47%	-62%	-65%	-59%
		MIROC	15%	27%	40%	59%
Mt Isa	$C_{rate,IG}$	Min	-17%	-100%	-100%	-100%
		Max	7%	13%	21%	28%
		Mean	-1%	-10%	-13%	-30%
		MIROC	6%	11%	17%	24%

In summary, it was found that on average the in-ground decay rate in Sydney and Brisbane would increase by 13% and 14%, respectively, while in Melbourne it could reduce by about 11% in 2100, in comparison with the 1990 level. There are some large variations in the results for the inland cities, particularly Mildura and Mt Isa which reflects variability in the projections of rainfall and temperature across different GCMs.

6.4 *Changes in component service life*

Changes in service life were calculated for housing components made out of steel and zinc, and for in-ground and above-ground timber housing components. More details on the housing components that were investigated and the changes to service results that result from climate change are provided in Section 7.2, where the implications for the maintenance of each housing type over an assumed 50 year asset life are considered.

Because the climate change factors are changing with time, the degradation depth is computed with the average of the degradation rate over the in-service duration. Total degradation depth under climate change can be re-written from Equation (20) as,

$$c_{cc} = \left[c_0 \int_0^t C_{rate}(t)dt \right] t^{n-1} \qquad (39)$$

where c_{cc} is the degradation depth in climate change, and c_0 is the degradation rate without climate change effects. Using this information, the process for estimation of service life changes due to climate change is illustrated in Figure 22. The blue line depicts the depth without climate change. The red line depicts the corrosion depth with climate change. For example, corrosion depth without climate change is estimated by Equation (7), with the corrosion rate computed by Equation (8) or (9), while corrosion depth with climate change is calculated using Equation (39), using the climate change factor $C_{rate,zinc}$ or $C_{rate,steel}$ as specified earlier in Equations (18) and (19), respectively.

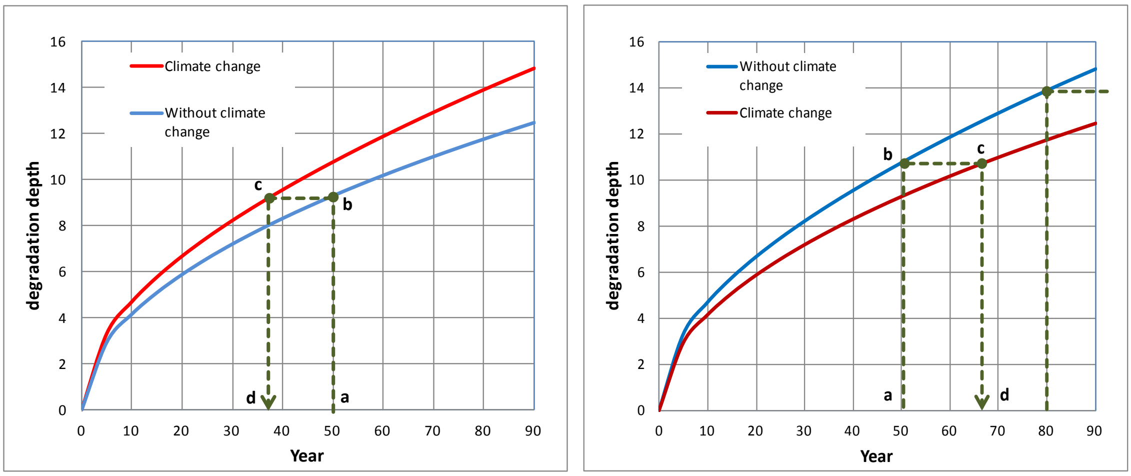


Figure 22: Method to determine service life change. Negative change means reduction of service life (left), whilst positive change means an increase in the service life (right).

As shown in Figure 22, the procedure to determine service life change due to climate change involves a series of interpolations to estimate the points a, b, c, d, as follows:

- From the known design service life (a) of the structural component (current designed standard, i.e. without climate change), determine corresponding degradation depth (b) on the without-climate-change curve. For example, in Figure 22 (left), the points (a) and (b) can be read as, a = 50 years and b = 9.2.
- On the climate-change curve, locate degradation depth (c) which is equal to (b).
- The new service life of a component, i.e. under climate change is at the point (d) that corresponds with (c). For example, in Figure 22 (left), d = 37 years.
- The change of service life is equal to (d-a), e.g. (37 - 50) = -13 years as show in Figure 22 (left). The negative change means there is a reduction of service life.

So in summary, negative change means there is a reduction in service life due to climate change, as shown in Figure 22 (left), whilst positive change means there is an increase in service life as depicted in Figure 22 (right). It should be noted, there are some cases where the change cannot be determined as illustrated in Figure 22 (right). For example, the design service life is 80 years, the corresponding depth is 13.9, but the respective point (c) cannot be located in the climate change curve, as it is out of the range of the climate change data projections available for the project (only up to 2100).

It should be noted the method described above is quite robust, as rather than giving a change in service life for a specific component in a specific location, it allows end users to choose a housing component of interest and to interpolate the change themselves. The results used in this study are presented in Section 7.2, aggregated for each house type, and expressed as the change in annual maintenance cost with climate change.

7. EVALUATION OF ADAPTATION PATHWAYS

This aspect of the project involved a number of key integration and synthesis steps. Firstly, it pulled together information developed earlier in the report at neighbourhood scale (Section 4) and building scale (Section 5), to provide an integrated, multi-scale picture of climate change vulnerability for our social housing case study. The results were then used to evaluate the efficacy of various climate adaptation responses, and as inputs into climate risk and adaptation planning workshops with project partners.

7.1 *Integrated vulnerability assessment*

To enable an integrated assessment, a Vulnerability Index was created based on the commonly used component measures of exposure, sensitivity and adaptive capacity. As these components are difficult to measure directly (Preston et al. 2011), a set of indicators were identified and used to capture different aspects of each component.

The focal scale of analysis was the individual housing asset. Of the 142,410 assets in our social housing dataset, 103,809 (or 72%) contained the full information required for the vulnerability assessment. For each of these assets, a range of variables related to indicators of exposure, sensitivity and adaptive capacity were calculated. Some of our measures refer to attributes of a specific housing asset, while others are related to the surrounding social and physical environment. This approach reflects differences in the availability of datasets and the areal units they correspond to. For example, we have used data on construction materials and age of housing assets, yet characteristics of the resident population could only be estimated using census data. As such, care must be taken when interpreting the results due to differences in the scale of data collection.

7.1.1 Indicators of heat exposure

Exposure to heat-related health risk has been considered at both the housing asset and neighbourhood scale. The purpose of our exposure indicators is to determine how exposure to extreme heat might be either ameliorated or exacerbated by the thermal performance of a housing asset in which an occupant may live, as well as the broader thermal performance of the neighbourhood in which this housing asset is located. As such, these indicators provide a measure of both the indoor and outdoor environment.

At the scale of the housing asset, the results have been drawn from the modelling of housing thermal performance and indoor environment, as outlined in Section 5. In particular we have employed as our measure of exposure at this scale, the total annual hours in which the Discomfort Index (DI) exceeds the threshold of 28, indicating severe risk of heat-related health impacts to occupants. These estimates were generated for the reference climate (centred around 1990) and prepared for each house type in each BCA climate zone. The impact of climate change has not been considered, as there was no comparable information for how other components of vulnerability, such as sensitivity and adaptive capacity might change over time. Using the housing typology (Section 2.4), this indicator was mapped to each asset in the social housing dataset.

At the neighbourhood scale, the measure of exposure was based on an understanding of land surface temperatures. As described in Section 4.1, Landsat TM thermal satellite imagery was used to derive estimates of land surface temperature. It was not feasible, however, for various technical reasons to derive this measure for the regional areas covered by the social housing dataset. As such, another related satellite derived measure known as impervious surface cover was used as an indicator of exposure at the neighbourhood scale. This was deemed appropriate as there is a good correlation between impervious surface and land surface temperature (Yuan and Bauer 2007).

To develop the impervious surface cover measure, the results of a linear spectral un-mixing analysis based on Landsat TM thermal data were used. This involved the

identification and extraction of three endmembers – grass, impervious surface and shade – to create an impervious surface fraction map that was used in our vulnerability assessment as a proxy measure of the level of heat exposure at neighbourhood scale.

To implement this approach, the spatial location of each housing asset in our social housing dataset was required. Almost half of the housing assets were geo-coded to street address level. For the other half, we used the centroid of the Australian Bureau of Statistics Mesh Block in which the housing asset was located to represent spatial location. Importantly, the Mesh Block boundaries from the 2011 Census of Population and Housing were used, as data from the 2011 Census had just been released at this stage in our project, providing temporal consistency with our social housing dataset.

To assign the neighbourhood exposure measure to each housing asset, a buffer of 100m was placed around each housing asset to define the immediate neighbourhood context, and the average impervious surface fraction within this buffer then calculated.

7.1.2 Indicators of resident sensitivity

Data on the residents living in each housing asset were not available for reasons of confidentiality and privacy. To construct the sensitivity indicators, data from the finest census geography at which demographic and socio-economic information is available was used. As noted above, the 2011 Census of Population and Housing had just been released at this stage in our project and thus Statistical Area Level 1 (SA1) was the unit adopted. This is equivalent in many respects to the Census Collection District (CCD) geography utilised in the 2006 Census and employed earlier in this project to explore spatial patterns of land surface temperature and low income households (Section 4).

The ABS TableBuilder Pro software was used to characterise the social housing population living in each SA1, which was filtered further based on the known heat-related health risk factors identified in Section 3. These factors included counts of population aged 65 years and older, children between 0-4 years old, those living alone, and those requiring assistance. These four factors provided the indicator variables for resident sensitivity. Results for each SA1 were assigned to individual housing assets, based on the Mesh Block in which the asset was located, as was described earlier.

To confirm appropriateness of this approach, de-identified resident data was secured from one of our social housing project partners to evaluate the level of concordance between actual social housing resident data and estimates derived from the Census. While there were some minor discrepancies, which is to be expected given that the ABS apply adjustments to small area estimates, it was concluded that ABS census data provided a reliable approximation of social housing populations for this project.

7.1.3 Indicators for adaptive capacity

Adaptive capacity is considered by many to be a rather nebulous concept (Smit and Wandel 2006, Patt et al. 2009). Most vulnerability studies that employ indicators of adaptive capacity draw heavily on the social dimensions of the concept, placing particular emphasis on sources of social capital (Adger 2003). While recognising the importance of these social dimensions, in this project a more biophysical approach has been taken. Several indicators of adaptive capacity were derived at the housing asset and neighbourhood scale, placing strong emphasis on physical capacities to respond.

At the scale of the housing asset, 'adaptive capacity' was defined as the potential to reduce the total annual hours the Discomfort Index (DI) is above the threshold of 28, which indicates severe thermal discomfort and risk of heat-related health impact. The methods used to quantify this indicator are described in Section 5.1. It involved the subtraction of the 'base case' thermal performance of a housing asset, from the thermal performance achieved through an 'expensive retrofit'. It thus represents the maximum potential for building retrofit to improve the thermal comfort of occupants.

