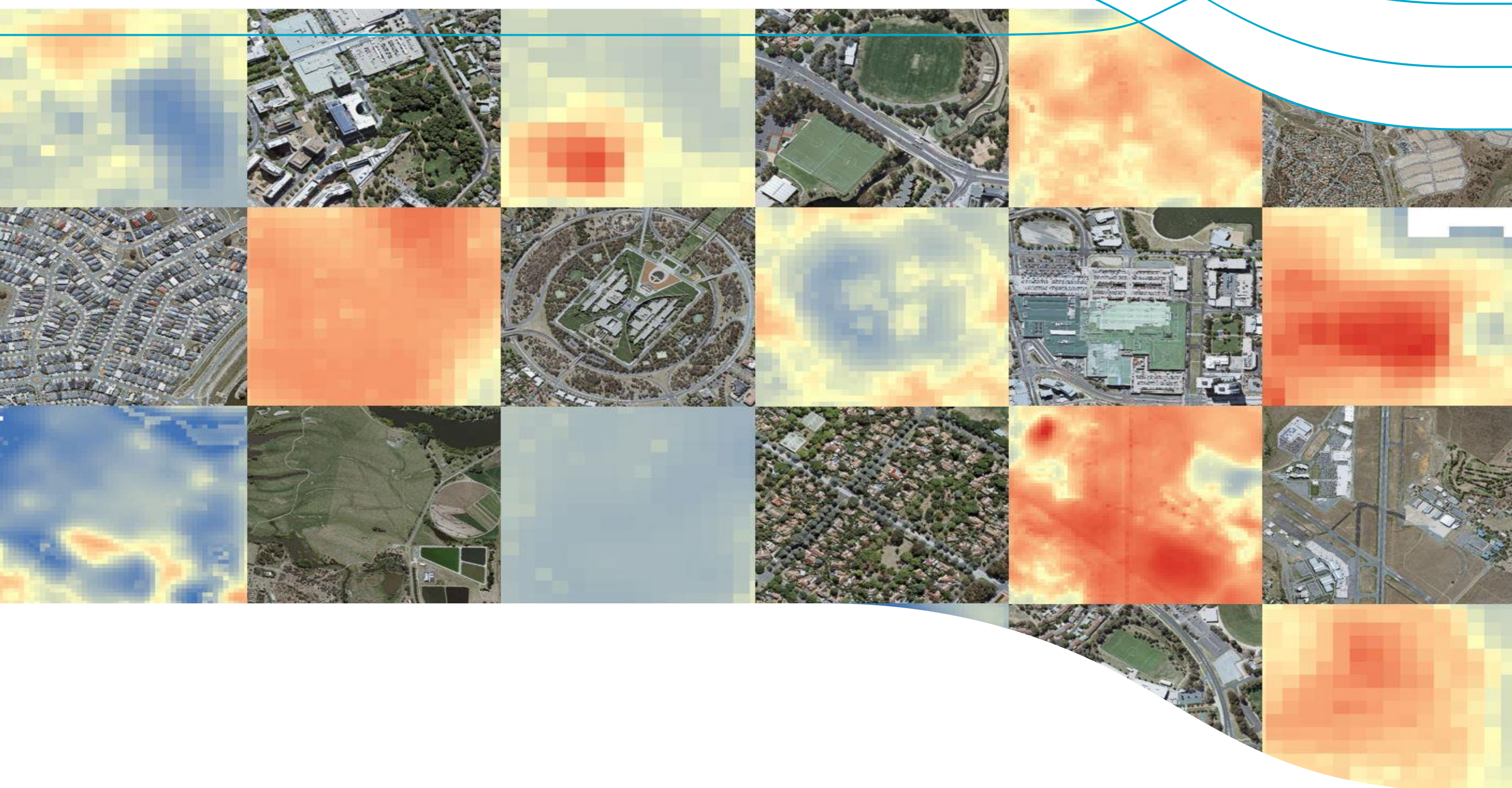
CSIRO LAND AND WATER
www.csiro.au

Mapping surface urban heat in Canberra

Jacqui Meyers, Drew Devereux, Tom Van Niel and Guy Barnett

6 December 2017



Suggested Citation

Meyers J, Devereux D, Van Niel T and Barnett G (2017) Mapping surface urban heat in Canberra. CSIRO, Australia.

Copyright

Important disclaimer

This work was funded by the ACT Government through the Environment, Planning and Sustainable Development Directorate with co-investment from CSIRO Land and Water.

Acknowledgments: We would like to thank staff at the Environment, Planning and Sustainable Development Directorate, in particular Catherine Keirnan for providing valuable advice and feedback throughout the project and Mick Clifford and Belinda Allison for providing data. We also thank Brenda Lin for reviewing the document, Stephen Sarre for providing advice and Karin Hosking for editorial assistance.

Contents

Executive Summary

Purpose and Method

High temperatures in urban areas have multiple impacts on health, resource use, air quality and environmental condition. Canberra experienced several heatwaves in the summer of 2016-17, with 18 days where temperatures exceeded 35 °C. Moreover, Canberra's climate is projected to become warmer, with more frequent and longer heatwaves, more days with extreme heat, and a potential associated increase in the number of heat-related illnesses and deaths. Cold nights are also a feature of Canberra's current climate, with 80 nights in 2017 recording below zero temperatures. Prolonged exposure to extreme temperatures can increase the risk of poor health in vulnerable populations, providing a challenge to reduce urban heat in summer while maintaining protection against winter cold.

In this project, we aimed to map the spatial patterns of urban heat and to a lesser extent cold in Canberra and to identify the neighbourhoods where high heat exposure coincides with high population vulnerability, building the evidence base for informed climate adaptation action.

Specific objectives and methods were to:

- Determine whether Canberra has an urban heat island by developing maps of land surface temperatures from satellite imagery for summer 2016–17 and winter 2017;
- Identify hot spots in summer and cool spots in winter by developing maps of land surface temperature for a hot morning in summer and a cool morning in winter 2017;
- Assess the contribution that land use, tree cover and other built and natural characteristics have in determining patterns of high land surface temperature distribution;
- Develop an index of potential heat-related population vulnerability using data from the ABS 2016 Census of Population and Housing to identify neighbourhoods with a high number of people who are older than 65 years, or younger than 5 years, or low-income households, defined as the lowest 25% of household incomes in the ACT;
- Identify areas where high land surface temperatures coincide with high potential heat-related population vulnerability;
- Provide the ACT Government with digital maps of land surface temperatures that can assist with climate adaptation planning in Canberra.

Key findings

- Canberra has a surface urban heat island at night in built-up areas that was around 8 °C warmer in summer and 6 °C warmer in winter than surrounding rural areas (based on seasonal land surface temperature measurements at approximately 10.45 PM Eastern Standard Time). This difference is largely caused by the nighttime release of heat that has been absorbed by buildings and pavements of urban areas during the day. This slow release of accumulated heat reduces night time cooling relief in summer.

- Land surface temperatures varied by as much as 22 °C in urban Districts and by up to 10 °C in suburban areas (based on data on a hot morning in February 2017 at 10.50 AM).
- Areas with above-average surface temperatures are characterised by large expanses of impervious surface cover such as rooftops and paving, and few trees, common in commercial and industrial areas, carparks and new housing developments. Areas that have been cleared for development or have low, sparse, dry vegetation cover, such as in grasslands, pasture and at Canberra Airport are also hotter as are many artificial playing surfaces. Residential areas with above-average surface temperatures were characterised by little tree cover and higher dwelling densities, particularly if the area was located near open pasture or grasslands.
- Heat-related health risk may be greatest when populations with high heat-related vulnerability are living in the hottest neighbourhoods. Clusters of neighbourhoods with high heat exposure and high population vulnerability were found in Gungahlin as well as some of the newer suburbs in west Belconnen and Molonglo Valley.
- Cooler areas on summer mornings typically have green irrigated vegetation, more tree cover, are near lake edges, or are shaded by buildings or topography. In rural areas, vegetation that has a higher proportion of tree canopy cover also tends to be cooler.
- Areas with below average surface temperatures in winter were found to be on the southern or southwestern sides of hills that are shaded from the winter morning sun and in cool pockets, frost hollows and valley bottoms that receive cold-air drainage (based on data for a winter morning in August 2017 at 9.50 AM).

Heat Mitigation Strategies

Urban heat can be reduced by adopting a mix of strategies and technologies that focus on urban design and the strategic use of vegetation, water and ‘cool’ materials that have higher solar reflectance and thermal emittance. The primary focus of these interventions is to increase the reflectivity and emissivity of surface materials so that less heat is stored in the urban environment, and to increase the cooling benefits through shade, evaporation, evapotranspiration, and by channelling breezes.

Potential heat mitigation options include:

- Planting vegetation in public spaces, along streets, in parks and on walls to provide shade, channel breezes and cool through evapotranspiration;
- Building with ‘cool’ materials or applying surface coatings to increase reflectivity and emittance;
- Paving with permeable or porous materials that enable water to infiltrate the soil and become available for evaporative cooling;
- Building shade structures made from cool materials to intercept solar radiation;
- Maintaining large areas of forest that create advection currents between hotter urban areas and cooler greenspace; and
- Irrigating vegetation and incorporating water features to increase cooling through evaporative processes and cooling breezes.

Potential Next Steps

This report provides maps and information to assist with developing strategies and prioritising actions for mitigating urban heat in Canberra. Three potential areas have been identified to translate this research into practice: taking action now using what we know, collecting more information to fill knowledge gaps, and strategic planning for transformational change. Taking this three-pronged approach across multiple ACT Government portfolios means 'no regrets' actions are implemented to bring about transformational change.

Taking action now:

- Identify priority areas for targeted urban heat mitigation actions;
- Look for opportunities to incorporate low-cost urban heat mitigation actions as part of existing work programs;
- Engage with peak bodies such as the Housing Industry Association and Property Council to identify opportunities to trial ‘cool’ materials and products;
- Implement small strategic trials to quantify cooling benefits, for example, create buffers of trees between hot rural areas and suburbs; strategically place shade structures beside small areas with hot surfaces; or trial the application of cool roof and cool coating technologies;
- Establish an urban heat monitoring program using satellite thermal imagery and field measurements to evaluate heat mitigation actions.

Filling knowledge gaps:

- Verify the relationship between surface and air temperatures throughout the day and across seasons with field based measurements;
- Establish how prevailing winds across rural land influences urban temperatures and whether the type of vegetation adjacent to suburban areas influences those temperatures;
- Determine the influence that different building densities, tree cover and land uses have on air temperature and how this information can be utilised to achieve multiple objectives related to urban temperatures, solar access and to channel breezes;
- Utilise modelling tools and field measurements to assess the cooling potential of different heat mitigation strategies and to maximise cooling potential without increasing winter heating costs.

Strategic planning for transformational change:

- Effective engagement to acknowledge and address different opinions, backgrounds and agendas on urban heat, so that they can be incorporated into planning processes;
- Enhance cross-portfolio climate adaptation planning by identifying actions that can satisfy multiple objectives, delivering co-benefits as part of a ‘whole-of-organisation’ approach;
- Assess how to incorporate actions into established programs, policies and management strategies; and
- Develop scenarios that incorporate estimates of urban temperature reductions under a range of heat mitigation strategies and use workshop and modelling processes to explore the potential to achieve multiple portfolio objectives and to address competing challenges and trade-offs.

1 Introduction

1.1 Context

The *ACT Climate Change Adaptation Strategy*[1] forms the basis for the ACT Government to develop actions to adapt to and reduce vulnerability to the potential impacts of climate change. Among several potential impacts in the ACT are increasing temperatures and more frequent and severe heat wave events[1]. Prolonged exposure to extreme temperatures (heat and cold) can increase the risk of temperature-related mortality and morbidity in vulnerable populations[2]. This can provide a challenge for urban planners and managers to reduce urban heat in summer while maintaining, or enhancing, protections against winter cold. Identification of public spaces that have high heat and cold exposure, and residential neighbourhoods that have high temperature exposure and high population vulnerability, allows targeting of remedial actions to reduce risk.

The aim of the project was to improve understanding of the spatial patterns of urban heat and cold in the ACT and associated population vulnerabilities, building the evidence base that is required to inform ACT Government decision making on climate adaptation actions.

1.2 Project Objectives

The objectives of the project were to:

1. Generate daytime land surface temperature maps for individual days in summer 2016–17 and winter 2017 using moderate resolution (30 m pixel size) Landsat 8 thermal infrared data;
2. Generate seasonal daytime and nighttime land surface temperature maps for summer 2016–17 and winter 2017, using coarse resolution (1 km pixel size) MODIS thermal infrared data;
3. Identify the hottest and coolest areas in metropolitan Canberra and assess the contribution of land-use type and other built and natural characteristics in determining these patterns; and
4. Develop a simple vulnerability index to identify residential areas where high land surface temperatures coincide with high populations of potentially heat sensitive people.

1.3 Structure of this Report

This Section has introduced the project context and objectives. Section 2 provides an overview of Canberra's climate, a description of why urban heat is a problem, how it is measured, and a discussion of heat sensitivity and population health. This is followed in Section 3 by a description of the methods and associated technical details that have been adopted in the project. The findings of the research are presented in Section 4, which includes maps showing land surface temperatures and population vulnerability for the whole of the ACT and for the metropolitan area. Detailed maps for individual Canberra Districts and Villages are provided in Appendix 1. Section 5 outlines potential heat mitigation strategies including urban design and the strategic use of 'cool' building materials, vegetation and water. The report concludes in Section 6 with a set of identified next steps targeting immediate actions, strategic opportunities, and future research.

2 Background

2.1 Climate in the ACT

The ACT has a climate with four distinct seasons characterised by warm to hot summers and cool to cold winters. The climate can be highly variable across the ACT, with the northern plains around 8 °C warmer in summer than at higher elevations in the southern Brindabella Ranges[3]. Cold nights are a feature of Canberra's climate, with 80 nights in 2017 recording below zero temperatures at Canberra Airport[4]. Canberra also commonly experiences heat wave conditions. In the summer of 2016–17, there were 18 days when the maximum daily temperature exceeded 35 °C[4].

Canberra's climate is projected to become warmer, with more frequent and longer heatwaves[1], more days with extreme heat, and a potential increase in the number of heat-related illnesses and deaths[5]. Warmer days are likely to start earlier in the season and end later[1].

2.2 Urban Heat Islands

Temperatures in many urban areas are warmer than their rural surroundings. This phenomenon is known as the 'Urban Heat Island' which refers to temperature differences attributable to urbanisation. Urban heat islands occur because buildings and hard paved surfaces absorb solar radiation and release it slowly back into the environment at night. As a consequence, the urban heat island is typically most evident at night[6]. Cooling at night is further reduced if the layout and design of buildings and streets traps the warm air making it even slower to release at night. Urban heat islands can have multiple impacts on health, resource use, and air quality[7].

Other factors also contribute to the urban heat island. On hard paved surfaces, surface water is washed away after rain and is not available in the soil for evaporative cooling. In addition, cities typically have less vegetation cover than surrounding areas and therefore receive less of the cooling benefits that vegetation provides through shade and evapotranspiration[8, 9]. Anthropogenic heat produced from human sources such as factories, vehicles and air-conditioners also contributes to the urban heat island[10].

2.3 Surface Urban Heat Island

In the absence of a dense network of meteorological stations to measure air temperature, satellite thermal infrared imagery is commonly used to estimate land surface temperatures instead[11]. The use of satellite remote sensing has been widely adopted for assessing urban heat in Australian cities[12, 13], including Canberra[14], and when integrated with other locally sourced information, can provide an effective way to assess current conditions and to monitor changes over time across a wide area.

The term 'urban heat island' is used when air temperature is measured, but when land surface temperatures are measured, the term 'surface urban heat island' is used. The presence of a surface urban heat island indicates that an urban heat island phenomenon is occurring. There is not always a direct relationship between air and surface temperatures, however, but air temperature hotspots often occur where there are high land surface temperatures[12].

Land surface temperatures are most similar to near-ground air temperatures early in the morning[15], but surface temperatures become more variable throughout the day, and are much faster to respond to sudden changes in shade, such as those caused by clouds passing overhead[15]. Large areas of greenspace tend to have cooler surface temperatures and cooler air temperatures, whereas dense, built-up areas will typically have warmer surface temperatures and air temperatures[16, 17]. There can be a disconnect between air temperature and surface temperature when it is windy[12] and between rooftop temperatures on tall buildings and temperatures measured at street level[17]. In most situations, however, land surface temperatures are useful for gauging the level of exposure to urban heat, even if there is not always a direct relationship with air temperature.

2.4 Population Vulnerability: Sensitivity of People to Extreme Heat

Optimal human health and physiological functioning relies on the maintenance of an internal body temperature within a narrow range around 36.8 ˚C[2]. Physiological and behavioural responses help to maintain body temperature within this range[5], but higher or lower core temperatures can lead to serious illnesses and in extreme cases, death[18].

In hot weather, core body temperature is maintained by shedding heat through the dilation of blood vessels in the skin and by sweating, although sweating can create health problems in some people owing to an associated increase in heart rate and cardiac function[19]. The ability to shed heat is compromised in some people, particularly those who are elderly[20, 21], or very young[21], or people who are unable to care for themselves[22, 23]. Excessive heat can also exacerbate some mental and physical health conditions[24, 25]. As a consequence, these groups of people are highly sensitive to prolonged exposure to extreme heat in their surrounding environment. Dressing in light clothing, keeping well-hydrated, using air-conditioning, and adopting various behavioural strategies, such as seeking refuge in cool places, can reduce heat exposure and therefore reduce heat-health risk[22, 26].

People in low socioeconomic circumstances may be particularly vulnerable to high heat exposure if high costs restrict their ability to cool their homes[27, 28]. This exposure is exacerbated in many low-income households by housing of poor quality and low thermal performance[29, 30]. In some Australian cities, low-income households are often found in some of the hottest parts of the city[31].

Heat mitigation within a city is therefore particularly beneficial for people who are sensitive to heat exposure through a combination of socioeconomic, health and age related vulnerability. By identifying the areas of highest heat exposure and areas with highest heat-related population vulnerability, it is possible to target actions that reduce urban heat in areas of greatest need[32].

Exposure to cold conditions in winter is also a health issue in Canberra[33] and some groups have a greater risk than others of poor health from prolonged exposure to cold conditions[34]. Risk factors are similar to those for people who are vulnerable to high heat exposure[35], with the elderly and very young at greatest risk[34]. Other studies have shown that pre-existing medical conditions, being female, living in low socioeconomic circumstances and exposure to cold indoor temperatures all increase the risk of poor health outcomes[35].

3 Methods and Technical Details

3.1 Land Surface Temperatures

3.1.1 Image Resolution, Frequency and Limitations

Two types of thermal remote sensing products were used for this study; moderate resolution Landsat 8 thermal imagery (collected every 16 days with 100 metre pixel resolution and downscaled to 30 metres) and coarse resolution MODIS thermal imagery (collected twice daily at 1 km resolution). Both Landsat 8 and MODIS imagery are captured when the satellites pass over mid-morning, while MODIS imagery is also captured during a second pass late in the evening. In this project, we use the finer resolution Landsat 8 imagery to assess daytime surface temperatures and the coarser resolution MODIS imagery to compare daytime with nighttime surface temperatures.

The surface temperatures gathered using these approaches provide an average of the on-ground temperatures observed within the area of each pixel, enabling generalisations to be made about the contribution of surface features to the pixel temperature. These generalisations become less precise as the pixel resolution decreases. Consequently, MODIS imagery, which has a 1 km pixel resolution, will provide less precise information than Landsat 8 imagery which has 30 metre pixel resolution.

It is important to note that surface temperature is not the same as air temperature. Satellite remote sensing provides a snapshot of surface temperatures at the time the satellite passes overhead. Consequently, it can’t be assumed the pattern of surface temperature observed when the satellite passes over will reflect surface temperature patterns observed at other times of the day.

While satellites are suitable for collecting information for horizontal surfaces with a clear sky view, such as rooftops, roads and the tops of tree canopies, they cannot capture information beneath tree canopies or on vertical surfaces such as the sides of buildings. For this reason, the surface temperature of steep slopes may be less precise and should be treated with caution. The same applies to surfaces with very low emissivity, such as highly reflective rooftops.

3.1.2 Daytime Land Surface Temperatures (Landsat 8)

The Landsat 8 thermal infrared data used for this study were collected by the United States Geological Survey at approximately 9.50 AM Eastern Standard Time (EST); 10.50 AM Daylight Saving Time (DST). Only two images in summer 2016–17 and two in winter 2017 were cloud free across all of metropolitan Canberra and were therefore suitable to be included in this project (Table 1). Any small areas of cloud cover detected over the non-urban areas were removed from the imagery before analysis.

Table 1. Daily and 9 AM weather conditions at Canberra Airport (Bureau of Meteorology Station 070351) on the days of the Landsat 8 imagery collected for this study.

Daily and 9 AM weather at Canberra Airport	Date of Landsat 8 imagery 23 Dec 2016	9 Feb 2017	1 June 2017	20 August 2017
Daily minimum air temperature	14.6 °C	17.5 °C	–4.2 °C	–3.0 °C
Daily maximum air temperature	31.8 °C	36.0 °C	13 °C	13.2 °C
Daily rainfall	0 mm	0 mm	0 mm	0.2 mm
9 AM air temperature	18.7 °C	22.4 °C	5.4 °C	5.1 °C
9 AM relative humidity	63%	68%	70%	63%

Two thermal bands are collected by Landsat 8 (Band 10 and Band 11), but calibration uncertainty in Band 11 created by stray light entering the sensors rendered Band 11 unsuitable for use. A single combined image covering the full geographic extent of the ACT for each sample date was stitched together from two smaller adjoining images. For each of these combined images, land surface temperatures were estimated following the method of Jimenez-Munoz and Sobrino[36, 37], using modifications appropriate for Landsat 8[38, 39]. Values for total atmospheric water vapour content were calculated using 9 AM temperature and relative humidity observations from Canberra Airport (see Table 1).

The required inputs were derived as follows. Land surface emissivity was estimated using an approach based on the normalized difference vegetation index (NDVI)[38, 40, 41]. This approach calculates the fractional vegetation cover for each pixel, which in turn is used to determine an emissivity value that is intermediate between vegetation and non-vegetation emissivity values. A pixel at the lower threshold is treated as containing no vegetation and may comprise bare soil, asphalt, brick, concrete and other similar surface materials. For high fractional vegetation cover, the upper threshold was set to 0.9863 as recommended by Yu et al.[38].

3.1.3 Seasonal Day and Night Land Surface Temperatures (MODIS)

MODIS imagery is collected twice daily, once in the morning at approximately 10.15 AM EST and again in the evening at approximately 10.45 PM EST. MODIS land surface temperature data has a coarse resolution of 1 km pixel size. Unlike Landsat, there is a MODIS land surface temperature product available from the United States Geological Survey, ready for use in science applications, produced using the generalised split-window land surface temperature algorithm (MOD11A1 v5).

Daytime and nighttime land surface temperature images were sourced for 81 days during the 2016–17 summer (from 7 December 2016 to 25 February 2017) and for 92 days over the winter season (from 1 June 2017 to 31 August 2017). Multiple images were combined to form a single composite image covering the full geographic extent of the ACT.

Areas of cloud cover and data of poor quality collected from high view zenith angles greater than 30 degrees were removed from the composite images. The remaining data in each image were used to derive a summer and winter seasonal averages for day and night on a per-pixel basis. On average, the number of images used to derive the daytime data for each pixel was 16.4 in summer and 18.6 in winter and for nighttime data it was 12.5 in summer and 18 in winter.

3.2 Natural and Built Urban Features

Some characteristics which may influence land surface temperatures include land use, percent tree canopy cover, dwelling density, dominant dwelling structure, and proximity to natural features such as grasslands. This study does not extend to estimates of impervious surface cover, or the type of materials used in construction, but this would be a useful inclusion in any further assessments.

Estimates of gross dwelling density and dominant dwelling structure were derived using data from the ABS 2016 Census of Population and Housing. Distance to grasslands was calculated within the software package ArcGIS[42] using grassland distribution data contained in the Canberra Vegetation Structure Map obtained through ACTmapi[43]. Land use was determined using the ACT Territory Plan Land-Use Zone map obtained from ACTmapi (version R184 dated 7th April 2017)[44].

Percent tree canopy cover was calculated using a map of Tree Canopy Cover provided by the ACT Government[45] that was derived, in part, using LiDAR data, an airborne survey method that measures distance to a target using laser light. This dataset was corrected, in this study, to exclude features taller than 30 metres in height. This was deemed necessary as a comparison with aerial photography found that trees in urban Canberra are rarely taller than 28 metres high. This correction removed many features such as tall light poles, power lines, cranes and other built structures that could have been misclassified as trees.

3.3 Population Vulnerability

3.3.1 Population Vulnerability Index

An aggregated population vulnerability index was created. There are many different factors that could be used to develop such an index and many possible techniques for constructing one[32, 46, 47]. Previous studies have found a correlation between several potential factors, so a smaller number of factors can capture a large proportion of the vulnerable population in a defined area[5].

The vulnerability index was created using data from the 2016 ABS Census of Population and Housing. Every five years, the census collects information about where people live, the type of dwelling they are living in, as well as various demographic and socioeconomic attributes that help to identify the neighbourhoods where vulnerable people are living.

Individual and household data are aggregated by the ABS to the area of a Mesh Block, which is the smallest area for which demographic and socioeconomic census data are available[48] and is designed to maintain confidentiality of individuals and households. Most residential Mesh Blocks contain between 30 and 60 dwellings, but if there are more dwellings in a large building or complex, then these will be grouped together in one Mesh Block, often resulting in a higher dwelling count[48].

The heat-related health risk of individuals was defined using data on the number of people within a Mesh Block who are older than 65 years, the number of children younger than 5 years, and the number of low-income households. For future assessments, an index such as the ABS SEIFA Index of Relative Socioeconomic Disadvantage would be a useful inclusion, but the SEIFA data sets for the ABS 2016 Census were not available at the time of this project and are scheduled for release in 2018.

Low-income households are commonly defined as the lowest 20% or 25% of households[29, 49]. The amount of disposable income within a household, however, will depend on the number of people living in the household and the age of the occupants. A 'modified OECD' equivalence scale is therefore used by the ABS to provide a more accurate measure of economic resources available to a standardised household[49]. In this project, households with an equivalised annual income of between $0 and $41,548 are defined as low-income, which represents the lowest 25% of household incomes in the ACT.

To populate the vulnerability index, data for the number of people and households in each Mesh Block were extracted from the ABS for the 2016 Census for each of the three age and income related population vulnerability factors. For each factor, the value for the 80th percentile of data values was determined and a score was assigned as follows. A vulnerability score of 1 was applied each time one of the following criteria were met within each Mesh Block: more than 18 people who were over 65 years of age; more than 10 children under 5 years of age; and more than 11 households with low incomes.

An aggregated vulnerability score was then created by summing the individual vulnerability scores, so that a Mesh Block that was in the top 20% for all three population vulnerability factors was given an aggregate score of 3, a Mesh Block that was in the top 20% for two of the population vulnerability factors would receive an aggregate score of 2, and so on.

3.3.2 Population Vulnerability in Heat Exposed Neighbourhoods

Mean land surface temperature was calculated for each Mesh Block to enable comparisons to be made with Mesh Block population vulnerability. The Mesh Block geography is not the same as the ACT Territory Plan geography that is used for planning within the ACT, but Mesh Blocks were used as they are relatively consistent in size across residential areas within the ACT, with most containing between 30 and 60 dwellings[48].

The mean land surface temperatures were classed into five classes, with each class containing 20% of Mesh Blocks, from the coolest land surface temperatures to the hottest. The two layers, population vulnerability and mean land surface temperatures, were then overlaid so that those areas with both high heat exposure and high population vulnerability could be identified.

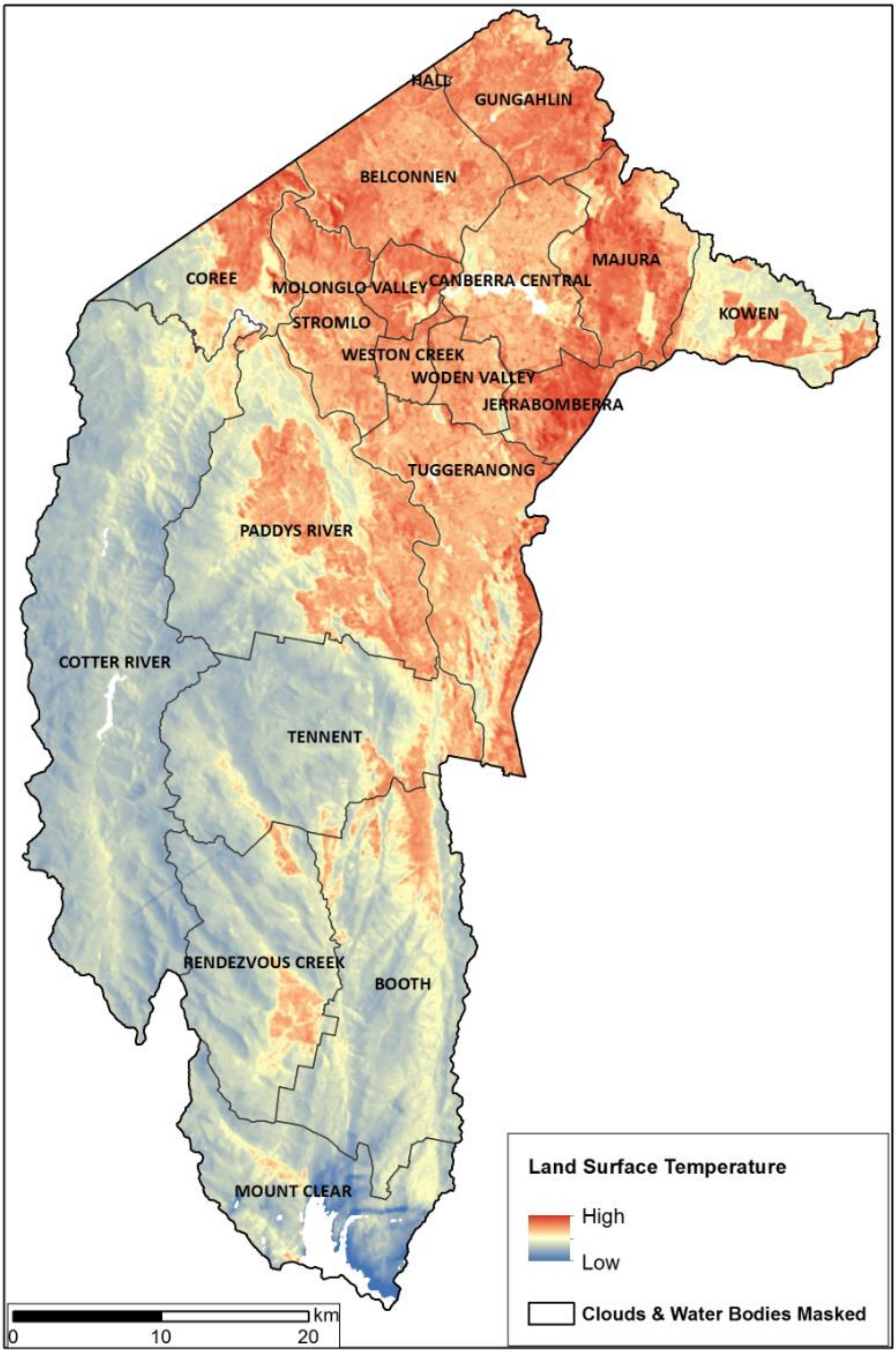


Figure 1a. Land surface temperatures for the ACT for 9 February 2017, based on Landsat 8 thermal remote sensing imagery (10.50 AM DST). Data for the southern-most tip of the ACT has been excluded owing to cloud cover.

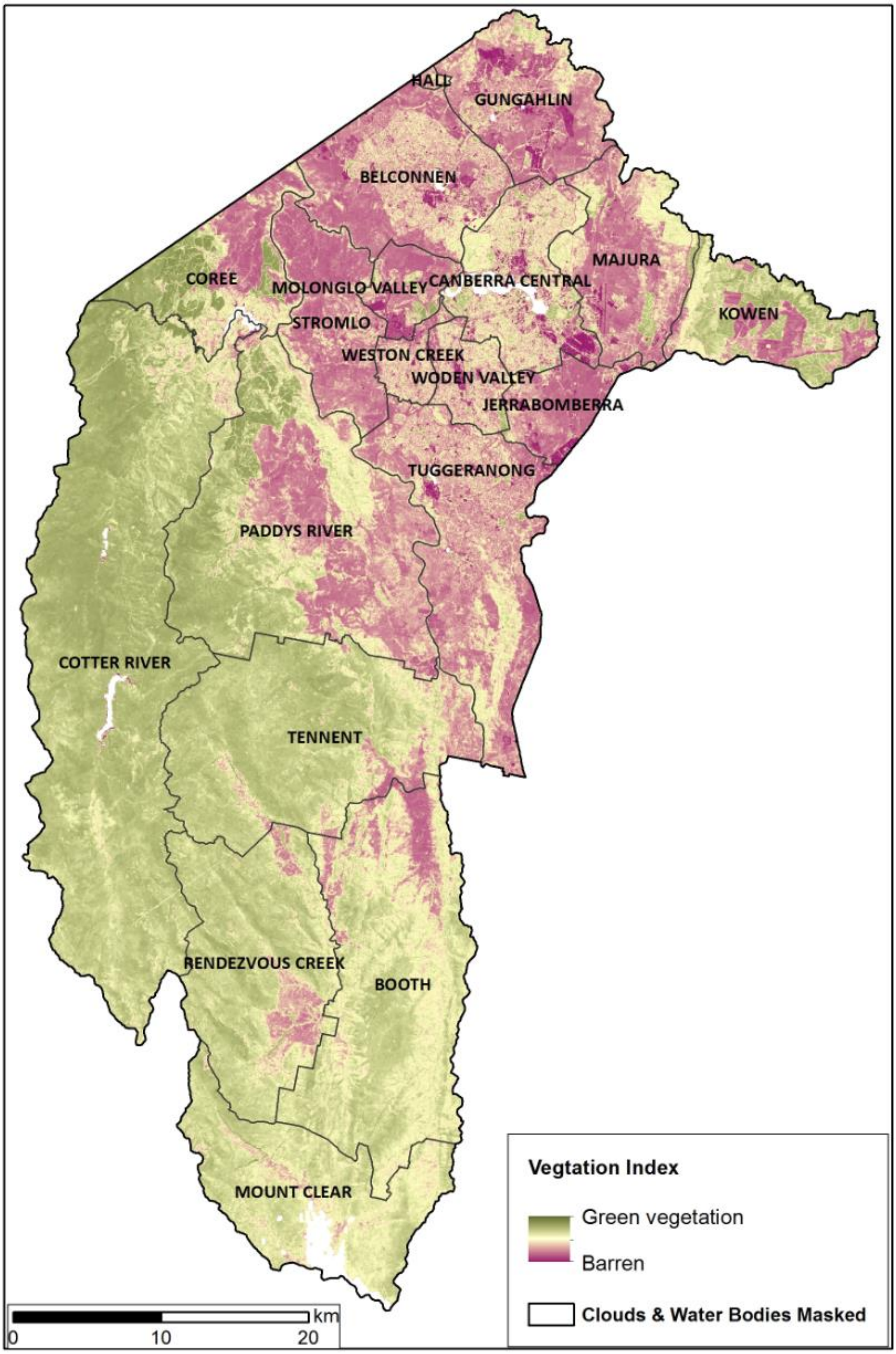


Figure 1b. Vegetation greenness index (NDVI) for the ACT for 9 February 2017, based on Landsat 8 remote sensing imagery (10.50 AM DST).

4 Results and Discussion

Land surface temperatures maps were derived from remote sensing imagery captured mid-morning and late in the evening. In this report, the term '*mid-morning*' is commonly interchanged with '*day*' or '*daytime*', and '*evening*' is commonly interchanged with '*night*' or '*nighttime*'.

4.1 Summer in the ACT: Where is it Hot?

The map of land surface temperatures for the 9th February 2017 (10.50 AM DST) covering the full extent of the ACT reveals cooler temperatures in the western and southern ranges and warmer temperatures in the northern and urban areas (Figure 1a). This is in line with general patterns of air temperature found throughout the ACT in summer, with warmer temperatures on the northern plains and cooler temperatures at higher elevations in the southern Brindabella Ranges[3].

The forests in the southwest of the ACT have the highest index for vegetation greenness (NDVI) (Figure 1b) whereas urban forests and suburban vegetation have moderate NDVI values. Still lower vegetation greenness/vigour is found in pasture, grasslands, and built-up areas. Areas with the lowest NDVI values are devoid of vegetation, or have very little vegetation cover. This includes water bodies and areas of paved or bare ground, including areas cleared for urban development.

Overall, there is a clear relationship between land surface temperature and NDVI (Figures 1a, b) in the ACT, with cooler temperatures associated with high NDVI and warmer temperatures with low NDVI. Other factors such as vegetation type, elevation, terrain, rainfall, wind, water bodies, soil moisture and the presence of rock outcrops will also influence land surface temperatures.

Jerrabomberra District had the highest mean land surface temperature (38.1 °C; 2.8 °C SD) at the time of image capture and Mount Clear District was the coolest (23.4 °C; 3.9 °C SD). When land surface temperatures are averaged for land use, 'Industrial Mixed Use' was the hottest land use (38.2 °C; 1.5 °C SD) and 'Mountains and Bushlands' was the coolest (25.1 °C; 3.7 °C SD).

4.2 Summer in Canberra's Urban Districts: Where is it Hot?

4.2.1 Summer Surface Urban Heat Island

Daytime and nighttime patterns are clearly evident in the urban areas of the ACT in the summer of 2016–17 (Figure 2a, b) even at the relatively course scale of 1 km pixel resolution. Cooler areas are evident in the forests and around Lake Burley Griffin (Figure 2a), while hotter areas are evident in grassland, pasture and areas cleared for development, particularly in the District of Majura near the airport, Jerrabomberra and the western Districts. The temperature signal for built-up areas is more mixed, ranging from cooler surface temperatures in central and inner-south suburbs to warmer surface temperatures in Gungahlin and west Belconnen. The surface urban heat island is not evident in the daytime map (Figure 2a), which is in line with similar findings from other cities.

In contrast, the surface urban heat island is clearly evident in the late evening (Figure 2b). The coolest areas at night are areas of grass and pasture and the forests in southern Tuggeranong, while the warmest areas are in built-up urban areas, particularly around Lake Burley Griffin. This pattern of higher temperatures in the urban area at night is typically caused by heat that has been absorbed into buildings, paved surfaces and water bodies. These areas store solar radiation on hot days and cool down more slowly at night than areas without urban development.

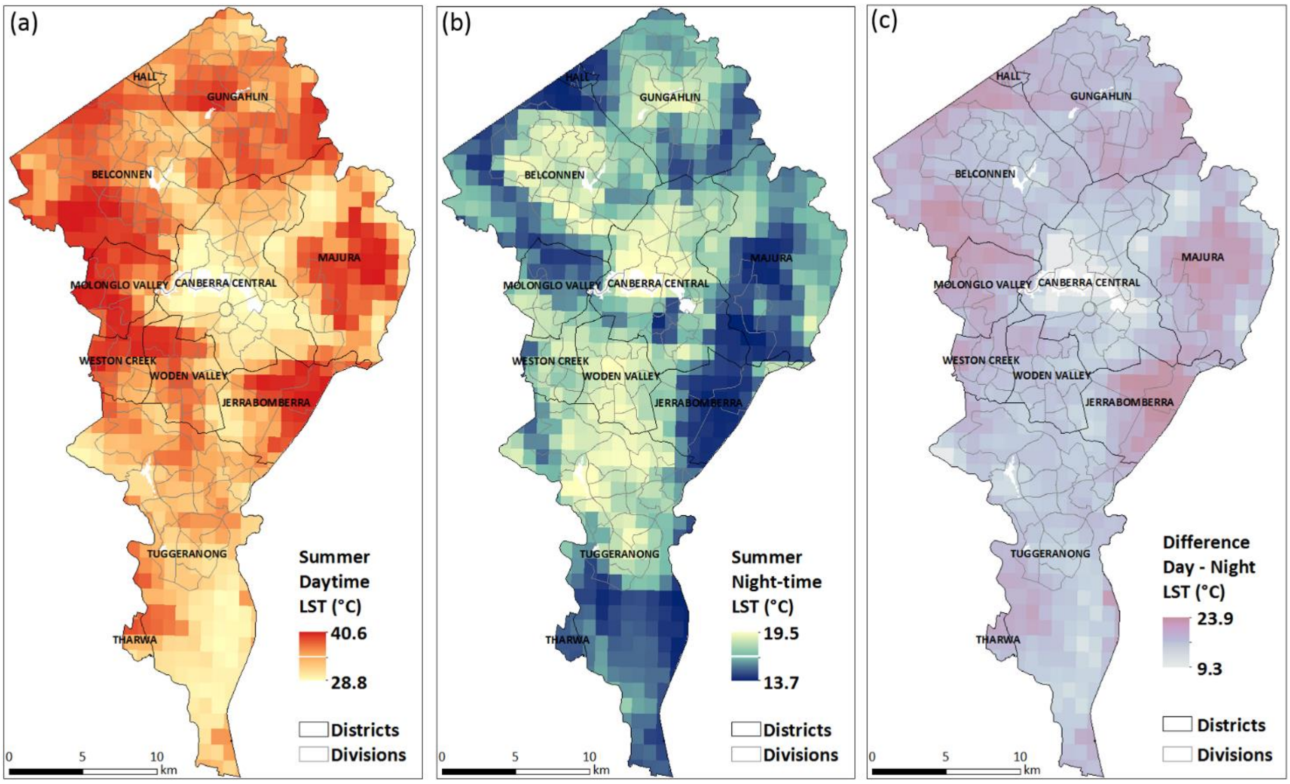


Figure 2. Summer 2016–17 seasonal land surface temperature maps for the urban Districts and Villages of the ACT; (a) morning at ~10.15 AM EST, (b) evening ~10.45 PM EST, (c) the morning to evening difference. The images were derived from MODIS remote sensing imagery.

The maps also show that there is less day to night temperature change in the lake areas (Figure 2c). This is most likely because the temperature of large bodies of water, like Lake Burley Griffin, varies little between day and night due to their high heat holding capacity[16]. Lakes can provide substantial cooling benefits during the day, but cooling benefits are limited when conditions are hot and still at night[50].

The forested areas also show less temperature change, being cooler during the day and at night. The grasslands and pasture show the highest day to night temperature change, from hot during the day to cool at night. Native grasslands and pastures tend to have low, open vegetation cover and patches of bare ground. Many of the grasses are C4 grasses which retain water in hot weather by greatly reducing transpiration[50, 51]. C4 grasses tend to keep their stomata closed during the day and open them at night, which in turn reduces daytime cooling.

While the daytime map shows clear temperature differences between the grassland and forested areas, the temperatures of the two vegetation types are more similar at night, while urban areas are clearly warmer.

Based on the coarse scale MODIS imagery, the mean summer land surface temperatures for the six main vegetation structure classes confirms that while the grasslands are the hottest vegetation type mid-morning, they are also the coolest in the evening (Table 2). On the other hand, forest vegetation is the coolest mid-morning, but is the most stable, cooling down the least at night.

Table 2. Mean summer land surface temperatures for vegetation structure classes for the areas shown in Figure 2 for the summer of 2016–17. The data are based on MODIS imagery at approximately 10.15 AM and 10.45 PM EST.

Vegetation Class	Mean Land Surface Temperature (°C) Day 10.15 AM	Evening 10.45 PM	Difference
Grassland	36.9	16.14	20.78
Open Woodland	36.4	16.61	19.84
Woodland	36.0	16.92	19.12
Urban Vegetation	35.9	17.8	18.07
Open Forest	35.2	17.1	18.11
Forest	34.4	17.1	17.27

4.2.2 Summer Daytime Land Surface Temperatures

A more detailed investigation of daytime patterns using the finer resolution Landsat 8 imagery (30 metre resolution) is now provided. Generally, daytime land surface temperatures of the area that includes the urban Districts and Villages show similar patterns of land surface temperature distribution between the December and February days (Figure 3). However, there is a shift in the hottest areas over the summer, from the north and east in December (Figure 3a) to grasslands, pasture and exposed areas in the east and west in February (Figure 3b). While not shown here, images of vegetation vigour (NDVI) suggest this geographic shift in the highest land surface temperatures may be associated with the curing of grasses and drying-out of grassed areas over the summer. This results in relatively higher temperatures in grasslands and pasture areas, particularly in late summer, compared to Canberra's built-up areas.

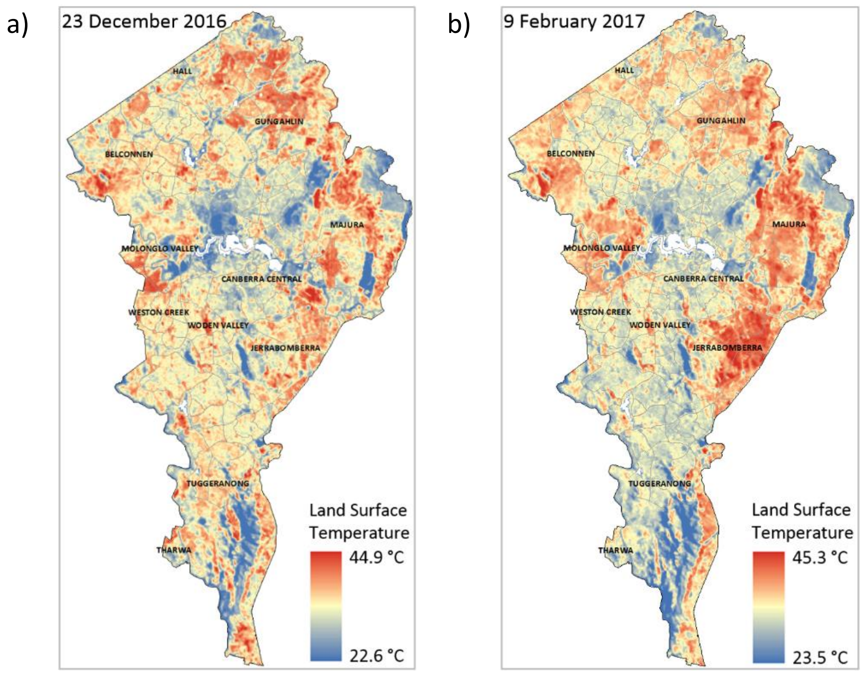


Figure 3. Land surface temperature maps for (a) 23 December 2016 and (b) 9 February 2017. The images were derived using Landsat 8 thermal remote sensing imagery at 10.50 AM DST.

4.2.3 Land Surface Temperatures on 9th February 2017

While the two land surface temperature maps for summer (Figure 3a, b) have similar ranges in temperature, subsequent analyses in this report will focus on the hotter of the two days, the 9th February 2017. This day follows on from a very dry January that received only 8.4 mm of rain at Canberra Airport. A maximum temperature at Canberra Airport of 36 °C and an overnight minimum of 17.5 °C were observed on 9th February 2017. It marked the beginning of a heatwave, with the next two days recording 41 °C and 41.6 °C respectively. At 10.50 AM, when the imagery was captured, the land surface temperatures in the *Urban Districts and Villages* area ranged between 23.5 °C and 45.3 °C, with a mean land surface temperature of 34.4 °C (Figure 4).

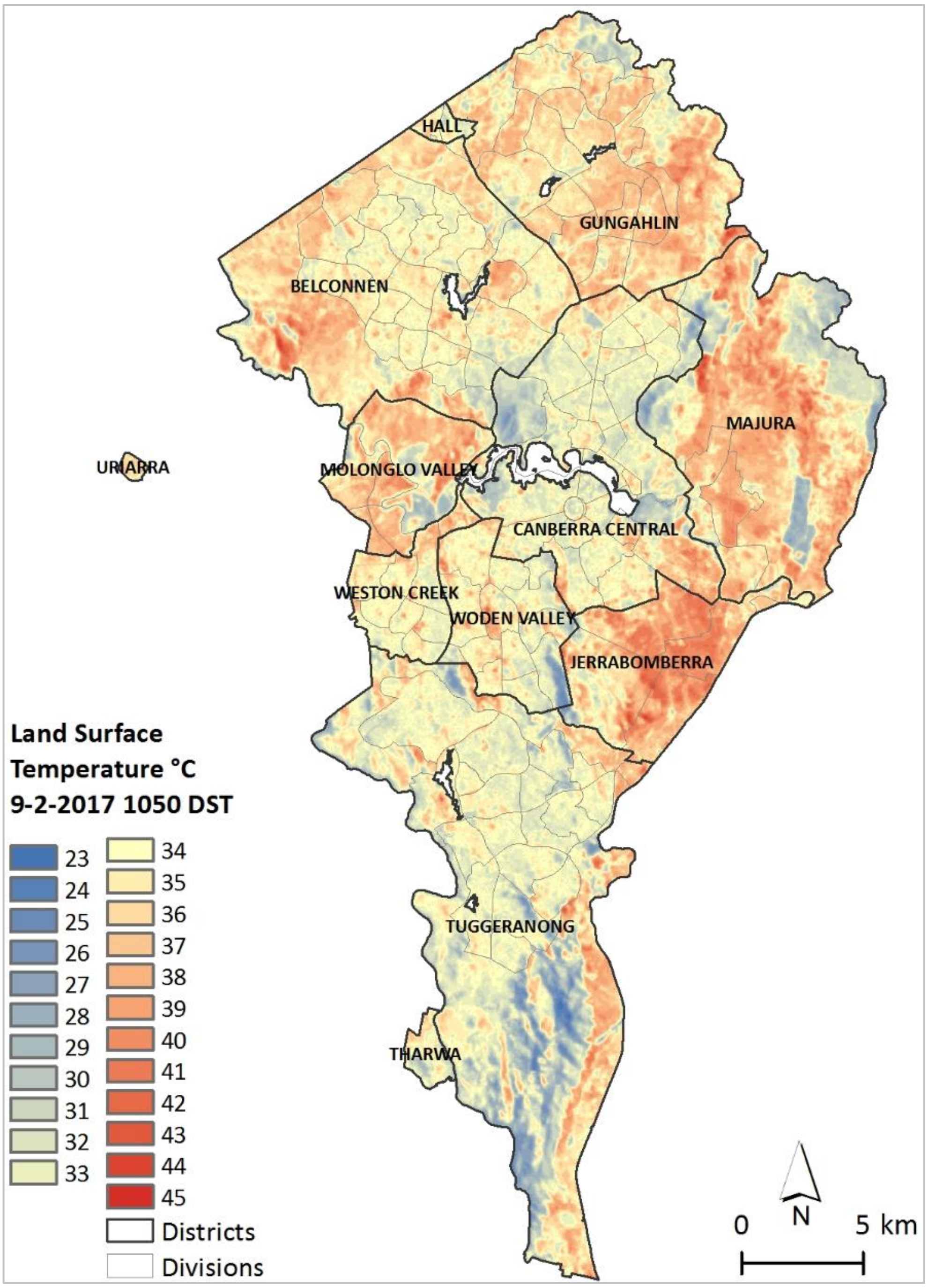


Figure 4. Land surface temperature for the urban Districts and Villages of the ACT on 9 February 2017. The image was derived from Landsat 8 thermal remote sensing imagery at 10.50 AM DST.

High land surface temperatures, defined as above the mean for the metropolitan area, were associated with a number of land uses and activities (Figure 5). Among these is land that has been cleared or is under construction for new urban developments, primarily on the outskirts of Canberra. Bare ground, dark paving and building materials typically have high surface temperatures on hot days[52]. As these areas become established over time, their surface characteristics and consequently surface temperatures will change. Ongoing monitoring could be used to determine the magnitude of this change over time.

Other more established urban developments in Canberra are also hot, particularly in Gungahlin. Many of these areas have less tree canopy cover and more impervious surface cover than cooler, older suburbs in Canberra. Other hot areas that stand out at this map scale are the industrial areas of Fyshwick, Mitchell and Hume, as well as Canberra Airport, large shopping centres, and natural grasslands and pasture. Along with the necessarily large expanse of hard impervious surface cover, much of Canberra Airport is surrounded by open, grassed vegetation with few trees, exacerbating the high surface temperatures in the area. Large shopping centres also have large expanses of impervious surface in roofing, carparks and paving.

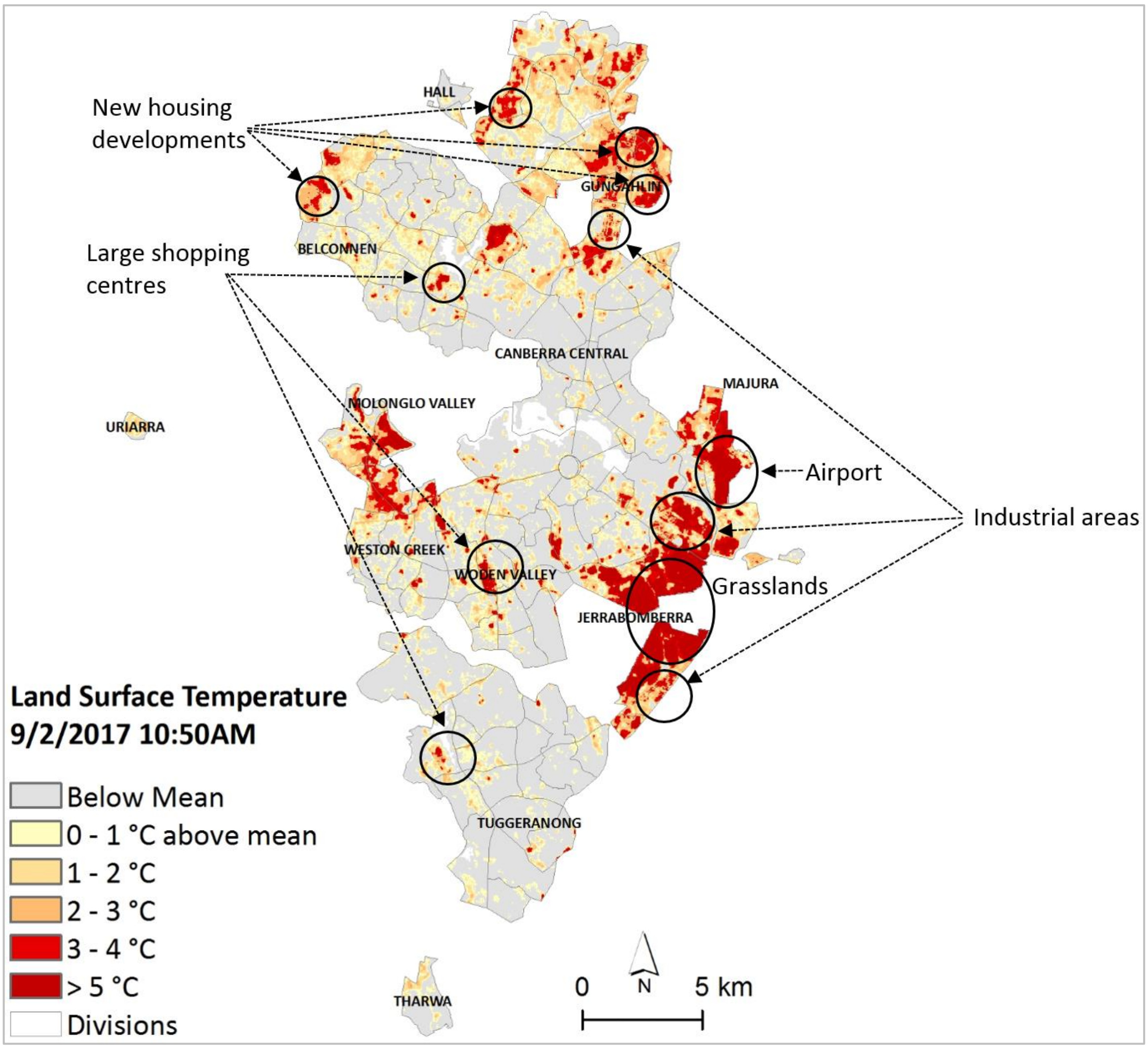


Figure 5. Hot spots defined as departures from 35 °C, which is the mean land surface temperature for the area shown. Temperature is derived from Landsat 8 thermal imagery on 9 February 2017 (10.50 AM DST).

Two sets of summer land surface temperature maps for each District and Village are included at the end of this report (Appendix 1, Figures S1 – S2). The first set of maps (Appendix 1, Figures S1) show land surface temperatures for each urban District and Village. The second set (Appendix 1, Figures S2) show hot spots and cools spots within metropolitan (suburban) areas. Hot spots and cool spots are represented as departures in land surface temperature from 34.4 °C, which is the mean land surface temperature for the spatial extent defined as *Urban Districts and Villages* (shown in Figure 4).

High land surface temperatures in the north and north-western suburbs may be exacerbated when hot northerly and westerly winds blow in from inland areas. Daily air temperature records from the Canberra Airport for 2016 and 2017 show that air temperatures were generally warmer when the prevailing wind was blowing from the north and northwest than when it was blowing from the south and southeast. During the summer period, 9 AM air temperatures were, on average, 5 °C warmer when the wind was blowing from the north and northwest than when it was blowing from the south and southeast. This air temperature difference increased, on average, to around 8 to 10 °C by 3 PM when winds were blowing from the west and northwest, compared to when it was blowing from easterly and southeasterly directions. Residential areas bordered by open grassland or pasture in the direction of the prevailing northerly and westerly winds may be more exposed to those hot winds in summer than residential areas protected by tree cover. This proposition could be tested with ground observations and further information on wind flow relative to both land use and vegetation cover.

4.2.4 Land Surface Temperature, Land Use and Vegetation

The land surface temperature map for 9 February 2017 was overlain with two maps; the Canberra Vegetation Structure map[43] for the *Urban Districts and Villages* area, and the ACT Territory Plan Land-Use Zone map[44] for the metropolitan area. The two different sized areas were used for vegetation structure and land use because many of the vegetation structure types occur outside of the metropolitan area, whereas some of the land uses assigned to areas outside of the metropolitan area do not reflect current land use.

There is a clear difference in mean land surface temperatures depending on the type of land use and the type of vegetation (Figure 6). On average, most vegetation types are cooler than most metropolitan land-use types, although the range of surface temperatures between different vegetation types and between different land uses is substantial.

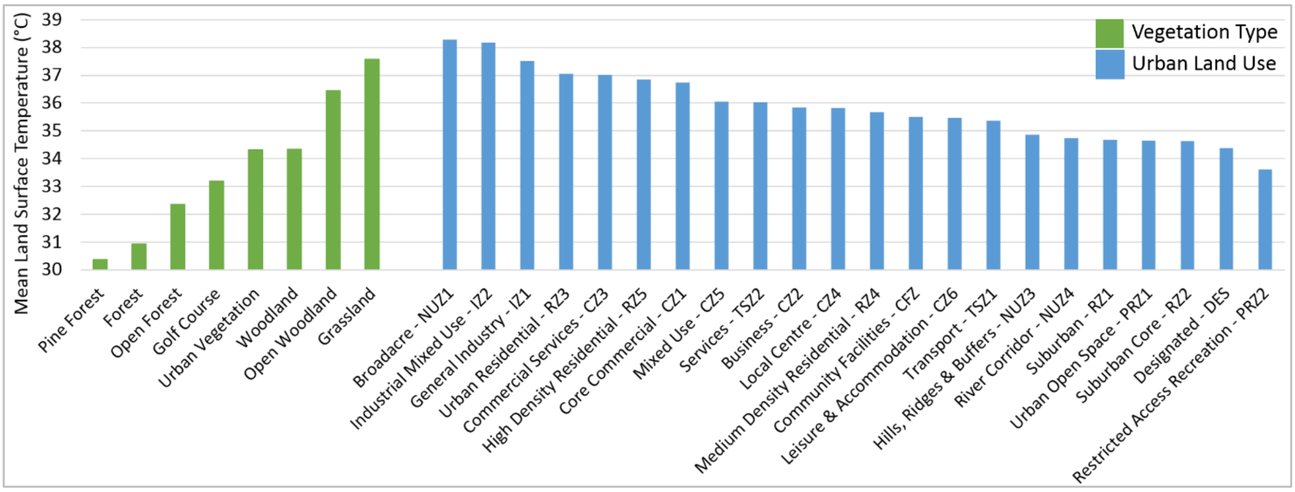


Figure 6. Mean land surface temperatures for each Territory Plan Land-Use Zone (blue) and Vegetation Structure class (green). Based on Landsat 8 remote sensing imagery for 9 February 2017 (10.50 AM DST).

Focusing just on land use (blue bars in Figure 6), ‘Broadacre’ (38.3 °C, 2.3 SD) and ‘Industrial Mixed Use’ (38.2 °C, 1.5 SD) both had mean land surface temperatures over 38 °C, almost 5 °C hotter than the coolest land use ‘Restricted Access Recreation’ (33.6 °C, 1.7 SD). ‘Restricted Access Recreation’ includes irrigated golf courses, which benefit from cooling through evaporation and evapotranspiration via the green vegetation. ‘Urban Open Spaces’ and other park and recreation areas were found to be, on average, cooler than most other categories of land use.

Industrial areas have been recorded as a hot land-use type in other cities[53, 54] and in Canberra from previous analyses of 2010 remote sensing imagery[14]. Industrial areas in Canberra tend to have large expanses of impervious surfaces (rooftops and paved surfaces) and few trees.

There was considerable variation in the mean land surface temperatures of different residential types. ‘Urban Residential’ is the hottest, followed by ‘High Density Residential’ and ‘Medium Density Residential’, with ‘Suburban’ and ‘Suburban Core’ the coolest (Figure 6). This suggests that higher urban densities may be associated with higher land surface temperatures, but other associated factors such as the amount of tree canopy cover or the age of the urban development may also be important.

Focusing on the different vegetation types (green bars in Figure 6), ‘Grassland’ (37.6 °C, 2.3 SD) is the hottest, while ‘Pine Forest’ (30.4 °C, 2.5 SD) and ‘Forest’ (30.9 °C, 2.1 SD) are the coolest. There was, on average, almost 7 °C difference between the hottest and coolest vegetation types. While pine forests have the coolest mean land surface temperature of the vegetation types, this does not necessarily mean that it is the preferred vegetation type for cooling in Canberra. Other factors such as the way air movement is blocked or channelled by different types of vegetation also need to be considered, as well as canopy height, density and spread, shade provision, planting density, water use, public amenity and ecological value.

Comparing the mean surface temperatures of land-use with those for different vegetation types shows ‘Broadacre’ and ‘Grassland’ have similar land surface temperatures. This is because the ‘Broadacre’ land use tends to be dominated by grass or pasture and some of the areas classed as ‘Broadacre’ land use overlap with areas classed as ‘Grassland’ vegetation type. The mean temperature of 'Grassland' is similar to the two 'Industry' classes (Figure 6). In Canberra, the industrial areas tend to be co-located near open grassed areas rather than forested areas, which may add to the high land surface temperatures across the broader area.

When the average percentage of tree canopy cover is compared to the mean land surface temperature of each land-use type (Figure 7a), there is a general trend that land surface temperatures are cooler where there is more tree cover. The same trend that occurs for broad land-use classes also occurs at the subclass level. For example, on average, higher density residential areas are associated with higher land surface temperatures and less tree cover (Figure 7b). The exception is 'Urban residential' which has a similar mean land surface temperature to the 'High density residential' land-use subclass, but slightly less tree canopy cover.

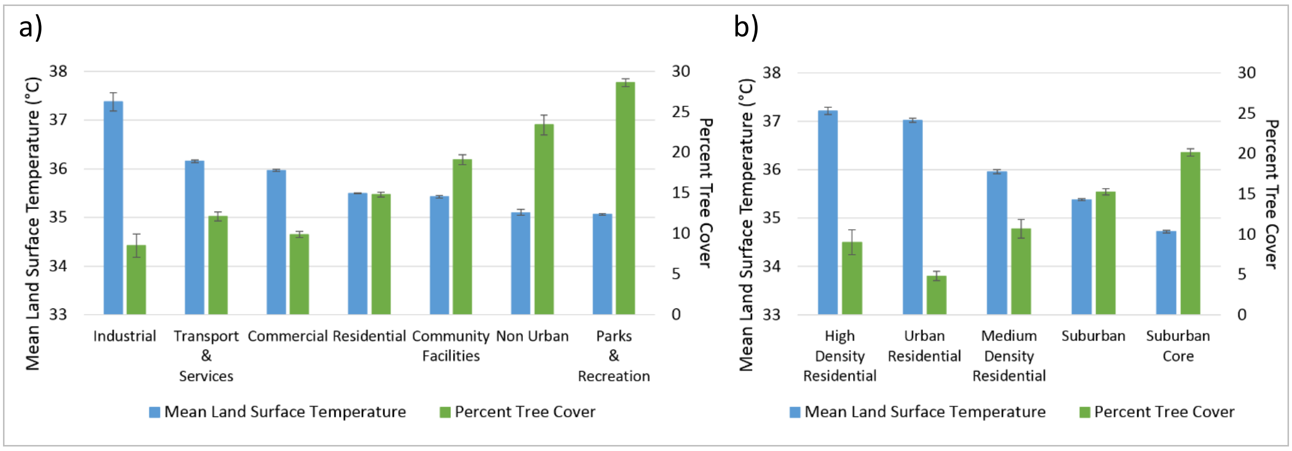


Figure 7. Mean land surface temperatures for Territory Plan land-use zones (blue) and percent tree canopy cover (green) for the metropolitan areas of Canberra. Standard error bars are shown, which is a measure of accuracy of temperature estimates. The temperature data are based on Landsat 8 imagery for 9 February 2017 (10.50 AM DST).