Several ‘adaptive capacity’ indicators have also been defined at the neighbourhood scale. Again, a strong biophysical approach has been taken. This includes ‘adaptive capacity’ represented by the potential for urban greening as a strategy for addressing the Urban Heat Island (UHI) effect and reducing urban temperatures. An indicator of urban greening potential was quantified as the amount of ‘plantable space’ within a 100m buffer around each housing asset. As with neighbourhood exposure, the results of a linear spectral un-mixing analysis based on Landsat TM thermal satellite data was used to provide the supporting data. In this particular case, a grass fraction map was used to construct this adaptive capacity measure, involving calculation of the average grass fraction within a 100m buffer to represent the potential role of urban greening.

In addition, another indicator of adaptive capacity was developed at the neighbourhood scale, representing the proximity of a housing asset to potential ‘cool places’ for respite during extreme heat. Potential ‘cool places’ were defined as publicly accessible sites such as libraries, museums, and shopping centres, where air-conditioning is likely to be available. A classification of potential ‘cool places’ was developed using the ‘Features of Interest’ dataset from PSMA, as well as information on areas zoned for commercial land use from the ABS, and internet searches for major shopping centre locations. To operationalise this indicator, the presence or absence of a potential ‘cool place’ within a 400m buffer of each housing asset was calculated. This aimed to capture ‘cool places’ within a theoretical five minute walk of a housing asset, with 400m being the distance commonly used in neighbourhood walkability literature (Schlossberg and Brown 2004).

7.1.4 Construction of composite vulnerability score

The first step in developing an integrated vulnerability score was to develop component indices of heat exposure, resident sensitivity, and adaptive capacity, by combining the Indicator Variables, just previously defined. This required a significant level of data pre-processing, as indicators had been derived at different scales, were expressed in different measurement units, all with different data ranges and distributions. As such, the first step involved a process of data standardisation for the measures derived from remote sensing, re-centring the data for each of these indicators around the mean by calculating Z-scores. If the data were not standardised, then data with different ranges would not contribute equally to the vulnerability analysis. For these indicators and the others, data was normalised between 0 and 1 for calculation of the component indices.

This pre-processing was applied to all indicators so that they could be combined, as shown in Figure 23. The Vulnerability Indices of exposure, sensitivity and adaptive capacity were constructed by adding the weighted Indicator Variable scores together. These Vulnerability Indices were combined into a Net Vulnerability score as follows,

$$Exposure\ + Sensitivity - Adaptive\ Capacity\ = Net\ Vulnerability \tag{40}$$

It should be noted many composite vulnerability assessments assume equal weighting of the input variables. This assumes each are ‘worth’ the same in the composite index (OECD 2008). Ideally, the weights assigned to indicators should reflect their relative importance (Tate 2012). This is the approach taken in this project, where Indicator Variables that were derived at the scale of housing asset for exposure and adaptive capacity have been weighted higher than those derived at neighbourhood scale. The rationale for this was based on greater confidence in the housing asset indicators and the significance of the indoor environment versus broader neighbourhood influences.

Indicator Variables that contribute to the Sensitivity Index were weighted equally as each Indicator Variable is collected on the same spatial scale and are thus considered to be equivalent health risk factors. It is acknowledged however, that the selection of

weights involves a value judgement, which can of course be questioned. To test the significance of the choice of weight on the overall Net Vulnerability outcome, a basic sensitivity analysis was undertaken. For this purpose, the weights for the exposure Indicator Variables were adjusted to 0.7 and 0.3, and for adaptive capacity to 0.7, 0.15 and 0.15, for the building and neighbourhood scale Indicator Variables, respectively.

To assess the relative magnitude of the impact of these changes in weights, the Net Vulnerability score was classified into three classes, with counts undertaken of the number of housing assets that moved from one Net Vulnerability class to another. The result was only a marginal change involving 5% of housing assets, with almost all of these changing from medium Net Vulnerability to low Net Vulnerability. As such, while the choice of weights is important, the weights shown in Figure 23 appear to be robust.

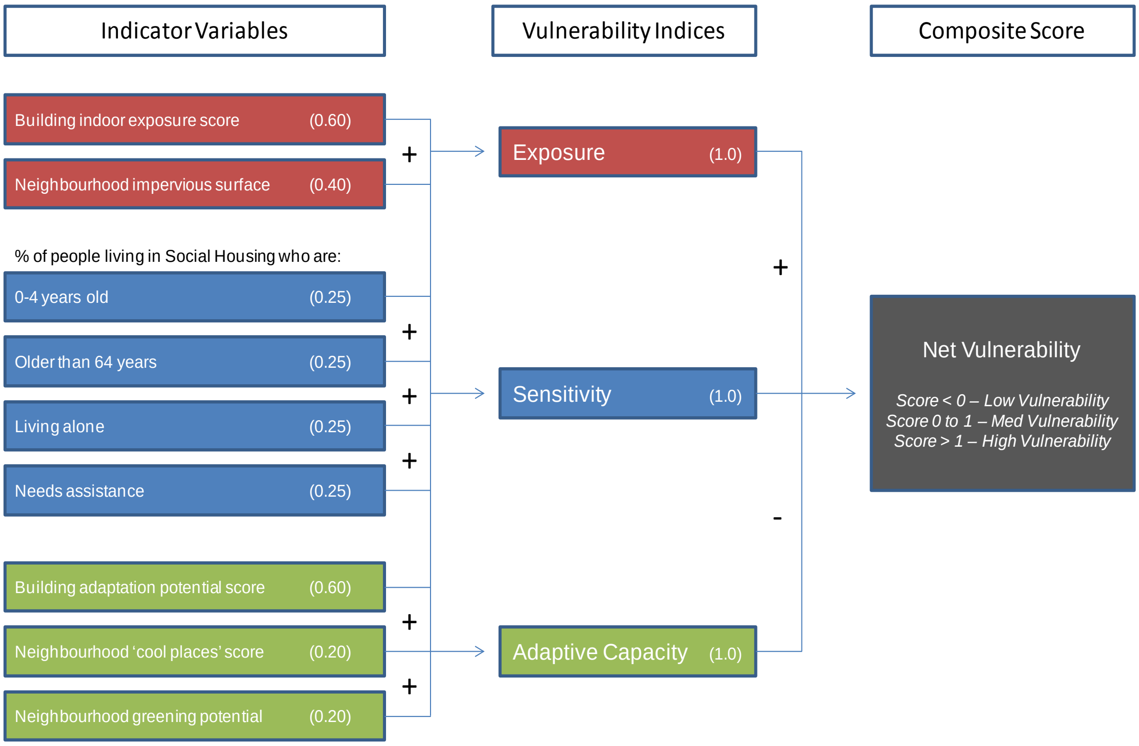


Figure 23: Indicator Variables and Vulnerability Indices used to construct the Composite Vulnerability Score, with the weights applied to Indicator Variables identified in brackets.

The main purpose of the Net Vulnerability Score was to integrate disparate information on exposure, sensitivity and adaptive capacity, derived from multiple scales of interest into a simple set of indices and composite score that can support adaptation planning.

While this approach may prove useful in helping to set policy priorities and for either benchmarking or monitoring adaptation performance, it must be remembered that the resulting score (or ranking of housing assets) is a relative measure and should be used with caution. This is due to the subjectivity of selecting weights, as well as the different scale at which Indicator Variables were collected, meaning the results are best viewed and interpreted at the portfolio level. While indicative of the relative performance of particular housing types in particular locations, the performance of each housing asset has not been directly measured for all indicator variables. Having said this, it is likely the variation in housing asset performance within a particular housing type is captured through the 'worst case', 'base case', 'cheap retrofit' and 'expensive retrofit' scenarios.

7.1.5 Summary results from vulnerability assessment

Development of a Net Vulnerability Score for each of the housing assets in the social housing dataset provides a standardised score that enabled identification of the most vulnerable housing assets and the ability to determine the relative contribution of component vulnerability indices. In Figure 24, all 103,809 housing assets for which we had full information to perform the vulnerability assessment are plotted showing how they each rate in terms of potential impact and adaptive capacity. The dashed red lines represent the top and bottom quintiles (20%) of data distributions, respectively.

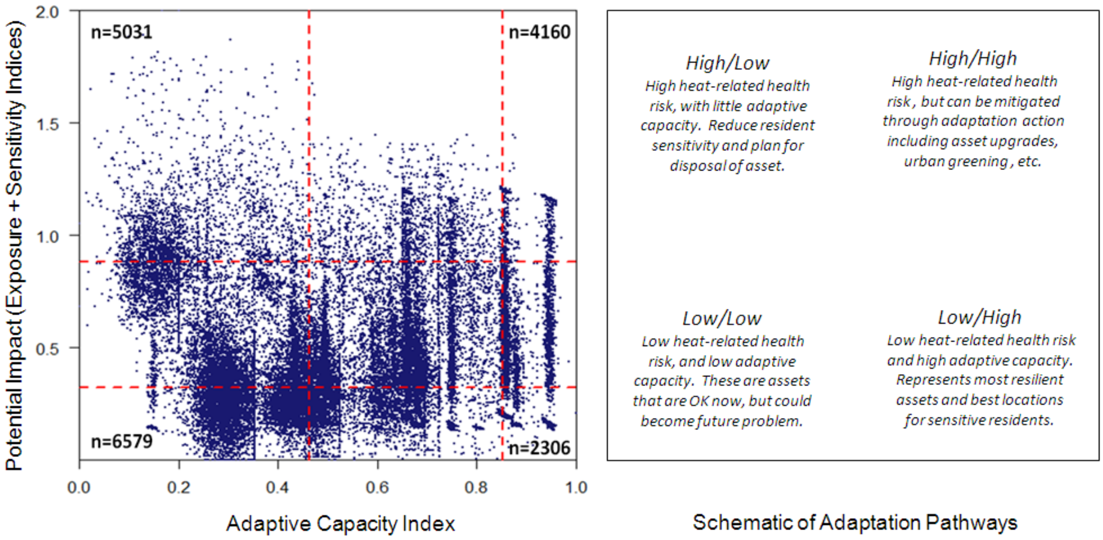


Figure 24: Scatter plot of 103,809 housing assets by their potential impact and adaptive capacity scores with red dashed lines indicating bottom and top quintiles of distribution.

The patterns in Figure 24 reveal there are 5,031 housing assets, representing 5% of the total portfolio that can be considered to have high potential impact and low adaptive capacity. These are the housing assets that are characterised by high exposure and population sensitivity, with limited adaptive capacity to respond. These should be the priority for climate adaptation planning. There are a further 4,160 (or 4%) that have high potential impact, but are also characterised by high adaptive capacity, meaning there are options available to mitigate the potential impact. On the other hand, when looking at the bottom 20% of housing assets with low potential impact, 6,579 of these (6%) also have low adaptive capacity, while a further 2,306 (2%) have high adaptive capacity. While not a problem at the moment, those housing assets with low potential impact and low adaptive capacity are the ones to watch carefully, as potential impact is likely to increase with climate change (Section 5.3), yet capacity to adapt remains low. Housing assets with low potential impact and high adaptive capacity can be considered the most resilient in the portfolio, and perhaps the best location for sensitive residents.