4.2.5 Heat Exposed Areas

Land surface temperatures have been mapped for individual urban Districts and Villages and are located at the end of this report (Appendix 1, Figures S1). Hot and cool spots for the suburban areas within each District were identified based on departures in temperature from 34.4 °C, which is the mean land surface temperature of the *Urban Districts and Villages* area shown in Figure 4 (Appendix 1, Figures S2). Viewing maps for a small area rather than the whole of the urban area at once can help to more precisely identify hot spots and cool spots.

Observing the summer land surface temperature maps reveals features of the built and natural environment that may contribute to the temperature measurements. It is important to note that the summer imagery was captured mid-morning at 10.50 AM (DST), and that morning shadows will influence local surface temperatures. It is not possible to report on land surface temperatures when the sun is directly overhead, or during the hottest part of the day, which is typically during the afternoon when shadows are cast from the west.

Based on the mapping in this report, areas and features that typically have above-average surface temperatures on summer mornings are:

- Areas with large expanses of impervious surface cover such as rooftops, carparks and paved surfaces, commonly found in commercial and industrial areas, major roads and intersections, and new housing developments;
- Areas that have been cleared or have low, sparse, dry vegetation cover such as Canberra Airport, land cleared for development, grassland and pasture, and unirrigated grass playing fields;
- Residential areas with large expanses of impervious surface cover, few trees, little irrigation and high dwelling densities; and
- Some artificial playing surfaces.

Areas and features typically with below average surface temperatures on summer mornings are:

- Irrigated areas, water features, and lakesides, such as irrigated playing fields, golf courses, wetlands and sewage settling ponds;
- Areas with green vegetation and tree or forest cover, such as green roofs, leafy suburbs and forests;
- Areas that are shaded by buildings or shade structures; and
- Areas that are shaded because of their topography.

Detailed views and interpretation of some of the areas and features that are commonly associated with high and low surface temperatures are provided below in Table 3.

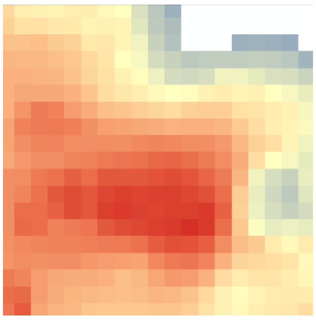
Table 3: Examples of features associated with above or below average land surface temperatures in Canberra and potential responses based on thermal imagery for 9 February 2017 (10.50 AM DST). For each location, the thermal imagery (30 metre resolution) is shown on the left and the associated aerial view is on the right using ACTmapi 2016 10 cm aerial photography. Red indicates higher temperatures and blue indicates lower temperatures.

Commercial areas

Shopping centres often have high surface temperatures owing to extensive areas of roofing and car parks that have little shade. The use of appropriate solar orientation, cool roofing and paving, built shade structures, trees and water features can help reduce surface temperatures in public places. See below.

Large shopping centres with extensive areas of roofing and carparks can reach very high temperatures. For example, the roof of Westfield Belconnen (below) has reached 42.3 °C.

In contrast, the small park to the east of the shopping centre has irrigated grass and trees and was almost 10 °C cooler. The cooling effects of Lake Ginninderra can be seen along the lake edge to the north of the shopping centre.



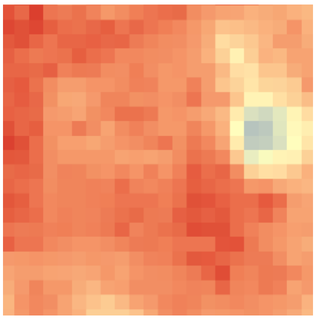
Small shopping centres, such as the Mawson shops (below), also have large areas of roofing that in this case have reached 40 °C. The carpark areas are also warmer, but trees planted in the carparks will provide additional shade as they become more established.

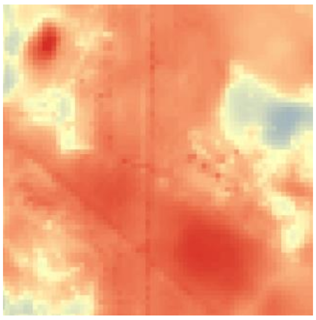
Industrial areas

Industrial areas typically have large expanses of roofing and paving and very few trees, resulting in almost uniform high surface temperatures. The adoption of cool roofs and green cover could reduce land surface temperatures in these areas, but care is required to avoid glare when increasing reflectivity of surfaces.

Industrial areas, such as Fyshwick (below), have large expanses of roofing and paving, with temperatures reaching 41.7 °C. The cooler temperature of the roof (32 °C) on the right hand side of the image may be because it is a cool roof or could be the result of a remote sensing anomaly caused by a low emissivity roof. Ground-truthing would determine which possibility is correct.

Canberra Airport and Majura Park have large areas of dry grass, impervious paving and rooftops that result in high surface temperatures. More tree cover in the carparks could reduce temperatures during the day. An irrigated golf course to the east highlights the cooling benefits that are provided by soil moisture, green vegetation and shade.



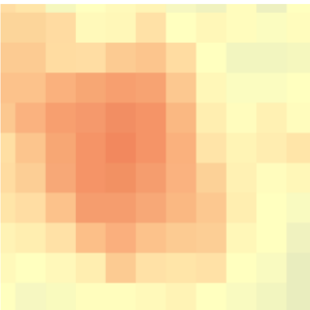


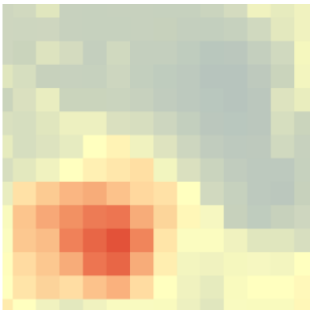

Playing fields

Surface temperatures in playing fields can be highly variable depending on the playing surface and soil moisture. For example, the surface temperatures of the playing fields (below) show that artificial turf was 8–9 °C hotter than the irrigated oval.

The **unirrigated** Narrabundah Neighbourhood Oval reached 39.1 °C. The short dry grass and little shade means there is high heat exposure on hot days.

Artificial turf, such as Willows Oval at the ANU, can become very hot on sunny days, reaching 41.1 °C, but cool down quickly at night. This artificial turf field was hotter than the 32.5 °C recorded for the **irrigated** North Oval located across Barry Drive.

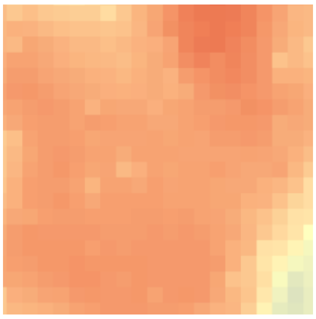





Residential areas

Surface temperatures can vary enormously between residential areas depending on several key factors including tree cover, dwelling density, irrigation and proximity to water and vegetation.

New residential areas, such as Bonner (below), with high density housing, large expanses of roofing and little tree cover can be uniformly hot in summer. These areas may potentially become cooler over time if tree canopy cover is increased.

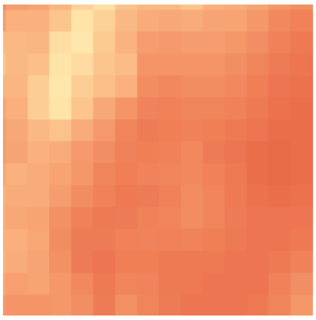


Residential areas, such as Reid (below), that have shady parks, significant tree canopy cover and irrigated gardens are cooler in summer. Verges that are wide enough to accommodate large shade trees provide extensive cooling benefits.

Roads and intersections

Roads and intersections have hard, impervious surfaces and can get very hot in summer if they are unshaded. They cool down slowly at night.

Large roads and intersections, particularly those that link urban areas, can be highly exposed and therefore exhibit extremely high temperatures.

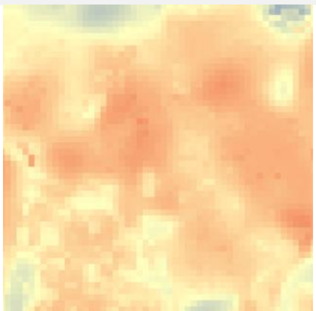


Smaller roads and intersections such as this residential area in Yarralumla, have cooler temperatures as a result of tree shade.

Cleared land

Land that has been cleared for development or other purposes, and is dry and exposed, will become hot on sunny days. Cleared land will typically cool down more quickly at night than built-up urban areas.

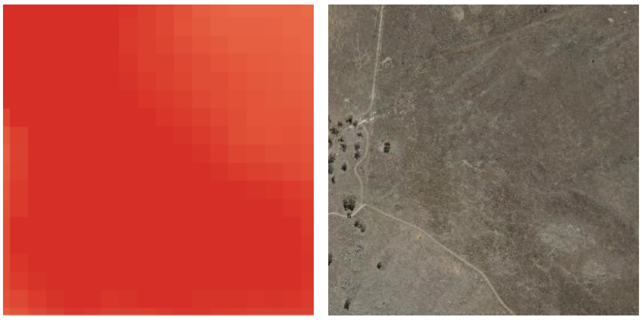
The surface temperature of areas such as this new development at Moncrieff will undergo change as the area becomes established. Future surface temperatures will depend on factors such as the choice of building materials, the amount of tree cover and the use of irrigation and water sensitive urban design.



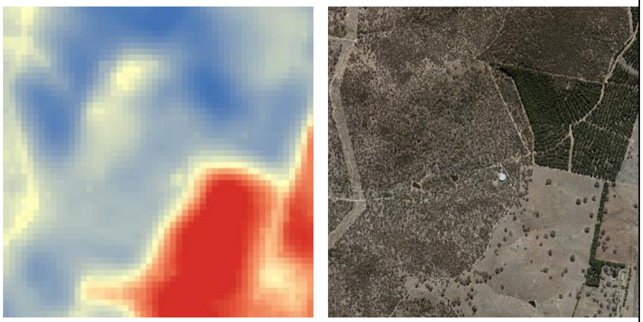
Natural vegetation

Canberra is home to a number of important ecological communities, including grasslands, woodlands and forests, supporting a range of threatened flora and fauna species, as well as affecting land surface temperatures.

Grasslands: Land surface temperatures, such as those in the Jerrabomberra grasslands (below), are influenced by the amount of vegetation cover. Grasslands are hot during the day, but cool off quickly overnight. The ACT Government is required to manage vegetation structure for the protection of biodiversity in this ecological community.



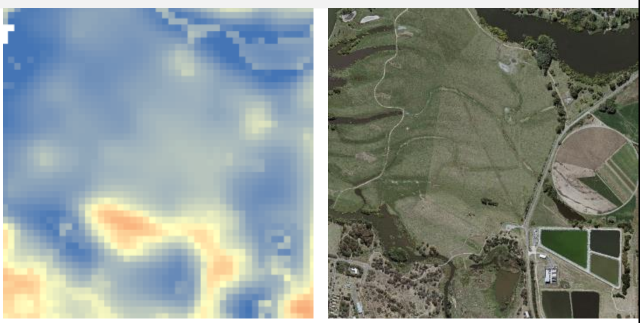
Forests: The contrast between the surface temperature of native forests and dry grassy areas is evident on the slopes of Mount Majura (below), with 17 °C difference between the pasture and the forested slopes. This is likely to be caused, in part, by shading of the western slopes at the time the image was captured and differences in vegetation type.



Lakes, wetlands and irrigation

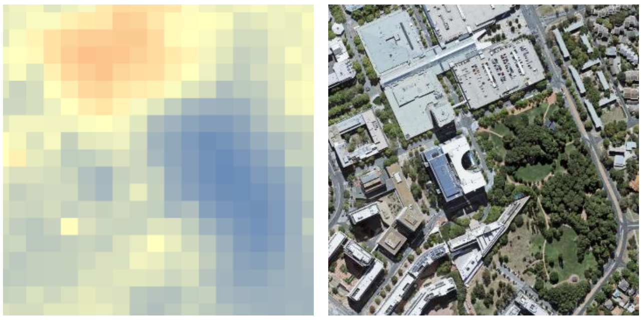
Lakes and rivers provide cooling benefits on hot days through evaporation. Irrigation also supports evapotranspiration.

Large water bodies, such as Lake Burley Griffin, and ponds and irrigated areas at the Jerrabomberra Wetlands and the Fyshwick Sewage Treatment Plant maintain relatively constant temperatures throughout the day and cool surrounding areas.



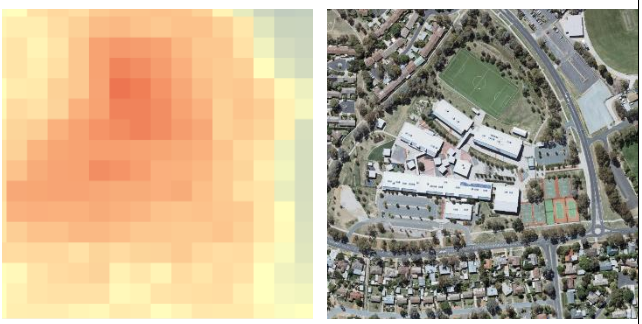
City Centre

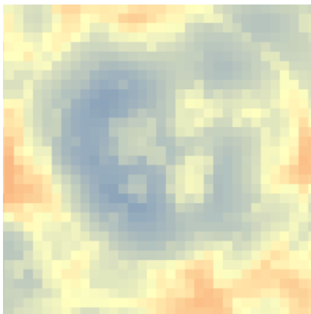
Glebe Park (below) with its tree cover and irrigated grass provides a cool retreat in the city. The buildings and covered walkways in the city do provide shade during the day, but stored heat in the buildings and roads will be shed slowly at night, contributing to the urban heat island.



Schools

Schools with hot roofs, exposed car parks, little shade and artificial playing surfaces can be hot in summer. Land surface temperatures at Kingsford Smith School, Holt (below) reached 39.8 °C.



Green roofs		
Green roofs provide shade and remove heat from the air through evapotranspiration. They can reduce energy consumption within the building and provide important ecosystem services.		
Rooftop gardens, such as that seen at Parliament House**,** that fully or partially cover a roof with grass, herbs, shrubs, or small trees can reduce surface temperatures significantly. Parliament House is cooler than the more traditional office buildings nearby.		

4.3 Vulnerable People in Hot Neighbourhoods

4.3.1 Population Vulnerability

Included in this report are maps of mean land surface temperatures and aggregated vulnerability scores for the metropolitan (suburban) area of Canberra (Figure 8). These are shown in greater detail for each urban District and Village in Appendix 1 (Figures S3 – S6). This includes maps of:

- Mean land surface temperatures for Mesh Blocks in the metropolitan area of Canberra in neighbourhoods where people live (Appendix 1, Figures S3);
- Aggregate vulnerability scores for each Mesh Block based on the three heat vulnerability criteria (Appendix 1, Figures S4);
- Aggregate vulnerability scores for the 40% hottest Mesh Blocks (Appendix 1, Figures S5);
- Aggregate vulnerability scores for the 20% hottest Mesh Blocks (Appendix 1, Figures S6).

An analysis of the distribution of vulnerability scores indicates that areas with high numbers of young children tend to be different to areas with lots of elderly people. When combined with areas that have a high number of low-income households, most suburbs in Canberra have populations with heat-health vulnerability for at least one of the vulnerability factors. Fewer neighbourhoods have a vulnerability score of 2 or 3 (Appendix 1, Figures S4). Vulnerable groups of people living in the hottest parts of Canberra will have the highest risk.

Maps showing individual vulnerability factors are not included as they are not the main focus of this report, but we make the following observations about their general patterns of distribution:

People older than 65 years are more likely to live in the older, more established suburbs of Canberra. There were few Mesh Blocks with large elderly populations in newer suburbs unless there were retirement villages and aged-care homes in these areas.

People younger than 5 years – Families with children aged under 5 years were more likely to live in the middle and outer suburbs of Canberra, but particularly in newer suburbs that have undergone considerable growth in recent years. In particular, newer suburbs on the outer edges of Belconnen, Gungahlin, Weston Creek and Tuggeranong had high numbers of young children. The lowest proportion of young children was recorded in the older, inner suburbs of Canberra.

Low-income households – Low-income households, which includes both private and public housing, are scattered throughout Canberra. This reflects the salt-and-pepper approach taken by the ACT Government for locating public housing throughout Canberra's suburbs and town centres. The urban renewal of public housing extends the provision of low-income housing to new suburbs.

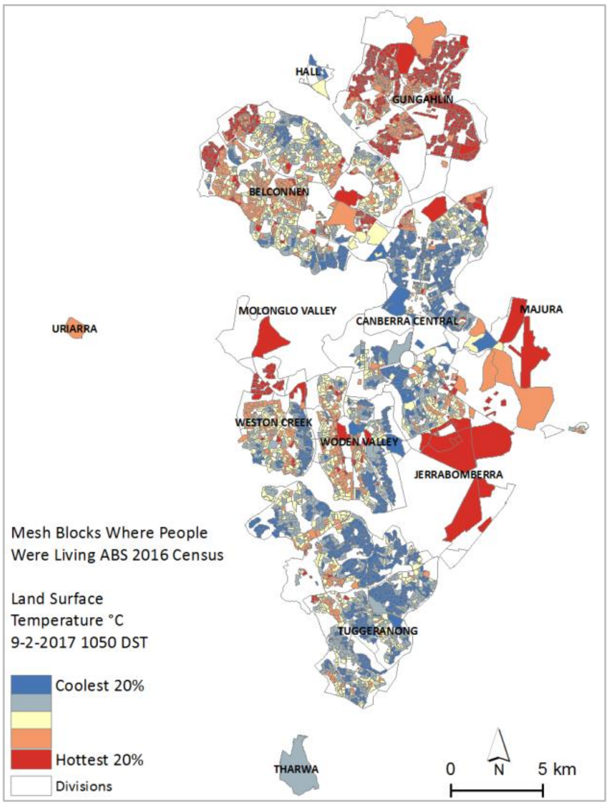
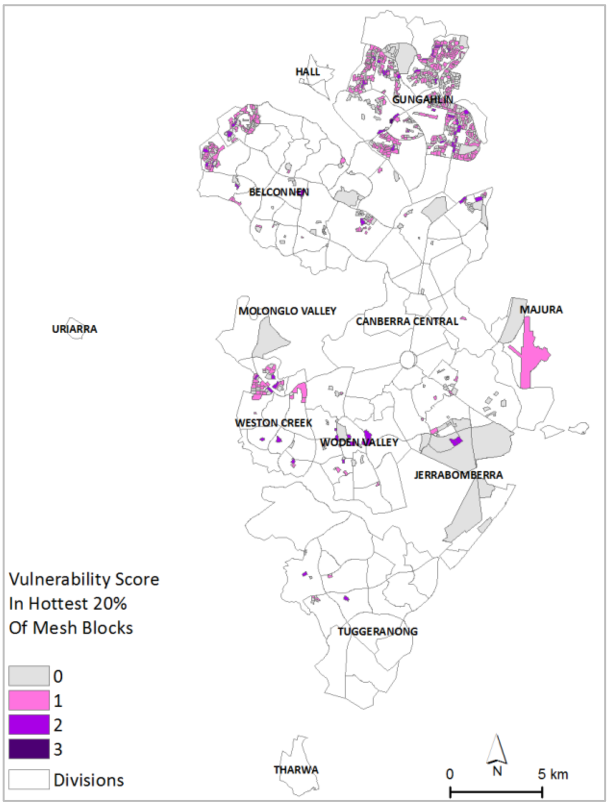
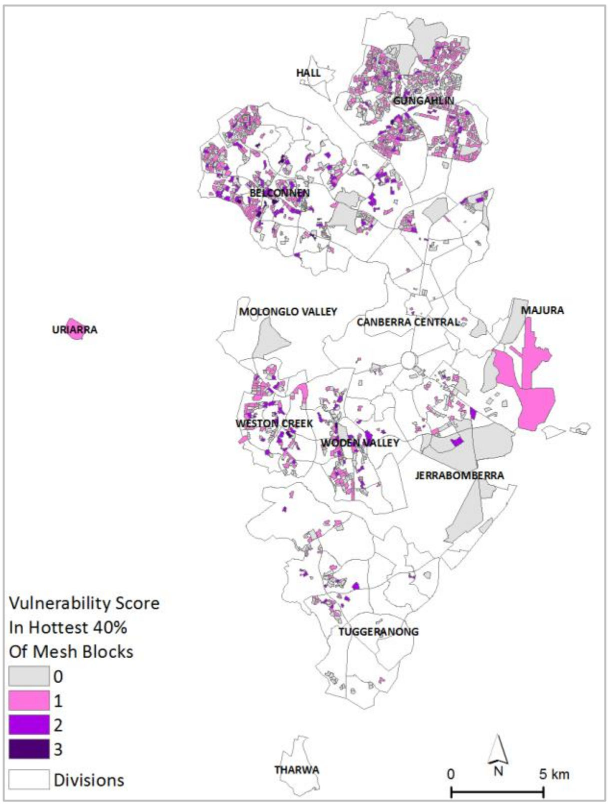


Figure 8.

- **Right: Mean land surface temperatures for Mesh Blocks in the metropolitan area of Canberra where people live;**
- **Below left: Aggregate vulnerability scores for the 20% hottest Mesh Blocks;**
- **Below right: Aggregate vulnerability scores for the 40% hottest Mesh Blocks.**





4.3.2 Population Vulnerability in Heat Exposed Neighbourhoods

There are 70 Mesh Blocks with a population vulnerability score of 2 or 3 that coincide with the hottest 20% of Mesh Blocks. More than half of these are located in Gungahlin, with 36 Mesh Blocks occurring in nine suburbs. Areas with high heat exposure and high population vulnerability are found in the following suburbs: Belconnen (Charnwood, Dunlop, Florey, Holt, Macgregor); Canberra Central (Watson); Gungahlin (Amaroo, Bonner, Casey, Franklin, Gungahlin, Harrison, Jacka, Ngunnawal, Nicholls); Jerrabomberra (Symonston); Majura (Watson); Molonglo Valley (Coombs, Wright); Tuggeranong (Greenway, Isabella Plains, Monash); Weston Creek (Fisher, Rivett, Stirling); and Woden Valley (Garran, Lyons, Pearce, Phillip). The spatial patterns of high population vulnerability and high heat exposure exist across a range of different dwelling types, from single detached houses, to attached dwellings, to mid-rise and high-rise apartment blocks.

4.3.3 Neighbourhood Land Surface Temperatures and Tree Cover

The relationship between mean land surface temperature for residential Mesh Blocks and for three factors: percentage tree canopy cover, gross dwelling density and distance to grasslands, was analysed using multiple linear regression modelling and tested for statistical significance (n = 3945). All three factors were significant with an adjusted R^2 of 0.58%. Additional factors, not assessed here, will also account for variations in land surface temperatures. Factors such as the type of building materials, urban geometry, proximity to forest and water bodies, local weather conditions, topography and airflow, are also likely to influence land surface temperature estimates.

The model showed a significant negative relationship between mean land surface temperature and percent tree cover ($p<0.001$) such that increasing tree canopy cover is associated with cooler surface temperatures. Likewise, cooler land surface temperatures are found in areas further away from grasslands ($p<0.01$) and in Mesh Blocks with lower dwelling density ($p<0.0001$). There is also spatial variation as District was also found to be a significant variable.

These results indicate that residential areas with a higher percentage of tree cover and lower gross dwelling density, that are located away from grasslands, will have cooler land surface temperatures. It is important to note, however, that not all Mesh Blocks that have lower mean surface temperatures have a high percentage of tree canopy cover. This suggests that multiple factors contribute to cool temperatures in the urban environment and not simply tree cover alone. For example, aerial views of four residential Mesh Blocks (Figure 9) show how quite distinct tree cover profiles can produce similar land surface temperatures. The four Mesh Blocks in Figure 8 can be characterised as:

A – A hot neighbourhood with little tree cover and bordering exposed grassed areas and areas cleared for new housing developments;

B – A cool neighbourhood with no tree cover, but surrounded by water. There may be some mixed signals here however, with pixels close to the water's edge;

C – A cool neighbourhood with a significant cover of deciduous trees. The area surrounds a leafy park on three sides and is close to irrigated parkland; and

D – A cool neighbourhood with a significant cover of native trees and close to native forest.

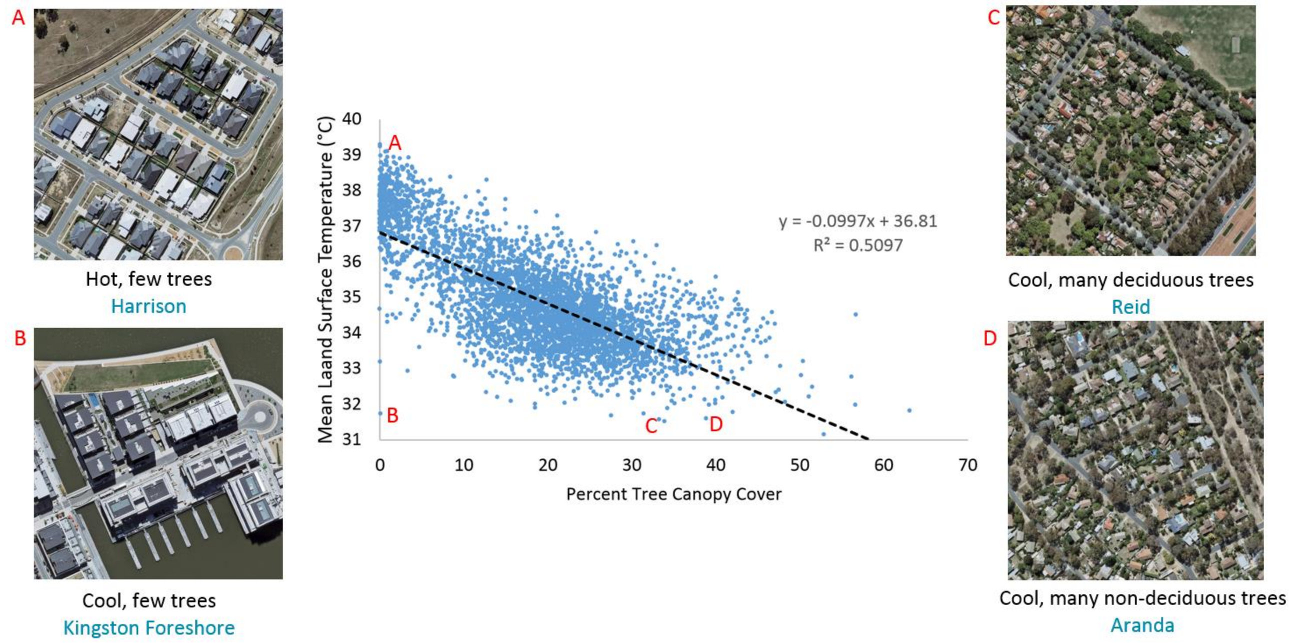


Figure 9. Mean land surface temperature (9 February 2017, 10.50 AM DST) and percent tree canopy cover for residential Mesh Blocks in the metropolitan (suburban) area of the ACT (n = 3945). Aerial views of four of these Mesh Blocks (A–D) show the types of features associated with the different temperature profiles.

4.4 Winter in Canberra: Where is it Cold?

4.4.1 Winter Surface Urban Heat Island

Daytime and nighttime patterns of surface urban heat island are evident in the winter season for the urban Districts of the ACT (Figure 10a, b). The coolest areas mid-morning in winter (Figure 9a) are located in forests and around Lake Burley Griffin, while warmer areas are evident in the grasslands and pasture, particularly at Jerrabomberra, as well as areas in west Belconnen and Weston Creek. As with the summer nighttime map, winter conditions during late evening are warmer around the lakes and built-up urban areas (Figure 10b). Parts of urban Gungahlin are cooler than some other built-up areas. The coldest areas in the evening in winter are the grasslands, the forests in southern Tuggeranong and the airport and surrounds.

The day to night temperature difference map is very similar to that for the summer season, with less temperature change in areas around Lake Burley Griffin, urban forests and built-up areas, while the greatest temperature difference is in areas with grassland or pasture (Figure 10c). As with the summer season, the winter surface heat island is evident, but the effect is not as strong in winter. Previous studies for many cities have shown that there is both a diurnal and seasonal cycle of surface urban heat island and that the phenomenon is larger in summer than in winter[55, 56].

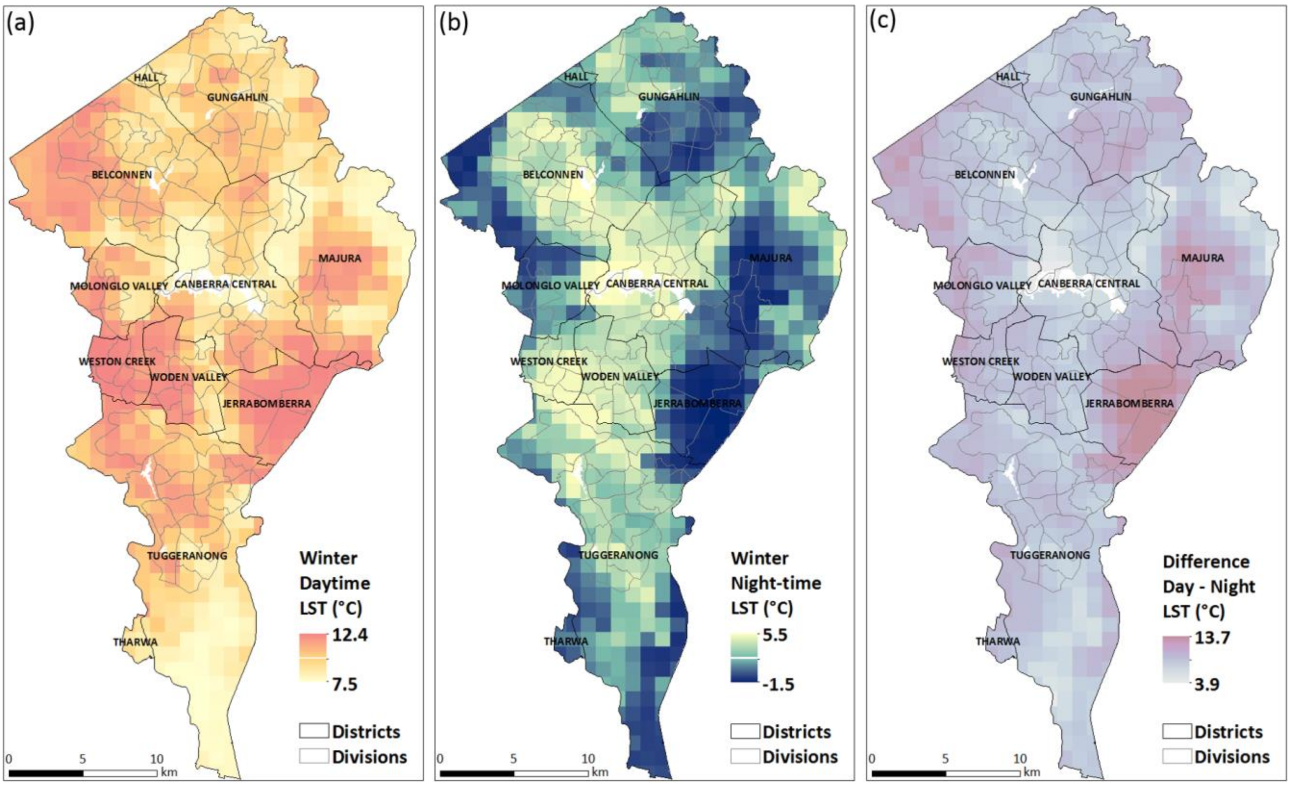


Figure 10. Winter 2017 seasonal land surface temperature maps for the urban Districts and Villages of the ACT; (a) morning at ~10.15 AM, (b) evening ~10.45 PM EST, (c) the morning to evening difference. The images were derived from MODIS remote sensing imagery.

4.4.2 Land Surface Temperatures on 20th August 2017

A map of land surface temperatures for the morning of 20 August 2017 (9.50 AM EST) after a cold clear night (overnight minimum temperature at Canberra Airport was –3 °C and maximum daily temperature was 13.2 °C) reveals that areas with very low land surface temperatures (Figure 11) are typically:

- Areas on the southern or southwestern sides of hills that are shaded from the winter morning sun. As the sun is well to the north in winter, some areas on the southern side of hills may receive little sun throughout the day;
- Some cool pockets in suburban areas, including suburbs in north Tuggeranong (Kambah and Wanniassa) and in north Belconnen (Fraser); and
- Frost hollows, or valley bottoms that receive cold-air drainage.

There are also pockets of warmer temperatures across Canberra, with large areas in Gungahlin, the grasslands in Jerrabomberra and Majura, and at the airport. As with the summer maps, larger shopping centres, industrial areas and areas under construction for new urban development are also warmer.

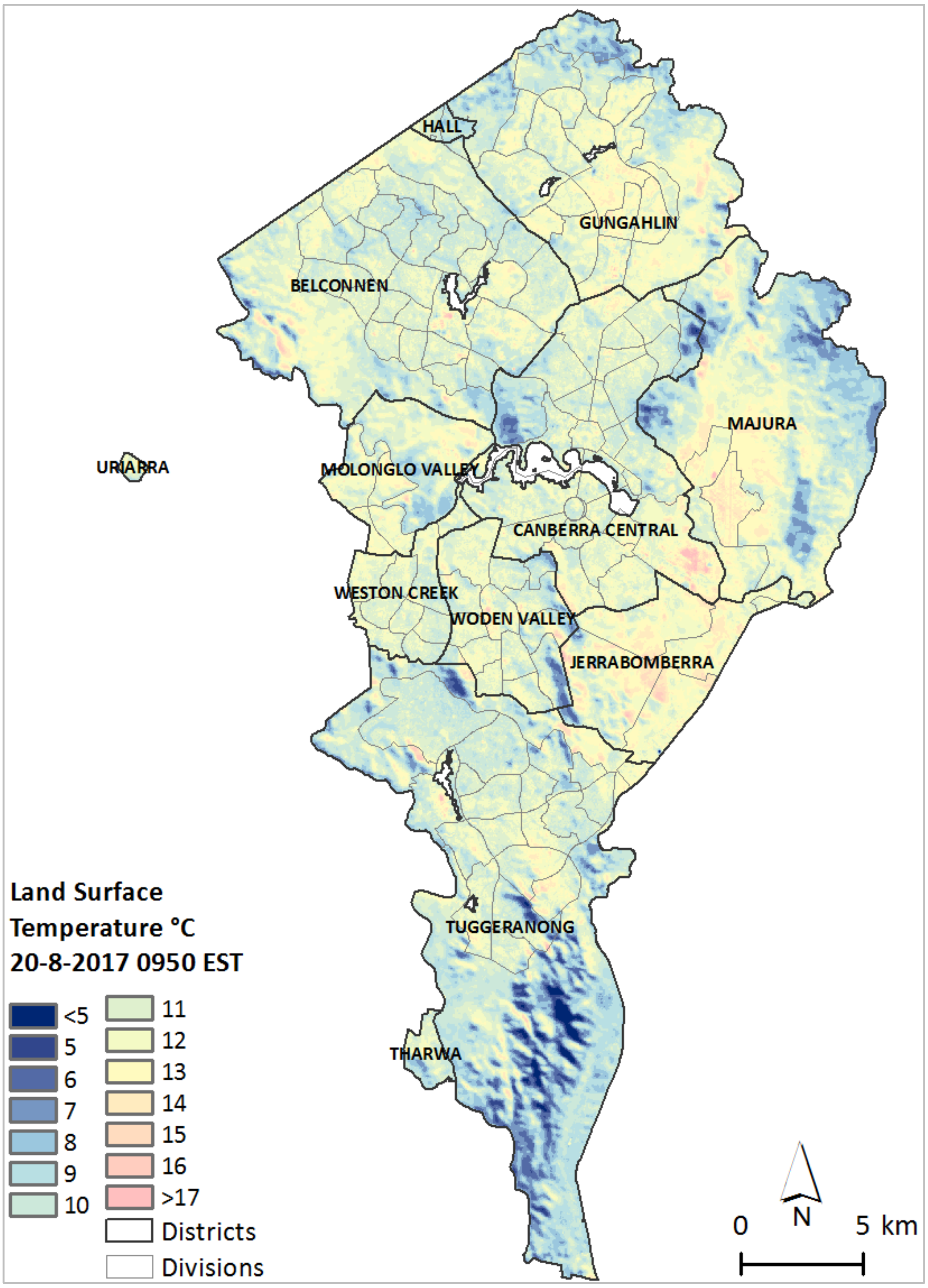


Figure 11. Land surface temperature for the urban Districts and Villages of the ACT on 20 August 2017. The image was derived from Landsat 8 thermal remote sensing imagery at 9.50 AM EST.

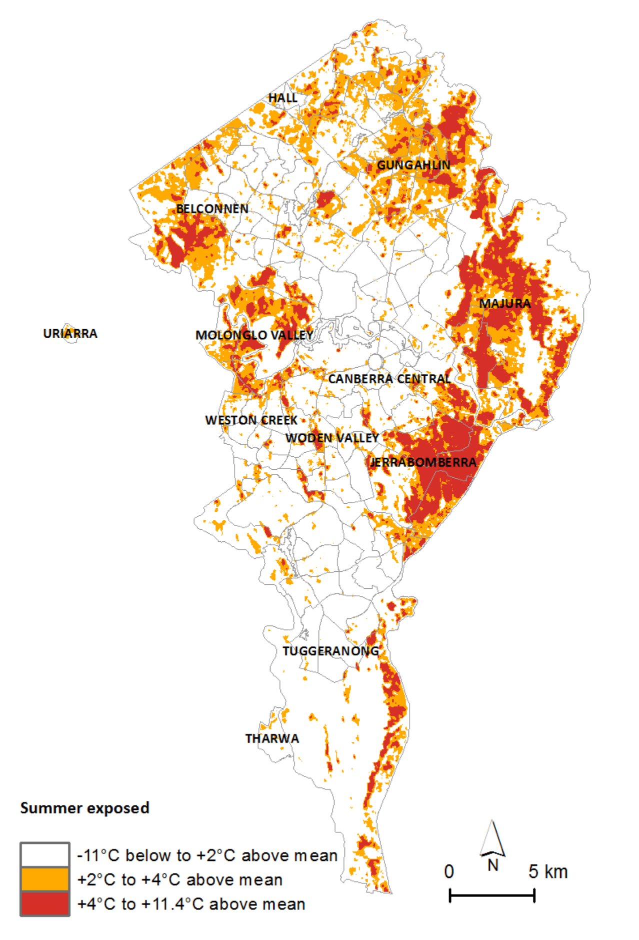
To provide a more detailed understanding of the local distribution of cooler temperatures across Canberra, surface temperatures for the morning of 20th August 2017 (09.50 AM) were mapped for each District and Village and are included at the end of this report (Appendix 1, Figure S1). These maps are based on departures from 11.4 °C, which is the mean land surface temperature of the broader *Urban Districts and Villages* area shown in Figure 11.

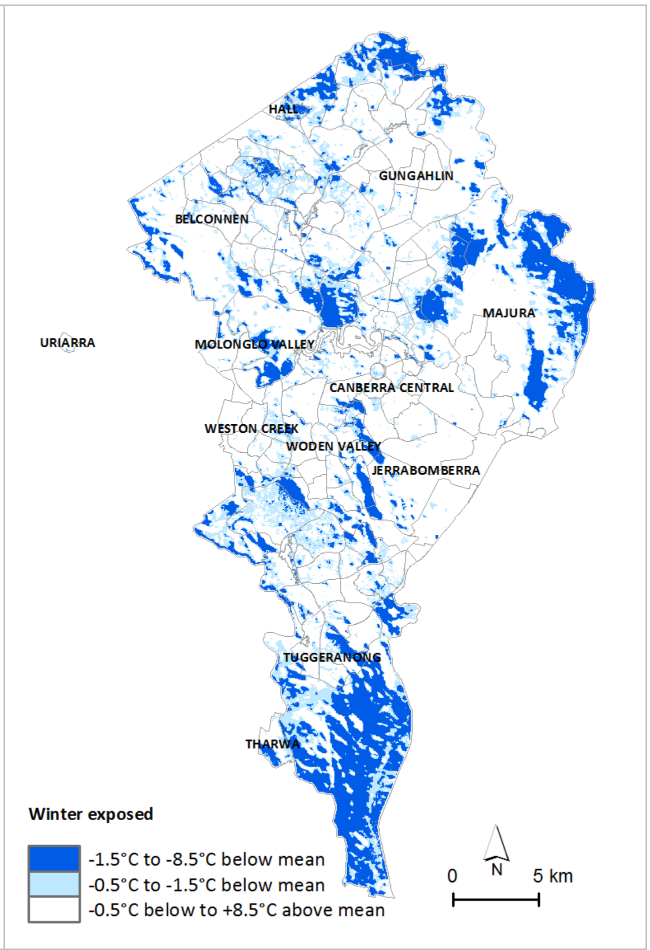
Canberra experiences cold winters and has a higher demand for heating energy in winter than cooling energy in summer[57]. Paying energy bills can be difficult for low-income households who spend a greater proportion of income on energy than higher income households, but the relative capacity to pay for energy is compromised by their expenditure on other necessities[27]. As such, there may be merit in overlaying the maps of cold exposure that have been generated with maps of population vulnerability, for each District and Village to inform broader government policy. This has not been included in this report

4.5 Hot in Summer and Cold in Winter

There are a small number of areas that are both hot on summer mornings and cold on winter mornings (Figure 12). In this report, 'hot' has been defined as land surface temperatures that are more than 2 °C above the mean in summer (9th February 2017, 10.50 AM DST), and 'cold' if they are more than 1.5 °C below the mean in winter (20th August 2017, 9.50 AM EST). None of these areas are in built-up urban areas. Most often, areas that are warm during the daytime in summer are also warm in winter, and conversely, the features that make areas cool in summer, also make them cool in winter. Yet there were several areas found to be both hot on summer mornings and cold on winter mornings:

- Areas on southern facing slopes that are exposed to the morning sun in summer, but do not receive the winter sun owing to the sun being well to the north in winter;
- The area around the Royalla Solar Farm, Guises Creek and Dunns Creek near the New South Wales border; and
- Areas west of Kowen Escarpment Nature Reserve and areas to the north of Jacka where there are many creek tributaries. While not verified for this report, these areas appear to be exposed in summer, but may also be areas where frost develops in winter due to cold-air drainage. As the air at the top of a hill cools at night, it becomes dense and heavy compared to surrounding air, and will drain to lower parts of the landscape.





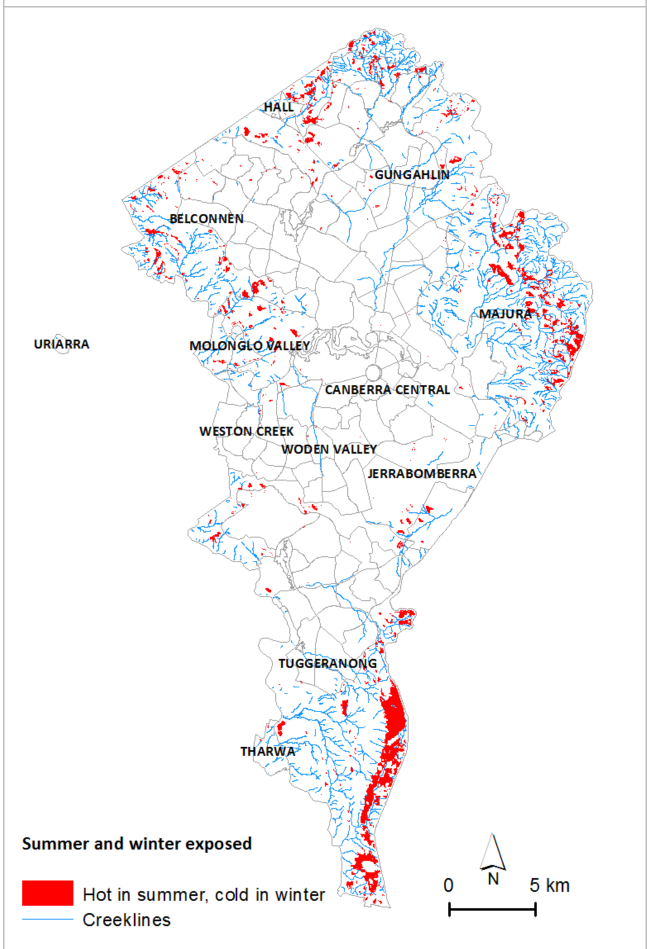


Figure 12.
Top left: Areas that are hot in summer (more than 2 °C above the mean of 34.4 °C on 9-2-2017);
Top right: Areas that are cold in winter (more than 1.5 °C below the mean of 11.4 °C on 9-2-2017);
Left: Areas that are hot in summer and cold in winter (more than 2 °C above the mean of 34.4 °C on 9-2-2017 and more than 1.5 °C below the mean of 11.4 °C on 9-2-2017).
Land surface temperatures are derived from Landsat 8 thermal imagery at 9.50 AM EST.

5 Surface Urban Heat Mitigation Strategies

With the combined effects of climate change and the urban heat island, there is a growing risk of heat-related illness in Canberra. Urban heat can be mitigated through a mix of strategies and technologies that include both engineered and ecological options. The primary focus of these is to reduce absorption of solar radiation into urban structures, to increase emissivity of surface materials so that less heat is stored, to increase shade, evaporation and evapotranspiration, and to embrace urban planning and design that enables heat to be quickly removed from the urban environment.

While conditions are projected to become warmer, with more frequent and severe heatwaves, Canberra also currently experiences cold winters that bring associated cold-related illnesses. It is therefore important when considering the planning and implementation of cooling strategies in summer, that this is done without exacerbating the cooler conditions experienced in winter.

The Guide to Urban Cooling Strategies[58] released by the Low Carbon Living CRC is a useful resource that includes urban heat mitigation strategies for different climate zones, including Canberra. It provides detail of design interventions to moderate urban microclimates and mitigate urban heat in public places and provides a useful accompaniment to this report. To this end, this report will not cover the same material in the detail that is provided in The Guide to Cooling Strategies[58], but instead provides a summary of strategies that are specifically relevant to the Canberra context.

Urban heat can be reduced by adopting a mix of strategies and technologies that focus on urban planning and design and the strategic use of cool building materials, vegetation and water. Potential heat mitigation options include:

- Building with cool materials or applying surface coatings to increase reflectivity and emittance;
- Paving with permeable or porous materials that enable moisture to evaporate into the air or infiltrate the soil where it is available for evaporative cooling;
- Building shade structures made from cool materials to intercept solar radiation;
- Vegetating neighbourhoods to provide shade, channel breezes and provide cooling benefits through evapotranspiration along streets, in public spaces, in parks and on walls and roofs;
- Maintaining large areas of forest to create advection currents between hot urban areas and cooler greenspace; and
- Using irrigation, water features and lakes to increase cooling through evaporation, evapotranspiration and by cooling breezes.

5.1 Cool Materials

The materials used in urban areas contribute significantly to urban heat. Consequently the choice of materials for pavements, walls and facades, roofs and awnings is critical and using materials with low thermal mass or high albedo should be preferred. Cool building materials have high albedo, which reflects heat away from the surface, and high emissivity, such that heat that is absorbed is readily released when ambient temperatures drop[59]. Cool materials and surface technologies that improve thermal efficiency and reduce thermal load are constantly being developed and tested.

5.1.1 Cool Roofs

Cool roofs have high solar reflectance and high emittance, and are available in a range of roofing materials and colours from light to dark. Alternatively, a heat-reflective coating can be applied to existing roofs. There are also several alternative roofing materials that are cooler than traditional roofs such as reflective roof tiles, light coloured metal roofing and cool membranes[16].

Cool roofs tend to stay within 6–11 °C of air temperature, unlike many traditional roofs that can be 30–45 °C hotter than air temperatures[16]. Cool roofs can reduce temperatures within the house, and lower energy costs by reducing the need for air-conditioning in summer. As cool roofs have lower surface temperatures, this can extend the life of a roof beyond that of a traditional roof.

Canberra currently has a higher demand for heating energy in winter than cooling energy in summer[57], so it is important to ensure there is adequate insulation under a cool roof to avoid an increased need for heating in winter. Studies have found however, that cool roof materials don't significantly increase the need for heating in winter in most locations, as the amount of solar radiation that is typically absorbed by horizontal surfaces in winter is a fraction of that absorbed in summer[59].

While cool roofs have high solar reflectance when they are new, reflectance is reduced over time with weathering and the accumulation of dirt[60]. Most of the original reflectance however, can be restored with washing. Consideration should be taken when choosing which buildings are most suited to cool roofing. Reflective roofs can bounce radiation onto taller surrounding buildings, transferring heat to them and can also cause unwanted glare [58, 60]. In densely built-up areas, reflective roofs are therefore likely to be most beneficial when there is a uniform roof height[60].

5.1.2 Cool and Permeable Paving

Large areas in cities are surfaced with impermeable paving, asphalt and concrete. These materials traditionally have low solar reflectance and can reach very high temperatures on hot days. Heat that is stored in pavement subsurfaces is released slowly at night adding to the urban heat island[61]. As demonstrated in this report, artificial playing surfaces can also be very hot.

Shading paved areas, and reducing the amount of surface area that is paved can reduce surface temperatures. Alternatively, choosing cooler paving compounds and binders, using light coloured materials, or coating surfaces with a reflective layer is also effective[61]. Paved surfaces can be cooler if they are permeable or porous as they allow moisture to infiltrate the soil where it is available for evaporative cooling[58]. There are also a variety of permeable or porous pavers such as porous asphalt, pervious concrete, permeable pavers, and grid pavements that allow water to percolate through spaces[61]. Other natural surface materials or manufactured composites that utilise a variety of materials such as resin or foam and are often porous may also be cooler.

There are several factors that should be considered when choosing cool paving materials. Firstly, choose a colour or surface coating that does not create uncomfortable glare and take note of surrounding structures to reduce the risk that reflected radiation could be absorbed by them instead.

5.1.3 Buildings and Built Shade Structures

Buildings and verandas cast shadows throughout the urban environment, creating shade in city centres and commercial areas. Smaller structures designed specifically to provide shade are an increasingly common feature in public areas such as over school playgrounds and toddler swimming pools where people may be exposed for long periods of time or are particularly sensitive to sun exposure. Built structures will be more effectively cooled if they are constructed with cool, light coloured materials and are open sided so as not to trap heat. Engineered shade structures can provide protection from rain and be designed to be both practical and aesthetic.

While buildings provide shade, they also reflect and emit stored heat which can be problematic on a hot day. Heat can become trapped between buildings such that the city can be slow to cool at night. To reduce this, the layout of the streets and buildings should be considered so that heat can escape the urban space[58]. Good orientation and design can take account of factors such as summer and winter sun paths, the direction of prevailing winds, as well as the impact that local features, buildings and landscapes may have on urban temperatures. This can help with harnessing the cooling benefits provided by shade, breezes and water bodies in summer, while at the same time optimising for sun exposure and thermal comfort and avoiding funnelling cold winds along streets in winter[62].

5.2 Vegetation

A report into Canberra's urban forest found that Canberrans particularly value trees in the landscape and that it engenders strong feelings in the community[63]. Canberra has a range of vegetation types, in gardens, along streets, in urban open spaces, and in parks and recreation areas. This report has demonstrated that different types of vegetation will modify land surface temperatures to different degrees on hot sunny days. Forested areas and irrigated vegetation are typically cooler in summer while grasslands and pasture with few trees are warmer. These are now discussed separately below.

5.2.1 Urban Forests and Street Trees

Urban vegetation and forests play a key role in modifying urban heat by cooling air and surface temperatures through shade and evapotranspiration. Shaded walls, roofs and pavements absorb less solar radiation, and trees planted along streets and in car parks provide shade for people and vehicles on hot days. The larger and more dense the tree canopy, the greater the cooling benefits, but the extent of cooling will also vary with the orientation of the streets and the time of year[64].

The potential for cooling through evapotranspiration is influenced by the size, structure and plant species, the amount of wind flow, and the amount of moisture in the soil and air[8, 65]. This report has shown that on hot days, irrigated playing fields are considerably cooler than unirrigated fields, which in turn are cooler than many artificial playing surfaces.

Plants also moderate the local climate by modifying or redirecting wind flow, filtering pollution and reducing runoff[50]. On hot days, when there is very little wind, advection currents over hot urban areas draw air from cooler green spaces, and the warmer urban air is then circulated back into the cooler greenspace[66]. The benefits of cool breezes generated from parkland areas are therefore most effective at reducing hot conditions at the times when they are most needed.

A general loss of tree canopy cover in public and private spaces is one of the features of increasing urban densification in many cities[67]. Urban consolidation, higher density housing and larger houses on smaller blocks all influence the amount of space available for trees. Consequently, care needs to be taken to ensure that green cover and green spaces are not lost through urban densification.

Tree shade on buildings can reduce the need for air-conditioning on hot days[68, 69]. Canberra currently has a higher demand for heating energy in winter than cooling energy in summer[57]. It is therefore important to select appropriate tree species and locate them around buildings so they confer cooling benefits in summer without creating the need for additional heating in winter[70, 71].

There are, of course, costs associated with planting and maintaining urban vegetation. They can present a safety hazard during windy weather and it can be challenging to maintain tree health during drought. While trees continue to provide shade, evapotranspiration rates can reduce when conditions are hot, dry or in drought, so cooling benefits may be reduced at these times[72, 73]. There was considerable tree mortality during the millennial drought in Canberra, and when deciding which trees to plant, it is worth considering species that are tolerant of heat stress conditions[74].

5.2.2 Grasslands and Pasture

Canberra's grasslands and pasture can be hot on summer days, but cool down quickly overnight. The Natural Temperate Grasslands are protected, and the ACT Government manages vegetation density to support the protection of these important communities and species. It is therefore not appropriate to plant trees in these areas. In other natural areas where the overstorey layer has been lost, restoring shrub and tree cover may help to reduce surface temperatures, but the potential impact on ecological communities requires further investigation.

In urban areas near grasslands, ensuring adequate tree and shrub cover along with the adoption of other heat mitigation strategies (e.g. cool building materials, porous paving, and irrigation) may help to reduce temperatures within the suburbs. The extent of the cooling benefits that could be achieved with these different mitigation options, however, would require further investigation.

5.2.3 Green Roofs

Rooftop gardens and planted balconies are common in cities where alternative greenspace is limited and are increasingly common for the multiple benefits they can bring. Green roofs can maintain a relatively stable temperature, reduce building energy consumption and provide habitat for wildlife[75, 76]. Parliament House is one of Australia's oldest and best-known green roofs and was shown in this report to have cool temperatures in summer. Green roofs can either fully or partially cover a surface with grass, herbs, shrubs or small trees[59]. If they support grass or low growing plants, they require a relatively thin layer of soil, whereas roofs that support shrubs and trees require considerable structural support given the weight of the soil, water and plants[60].

5.2.4 Green Walls

Walls covered in greenery, either as plants that climb, or cling, hang or drape over or on facades and frames confer cooling benefits. These cooling benefits will vary depending on the plant density, irrigation regime, and orientation of the wall[58]. As living infrastructure, plants require maintenance and ongoing management, and a site specific assessment is necessary to design the appropriate system.

5.3 Urban Water

5.3.1 Lakes and Ponds

The temperature of large bodies of water remains relatively constant throughout the day and can play a significant role in moderating temperatures[8]. While cooling benefits from large lakes can be substantial on a hot day, this benefit is minimal on a hot, still night due to their high heat holding capacity[50].

On a hot day, water bodies cool the environment through evaporative cooling and the movement of air over the lake surface, providing cooler air to areas downwind[77]. The size and length of the downwind spread will depend on the wind speed and the morphology of the surrounding urban areas. The location and design of buildings and vegetation treatments downwind of a water body can either obstruct or facilitate the flow of these cooling breezes.

5.3.2 Water Sensitive Urban Design

Water sensitive urban design aims to capture and retain water in the landscape and has benefits for reducing runoff, improving stormwater quality and reducing the use of potable water for irrigation. Lakes and ponds create cool spaces and provide an alternative water source for irrigating green spaces, which in turn confers cooling benefits to the urban environment. The Inner-North Reticulation Network provides several examples of water sensitive urban design.

5.3.3 Water Features

Fountains, misters and running water cool the environment through evaporative cooling and are an effective cooling strategy for dry environments like Canberra. They are an aesthetic addition to public spaces and can be a fun addition to children’s play areas. Public water features do require ongoing monitoring and maintenance however, and water scarcity during drought can impact their use.

6 Potential Next Steps: From Research to Practice

This report includes maps and information to assist with developing strategies and prioritising actions for mitigating urban heat impacts in Canberra. Three potential areas have been identified to translate these research findings into practice. These include: taking action now using what we know, collecting more information to fill knowledge gaps, and strategic planning for long-term change. Taking this three-pronged approach, strategic planning across multiple ACT Government portfolios can be progressed to overcome business-as-usual inertia, while 'no regrets' actions are implemented.

6.1 Taking Action Now Using What We Know

The findings of this research demonstrate that urban heat can be mitigated through the strategic use of cool building materials, vegetation and water. The primary focus of these interventions is to increase the reflectivity and emissivity of surface materials so that less heat is stored in the urban environment, and to increase the cooling benefits through shade, evaporation, evapotranspiration, water and by channelling breezes.

Actions that can be taken now include:

- Use the maps of land surface temperature and population vulnerability for each urban District and Village (Appendix 1) to identify the priority areas for targeted urban heat mitigation actions;
- Examine existing work programs and look for opportunities to incorporate low-cost urban heat mitigation actions as part of these planned activities to retrofit or 'build in' climate adaptation;
- Engage the urban development industry, through peak bodies such as the Housing Industry Association and Property Council, to identify opportunities to trial cool materials and products;
- Implement trials on a small, but strategic scale in a 'learning-by-doing' approach to quantify air and surface temperature benefits before, during and after remedial actions are implemented, for example, create buffers of trees between hot rural areas and suburbs; strategically place shade structures beside small areas with hot surfaces; or trial the application of cool roof and cool coating technologies;
- Establish an urban heat monitoring program using satellite thermal imagery and field measurements to evaluate heat mitigation actions.

6.2 Collecting More Information to Fill Knowledge Gaps

Satellite imagery has been used to measure land surface temperature in this project. This provides a low-cost means of prioritising neighbourhoods for heat mitigation actions, but relies on assumed relationships between land surface temperature and air temperature. A key next step would be to verify and validate the findings of the project with field based measurements. There are also tools such as urban climate modelling at a range of scales that could be used to support decision making through robust assessment of the effectiveness of different urban heat mitigation actions.

Critical areas to address are:

- Verify the relationship between surface and air temperatures throughout the day and across seasons with field based measurements;
- Establish how prevailing winds across rural land influences urban temperatures and whether the type of vegetation adjacent to suburban areas influences those temperatures;
- Determine the influence of different building densities, tree cover and land use have on air temperature and how this information can be utilised to achieve multiple objectives related to urban temperatures, solar access and to channel breezes;
- Determine the level of air and land surface temperature reductions that can be achieved through the implementation of different combinations of urban heat mitigation strategies;
- Utilise modelling tools and field measurements to assess the cooling potential of different heat mitigation strategies and to maximise cooling potential without increasing winter heating costs.

6.3 Strategic Planning for Long-Term Change

Urban heat and its mitigation is an issue that crosses multiple portfolios of government and impacts many sectors of industry and the community. Taking collective action requires first a recognition of the problem and then a willingness to take action once solutions have been identified. The level of knowledge and experience with climate adaptation will vary across government, industry and the community.

Opportunities to support longer term strategic planning for transformational change include:

- Effective engagement to acknowledge and address different opinions, backgrounds and agendas on urban heat, so that they can be incorporated into planning processes;
- Enhance cross-portfolio climate adaptation planning by identifying actions that can satisfy multiple objectives, delivering co-benefits as part of a ‘whole-of-organisation’ approach;
- Assess how to incorporate actions into established programs, policies and management strategies; and
- Develop scenarios that incorporate estimates of urban temperature reductions under a range of heat mitigation strategies and use workshop and modelling processes to explore the potential to achieve multiple portfolio objectives and to address competing challenges and trade-offs.

7 References

1. ACT Government (2016) ACT climate change adaptation strategy – living with a warming climate. ACT Government, Canberra, Australia.
2. Parsons K (2014) *Human thermal environments: the effects of hot, moderate and cold temperatures on human health, comfort and performance* CRC Press, London, UK Third Ed.
3. Office of Environment and Heritage (2015) Australian Capital Territory: climate change snapshot. Sydney, Australia.
4. Bureau of Mereorology (2017) Climate data online, [Accessed 28th November 2017]. <http://www.bom.gov.au/climate/data/>
5. Loughnan M, Tapper N, Phan T, Lynch K, & McInnes J (2013) A spatial vulnerability analysis of urban populations during extreme heat events in Australian capital cities. Gold Coast, Australia, p 128.
6. Arnfield AJ (2003) Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology* 23(1):1-26.
7. Akbari H & Konopacki S (2005) Calculating energy-saving potentials of heat-island reduction strategies. *Energy Policy* 33(6):721-756.
8. Oke TR (1987) *Boundary layer climates* Methuen, London, UK 2nd Ed.
9. Oke TR (1981) Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. *Journal of Climatology* 1(3):237-254.
10. Rizwan AM, Dennis YCL, & Liu CH (2008) A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences* 20(1):120-128.
11. Feizizadeh B, Blaschke T, Nazmfar H, Akbari E, & Kohbanani HR (2013) Monitoring land surface temperature relationship to land use/land cover from satellite imagery in Maraqeh County, Iran. *Journal of Environmental Planning and Management* 56(9):1290-1315.
12. Coutts AM*, et al.* (2016) Thermal infrared remote sensing of urban heat: Hotspots, vegetation, and an assessment of techniques for use in urban planning. *Remote Sensing of Environment* 186:637-651.
13. Deilami K, Kamruzzaman M, & Hayes JF (2016) Correlation or causality between land cover patterns and the urban heat island effect? Evidence from Brisbane, Australia. *Remote Sensing* 8(9):716.
14. Mahmuda S & Webb R (2016) Climate adaptation and urban planning for heat islands: a case study of the Australian Capital Territory. *Australian Planner* 53(2):127-142.
15. Good EJ (2016) An in situ-based analysis of the relationship between land surface "skin" and screen-level air temperatures. *Journal of Geophysical Research-Atmospheres* 121(15):8801-8819.
16. U.S. Environmental Protection Agency (2008) *Reducing urban heat islands: compendium of strategies.* U.S. Environmental Protection Agency, Washington DC.
17. Roth M, Oke TR, & Emery WJ (1989) Satellite-derived urban heat islands from three coastal cities and the utilization of such data in urban climatology. *International Journal of Remote Sensing* 10(11):1699-1720.
18. Health and Safety Professionals Alliance (2012) The core body of knowledge for generalist OHS professionals Tullamarine, VIC.

19. Hanna EG & Tait PW (2015) Limitations to thermoregulation and acclimatization challenge human adaptation to global warming. *International Journal of Environmental Research and Public Health* 12(7):8034-8074.
20. Josseran L*, et al.* (2010) Assessment of a syndromic surveillance system based on morbidity data: results from the Oscour network during a heat wave. *PLoS One* 5(8):e11984.
21. Kovats RS, Hajat S, & Wilkinson P (2004) Contrasting patterns of mortality and hospital admissions during hot weather and heat waves in Greater London, UK. *Occupational and Environmental Medicine* 61(11):893-898.
22. Bouchama A*, et al.* (2007) Prognostic factors in heat wave-related deaths - A meta-analysis. *Archives of Internal Medicine* 167(20):2170-2176.
23. Kilbourne EM, Choi K, Jones TS, & Thacker SB (1982) Risk factors for heatstroke. A case-control study. *Journal of the American Medical Association* 247(24):3332-3336.
24. Larrieu S*, et al.* (2008) Factors associated with morbidity during the 2003 heat wave in two population-based cohorts of elderly subjects: PAQUID and Three City. *European Journal of Epidemiology* 23(4):295-302.
25. Khalaj B, Lloyd G, Sheppeard V, & Dear K (2010) The health impacts of heat waves in five regions of New South Wales, Australia: a case-only analysis. *International Archives of Occupational and Environmental Health* 83(7):833-842.
26. Vandentorren S*, et al.* (2006) August 2003 heat wave in France: risk factors for death of elderly people living at home. *European Journal of Public Health* 16(6):583-591.
27. Nance A (2017) Energy access and affordability policy research. A report for the Australian Council of Social Service. The Energy Project Pty Ltd.
28. Farbotko C & Waitt G (2011) Residential air-conditioning and climate change: voices of the vulnerable. *Health Promotion Journal of Australia* 22:S13-S16.
29. ACOSS (2011) Poverty and its causes. *Poverty Report, October 2011 Update*. Australia.
30. Balbus JM & Malina C (2009) Identifying vulnerable subpopulations for climate change health effects in the United States. *Journal of Occupational and Environmental Medicine* 51(1):33-37.
31. Barnett G*, et al.* (2013) Pathways to climate adapted and healthy low income housing. Gold Coast, Australia, p 95.
32. Bao JZ, Li XD, & Yu CH (2015) The construction and validation of the heat vulnerability index, a review. *International Journal of Environmental Research and Public Health* 12(7):7220-7234.
33. Department of Environment and Energy (2017) Climate change impacts in the Australian Capital Territory, [Accessed 22nd Novemeber 2017]. <http://www.environment.gov.au/climate-change/climate-science-data/climate-science/impacts/act>
34. Hajat S & Barnard LT (2013) *Cold-Related Mortality and Morbidity. Climate vulnerability: Understanding and addressing threats to essential resources. Volume 1 - Vulnerability of human health to climate* Elsevier, USA pp 157-164.
35. Conlon KC, Rajkovich NB, White-Newsome JL, Larsen L, & O'Neill MS (2011) Preventing cold-related morbidity and mortality in a changing climate. *Maturitas* 69(3):197-202.
36. Jimenez-Munoz JC & Sobrino JA (2003) A generalized single-channel method for retrieving land surface temperature from remote sensing data. *Journal of Geophysical Research-Atmospheres* 108(D22):4688.
37. Jimenez-Munoz JC*, et al.* (2009) Revision of the single-channel algorithm for land surface temperature retrieval from Landsat thermal-infrared data. *IEEE Transactions on Geoscience and Remote Sensing* 47(1):339-349.