The results have also been further analysed to determine how Net Vulnerability and the component Vulnerability Indices of exposure, sensitivity and adaptive capacity vary by BCA climate zones and housing type. The results are shown in Figure 25 and Figure 26, respectively. With regard to the BCA climate zones, it can be seen that climate zone 1 (CZ1) and climate zone 3 (CZ3) are where the majority of housing assets with high potential impact and low adaptive capacity can be found. This is not surprising, as Townsville was selected as the reference city for CZ1 with hot humid summers, while the reference city for CZ3 was Mt Isa, characterised by hot dry summers. This indicates that in the absence of air-conditioning there are limits to the level of adaptation that can be achieved through building retrofit and neighbourhood improvement. It should also

be noted that this represents the current pattern of vulnerability, which will be further exacerbated through climate change impacts in these locations. There is a significant spread of housing assets in Climate Zone 2 (CZ2) which is represented by Brisbane.

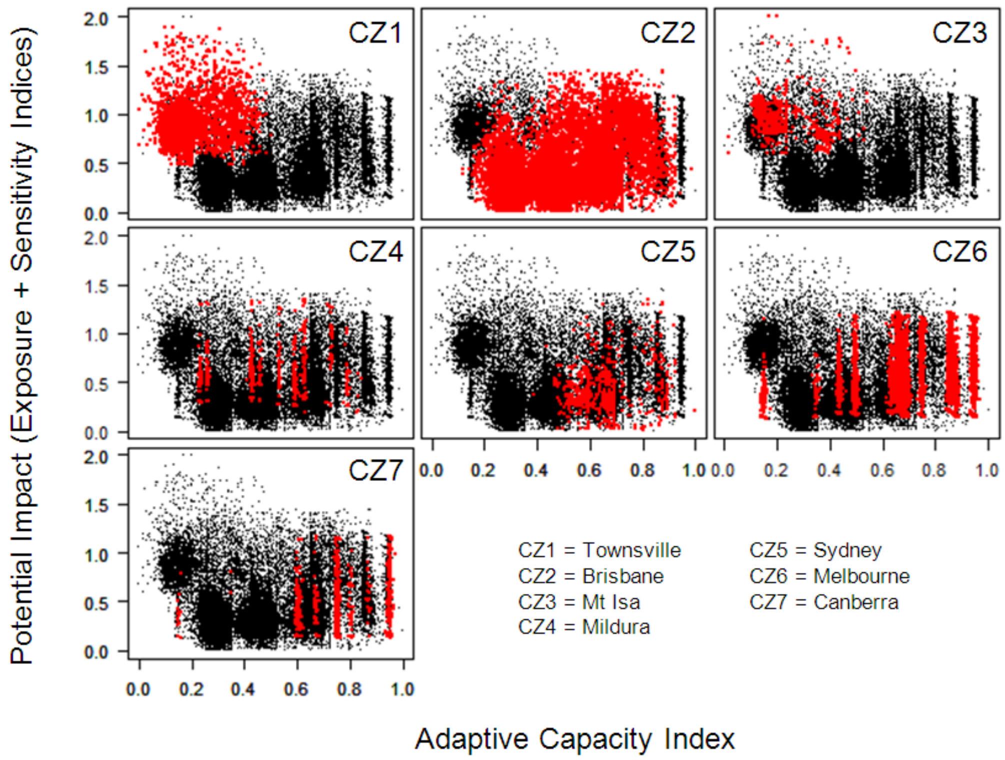


Figure 25: Scatter plot of 103,809 housing assets by their potential impact and adaptive capacity indices, with black dots showing full data and red dots only that climate zone.

With regard to the remaining climate zones shown in Figure 25, characterised by more temperate climates, there appears to be significant sources of adaptive capacity across a range of potential impacts. Of particular focus, should be those housing assets with low adaptive capacity. As noted earlier, given that potential impact is likely to increase with climate change, it is these housing assets that may cause concern in the future.

Now the influence of climate zone has been examined, the next step was to establish the role of housing type, to determine if particular housing types are characterised by higher Net Vulnerability than others. The results of this analysis are shown in Figure 26 for the ten housing types of interest in this project, as described in Section 2.4. It can be seen that House Types A1 and C2 as well as low-rise flats E1 and F1 have the highest number of housing assets with high potential impact and low adaptive capacity. These tend to be located in climate zones CZ1 (Townsville), CZ3 (Mt Isa) and to a lesser extent CZ2 (Brisbane). Of note, is that the high-rise flats (G1 and H1), while possessing a range of potential impact, generally also have high adaptive capacity.

Figure 20 presented earlier in Section 5.4 showed that House Type D1 performed the best in terms of reducing severe heat-related health risk, when tested using weather data from the January 2009 heatwave event. It also performs well in Figure 26, but with a large range in adaptive capacity available. Of interest, is that potential impact in some cases is still relatively high, suggesting this may be driven by high sensitivity of occupants and high exposure at neighbourhood scale, rather than building exposure.

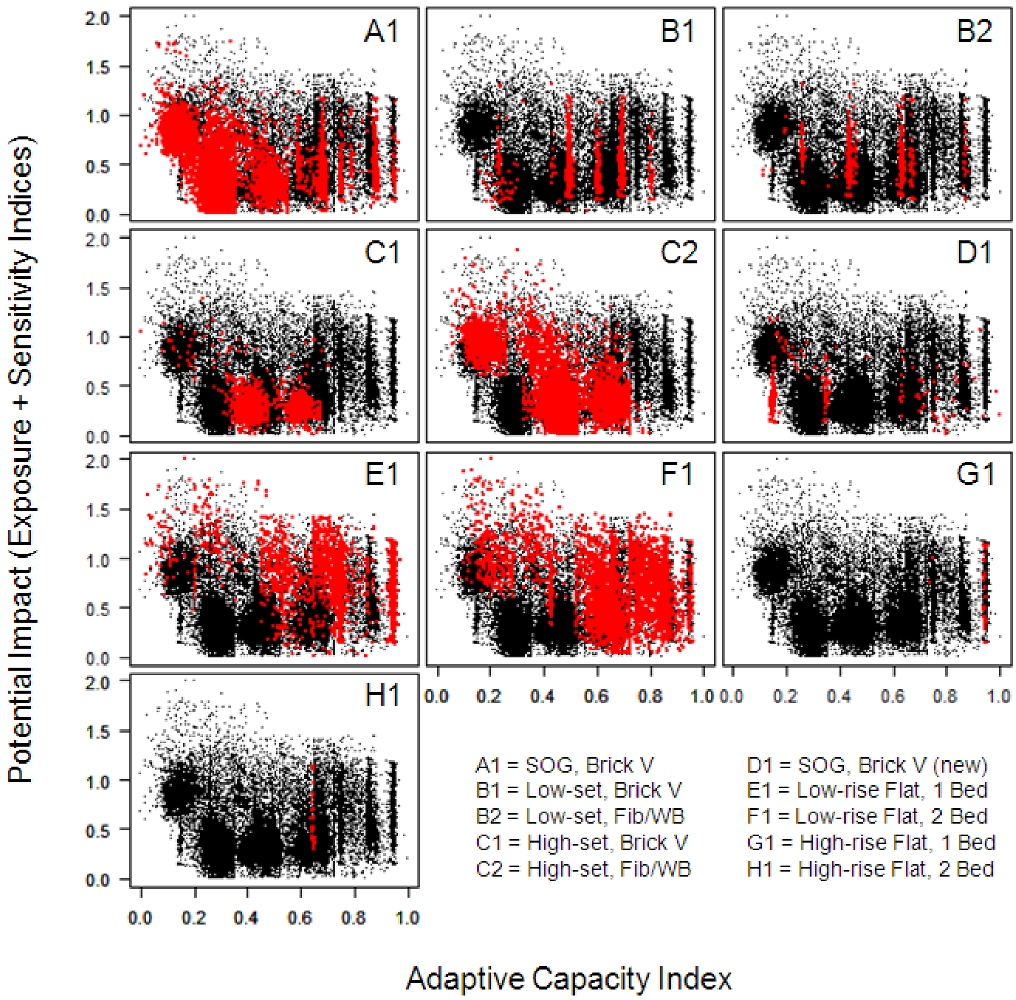


Figure 26: Scatter plot of 103,809 housing assets by their potential impact and adaptive capacity indices, with black dots showing full data and red dots only that housing type.

Finally, the last step in the vulnerability assessment was to explore the effectiveness of the various adaptive capacity indicators, identified in Section 7.1.3, in contributing to a reduction in the potential impact score. The results are presented in Figure 27 where it can be seen that for housing assets located in climate zones with hot humid summers (CZ1) and hot dry summers (CZ3), there is little capacity for the adaptation measures identified to reduce potential impact. Neighbourhood greening is identified as the most promising option in these places, but can only mitigate up to 20% of potential impact. On the other hand, in more temperate locations there is a significant role for building retrofits, particularly for house types with slab-on-ground construction (A1 and D1), whereby in many cases, almost all of the potential impact can be mitigated. Of note, neighbourhood 'cool places' can play a complementary role, particularly in locations where other adaptation measures are less effective, but should not be relied on solely.