38. Yu XL, Guo XL, & Wu ZC (2014) Land surface temperature retrieval from Landsat 8 TIRS: comparison between radiative transfer equation-based method, split window algorithm and single channel method. *Remote Sensing* 6(10):9829-9852.
39. Buck AL (1981) New equations for computing vapour-pressure and enhancement factor. *Journal of Applied Meteorology* 20(12):1527-1532.
40. Lo CP & Quattrochi DA (2003) Land-use and land-cover change, urban heat island phenomenon, and health implications: a remote sensing approach. *Photogrammetric Engineering and Remote Sensing* 69(9):1053-1063.
41. Sobrino JA & Raissouni N (2000) Toward remote sensing methods for land cover dynamic monitoring: application to Morocco. *International Journal of Remote Sensing* 21(2):353-366.
42. Environmental Systems Research Institute (ESRI) (2015) *ArcGIS Release 10.3.* Redlands, CA.
43. Wimpenny C, Howland B, & Fletcher D (2015) A simple but useful map of vegetation structure in and near Canberra. Technical Report 33. Environment and Planning Directorate, ACT Government, Canberra.
44. ACT Government (2017) Territory plan, [Accessed 12th April 2017]. <http://www.legislation.act.gov.au/ni/2008-27/current/default.asp>
45. ACT Government (2017) Transport Canberra and City Services - tree canopy map for Canberra. ACT Government, Canberra.
46. Reid CE*, et al.* (2009) Mapping community determinants of heat vulnerability. *Environmental Health Perspectives* 117(11):1730-1736.
47. Rinner C*, et al.* (2010) The role of maps in neighborhood-level heat vulnerability assessment for the city of Toronto. *Cartography and Geographic Information Science* 37(1):31-44.
48. ABS (2016) Australian Statistical Geography Standard (ASGS): Volume 1 - Main structure and greater capital city statistical areas, July 2016. Mesh Blocks (MB) [Accessed 22 September 2017]. <http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/1270.0.55.001~July%202016~Main%20Features~Mesh%20Blocks%20(MB)~10012>
49. ABS (2017) Household income and wealth, Australia, 2015-16, [Accessed 22 September 2017]. <http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/6523.0~2015-16~Main%20Features~Characteristics%20of%20Low,%20Middle%20and%20High%20Income%20Households~8>
50. Gunawardena KR, Wells MJ, & Kershaw T (2017) Utilising green and bluespace to mitigate urban heat island intensity. *Science of The Total Environment* 584-585:1040-1055.
51. Doick KJ, Peace A, & Hutchings TR (2014) The role of one large greenspace in mitigating London's nocturnal urban heat island. *Science of the Total Environment* 493:662-671.
52. Mallick J, Singh CK, Shashtri S, Rahman A, & Mukherjee S (2012) Land surface emissivity retrieval based on moisture index from LANDSAT TM satellite data over heterogeneous surfaces of Delhi city. *International Journal of Applied Earth Observation and Geoinformation* 19:348-358.
53. Weng QH, Lu DS, & Schubring J (2004) Estimation of land surface temperature-vegetation abundance relationship for urban heat island studies. *Remote Sensing of Environment* 89(4):467-483.
54. Guo Z, Wang SD, Cheng MM, & Shu Y (2012) Assess the effect of different degrees of urbanization on land surface temperature using remote sensing images. *18th Biennial ISEM conference on ecological modelling for global change and coupled human and natural system,* Procedia Environmental Sciences, eds Yang Z & Chen B, Vol 13, pp 935-942.

55. Imhoff ML, Zhang P, Wolfe RE, & Bounoua L (2010) Remote sensing of the urban heat island effect across biomes in the continental USA. *Remote Sensing of Environment* 114(3):504-513.
56. Peng S*, et al.* (2012) Surface urban heat island across 419 global big cities. *Environ Sci Technol* 46(2):696-703.
57. ACT Government (2015) Electricity and natural gas consumption: Trends in the Australian Capital Territory 2009-2013. Environment and Planning Directorate, ACT Government, Canberra.
58. Osmond P & Sharifi E (2017) Guide to urban cooling strategies. Low Carbon Living CRC, Australia.
59. Hosseini M & Akbari H (2016) Effect of cool roofs on commercial buildings energy use in cold climates. *Energ Buildings* 114:143-155.
60. Hoverter SP (2012) Adapting to urban heat: A toolkit for local governments. Harrison Institute for Public Law, Georgetown Climate Center, New Jersey, USA.
61. U.S. Environmental Protection Agency (2012) Cool pavements. In: Reducing urban heat islands: compendium of strategies., U.S. Environmental Protection Agency, Washington DC.
62. McGee C, Reardon C, & Clarke D (2017) Passive design - Orientation. Your Home: Australia's guide to environmentally sustainable homes. Department of the Environment and Energy, Commonwealth of Australia.
63. Cooper M (2011) Report on the Investigation into the Government's tree management practices and the renewal of Canberra's urban forest: Summary and Recommendations. Office of the Commissioner for Sustainability and the Environment, Canberra.
64. Lin BB, Meyers J, Beaty RM, & Barnett GB (2016) Urban green infrastructure impacts on climate regulation services in Sydney, Australia. *Sustainability,* 8(8).
65. Armson D, Stringer P, & Ennos AR (2012) The effect of tree shade and grass on surface and globe temperatures in an urban area. *Urban Forestry & Urban Greening* 11(3):245-255.
66. Jansson C, Jansson PE, & Gustafsson D (2006) Near surface climate in an urban vegetated park and its surroundings. *Theoretical and Applied Climatology* 89:185-193.
67. Lin B, Meyers J, & Barnett G (2015) Understanding the potential loss and inequities of green space distribution with urban densification. *Urban Forestry & Urban Greening* 14(4):952-958.
68. Alexandria E & Jones P (2008) Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment* 43(4):480-493.
69. Barnett G, Meyers J, Ren Z, & Chen D (2015) Tree shade and thermal performance of housing in Western Sydney, Australia in *The 3rd International Conference on Building Energy and Environment (COBEE), July 12-15 2015* Tianjin, China.
70. McPherson EG, Simpson JR, Xiao Q, & Wu C (2011) Million trees Los Angeles canopy cover and benefit assessment. *Landscape and Urban Planning* 99(1):40-50.
71. Pandit R & Laband DN (2010) Energy savings from tree shade. *Ecological Economics* 69(6):1324-1329.
72. Nitschke CR*, et al.* (2017) The influence of climate and drought on urban tree growth in southeast Australia and the implications for future growth under climate change. *Landscape and Urban Planning* 167:275-287.
73. Pedersen BS (1998) The role of stress in the mortality of midwestern oaks as indicated by growth prior to death. *Ecology* 79(1):79-93.
74. May PB, Livesley SJ, & Shears I (2013) Managing and monitoring tree health and soil water status during extreme drought in Melbourne, Victoria. *Arboriculture & Urban Forestry* 39(3):136-145.

75. Wong NH, *et al.* (2003) The effects of rooftop garden on energy consumption of a commercial building in Singapore. *Energ Buildings* 35(4):353-364.
76. Teemusk A & Mander U (2006) The use of greenroofs for the mitigation of environmental problems in urban areas. *Wit Trans Ecol Envir* 93:3-17.
77. Theeuwes NE, Solcerova A, & Steeneveld GJ (2013) Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city. *Journal of Geophysical Research-Atmospheres* 118(16):8881-8896.

Acronyms

°C	Degrees Celsius
ABS	Australian Bureau of Statistics
ABS 2016 Census	Australian Bureau of Statistics 2016 Census of Population and Housing
ACT	Australian Capital Territory
Cool materials	Materials that have high solar reflectance and thermal emittance
CSIRO	Commonwealth Scientific and Industrial Research Organisation
District	Administrative area within the ACT. There are 19 Districts (e.g. Belconnen, Tuggeranong). A District may contain a number of Divisions/Suburbs
Division	Suburb. An administrative area within the ACT. There are 116 Divisions within the ACT (e.g. Aranda, Kambah)
DST	Daylight saving time
EST	Eastern standard time
Grassland	Includes native grassland, derived native grassland and pasture
LST	Land surface temperature
LiDAR	Light Detection and Ranging; a survey method that measures distance to a target using laser light
Mesh Block	A statistical area defined by the ABS. Mesh Block are the finest resolution of census geography for which for which Census data are available.
Metropolitan area	The area that includes the urban Divisions (suburbs)
MODIS	MODIS is an instrument aboard the Terra satellite
NDVI	Normalized Difference Vegetation Index
SD	Standard deviation – a measure of how dispersed a set of data is from its mean
SEIFA	Socioeconomic indexes for areas
Urban Districts and Villages	The area that includes the urban Districts (Belconnen, Canberra Central, Gungahlin, Jerrabomberra, Majura, Molonglo Valley, Tuggeranong, Weston Creek, Woden Valley) and the Villages of Hall, Tharwa and Uriarra.

Appendix 1: District and Village Maps of Land Surface Temperature Vulnerability

The following section includes maps for individual urban Districts and Villages. Maps of land surface temperatures (LST) for summer (S1 – S6) are derived using Landsat 8 thermal infrared sensor imagery for 9 February 2017 (10.50 AM DST) and maps for winter (W1 – W2) are derived using imagery for 20 August 2017 (9.50 AM EST).

Maps in this section include:

Summer

- S1 – Land surface temperatures for each urban District or Village for 9 February 2017 (10.50 AM DST);
- S2 – Hot spots and cool spots within urban Divisions/Suburbs based on departure from 34.4 °C, which is the mean land surface temperature of the *Urban Districts and Villages* area shown in Figure 4;
- S3 – Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing;
- S4 – Vulnerability score for Mesh Blocks where people live, based on the 20% of Mesh Blocks that have the highest number of people who are older than 65 years, or younger than 5 years, or the highest number of low-income households, which is defined as the lowest 25% of household incomes in the ACT.
- S5 – Vulnerability score within the hottest 40% of Mesh Blocks;
- S6 – Vulnerability score within the hottest 20% of Mesh Blocks;

Winter

- W1 – Land surface temperatures for each urban District or Village for 20 August 2017 (9.50 AM EST);
- W2 – Cool spots within urban Divisions/Suburbs based on departure from 11.4 °C, which is the mean land surface temperature of the *Urban Districts and Villages* area shown in Figure 11.

Belconnen

<u>Summer</u> Land Surface Temperature, 9-2-2017 10.50AM

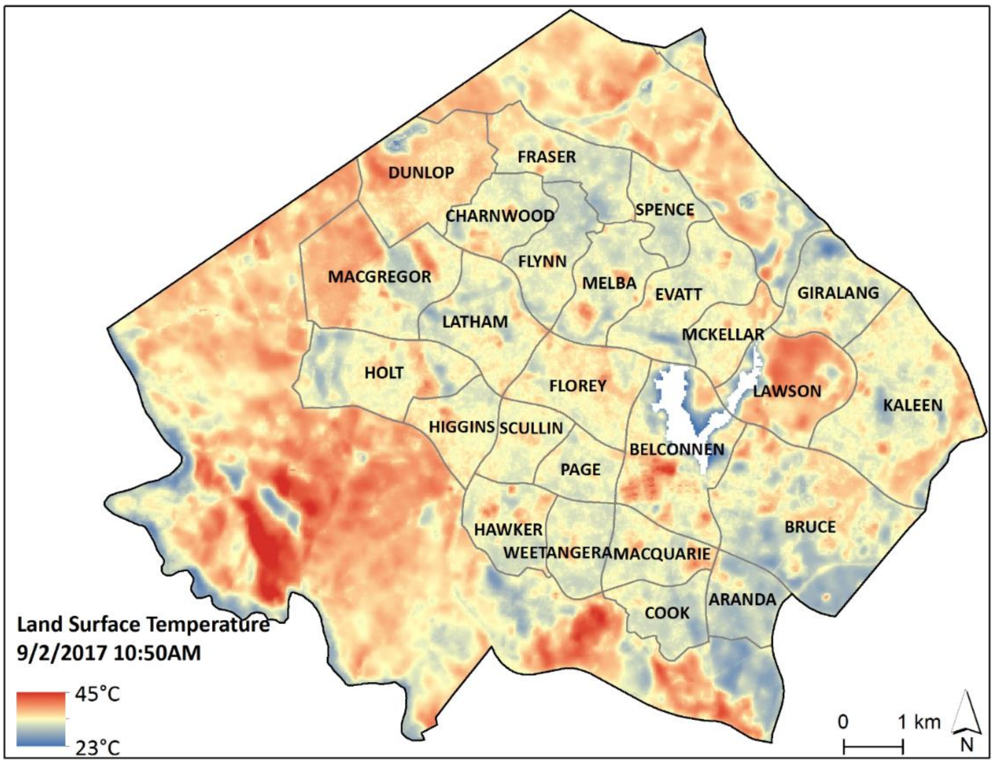


Figure S1: Land surface temperatures for 9 February 2017 (10.50 AM DST) derived using Landsat 8 thermal data.

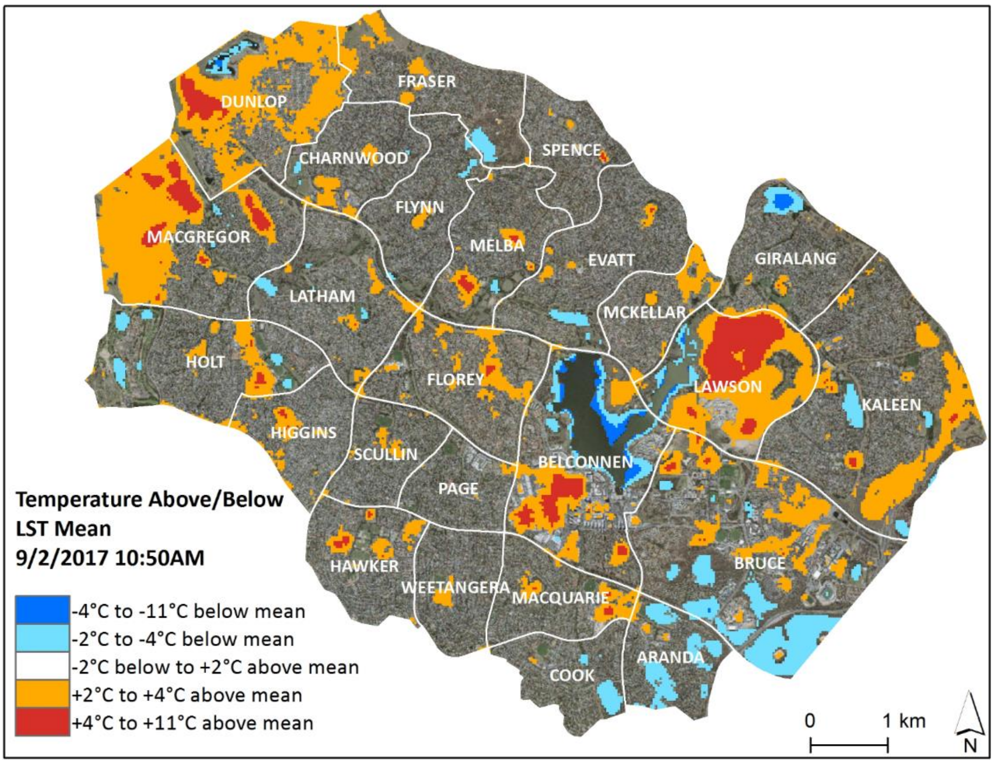


Figure S2: Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

Summer Neighbourhood Heat Exposure and Vulnerability

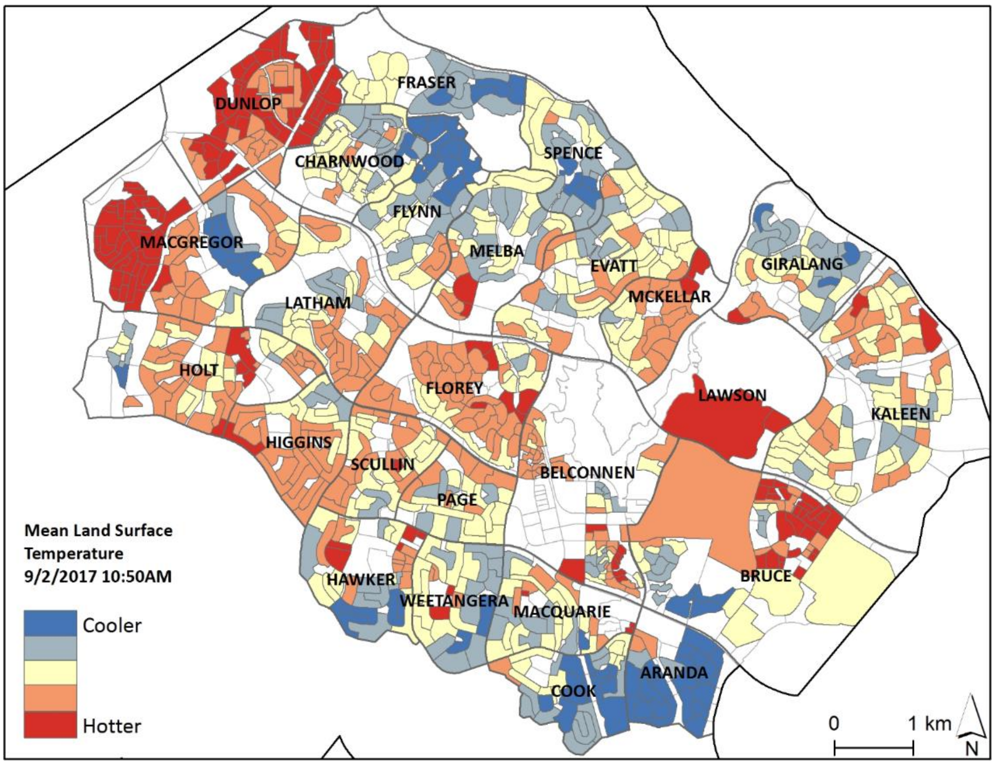


Figure S3: Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.

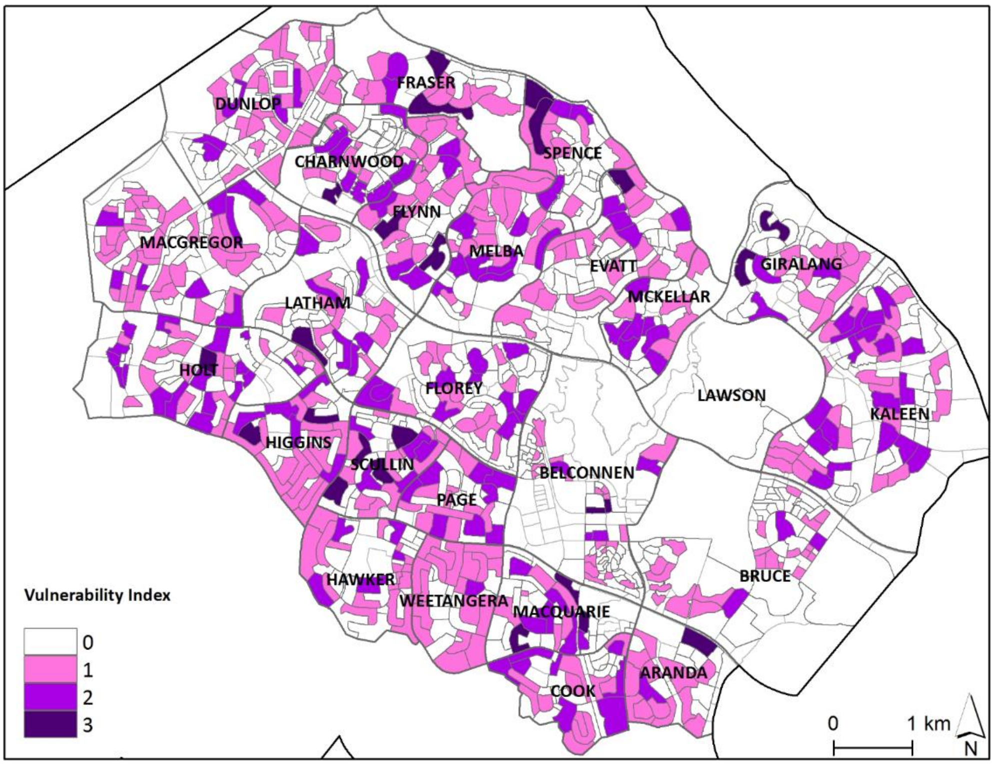


Figure S4: Vulnerability score; based on the cumulative score for Mesh Blocks with the highest 20% for each of three heat vulnerability factors; the number of people over 65 years, or under 5 years, or the number of low-income households.

Summer Neighbourhood Heat Exposure and Vulnerability Combined

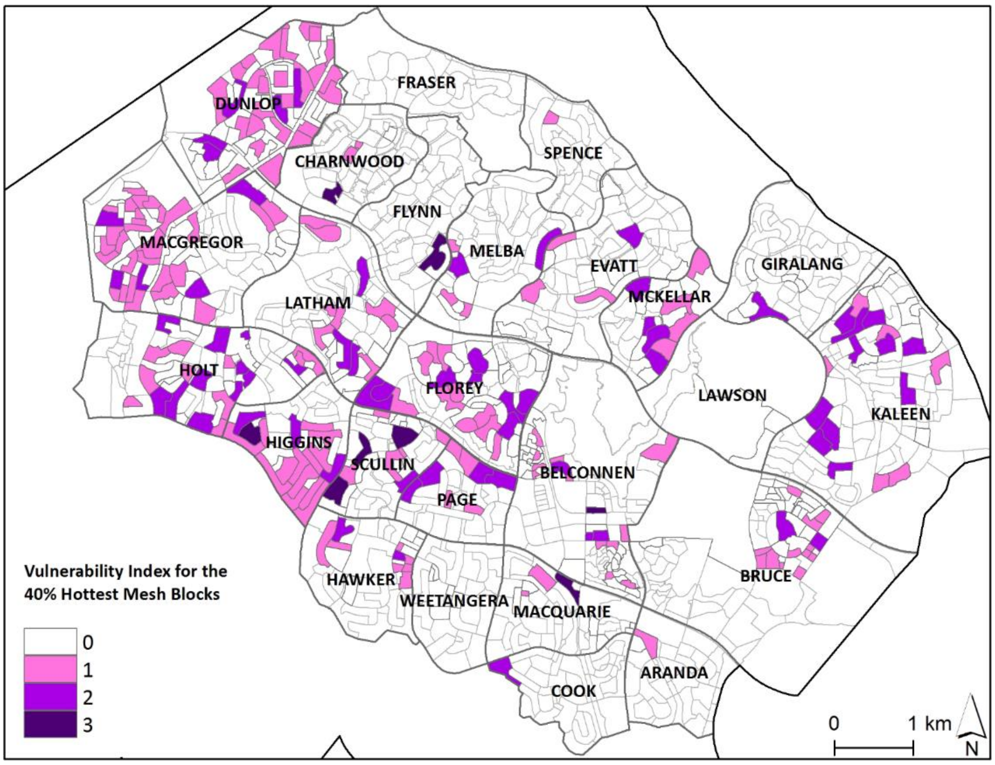


Figure S5: Vulnerability scores within the hottest 40% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

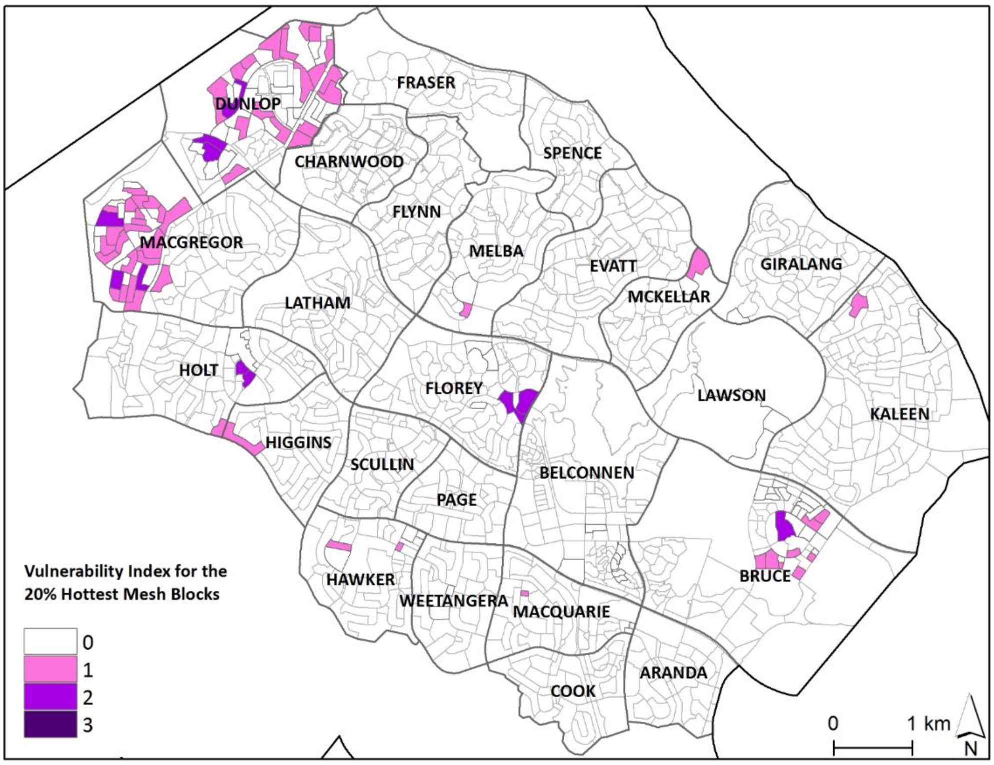


Figure S6: Vulnerability scores within the hottest 20% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

Winter Land Surface Temperature, 20-8-2017 9.50AM

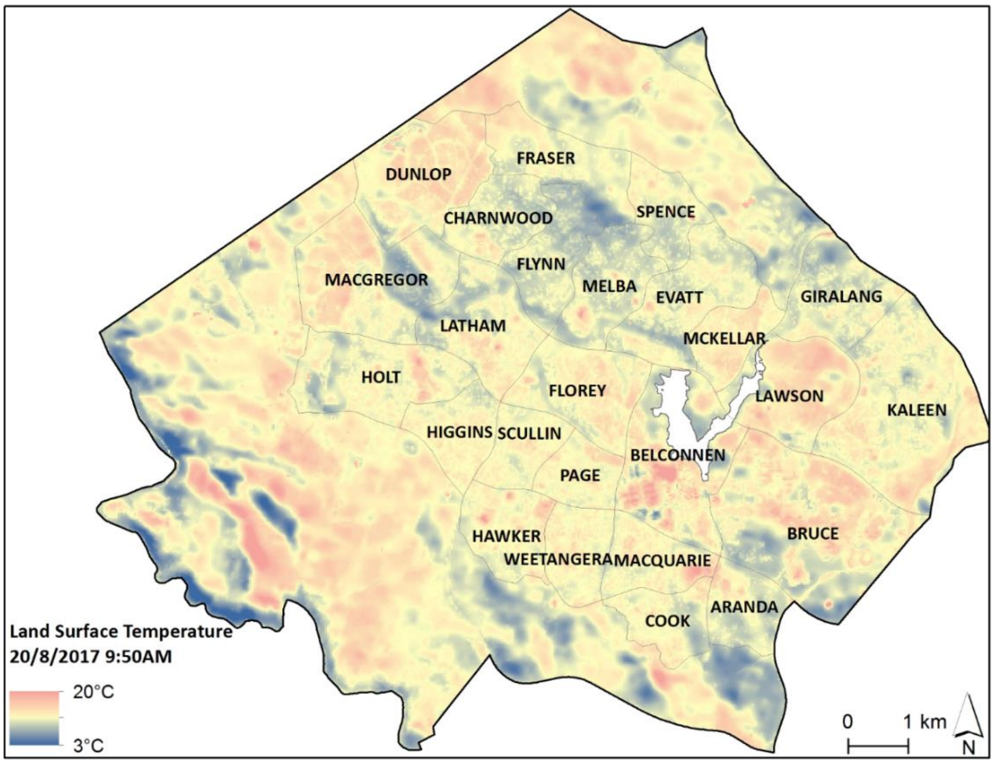


Figure W1: Land surface temperatures for 20-8-2017 (9.50 AM EST) derived using Landsat 8 thermal data.

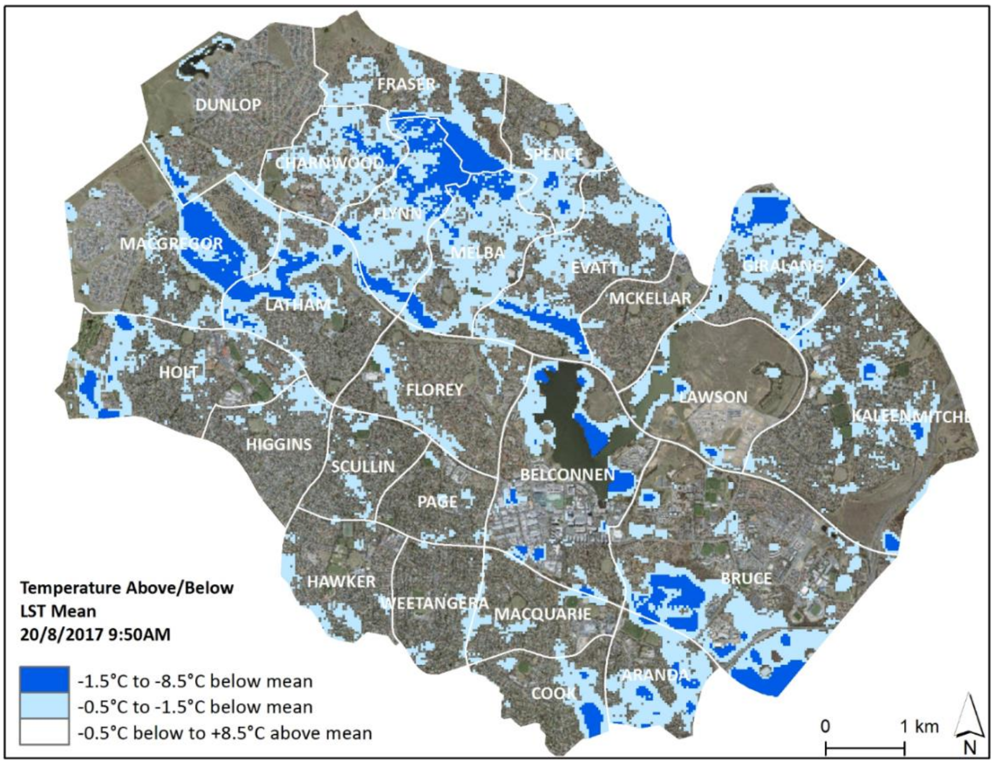


Figure W2: Cool spots; departure from the mean land surface temperature of 11.4 °C.
ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

Canberra Central

Summer Land Surface Temperature, 9-2-2017 10.50AM

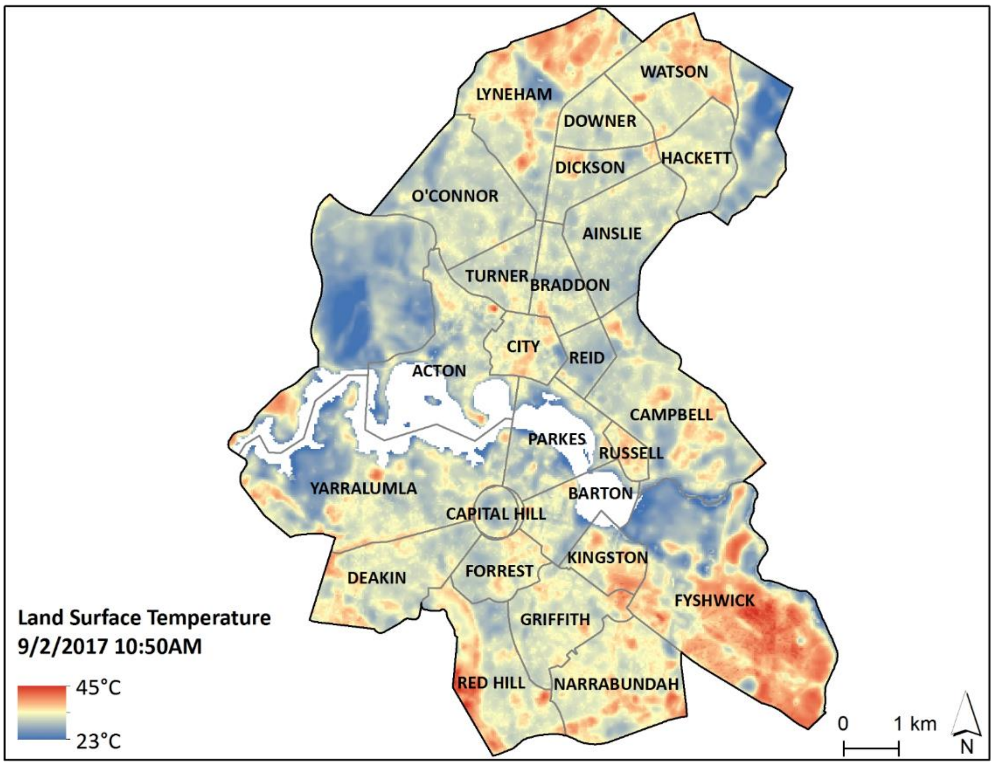


Figure S1: Land surface temperatures for 9 February 2017 (10.50 AM DST) derived using Landsat 8 thermal data.