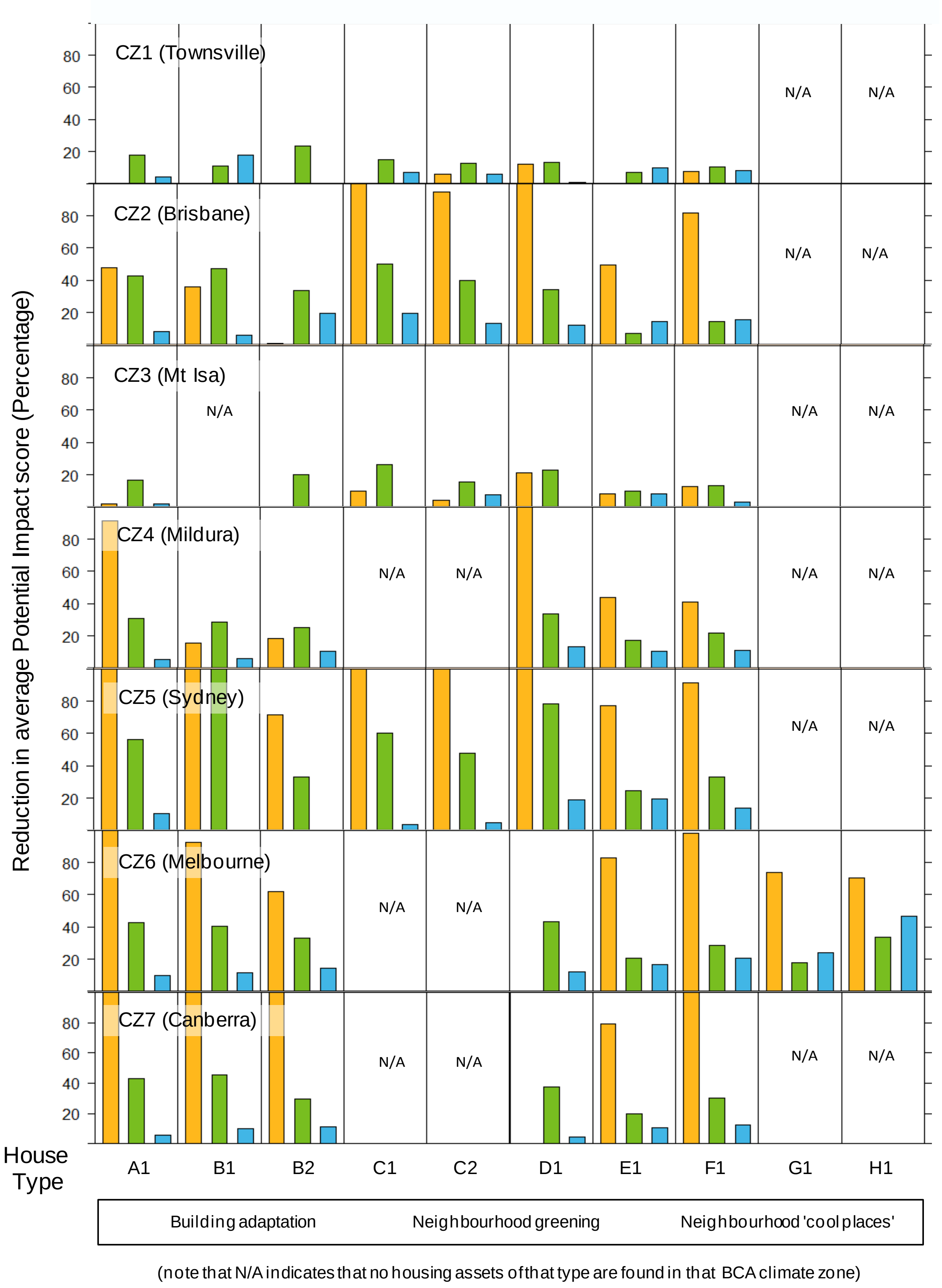


Figure 27: Effectiveness of the adaptive capacity measures in reducing potential impact for each housing type, within each reference city, for the reference and future climates.

7.2 *Climate change and housing maintenance*

This section of the report details the methodology used to develop a housing asset maintenance model for estimating the maintenance requirements of the housing asset types described in the housing typology (Section 2.4). The purpose of the model was to characterise the maintenance cost profile, over time, for each of the housing types, and to estimate the expected difference in maintenance costs due to climate change.

The model was then extended to identify potential opportunities across the portfolio, where investment in housing asset upgrades for climate adaptation may be possible, given assumptions about the maintenance budget that is available. It was assumed the focus of upgrades was to improve the thermal performance of housing assets to reduce the heat-related health risk to housing occupants, as described in Section 3.

7.2.1 Model development and assumptions

The model was developed using Microsoft Excel (Version 2007). It used Visual Basic scripts to run and capture simulation statistics. Variability was introduced through cost and life schedules for key housing maintenance components, as well as through key assumptions regarding housing asset life and the policies concerning asset renewal Housing assets modelled were those identified in the housing typology (Section 2.4).

Housing component costs and life

The model separated each housing asset into its component parts and then simulated component breakdowns over the asset life. Output from each model run was captured and summed to determine expected costs. This process was duplicated for a portfolio of assets (minimum 1000) with the median costs retained. This was repeated 50 times, with the median vector of costs from the 50 runs used to characterise the asset type.

Information on housing assets and their primary components and materials was taken from the social housing dataset used to construct the housing typology. This list of key components was then generalised and a table of expected costs and expected service life prepared using information maintained by CSIRO from previous research (Tucker et al. 2002, Johnston et al. 2002, McFallan and Tucker 2002). Each component was listed with information on major costs and life (representing a replacement), minor costs and life (representing a repair), and annual costs. All maintenance cost data was converted to current costs using an adjustment based on the Consumer Price Index (CPI). It is important to note, that like any other model input, the maintenance costs can be easily modified as new or better data becomes available, or for the purpose of sensitivity analysis and scenario planning that aims to account for cost uncertainties.

The data on maintenance components was paired with a measure of variation. For maintenance costs a simple random function generating a value with an absolute maximum difference of 25% of the specified cost was used. For component life, it was assumed that this variation would follow a Weibull distribution (Weibull 1951), where the failure rate is proportional to a power of time. In this case, expected component life was used as the scale parameter and a random function ≤1 as the shape parameter.

Portfolio makeup and asset renewal policy

The social housing dataset described in Section 2.4 was used to define the makeup of the portfolio. In particular, this included information on the age distribution of housing assets, summarised by the housing type and by BCA climate zone, to enable impacts of climate change on material durability and service life to be incorporated (Section 6).

It was assumed housing assets would be disposed of when the asset reached between forty five and fifty years of age (Earl et al. 2003). It was then assumed the asset would be replaced by acquiring an asset through spot purchase or construction. Where a

spot purchase was made, the replacement asset was assumed to be less than five years old. This process was random and no consideration was given to portfolio alignment policy or to early disposal of assets in need of significant maintenance.

Portfolio costs were captured by estimating the expected cost of maintenance for a given year dependent on the age of each asset in the portfolio and summing. This was done for both the climate change scenario as well as the current case for comparison.

Upgrade candidates and maintenance backlog

Housing assets built post 2005 were assumed to meet the Building Code of Australia (BCA) requirements for energy efficiency, and were excluded from being an upgrade candidate as were any newly acquired assets. It was assumed all other assets had not undergone any upgrade to minimise the impact of heat stress on occupants. Further, the upgrade that has been costed was that identified in Section 5.3 as a 'cheap retrofit' and is considered the minimum upgrade required to improve the asset performance.

The model attempted to capture maintenance backlog. It included a switch to choose whether to address maintenance backlog prior to carrying out upgrades, or alternatively to ignore any backlog and complete upgrades as soon as surplus maintenance budget was available. This enabled an assessment of the minimum budget required to meet future maintenance and upgrade needs. This portfolio component of the modelling has been informed by previous research from McFallan (2007) and McFallan et al. (2010).

7.2.2 Impact of climate change on housing maintenance

To understand the potential impact of climate change on housing asset maintenance, the life of each housing component was weighted by the projected impact of climate change. This was done for each asset at the time of failure generation, thus allowing for component failure variability to be retained and removing any systematic forcing.

As the climate change weightings were derived from the material durability and service life modelling presented in Section 6, the only components impacted by this analysis were the steel components (i.e. roofing, gutter and down pipes), timber components that are in-ground (i.e. fence posts and retaining walls), and timber components above ground (i.e. timber window frames and cladding). While a number of Global Climate Models (GCMs) were used in the material durability modelling in Section 6, the results that have been applied here are from the MIROC-M model. This was the best model for replicating observed climate (Perkins et al. 2007) and provides internal consistency with the thermal performance and indoor environment modelling outlined in Section 5.

The model was run for each housing type in each climate zone with the overall results documented in Table 14. While the thermal performance analysis suggested there was little difference in the performance of housing assets based on roofing material, this was deemed important from a maintenance perspective and therefore a simulation was run for each house type, firstly with a ceramic tile roof, and then with a colorbond roof.

It should be noted, that due to significant variation in the size of apartment complexes and not being able to determine appropriate cost proportions to apply, it was deemed best not to include external components in the maintenance analysis for the low-rise (E1 and F1) and high-rise apartments (G1 and H1), other than windows and external doors. The results that have been generated for these apartments therefore only include internal components requiring maintenance, and will be an underestimate.

Table 14: Summary statistics from model runs for each housing type and climate zone.

House Type	Asset Count	Benchmark Value Each	Total Value of Portfolio	Maintenance (%Spend)	Maintenance (Annual Budget)	Upgrade (Unit Cost)	Upgrade (Total Budget)
A1	18648	$300,000	$5,594,400,000	1.65%	$92,307,600	$3,688	$68,773,824
B1	6589	$300,000	$1,976,700,000	1.65%	$32,615,550	$3,688	$24,300,232
B2	2393	$300,000	$717,900,000	1.65%	$11,845,350	$3,688	$8,825,384
C1	2417	$300,000	$725,100,000	2.10%	$15,227,100	$8,688	$20,998,896
C2	10101	$300,000	$3,030,300,000	2.10%	$63,636,300	$8,688	$87,757,488
D1	506	$300,000	$151,800,000	1.50%	$2,277,000	$8,400	$4,250,400
E1	28893	$250,000	$7,223,250,000	0.50%	36116250	$8,688	$251,022,384
F1	31598	$250,000	$7,899,500,000	0.60%	47397000	$8,688	$274,523,424
G1	1927	$250,000	$481,750,000	0.50%	2408750	$5,688	$10,960,776
H1	5073	$250,000	$1,268,250,000	0.60%	7609500	$5,688	$28,855,224
Totals	108145		$29,068,950,000		$311,440,400		$780,268,032

Summary of housing type assessment

Given that ten housing types have been considered in this maintenance analysis, the results for House Type B1 are provided here to provide an introduction to the modelling results. Readers are referred to Appendix 1 to find the results for other housing types.

Analysis shows that the maintenance budget ($230,000) for House Type B1 would be similar to the benchmark asset value ($300,000) over the life of the asset. As shown in Figure 28, there is significant variation in the amount of maintenance that is required, with an average expected annual cost of $4,600. It can also be seen in Figure 28, the expected impact of projected climate change on maintenance costs is very small, in the order of 5% and may be smaller than the variation expected between other assets of this housing type. Nonetheless, when considered at the portfolio level an additional 5% budget requirement is significant, particular in a resource-constrained environment.

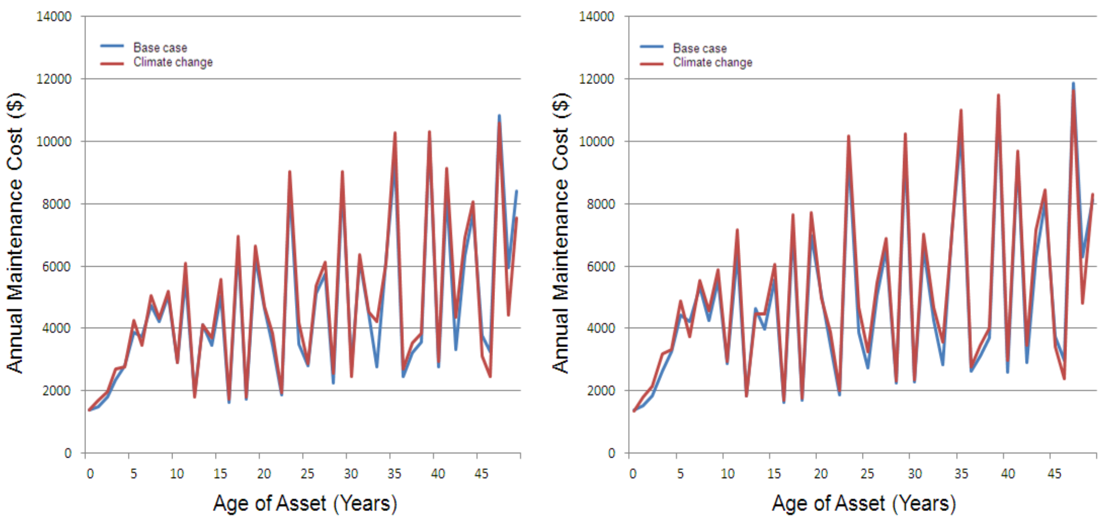


Figure 28: Expected lifecycle costs for maintaining a Type B1 housing asset showing impact of climate change. Results for a ceramic tile roof (left) and colorbond roof (right).

At the portfolio level, considering all 6589 assets that have been mapped to House Type B1, it can be seen in Figure 29 that there is significant investment required over time. Based on the age distribution of this portfolio, however, opportunities do exist to undertake early upgrades (up to 1000 assets) by 2022 and so with a targeted upgrade program, this could result in significant reductions in the level of health risk to tenants.

Based on an assumed maintenance budget of 1.65% of the asset value, the results presented in Figure 29 show what can be achieved given two different upgrade and renewal policies. If surplus maintenance budget in any given year is directed to asset upgrade, then about 50% of the portfolio can be upgraded over the next 20 years. On the other hand, if surplus maintenance budget is invested in backlog maintenance first then upgrade programs, 40% of the portfolio could be upgraded over similar timelines.

Of note in Figure 29, is that in the short term, there are periods where the expected maintenance budget of 1.65% of total portfolio value would not be sufficient to support maintenance requirements. In this situation, any shortfall could result in considerable reduction in asset condition, without targeted follow-up through maintenance programs.

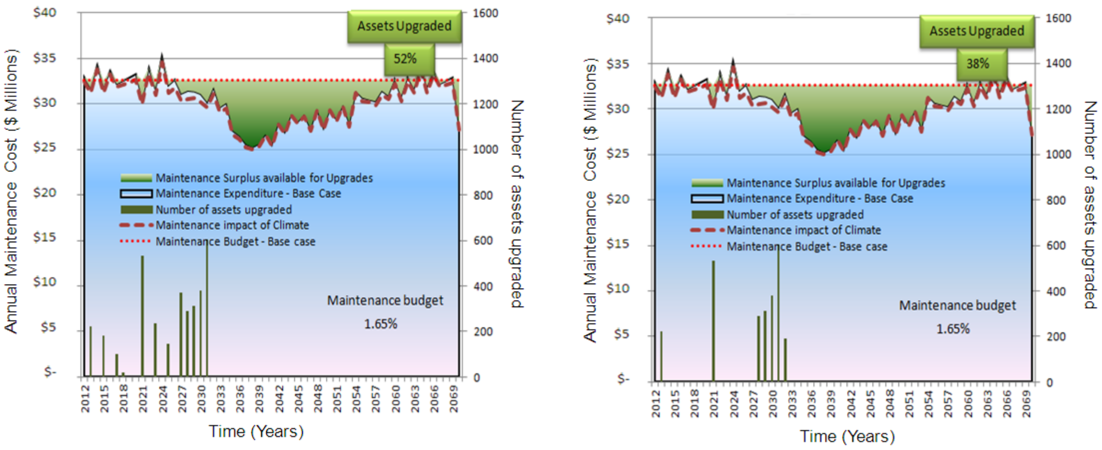


Figure 29: Portfolio level maintenance and upgrade costs for Type B1 housing asset with ceramic tile roof, showing results for where maintenance budget surplus is directed to asset upgrades (left) and surplus directed to backlog first and then upgrades (right).

This highlights the importance of a broader portfolio perspective, considering the full range of housing types and age distributions, so as to identify the peaks and troughs in maintenance requirements, to gain a strategic, long-term perspective on opportunities for asset upgrade and climate adaptation. This portfolio perspective is explored below.

Summary of portfolio level assessment

To understand the implications of climate change for the entire social housing portfolio for which we had suitable durability and maintenance data (108,145 assets), it was necessary to disaggregate the housing portfolio into regions as defined by the BCA climate zones. With housing assets organised by BCA climate zones, degradation models were applied based on the projected changes in local climate. Results were then combined to provide a portfolio view of the impacts of climate change on housing maintenance cost. This was compared with results from a second model run with no climate change. Outcomes from the portfolio level assessment are shown in Figure 30.

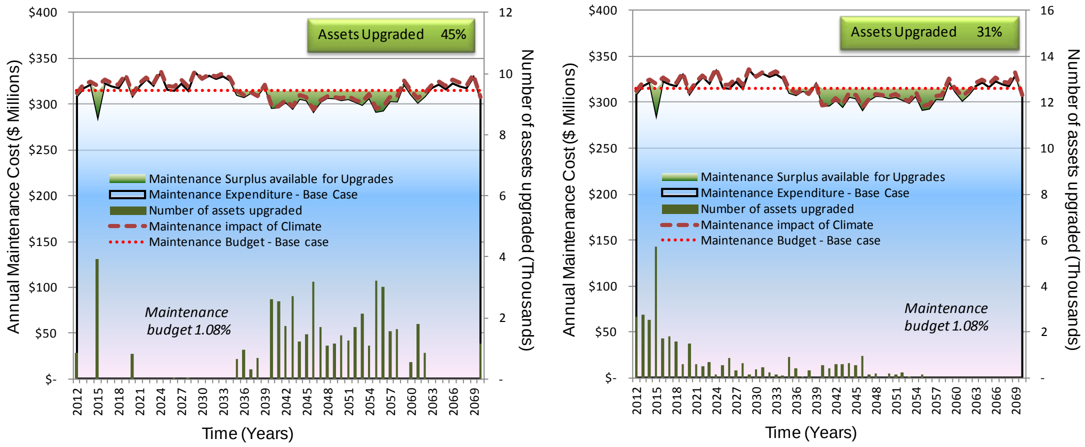


Figure 30: Maintenance and upgrade costs for entire social housing portfolio, where budget surplus is directed to upgrades (left) and backlog first and then upgrades (right).

Two options for the allocation of maintenance budgets are explored in Figure 30. The first of these (shown on the left) assumes maintenance budget is allocated by house type, and where surplus budget is available it is used to fund upgrades for that type only. Under this scenario, 31% of the social housing portfolio can be upgraded, with the majority of upgrades occurring before 2030. An alternative and perhaps more realistic scenario is shown in Figure 30 (right), where maintenance budget is allocated by housing type, but surplus is directed towards backlogs for other house types before upgrades are undertaken. The upgrades are allocated to each of the house types randomly. In reality, decisions on which assets to upgrade would be prioritised based on more information i.e. resident need and asset lifecycle stage. It can be seen that 45% of the portfolio could be upgraded under this scenario, but most upgrades don't start occurring until after 2030, when the maintenance backlog has been addressed.

Armed with information about which housing types, or more specifically which housing assets, are particularly vulnerable under climate change will enable portfolio managers to consider which strategies concerning asset upgrades, maintenance, and acquisitions are most likely to alleviate heat-related health risk. Clearly a complex set of trade-offs are involved whereby a focus on maintenance backlog, sees delays in asset upgrades. Neglecting either one may have consequences for health and well being of occupants.

The model that has been built in this project has been implemented in Microsoft Excel and provides a simple, yet powerful way to explore different pathways to more climate adapted and healthy social housing, within limits and constraints of available budgets. The best approach will vary from place to place, with upgrades in locations with hot and humid summers, such as Townsville and Mt Isa identified as a priority now, whereas in other more temperate locations a better balance between maintenance and upgrades might be possible to achieve, if upgrades are less time sensitive. What the model shows is that to undertake both at the same time requires additional funding, and thus the model may help build the case for budget bids for climate adaptation capital works.

7.3 *Adaptation planning and management*

In February 2013, the research results were presented at a workshop to staff of the social housing partner that is based in southern Australia. An additional presentation explored the organisation's assets exposure to bushfire, flood and sea-level rise.

Following the presentations, staff joined with the CSIRO research team to conduct a preliminary risk assessment using facilitated scenario-building exercises to examine the implications of climate change for the organisation's housing assets and residents.

These scenarios were:

- The 'Do Nothing' scenario, which explored the inherent risks entailed by having no existing risk controls or any planned response;
- The 'Do Everything' scenario, which helped to define the adaptation goal for participants. It explored an ideal range of responses that achieved adaptation for the portfolio and eliminated risks to residents; and
- The 'Real World' scenario helped to define an adaptation planning pathway.

Participants were given three time periods: 'Now', 'Year 3', and 'Year 5', and were asked to allocate the actions required in each period to achieve the adaptation goal.

They were then asked to organise their outputs into groups based on the organisation's risk framework, and then rank the three most important outputs of each exercise. The output generated as part of this process is contributing to the development of a climate risk register within the organisation. The output of the 'real world' scenario has been used to define immediate steps within the organisation towards climate adaptation.

This first workshop was a pilot in an on-going organisational process of building awareness among staff of the implications of climate change for its assets and the residents that live in them. The influencing approach aims to normalise climate change risks as a legitimate business concern, using presentations and workshops to co-create adaptation pathways, based on the assumption that staff know the business best and as business actors must 'own' the problem and its solution. This approach facilitates information exchange between organisational silos, alerting actors to organisational processes suited to intervention or inclusion of adaptation measures. This has already led to one significant point of intervention at the level of strategic asset planning, which will now consider a range of climate change risks, thus helping mainstream adaptation.

This process is also being supported by the tools and analysis generated as part of this project. The heat vulnerability maps will be integrated into the organisation's geospatial information system and can be used by planners and the maintenance program to help identify assets and residents in vulnerable areas and prioritise them for appropriate intervention. Likewise, the portfolio-wide analysis of vulnerability to heat is enabling a strategic approach to managing potential impact and sources of adaptive capacity.

These conversations with our social housing project partners on adaptation planning and management are continuing, but with the project now complete, greater emphasis is being placed on engaging more broadly with the low income housing sector. This includes further exploration of the barriers/opportunities for generalisation, presentation of the research findings at relevant conferences, and publication in scientific journals.

8. DISCUSSION OF THE MAIN FINDINGS

Using social housing as a case study, the project had four main research objectives:

- Model vulnerability of housing and tenants to selected climate change impacts;
- Identify/evaluate engineering, behavioural and institutional adaptation options;
- Scope co-benefits of climate adaptation for human health and well-being; and
- Develop house typologies and climate analogues for national generalisations.

The project was undertaken within limited timeframes due to delays in securing data access, yet the scope has been successfully delivered and project objectives satisfied.

This section summarises the main findings of the research and the generalisations that can be made. There has been an underlying focus on human health and well-being in the project and discussion of co-benefits is addressed throughout instead of separately.