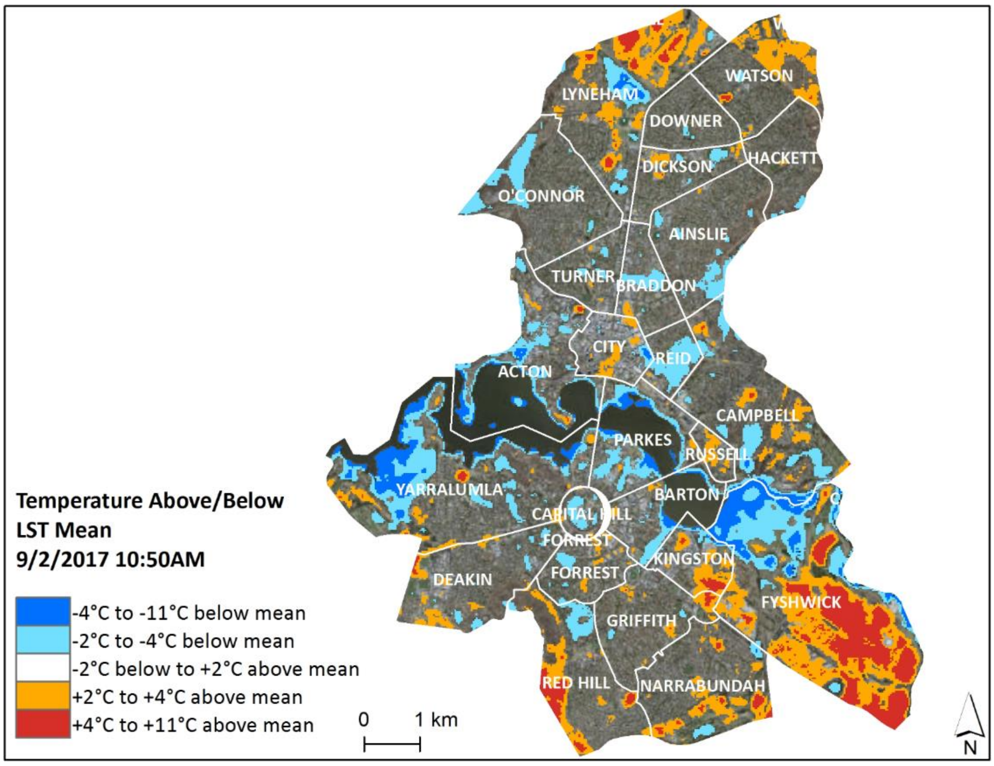


Figure S2: Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

Summer Neighbourhood Heat Exposure and Vulnerability

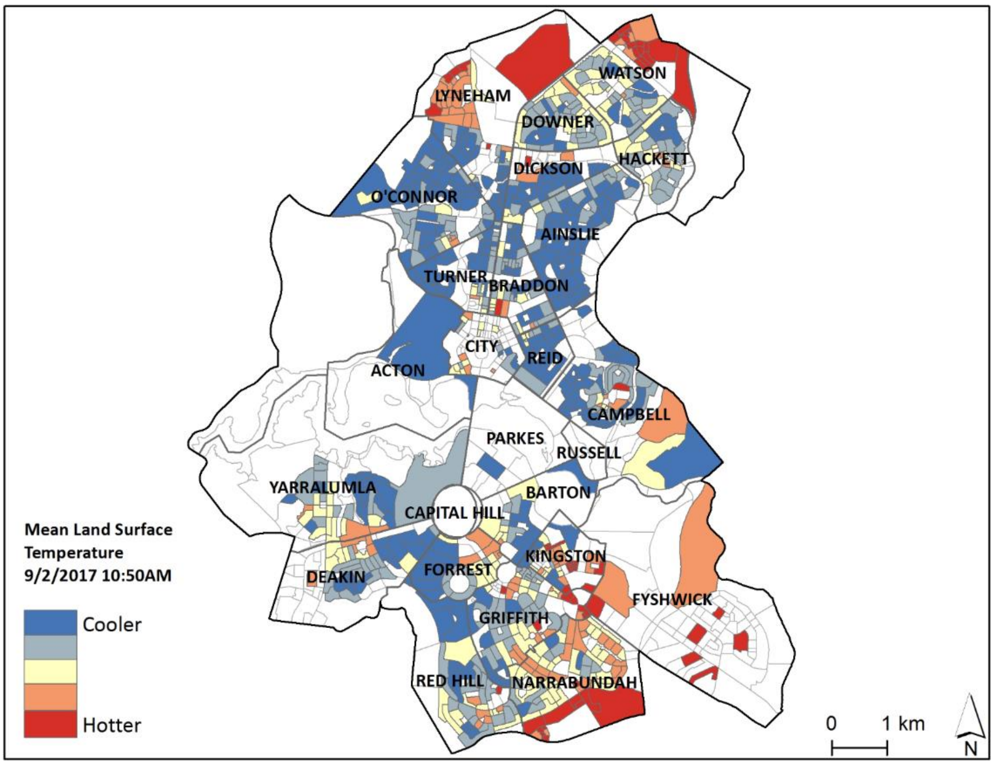


Figure S3: Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.

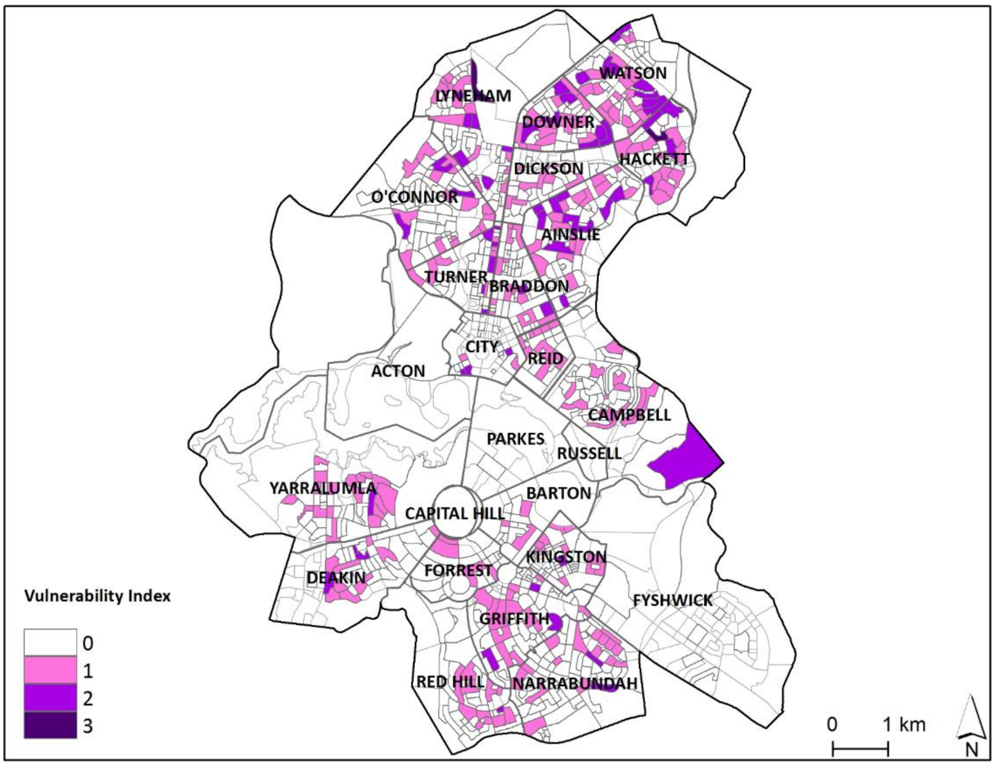


Figure S4: Vulnerability score; based on the cumulative score for Mesh Blocks with the highest 20% for each of three heat vulnerability factors; the number of people over 65 years, or under 5 years, or the number of low-income households.

<u>Summer</u> Neighbourhood Heat Exposure and Vulnerability Combined

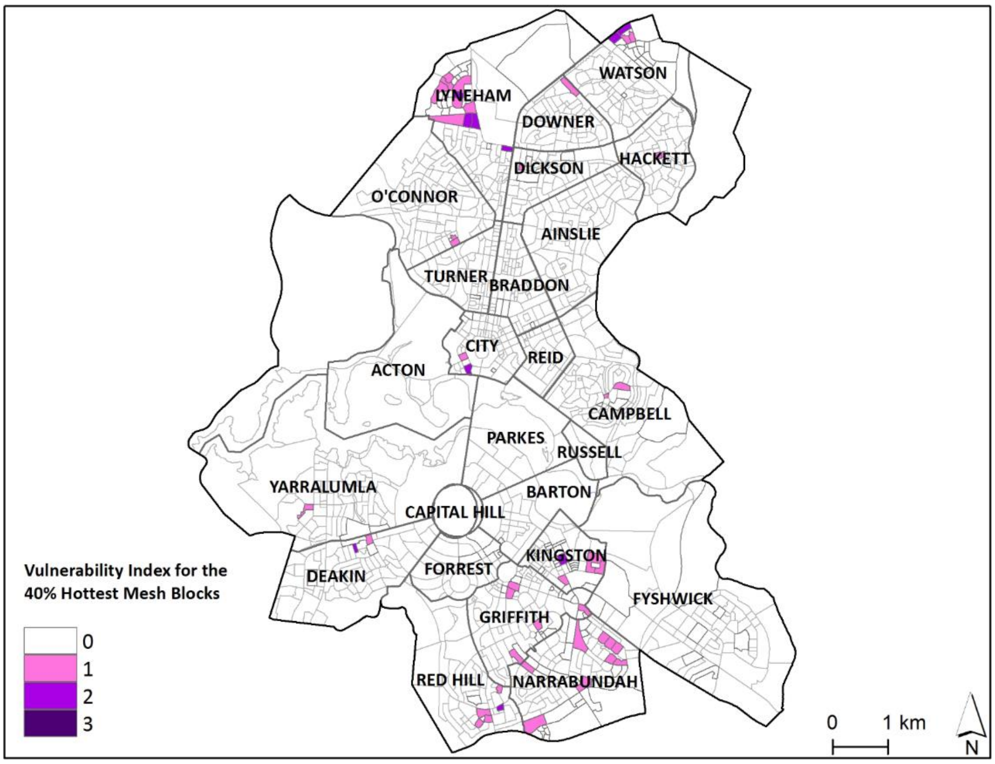


Figure S5: Vulnerability scores within the hottest 40% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

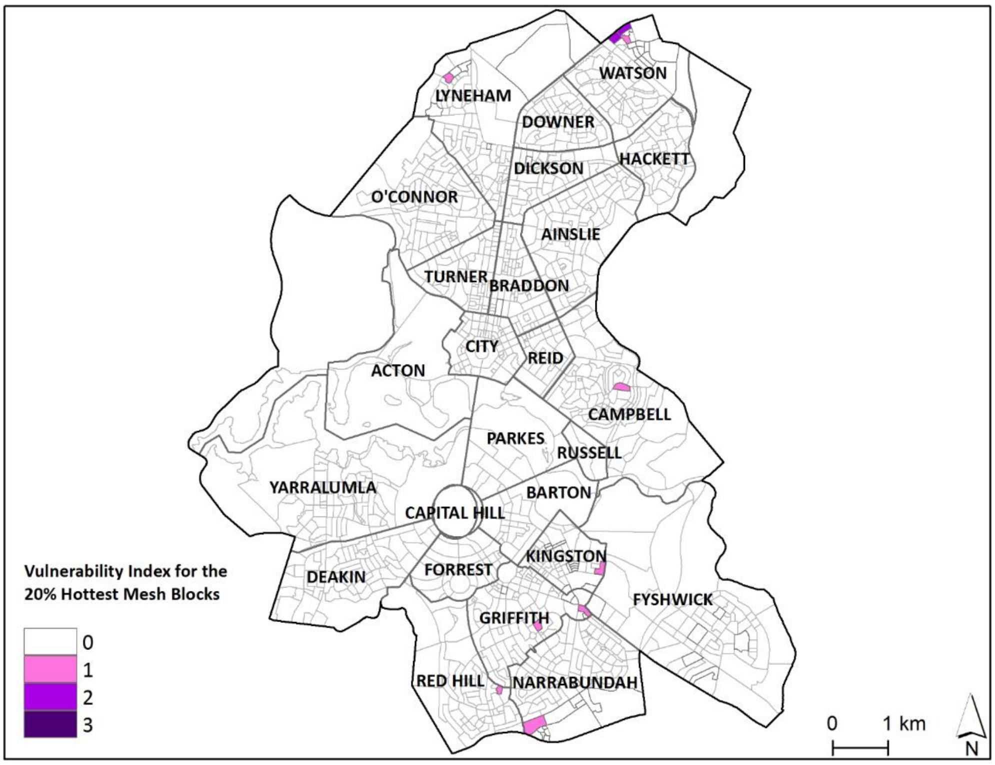


Figure S6: Vulnerability scores within the hottest 20% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

<u>Winter</u> Land Surface Temperature, 20-8-2017 9.50AM

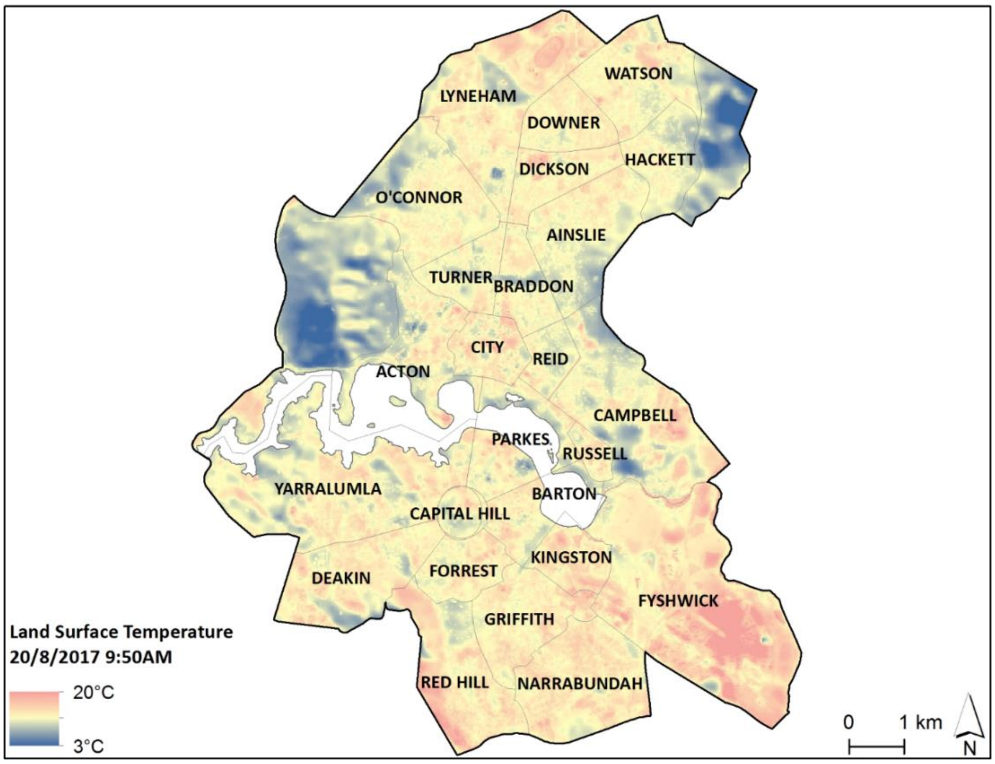


Figure W1: Land surface temperatures for 20-8-2017 (9.50 AM EST) derived using Landsat 8 thermal data.

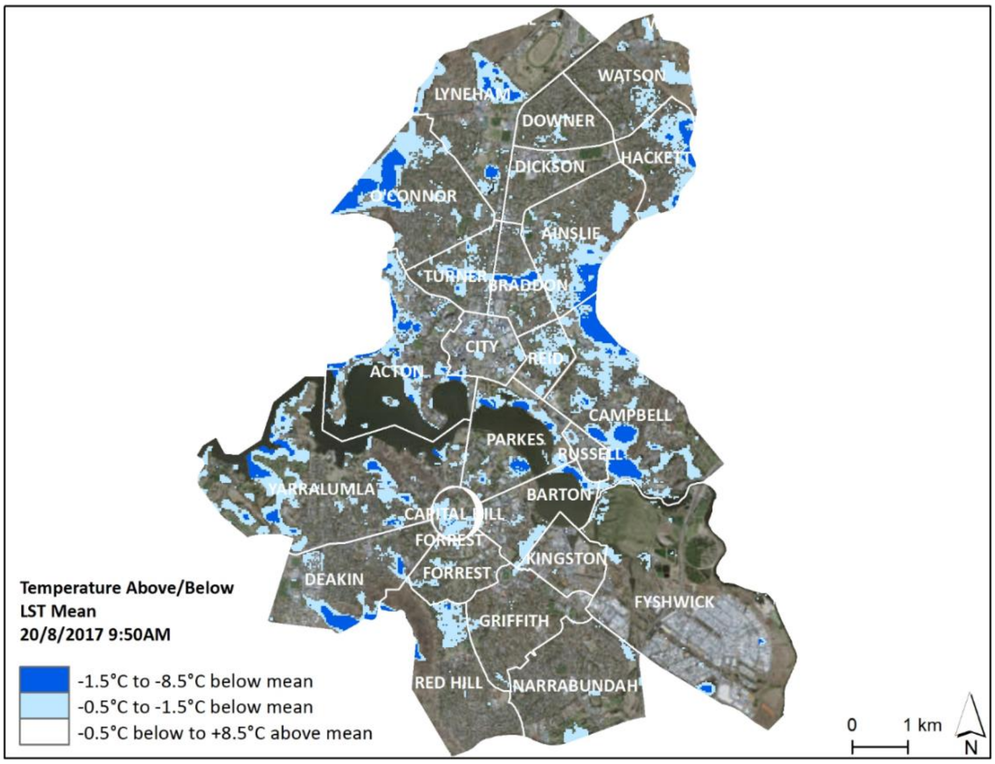


Figure W2: Cool spots; departure from the mean land surface temperature of 11.4 °C.
ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

Gungahlin

Summer Land Surface Temperature, 9-2-2017 10.50AM

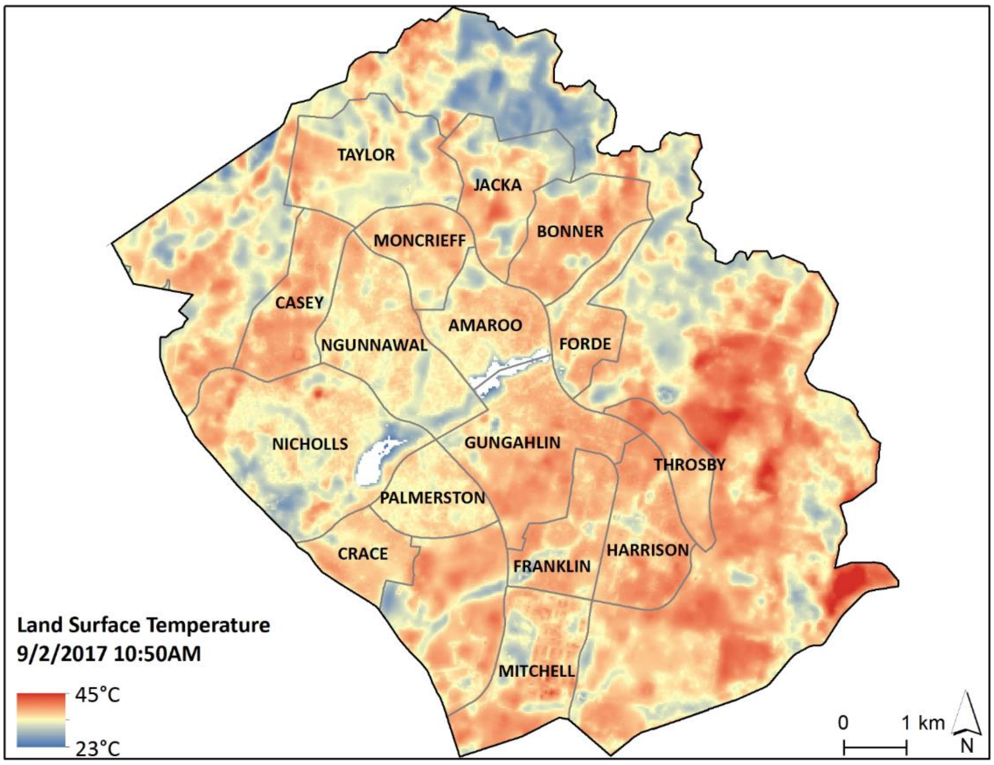


Figure S1: Land surface temperatures for 9 February 2017 (10.50 AM DST) derived using Landsat 8 thermal data.

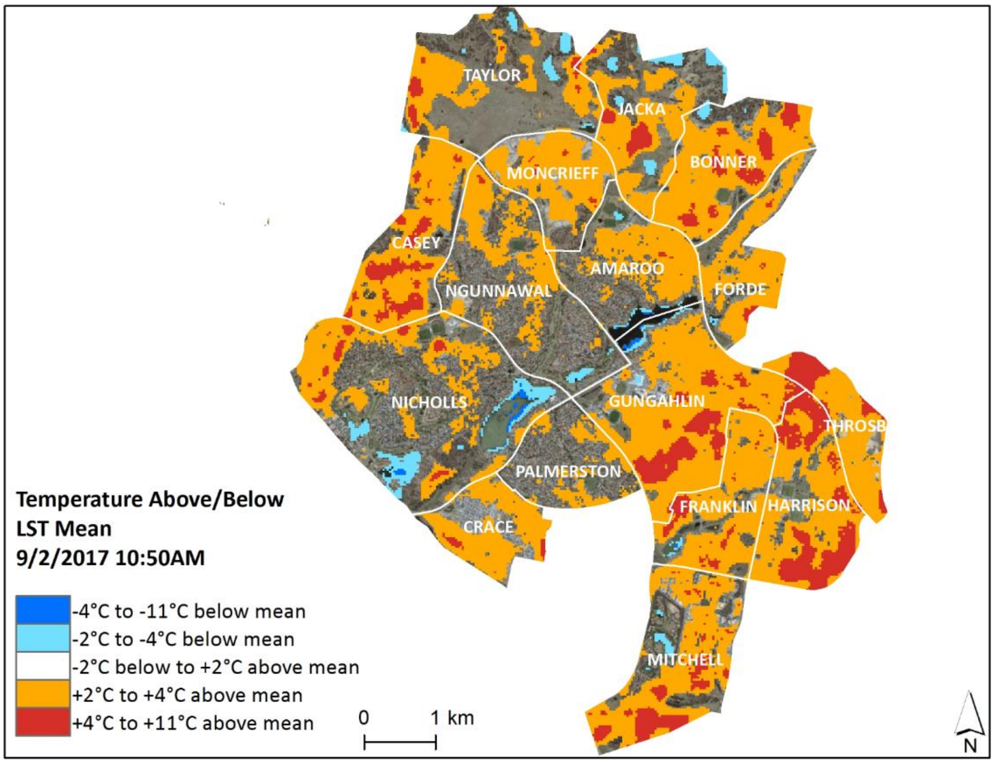


Figure S2: Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

Summer Neighbourhood Heat Exposure and Vulnerability

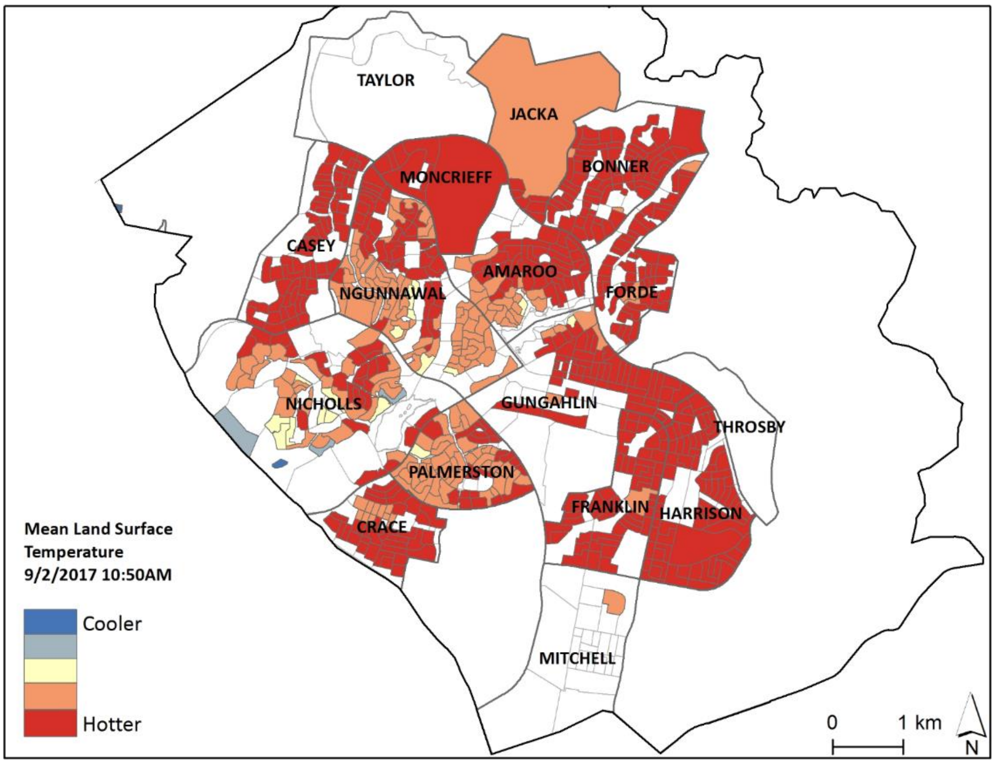


Figure S3: Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.

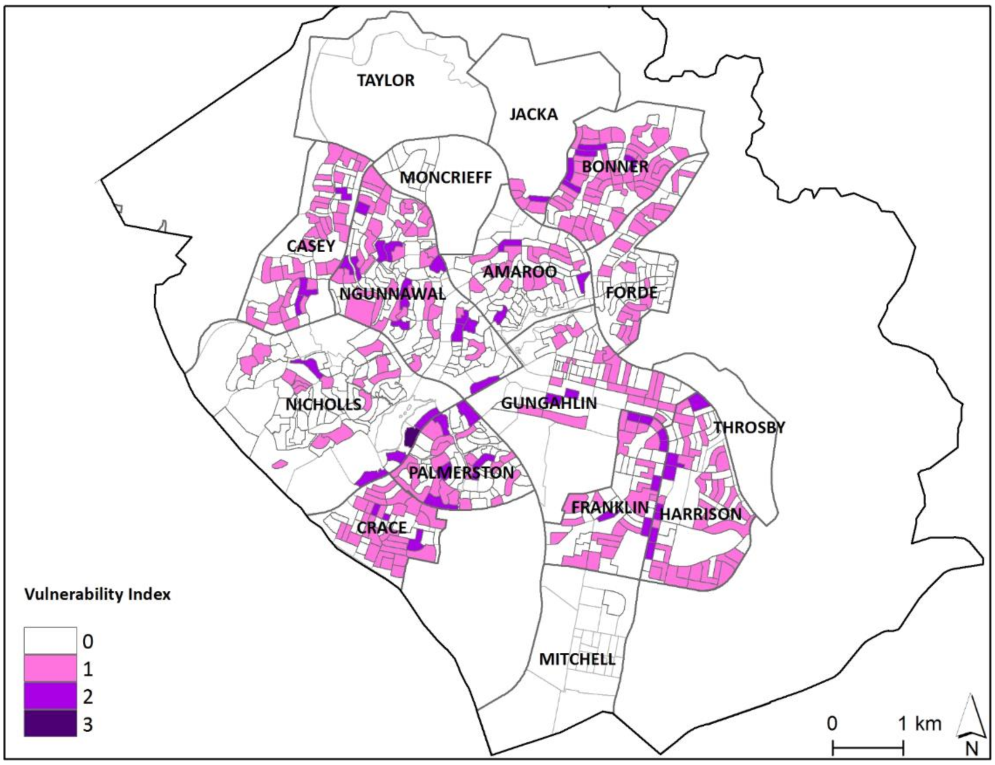


Figure S4: Vulnerability score; based on the cumulative score for Mesh Blocks with the highest 20% for each of three heat vulnerability factors; the number of people over 65 years, or under 5 years, or the number of low-income households.