8.1 *Vulnerability of housing and residents*

The residential house energy rating software *AccuRate* was used to assess the thermal performance and indoor environment of common low income housing types. This was done using the Discomfort Index (DI) measure. The number of hours DI exceeded the threshold value of 28 was quantified for each house type in each climate zone. This threshold identifies the point where it becomes difficult to maintain a stable core body temperature of 37^{0}C, representing severe heat-related health risk. Key findings from the assessment of housing performance under climate change and heatwaves were:

- All house types exceeded DI > 28 during simulations of a five-day period during the January 2009 Melbourne heatwave. DI values for the 'worst case' scenario for each house type commonly exceeded the outdoor DI values, amplifying the heat-related health risk. There were also temporal lags, were house types with high thermal mass were slower to shed DI values, once outdoor cooling began.
- Under projected climate change using the MIROC-M model and A1FI emission scenario, housing types in climate zones with hot and humid summers are most vulnerable. In these locations, housing retrofits cannot sufficiently mitigate the level of severe heat-related health risk. Air-conditioning is increasingly required to maintain safe indoor thermal environment for occupants. In more temperate locations, basic retrofits can largely ameliorate climate change in the short term.
- Some housing types perform better than others under climate change, but most variation in thermal performance is due to quality rather than type of housing. If building orientation is good, than in most situations building retrofits can lead to significant improvement in performance. With good orientation, the two most important improvements are roof colour and ceiling insulation. Depending on the housing type, there may be little benefit from other additional improvements.
- Of note is that household heating and cooling energy requirements are also likely to change. Comparing the reference cities in 1990 and 2070, the overall trend is for a reduction in energy for heating and an increase in that for cooling. In particular, Sydney and Brisbane, which currently have balanced heating and cooling loads, will need up to three times as much energy for cooling by 2070.

Beyond housing performance, the project also investigated neighbourhood context and the role of place. Spatial analysis of Adelaide, Melbourne, Sydney and Brisbane has shown low income housing is typically concentrated in the hottest parts of the city, as measured by land surface temperatures. Furthermore, heat-related health risk factors

are more prevalent in low income households, with this vulnerable population living in areas with the highest heat exposure, and in housing that may further exacerbate risk.

8.2 *Evaluation of adaptation pathways*

An integrated vulnerability assessment was undertaken to inform the identification and evaluation of climate adaptation pathways. This involved collation of information on exposure, sensitivity and adaptive capacity at both building and neighbourhood scale. The vulnerability of 103,809 social housing assets was assessed. Comparing results for potential impact and adaptive capacity, four adaptation pathways were revealed:

- Pathway 1 involves housing assets that possess high potential impact and low adaptive capacity. There were 5,031 housing assets, representing 5% of the social housing portfolio in this category. These assets are characterised by high vulnerability and are a priority for climate adaptation planning. This could involve relocation of any sensitive residents to reduce potential impact, better matching of future residents based on heat-related health risk factors, and planning for asset disposal at the earliest opportunity to mitigate the risk.
- Pathway 2 involves housing assets with both high potential impact and high adaptive capacity. There were 4,160 housing assets (4% of the portfolio) in this category. These assets pose severe heat-related health risk to occupants, but there is scope to reduce this potential impact through adaptation action. These assets are candidates for priority upgrades to improve thermal performance.
- Pathway 3 involves housing assets with low potential impact and high adaptive capacity. These are the most climate resilient assets in the portfolio, and the best location for heat-sensitive occupants. Comprising only 2,306 housing assets or 2% of the portfolio, these housing assets should be examined further to provide analogues of what to try and replicate. Acquisition of new housing assets should be targeted through this pathway, building greater resilience.
- Pathway 4 involves 6,579 housing assets or 6% of the portfolio. It is made up of assets with low potential impact and low adaptive capacity. These housing assets are not a problem at the moment, but need to be watched carefully into the future, as potential impact will increase with climate change (Section 5.3).

Overall, the findings of this vulnerability and adaptation assessment suggest that there are significant opportunities for adaptation action to reduce severe heat-related health risk within the social housing portfolio examined as part of this project, and low income housing more generally. This includes through building upgrades, urban greening, and the development of 'cool places' for respite. Urban vegetation was identified as the dominant control on land surface temperatures, but where this is not feasible or as a bridging strategy, the upgrade of assets through changes to roof colour and increasing ceiling insulation can help reduce indoor temperature extremes. A range of adaptation action across multiple scales will be required to best reduce heat-related health risks.

8.3 *Towards national generalisation*

As outlined in Section 2.4, a typology of low income housing was constructed using the social housing dataset developed from data provided by project partners. The typology was classified according to measures available in the NEXIS database maintained by Geoscience Australia. It has been used in conjunction with the BCA climate zones to determine where else in Australia, similar housing in similar climates might be found, thus making it possible to generalise the findings in this study more broadly, with care.

So the first thing to point out is that social housing, which comprises public-owned and community-owned rental housing properties, represents 13% of all low income housing

in Australia (defined by an equivalised household income of $1-399 per week). The social housing dataset constructed for this project, represents about 35% of Australia's 406,000 households that are being assisted by social housing nationally (Australian Institute of Health and Welfare 2010). The findings cover all major BCA climate zones and can be considered reasonably representative and generally applicable to most types of social housing in Australia, with the notable exception of indigenous housing.

The ability to generalise findings more broadly is limited by the different landlord and tenure types that are captured by our definition of low income housing. So while 13% of low income households are in social housing, a further 25% are located in private rental, and another 57% who own or are in the process of purchasing their house. The implications of this for broader generalisation of findings are summarised as follows:

- Low income households are more sensitive to heat-related health risk than the general population. This is irrespective of landlord or tenure type. As such, the findings of the literature review (Section 3) and the identification of heat-related health risk factors are thus generally applicable to all low income housing types.
- At the neighbourhood scale, the results of the spatial analysis of the relationship between low income households and land surface temperature undertaken in four Australian cities (Section 4), was not specific to social housing and is valid for all low income housing types. This analysis was performed on four cities only, but the results are thought to be generally applicable elsewhere, in that low income households are often located in the hottest parts of an urban area.
- There are few barriers to generalisation of the housing performance modelling (Section 5) and changes in material durability and service life (Section 6). This is because these were biophysical based assessments, so provided that the housing types are reasonably representative of those that are being considered in private rental or owner/purchasing situations, it is valid to apply the results.

Where it is less appropriate to generalise, is identification and evaluation of adaptation pathways undertaken in Section 7, which involved a vulnerability assessment based on information on sensitivity, exposure and adaptive capacity specific to social housing data provided by project partners. While there may be some general lessons and insights that are useful more broadly, the nature of vulnerability and the adaptation pathways available will most likely differ for other low income housing with different landlord or tenure types. For example, in the private rental housing sector, matters are complicated by a 'split incentive' between the private landlords and their tenants that will often discourage action on climate change, as the landlord won't accrue any direct benefit from such investment. For those who own or are purchasing their homes, there may be a different set of constraints and pressures that will influence adaptation action.

It should also be noted that there are differences in landlord type within social housing, whereby State Housing Authorities may deal with issues of housing maintenance and climate adaptation differently to the community housing sector. For example, public housing is typically older and of poorer quality than community housing, with significant maintenance backlogs that will require attention, before adaptation can be considered.

The key message for other low income housing types, beyond social housing, is that there are a range of things that can be done. In many situations, it may only be the building scale that can be influenced, as private individuals have little influence over the broader neighbourhood scale. However, as stated above, those in low income private rental are probably the most constrained of all low income housing types with regard to the range of adaptation options available to them, given the 'split incentive'. It is in these situations that institutional and behavioural adaptation becomes important, as well as the role of government and other agencies in ensuring there are public 'cool places' in these locations that can be sought by residents for respite during heatwaves.

9. GAPS AND FUTURE RESEARCH

The large range of methods and the level of integration and cross-scale interactions in this project presented a variety of challenges. Many of these are now discussed in terms of limitations associated with the data that has been used, or caveats required given modelling complexities, assumptions made, and other sources of uncertainty. The report then ends with a high level summary of future research and next steps.

9.1 *Data limitations and caveats*

There are key limitations and areas for improvement in understanding relationships between heat exposure and heat-related health risk factors. Satellite imagery has been used to measure land surface temperature and impervious surface fraction, as proxy measures of local heat exposure. While there were good reasons for taking this approach, we did not measure directly how low income households experience heat.

Another limitation of the study was the use of population census data and heat-related health risk factors as opposed to direct health impacts data from individuals. It is thus an ecological study and care must be taken when interpreting the results as they apply to populations and not to specific individuals. Also heat-related health risk factors were used rather than primary data on mortality or morbidity, as the latter was not available.

Similarly, it should be noted that assessment of housing performance using *AccuRate* has relied on the identification of ten common low income housing types. The results are thus indicative of the relative performance of particular housing types in particular locations, but the performance of each housing asset has not been directly measured.

In terms of durability modelling, more accurate assessments of changes in atmospheric corrosion of metal could be made if the pattern of surface ‘washing’ of materials due to changes in rainfall could be estimated. The effects of CO_2 concentrations have also not been considered. While it may be possible to adapt more sophisticated models of metal corrosion or timber decay, this was not deemed appropriate given the difficulties associated with specifying the additional climate change parameters required by these more sophisticated models. Putting sources of uncertainty into perspective, Nguyen et al. (2013) estimated that there was considerably more uncertainty associated with the modelling of corrosion and decay for engineering purposes, than in the climate models developed to project future degradation rates. Given the most appropriate degradation models were employed, our methods are considered robust and assumptions sound.

With regard to the estimate of the impact of climate change on housing maintenance costs, this was based on the results of the durability modelling for particular materials (i.e. steel, zinc coatings and timber). Other construction materials, such as concrete, were not considered. Neither was the influence of climate-induced footing movements in expansive clays, which can damage housing assets with masonary walls due to their rigid construction. Consequently, the full potential impact of climate change on housing maintenance costs has not been assessed, thus the results will be an underestimate.

9.2 *Other issues or gaps identified*

The vulnerability assessment undertaken in this project is seen as a first step, with considerable room for improvement. Given the multiple scales of information from building to neighbourhood that it relies upon, it provides a useful picture of current vulnerability but few insights as to how this might change in the future. While the project has generated information on how building performance might change with climate change, there was no comparable information about how the social housing population, and neighbourhoods they live in, might change over the same timeframes.

This would be required to represent the complex and dynamic interactions between people, housing and place, and how this could collectively shape future vulnerability.

Another major gap has been the lack of focus on social or institutional sources of adaptive capacity for consideration in the vulnerability assessment. In this project, the emphasis has been on the biophysical nature of exposure and adaptive capacity, with consideration of individual and social factors only through our measures of sensitivity. It is argued, however, that this biophysical focus provides a good starting point for an adaptation planning process and that the social, behavioural and institutional aspects of adaptive capacity are more fluid and dynamic and best explored by the end users, as has been outlined earlier through the workshop process described in Section 7.3.

This is a very important point. Further research is required to understand how capacity to respond to climate change vulnerability and the adaptation options identified, might vary among different types of low income housing. This includes understanding how different tenure and/or landlord arrangements might affect the diversity of adaptation options available, the capability and resources to act on a response, through to the motivations for action, and the scale of influence that can be achieved. In other words, installing ceiling insulation or planting a tree might be what is required, but the barriers to and pathways for implementation of these adaptation actions may vary significantly between low income social housing, private rental, and private ownership/purchasing.

Furthermore, there is a considerable role for government, but translating this type of integrated, cross-scale research into policy is not straightforward. Part of the problem, is the diversity of policy domains implicated, which include health, housing, planning, energy, climate change, just to name a few. More research will likely be required to quantify in financial terms, not only the benefits for human health and well-being that can be gained through improvements to low income housing, but also the energy and carbon savings, and other social outcomes that might follow. It is also important to recognise that houses sit within a neighbourhood context, and that adaptation actions identified such as urban greening and cool places, will necessitate collaboration with land use planning and urban design professionals who shape our built environment.