Summer Neighbourhood Heat Exposure and Vulnerability Combined

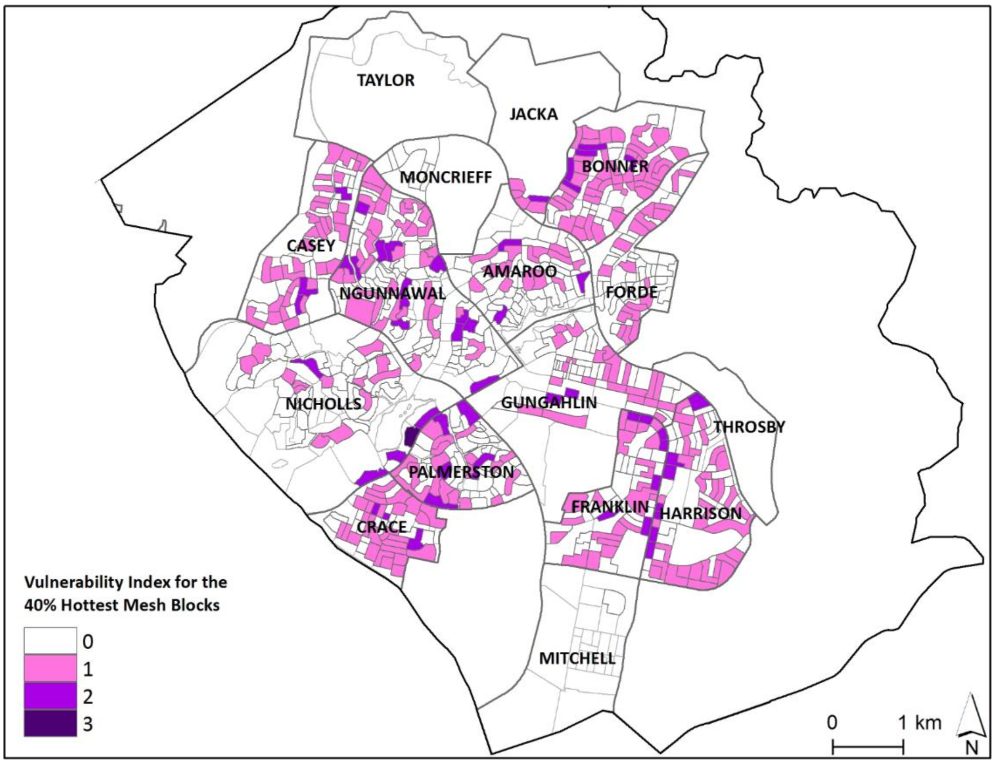


Figure S5: Vulnerability scores within the hottest 40% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

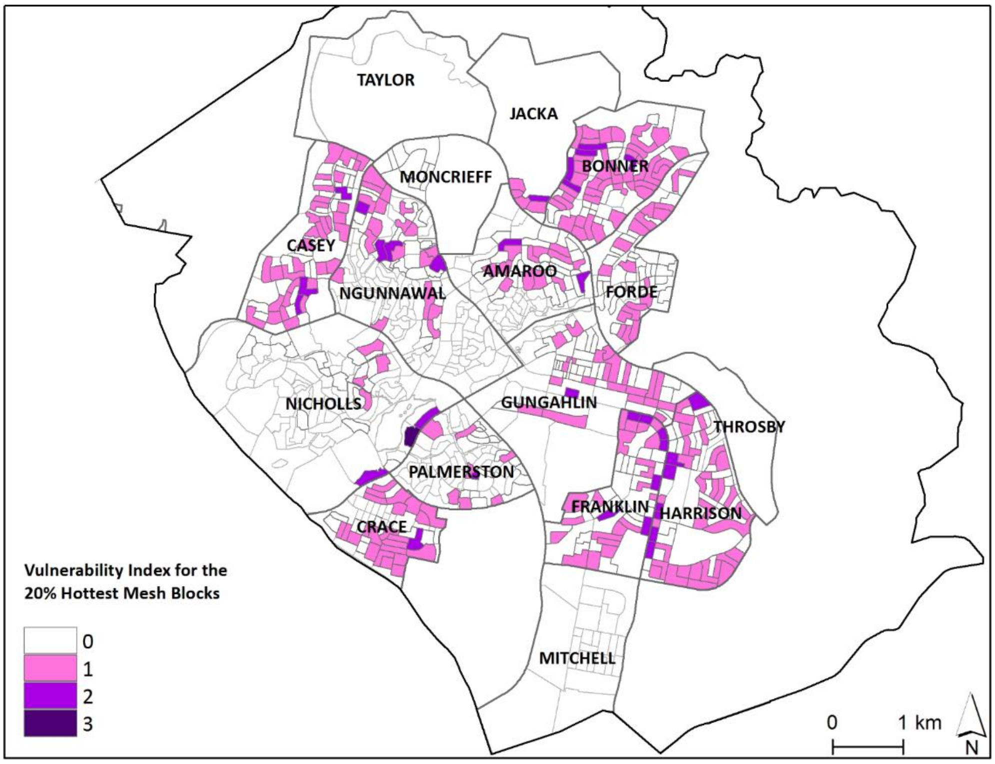


Figure S6: Vulnerability scores within the hottest 20% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

Winter Land Surface Temperature, 20-8-2017 9.50AM

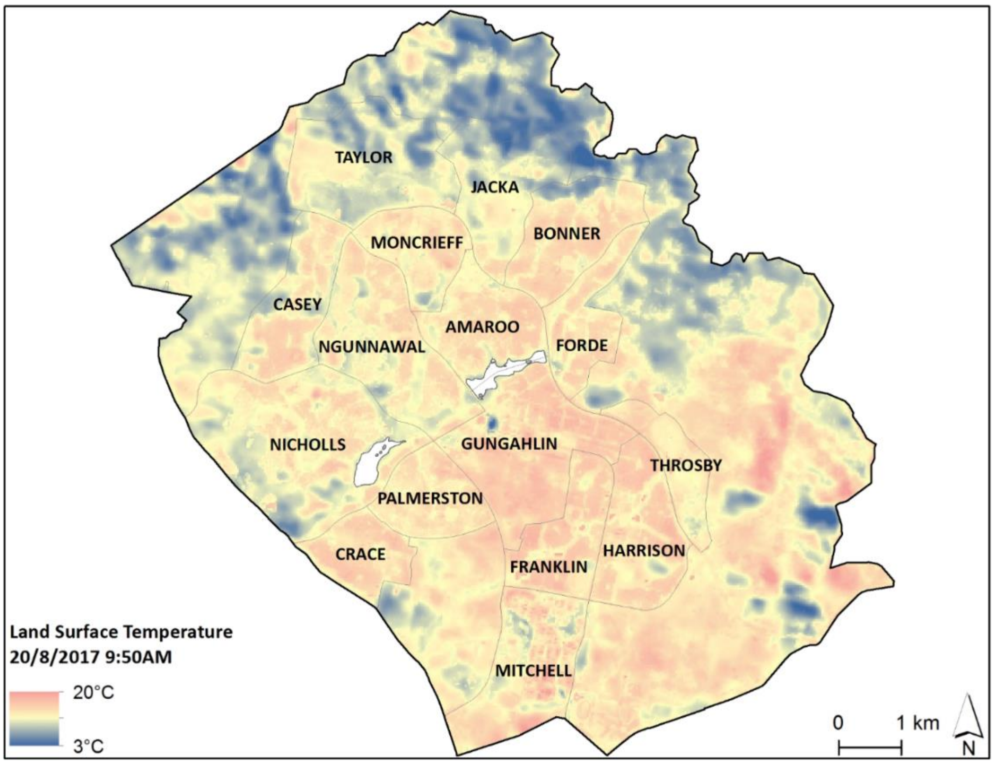


Figure W1: Land surface temperatures for 20-8-2017 (9.50 AM EST) derived using Landsat 8 thermal data.

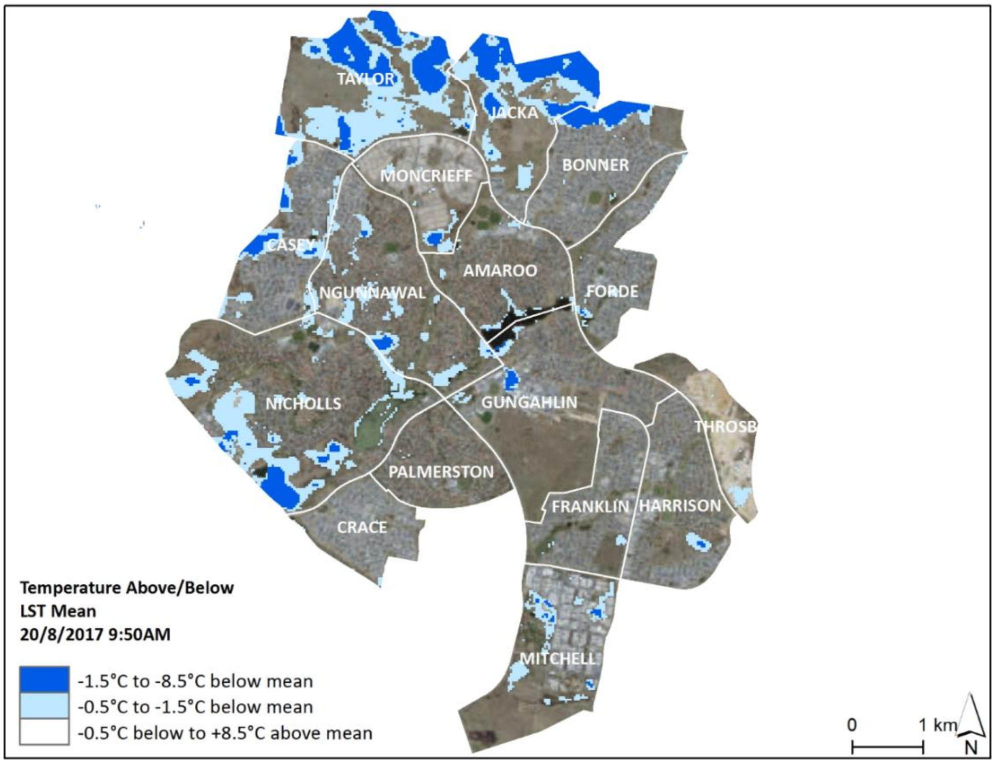
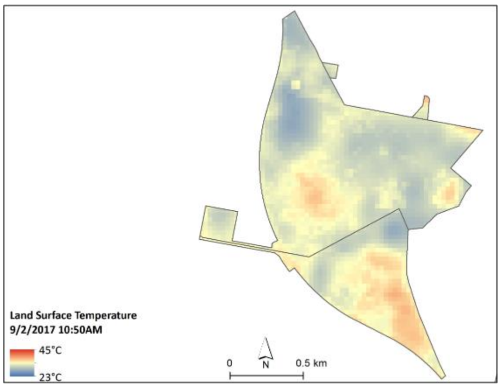


Figure W2: Cool spots; departure from the mean land surface temperature of 11.4 °C.
ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

Hall

Summer Land Surface Temperature, 9-2-2017 10.50AM



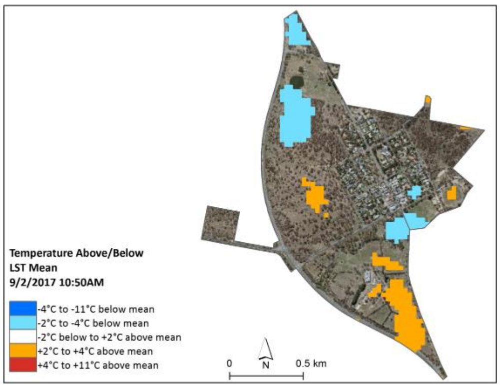


Figure S1 (left): Land surface temperatures for 9-2- 2017 (10.50 AM DST) derived using Landsat 8 thermal data.
Figure S2 (right): Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

Summer Neighbourhood Heat Exposure and Vulnerability

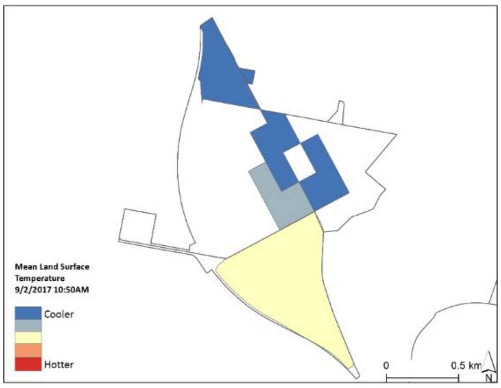
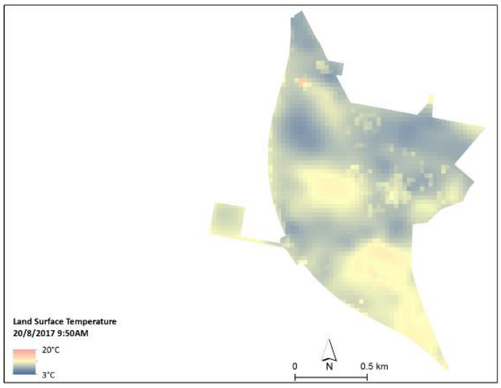


Figure S3 (left): Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.
Figure S4 (right): Vulnerability score; based on Mesh Blocks with the highest 20% for each of three vulnerability factors, the number of people over 65 years, or under 5 years, or the number of low-income households.

Winter Land Surface Temperature, 20-8-2017 9.50AM



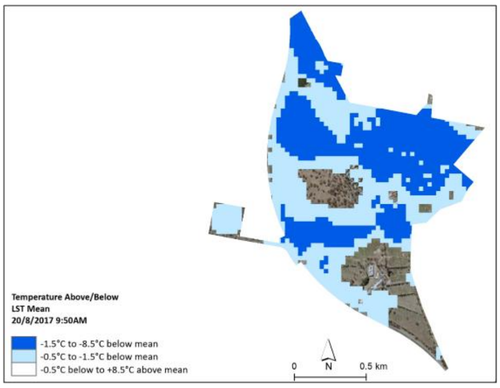


Figure W1 (left): Land surface temperatures for 20-8-2017 (9.50 AM EST) derived using Landsat 8 thermal data.
Figure W2 (right): Cool spots; departure from the mean land surface temperature of 11.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

Jerrabomberra

<u>Summer</u> Land Surface Temperature, 9-2-2017 10.50AM

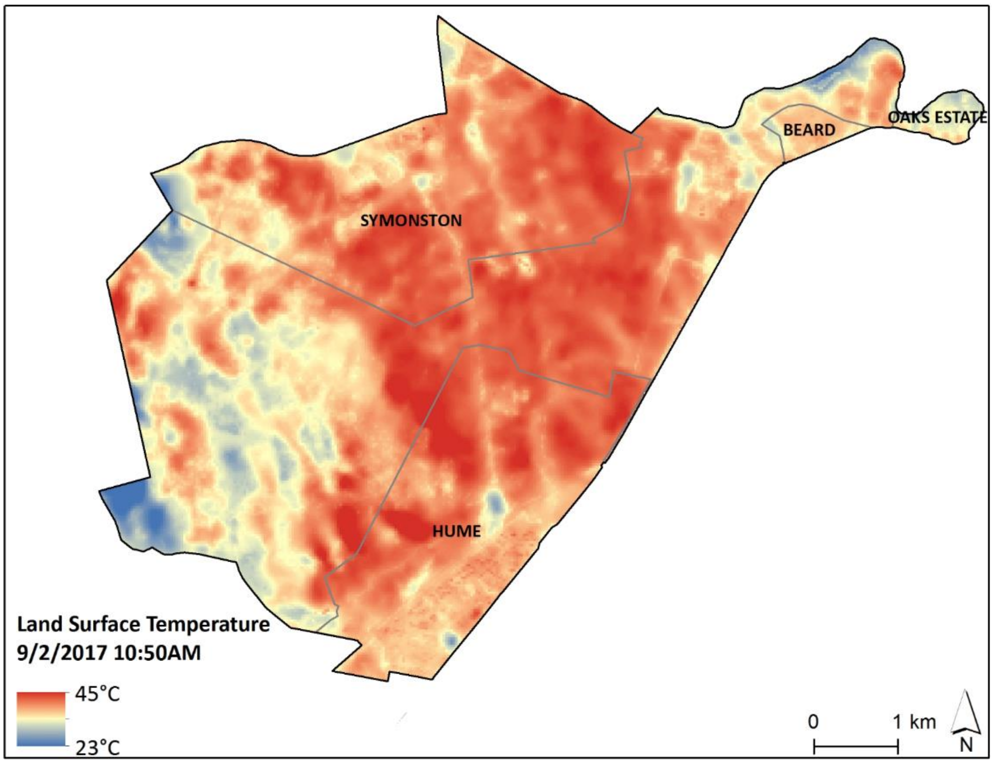


Figure S1: Land surface temperatures for 9 February 2017 (10.50 AM DST) derived using Landsat 8 thermal data.

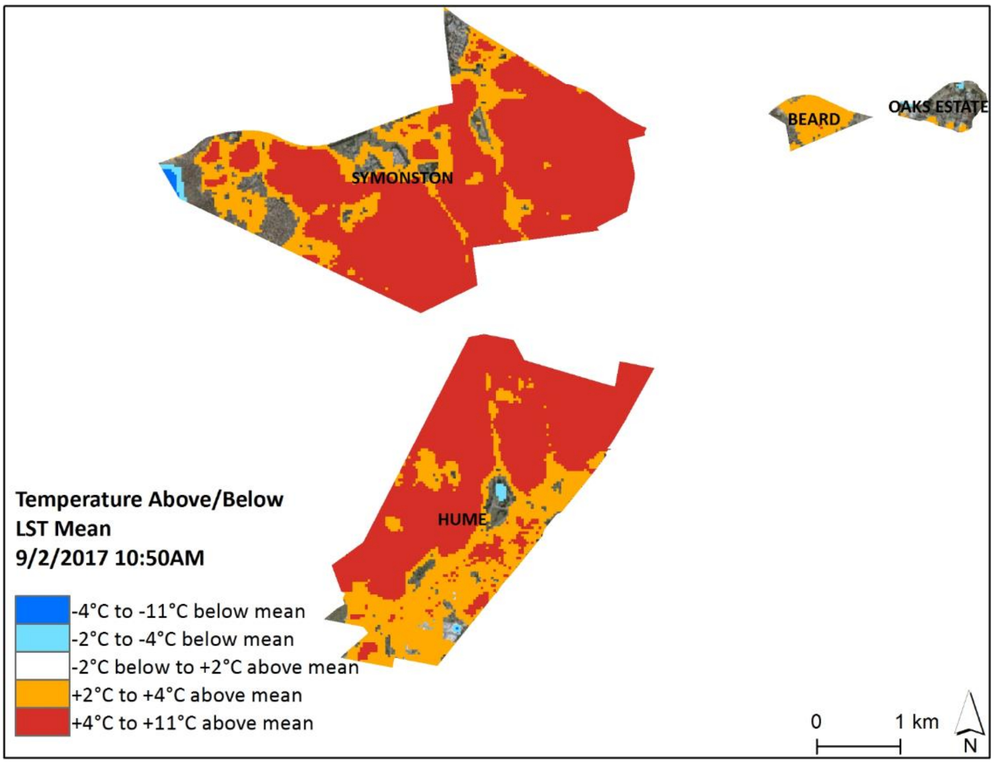


Figure S2: Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

<u>Summer</u> Neighbourhood Heat Exposure and Vulnerability

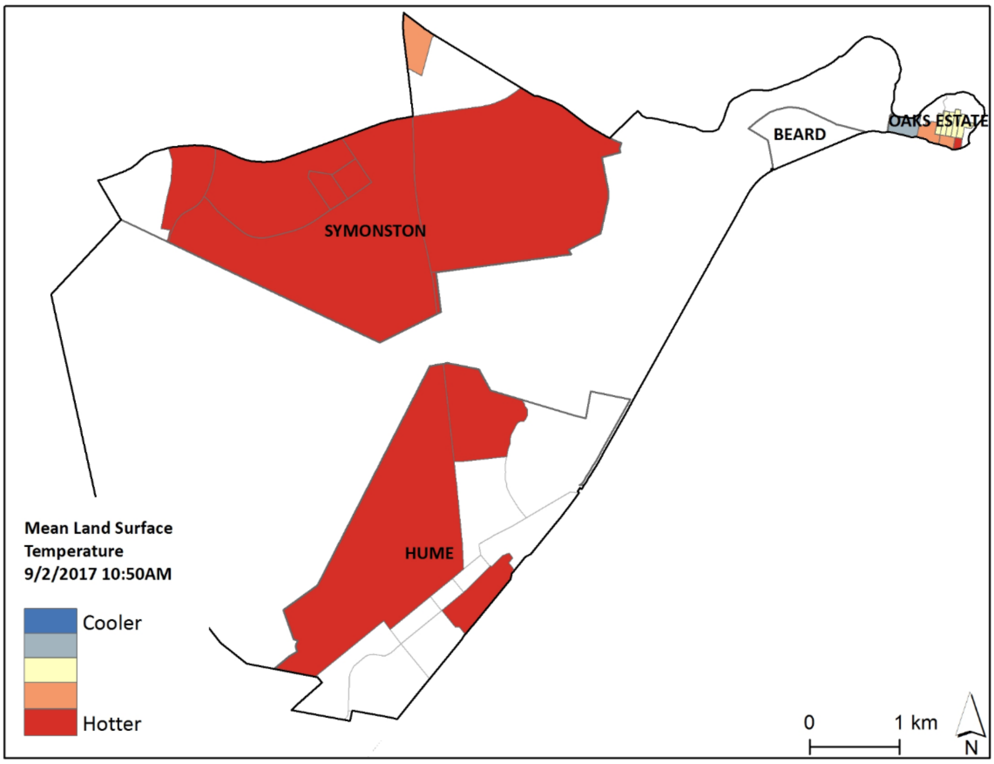


Figure S3: Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.

Figure S4: Vulnerability score; based on the cumulative score for Mesh Blocks with the highest 20% for each of three heat vulnerability factors; the number of people over 65 years, or under 5 years, or the number of low-income households.

Summer Neighbourhood Heat Exposure and Vulnerability Combined

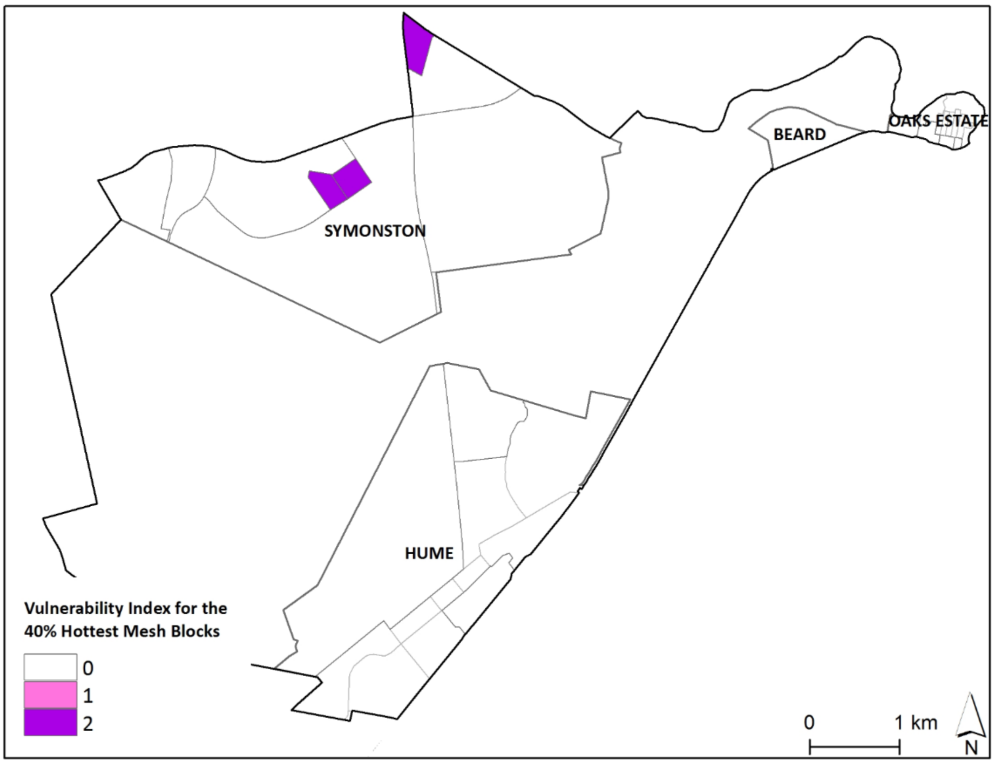


Figure S5: Vulnerability scores within the hottest 40% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

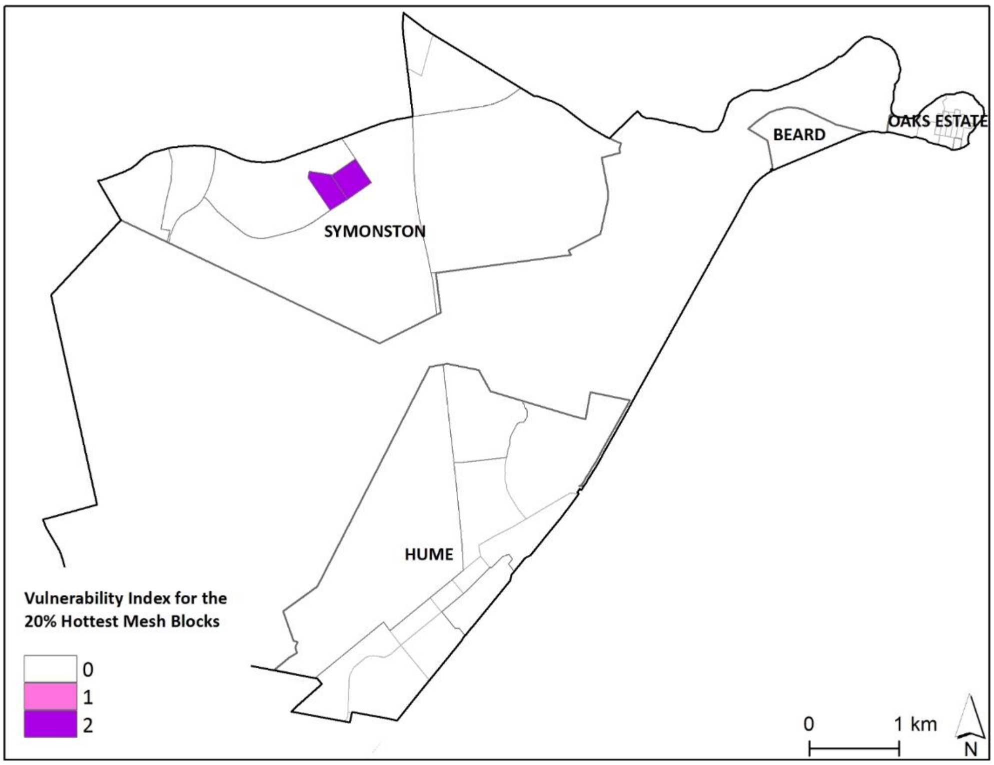


Figure S6: Vulnerability scores within the hottest 20% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

<u>Winter</u> Land Surface Temperature, 20-8-2017 9.50AM

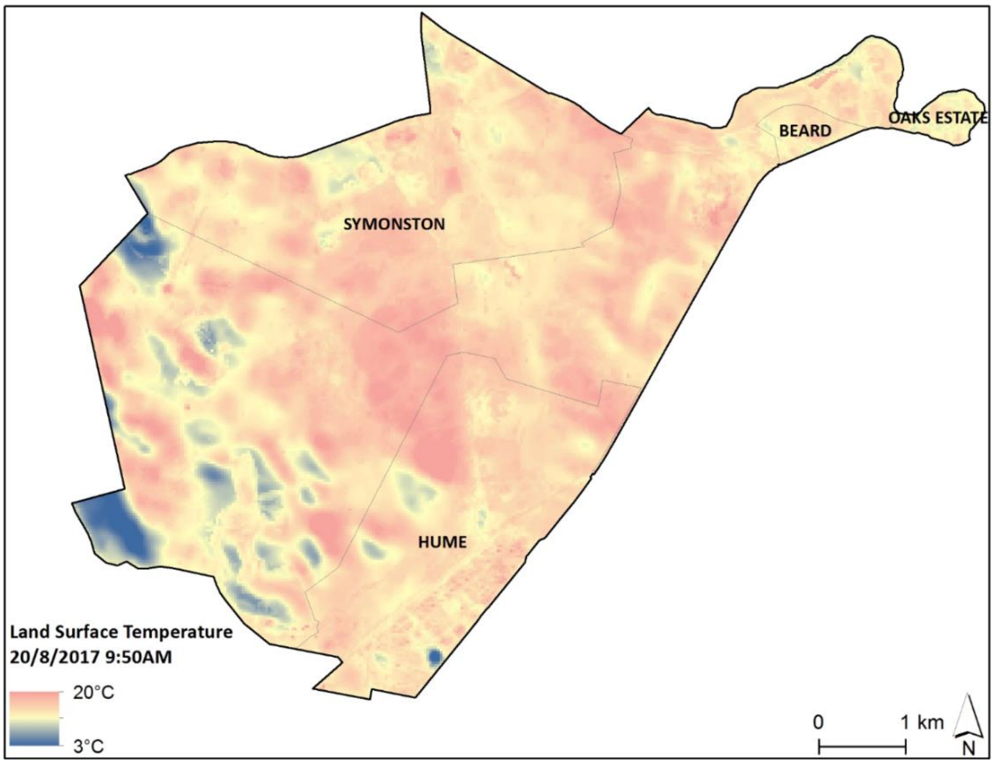


Figure W1: Land surface temperatures for 20-8-2017 (9.50 AM EST) derived using Landsat 8 thermal data.

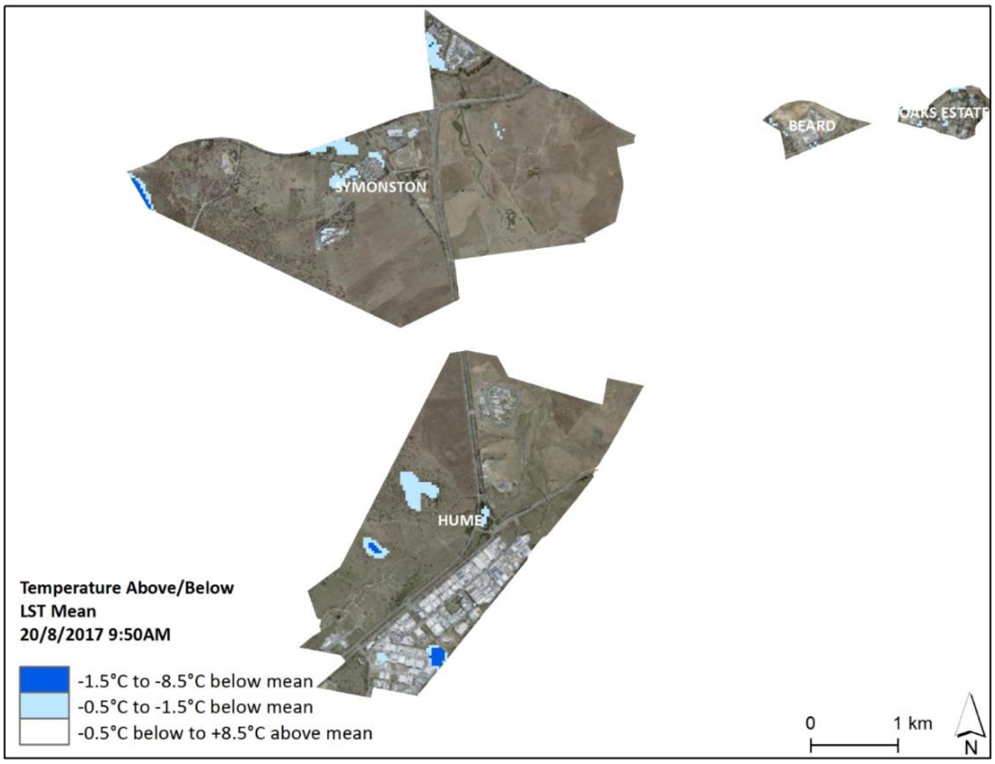


Figure W2: Cool spots; departure from the mean land surface temperature of 11.4 °C.
ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

Majura

<u>Summer</u> Land Surface Temperature, 9-2-2017 10.50AM

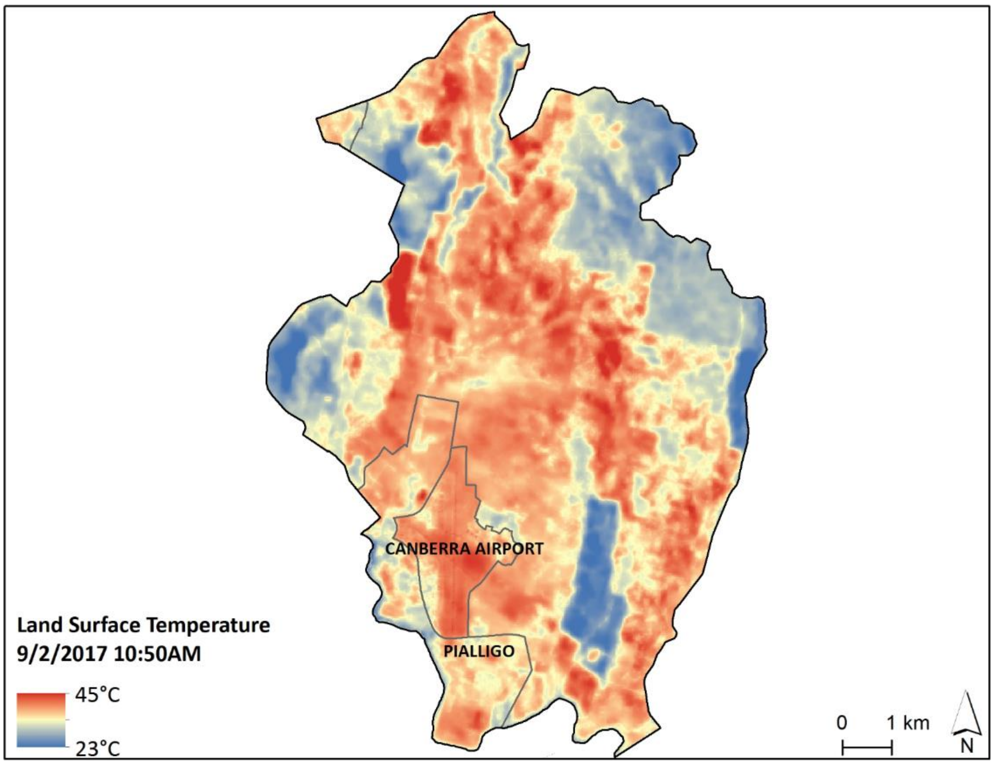


Figure S1: Land surface temperatures for 9 February 2017 (10.50 AM DST) derived using Landsat 8 thermal data.