9.3 *Conclusions and next steps*

This project has found low income households and the housing and neighbourhoods they live in, can exacerbate heat-related health risk. At the same time, however, apart from a relatively small number of situations where there was high potential impact and low adaptive capacity, there were a range of options available to help mitigate this risk.

For instance, social interventions might include heatwave warnings and outreach to particularly vulnerable populations. Ecological interventions could include urban greening and water sensitive urban design. Engineering solutions could focus on building design and energy efficiency, through to cool roofs and pavements. The bottom line is a range of strategies will be required and will vary from place to place.

Over the long term, some active strategies may give way to more passive strategies. For example, social and institutional interventions may be a short term focus with more immediate benefits, while engineering and ecological solutions are implemented and become effective. For example, with urban greening, it takes time for plants to grow.

Next steps are to further distil the project findings into a set of guidelines for climate adaptation in low income housing. With a strong focus on social housing in this project, a necessary prerequisite is further research on what the findings mean for other low income housing, and how the capacity to respond and options available might vary.

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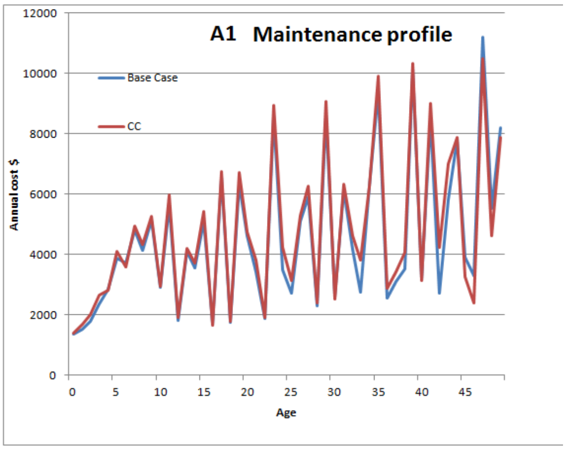
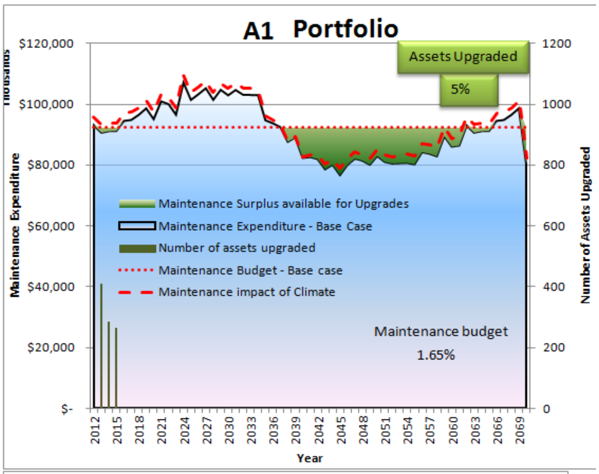
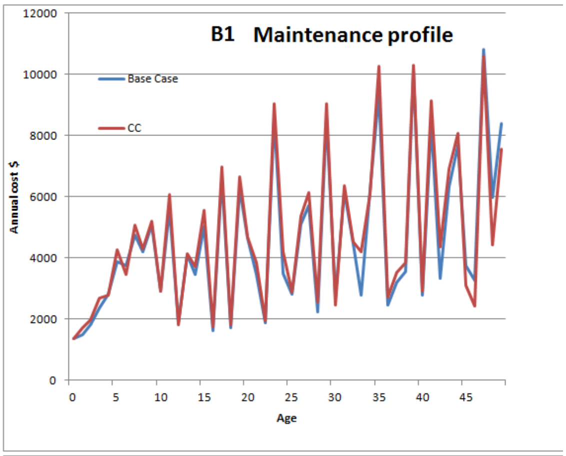
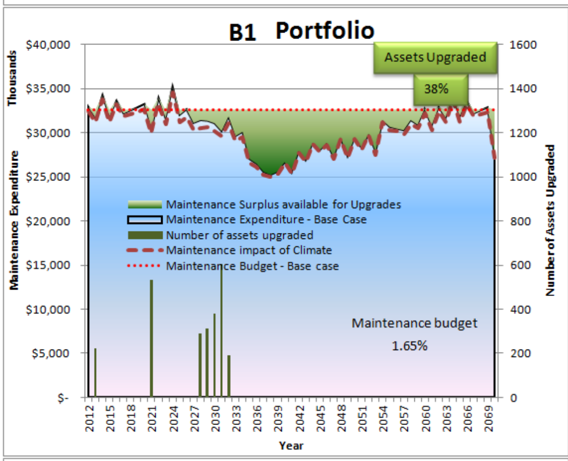
APPENDIX 1: MAINTENANCE AND PORTFOLIO MODELLING

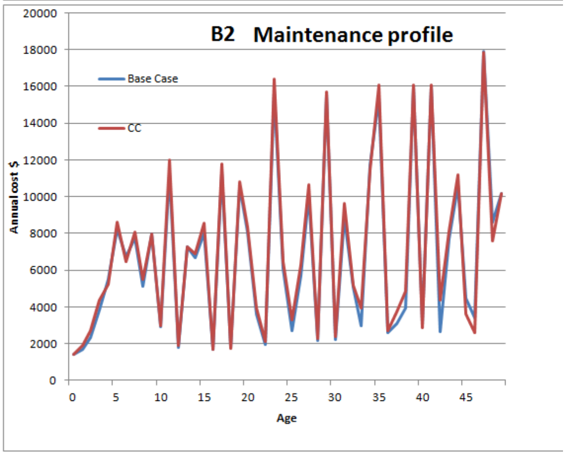
Charts on the left show the expected lifecycle costs for maintaining each housing type (with a ceramic tile roof), showing the impact of climate change. Note that for the low-rise and high-rise house types (E1, F1, G1, and H1) that only the internal components have been considered, so there is no effect of climate change. On the right, portfolio results when maintenance budget surplus is directed to backlog first, then upgrades.

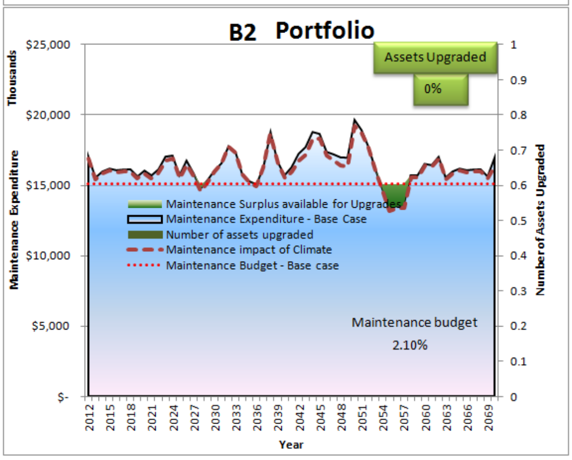


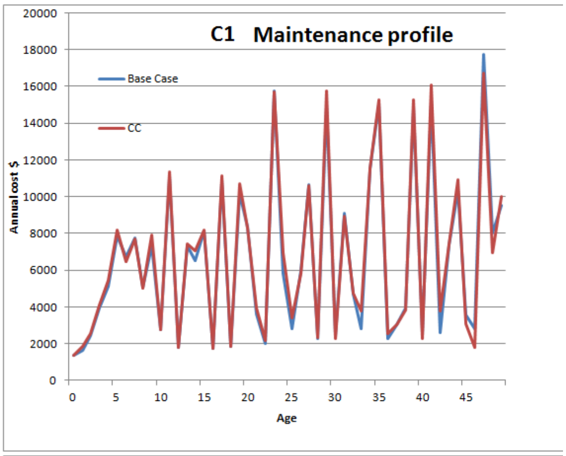


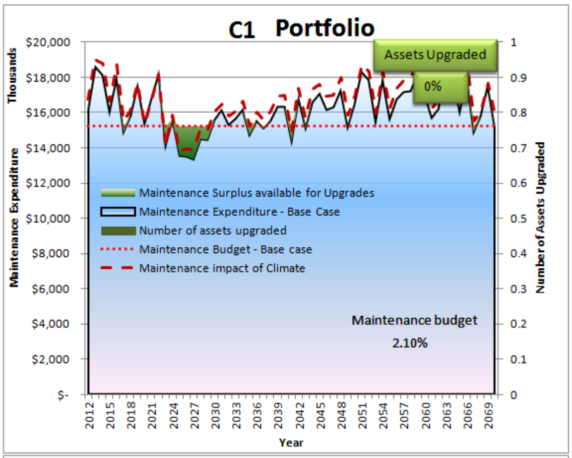


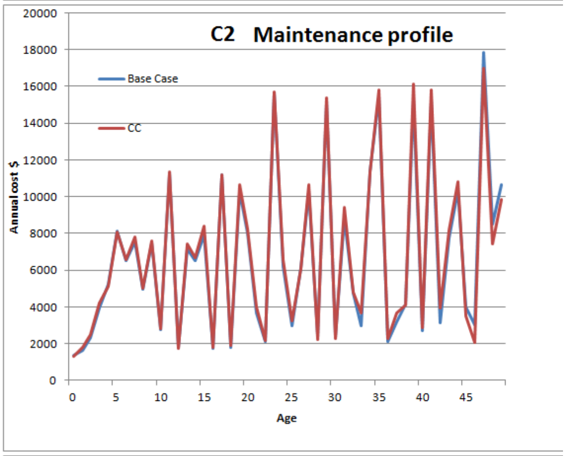


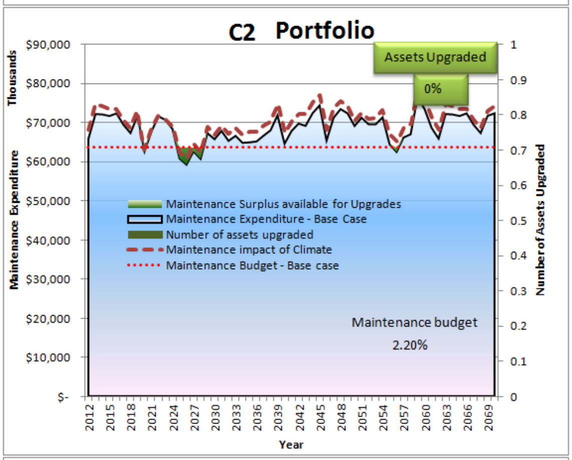


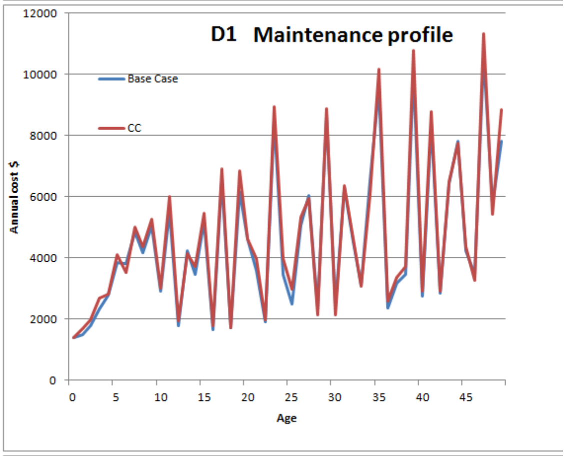


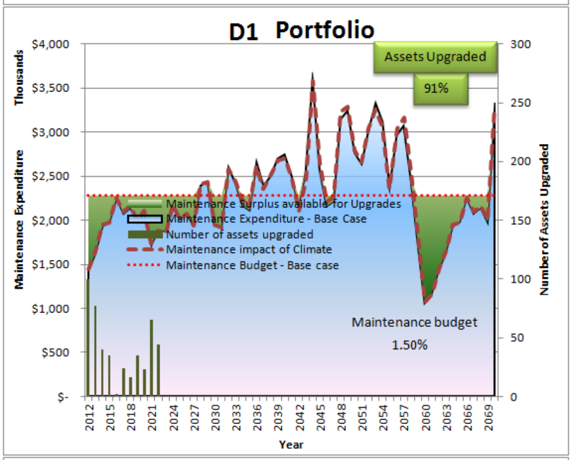

C1 Maintenance profile
Base Case
CC
Annual cost $
Age

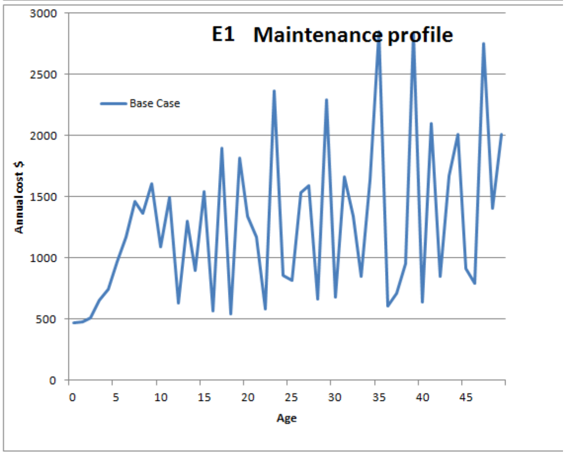

C1 Portfolio
Assets Upgraded
0%
Thousands
Maintenance Expenditure
Number of Assets Upgraded
Maintenance Surplus available for Upgrades
Maintenance Expenditure - Base Case
Number of assets upgraded
Maintenance Budget - Base case
Maintenance impact of Climate
Maintenance budget
2.10%
Year

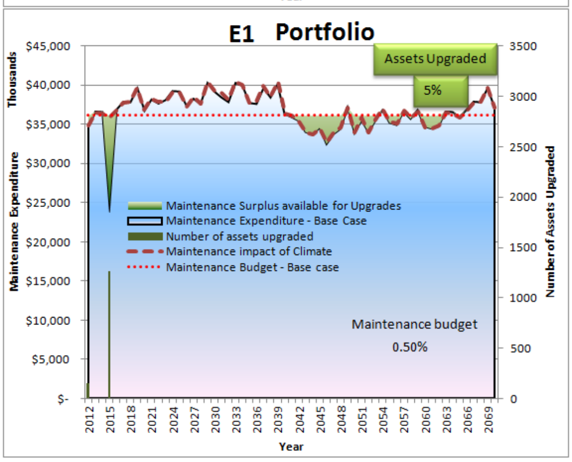

C2 Maintenance profile
Base Case
CC
Annual cost $
Age

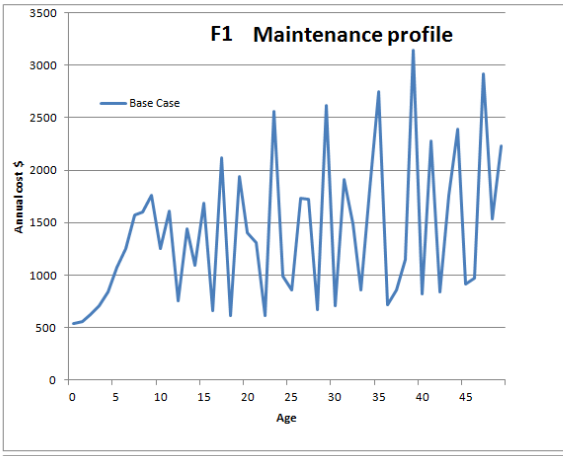

C2 Portfolio
Assets Upgraded
0%
Thousands
Maintenance Expenditure
Number of Assets Upgraded
Maintenance Surplus available for Upgrades
Maintenance Expenditure - Base Case
Number of assets upgraded
Maintenance impact of Climate
Maintenance Budget - Base case
Maintenance budget
2.20%
Year

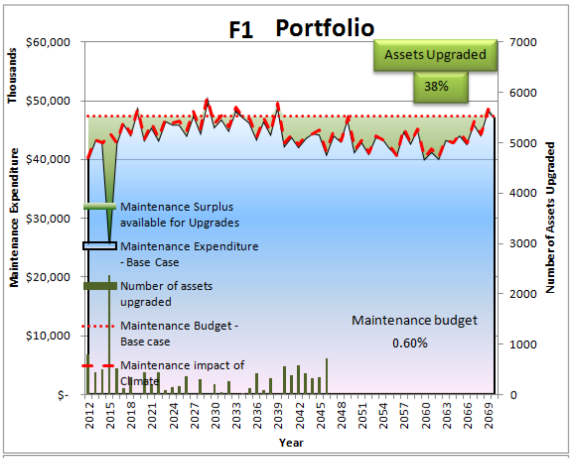

D1 Maintenance profile
Base Case
CC
Annual cost $
Age

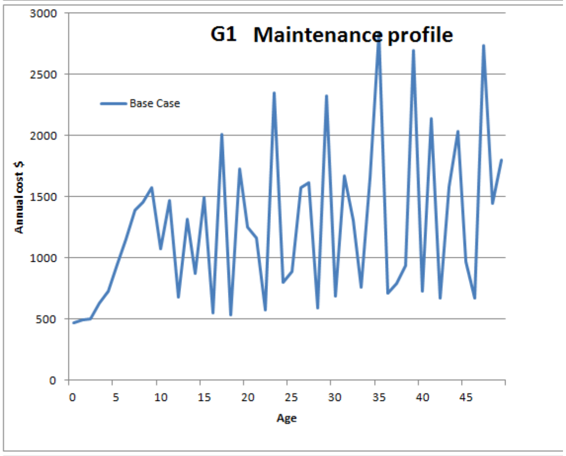

D1 Portfolio
Assets Upgraded
91%
Thousands
Maintenance Expenditure
Number of Assets Upgraded
Maintenance Surplus available for Upgrades
Maintenance Expenditure - Base Case
Number of assets upgraded
Maintenance impact of Climate
Maintenance Budget - Base case
Maintenance budget
1.50%
Year

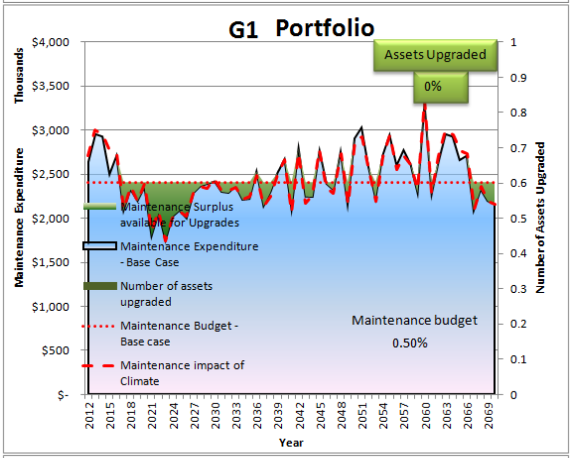

E1 Maintenance profile
Base Case
Annual cost $
Age

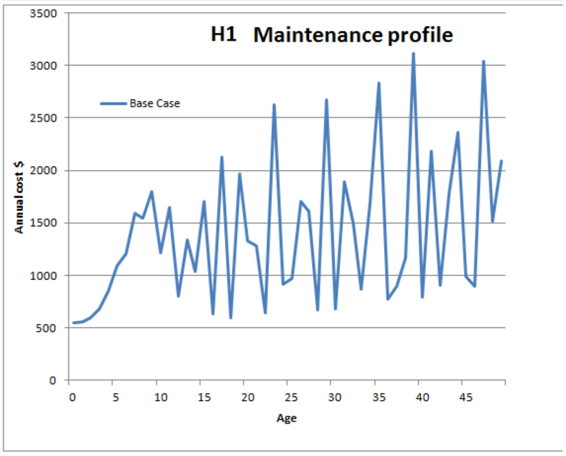

E1 Portfolio
Assets Upgraded
5%
Thousands
Maintenance Expenditure
Number of Assets Upgraded
Maintenance Surplus available for Upgrades
Maintenance Expenditure - Base Case
Number of assets upgraded
Maintenance impact of Climate
Maintenance Budget - Base case
Maintenance budget
0.50%
Year

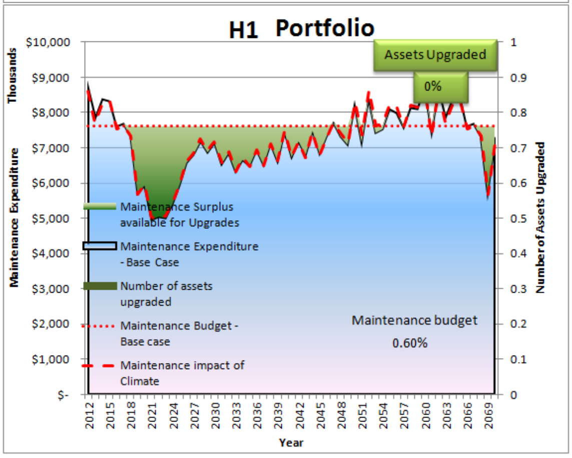

F1 Maintenance profile
Base Case
Annual cost $
Age


F1 Portfolio
Assets Upgraded
38%
Thousands
Maintenance Expenditure
Number of Assets Upgraded
Maintenance Surplus available for Upgrades
Maintenance Expenditure - Base Case
Number of assets upgraded
Maintenance Budget - Base case
Maintenance impact of Climate
Maintenance budget
0.60%
Year


G1 Maintenance profile
Base Case
Annual cost $
Age


G1 Portfolio
Assets Upgraded
0%
Thousands
Maintenance Expenditure
Number of Assets Upgraded
Maintenance Surplus available for Upgrades
Maintenance Expenditure - Base Case
Number of assets upgraded
Maintenance Budget - Base case
Maintenance impact of Climate
Maintenance budget
0.50%
Year


H1 Maintenance profile
Base Case
Annual cost $
Age


H1 Portfolio
Assets Upgraded
0%
Thousands
Maintenance Expenditure
Number of Assets Upgraded
Maintenance Surplus available for Upgrades
Maintenance Expenditure - Base Case
Number of assets upgraded
Maintenance Budget - Base case
Maintenance impact of Climate
Maintenance budget
0.60%
Year

CSIRO

NCCARF
National
Climate Change Adaptation
Research Facility