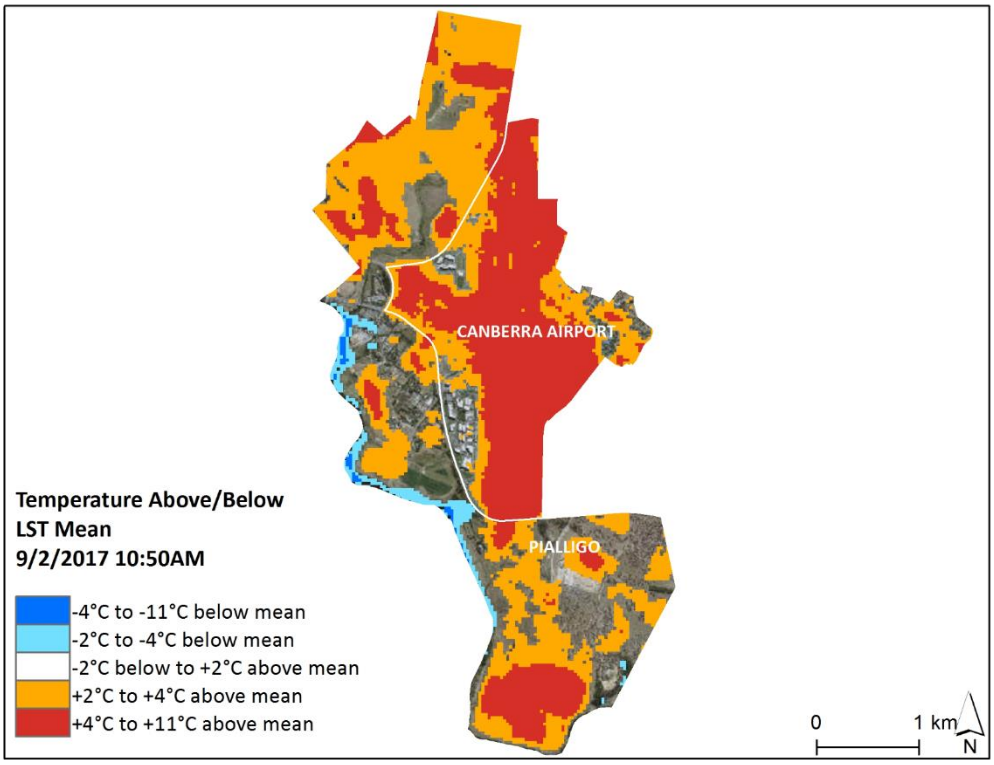


Figure S2: Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

Summer Neighbourhood Heat Exposure and Vulnerability

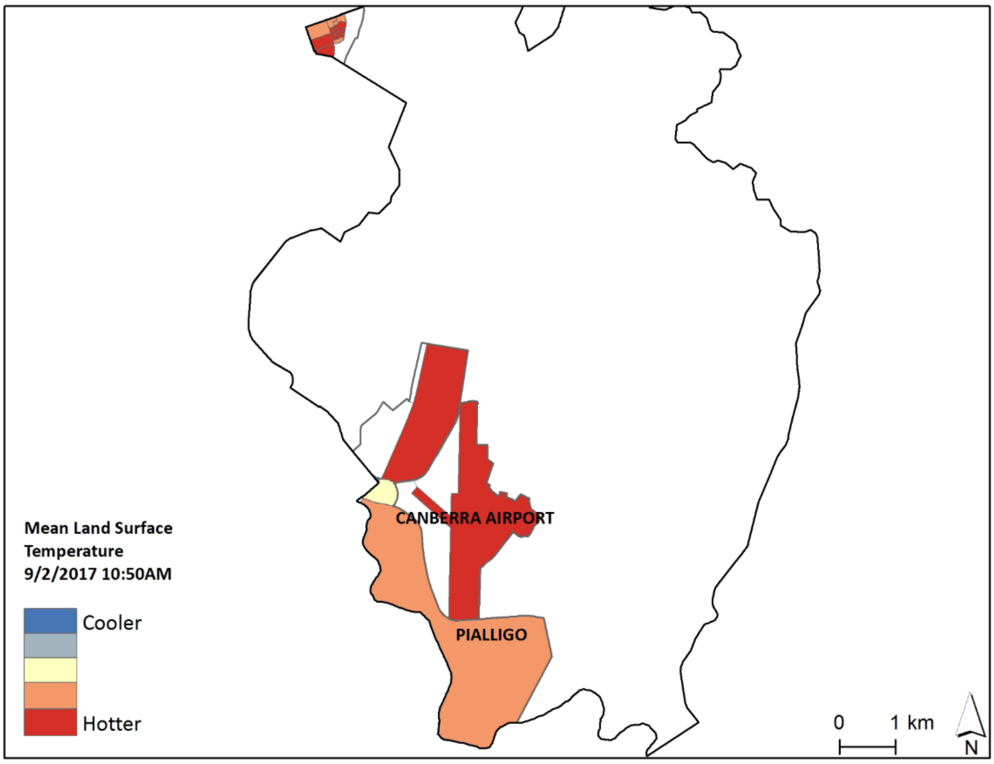


Figure S3: Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.

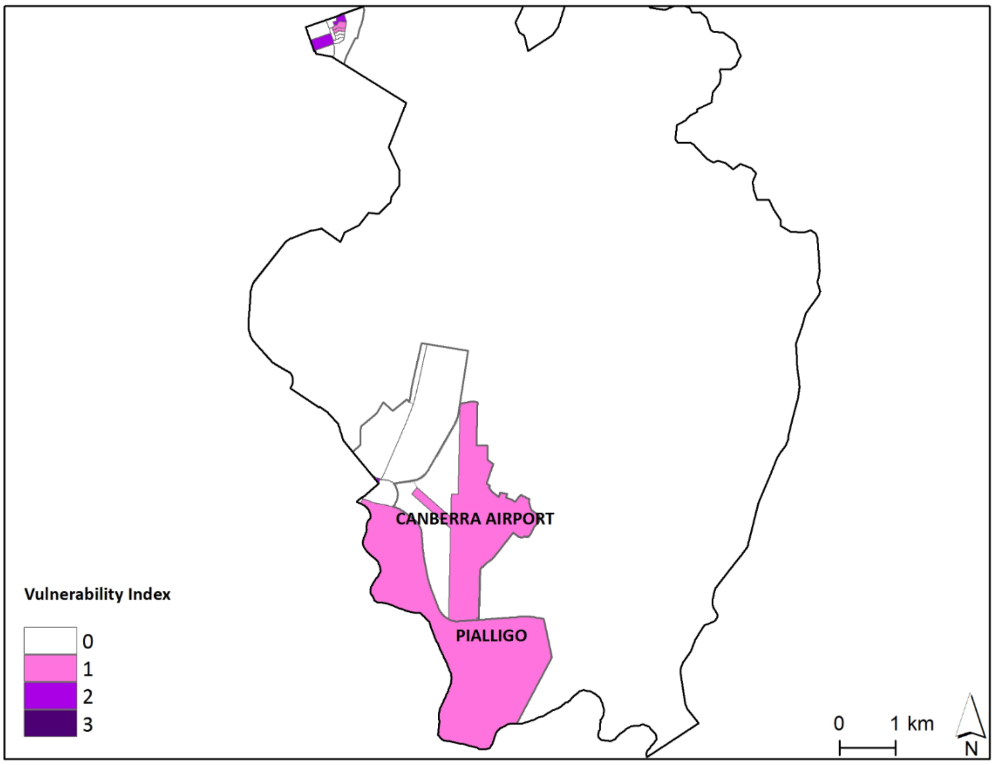


Figure S4: Vulnerability score; based on the cumulative score for Mesh Blocks with the highest 20% for each of three heat vulnerability factors; the number of people over 65 years, or under 5 years, or the number of low-income households.

Summer Neighbourhood Heat Exposure and Vulnerability Combined

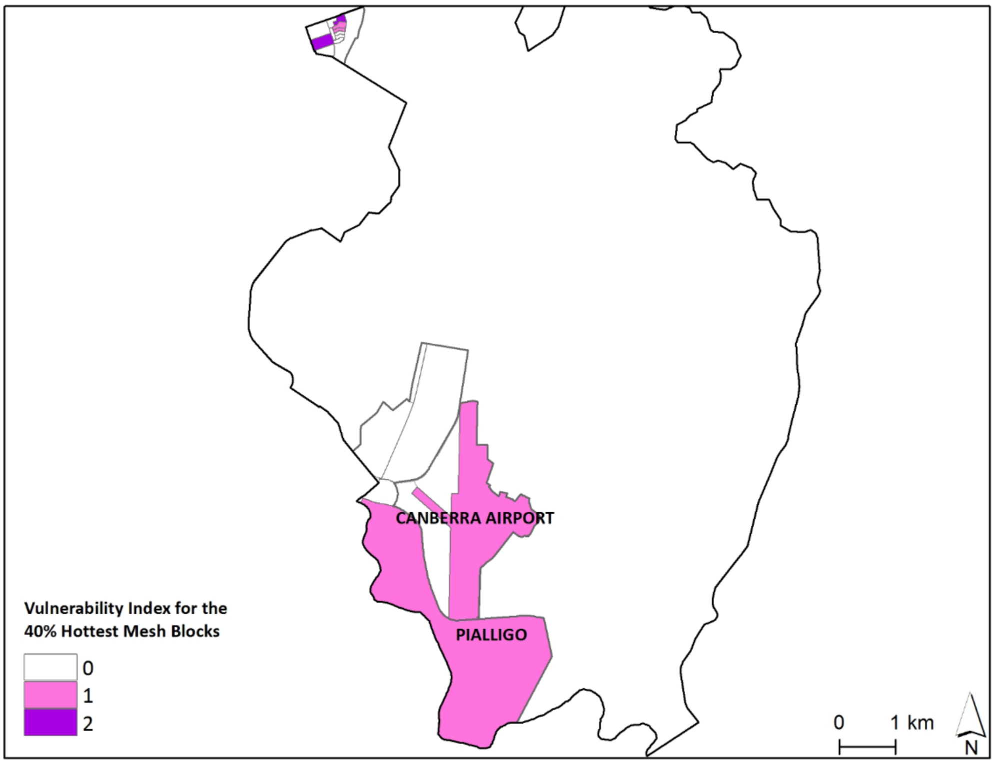


Figure S5: Vulnerability scores within the hottest 40% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

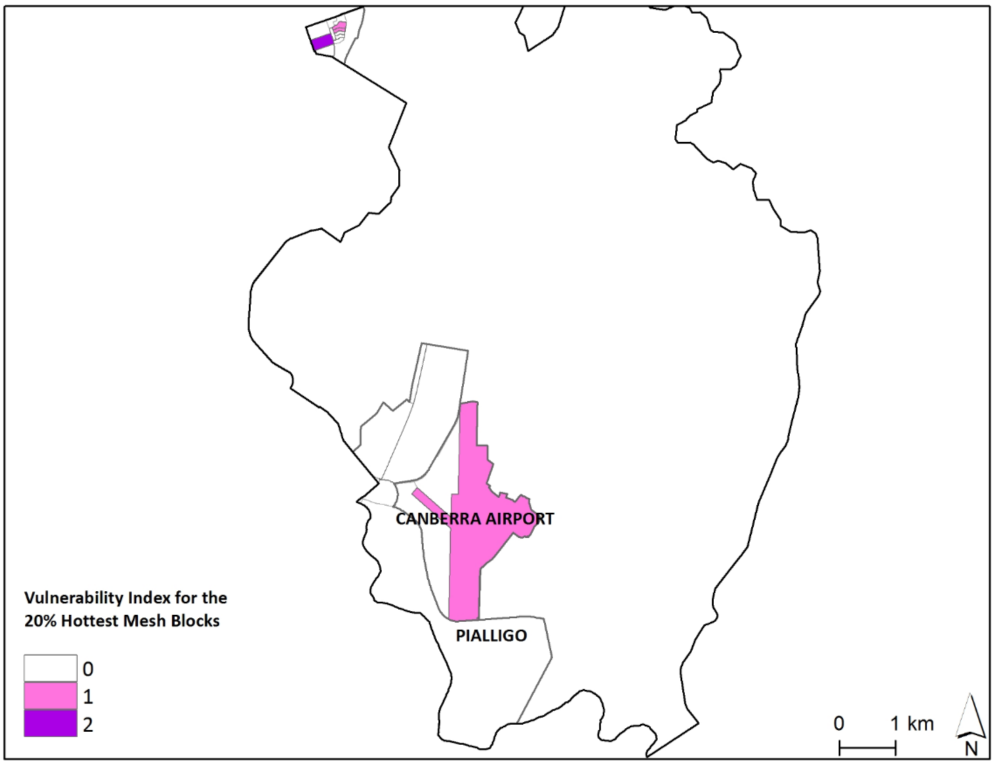


Figure S6: Vulnerability scores within the hottest 20% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

<u>Winter</u> Land Surface Temperature, 20-8-2017 9.50AM

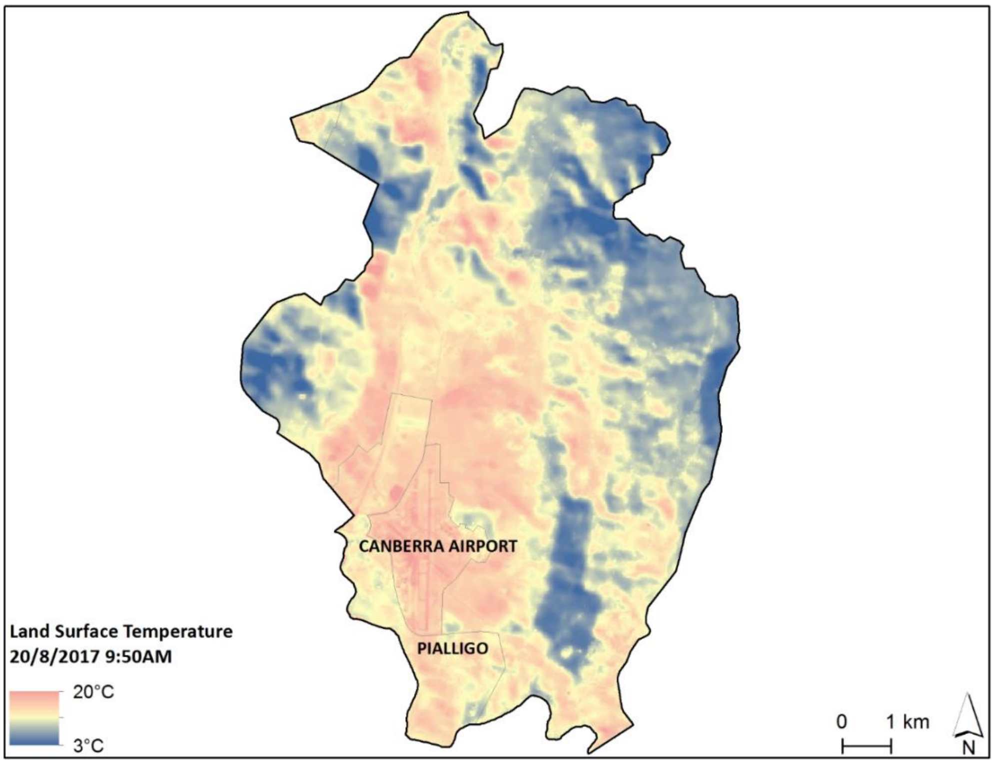


Figure W1: Land surface temperatures for 20-8-2017 (9.50 AM EST) derived using Landsat 8 thermal data.

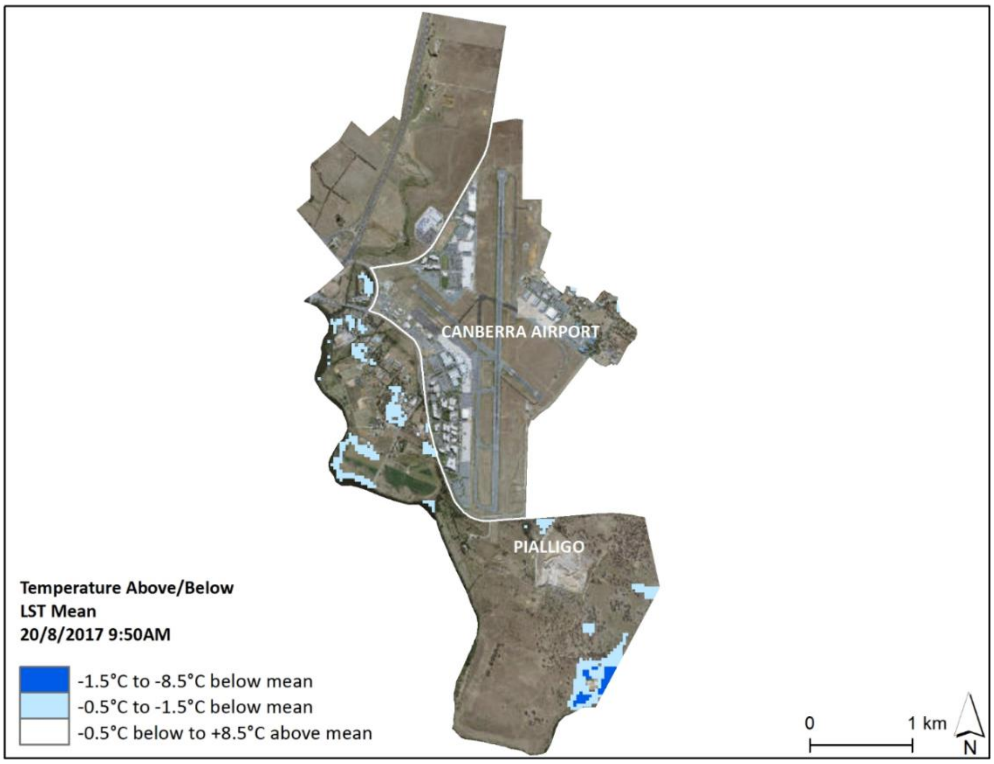


Figure W2: Cool spots; departure from the mean land surface temperature of 11.4 °C.
ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

Molonglo Valley

<u>Summer</u> Land Surface Temperature, 9-2-2017 10.50AM

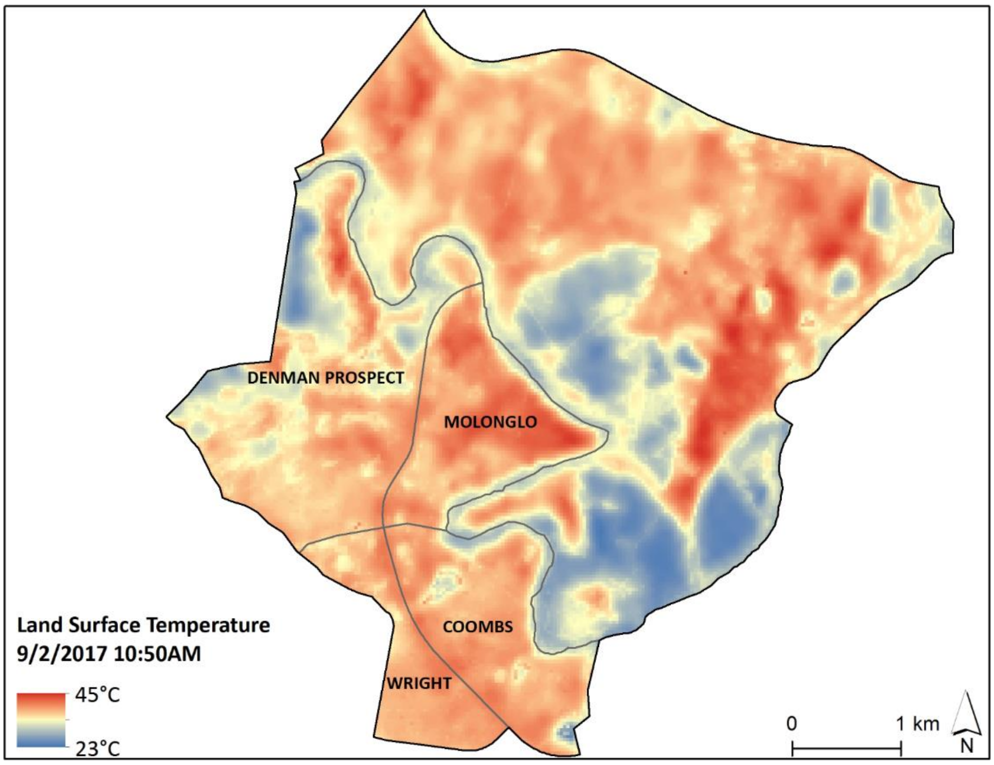


Figure S1: Land surface temperatures for 9 February 2017 (10.50 AM DST) derived using Landsat 8 thermal data.

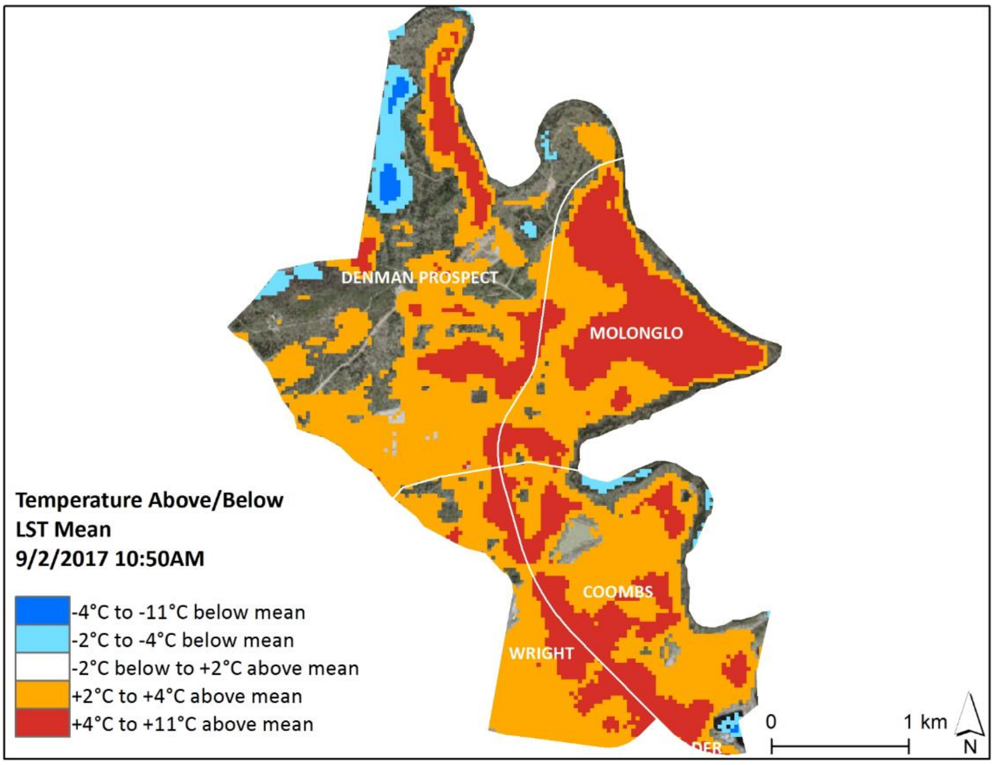


Figure S2: Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

<u>Summer</u> Neighbourhood Heat Exposure and Vulnerability

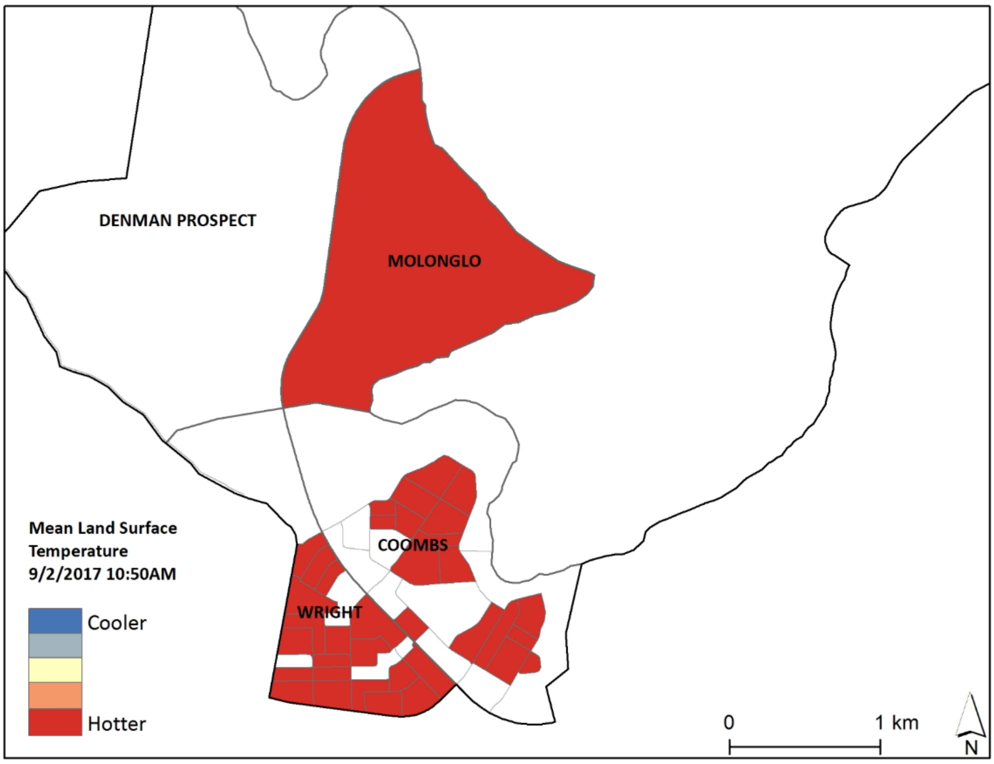


Figure S3: Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.

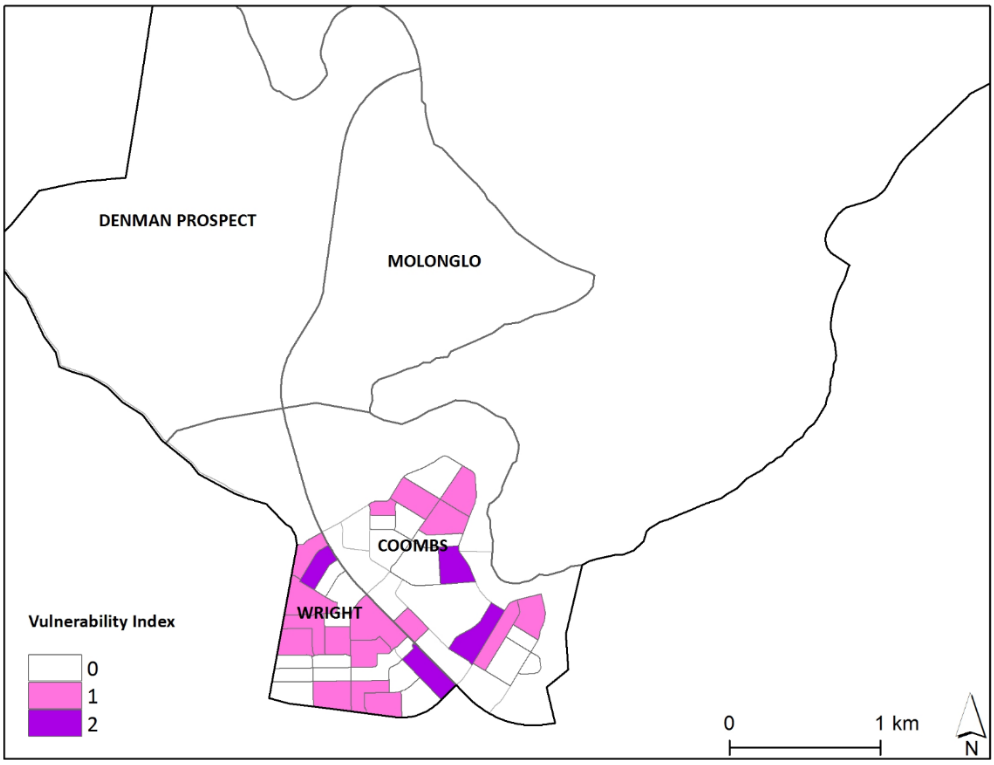


Figure S4: Vulnerability score; based on the cumulative score for Mesh Blocks with the highest 20% for each of three heat vulnerability factors; the number of people over 65 years, or under 5 years, or the number of low-income households.

Summer Neighbourhood Heat Exposure and Vulnerability Combined

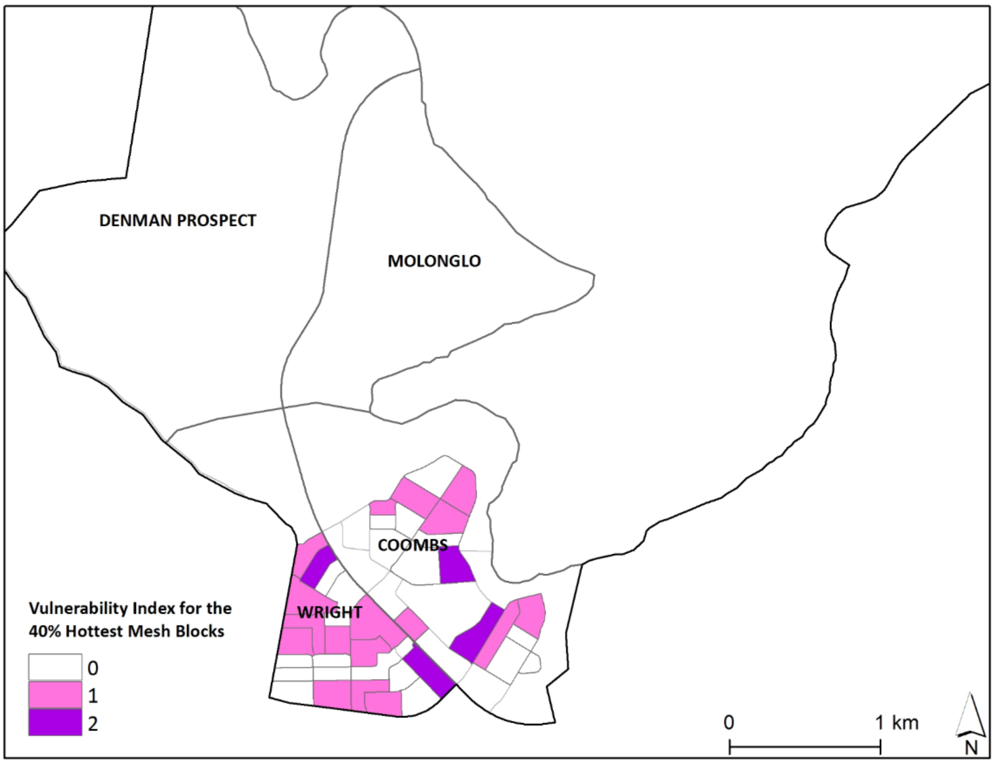


Figure S5: Vulnerability scores within the hottest 20% and 40% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

Winter Land Surface Temperature, 20-8-2017 9.50AM

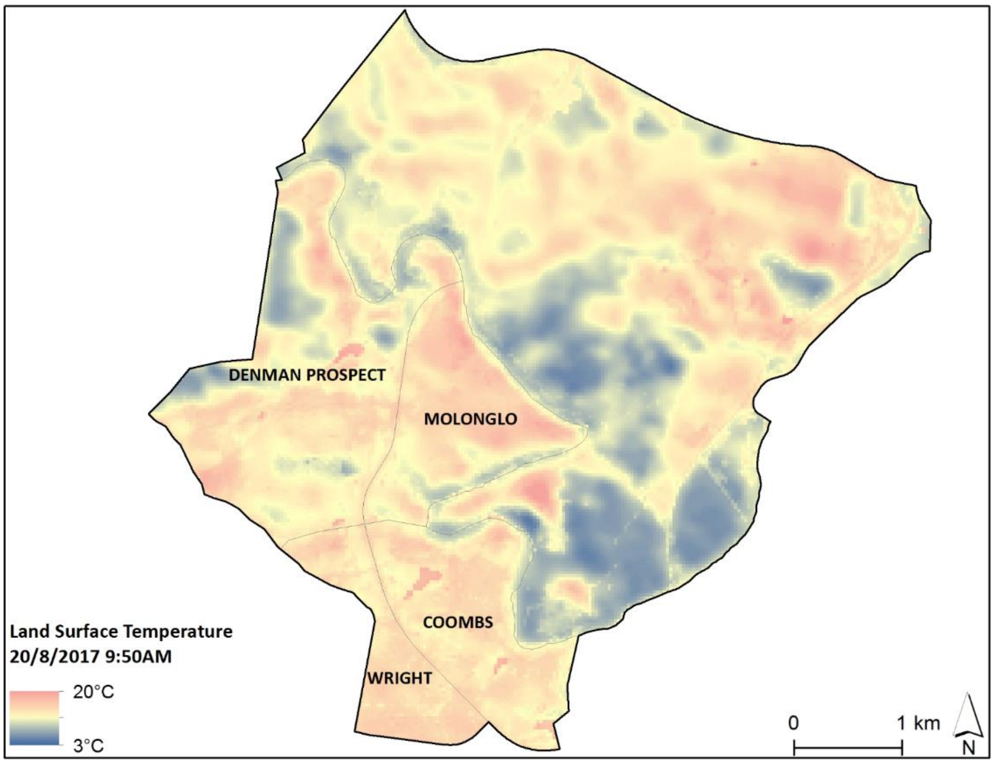


Figure W1: Land surface temperatures for 20-8-2017 (9.50 AM EST) derived using Landsat 8 thermal data.

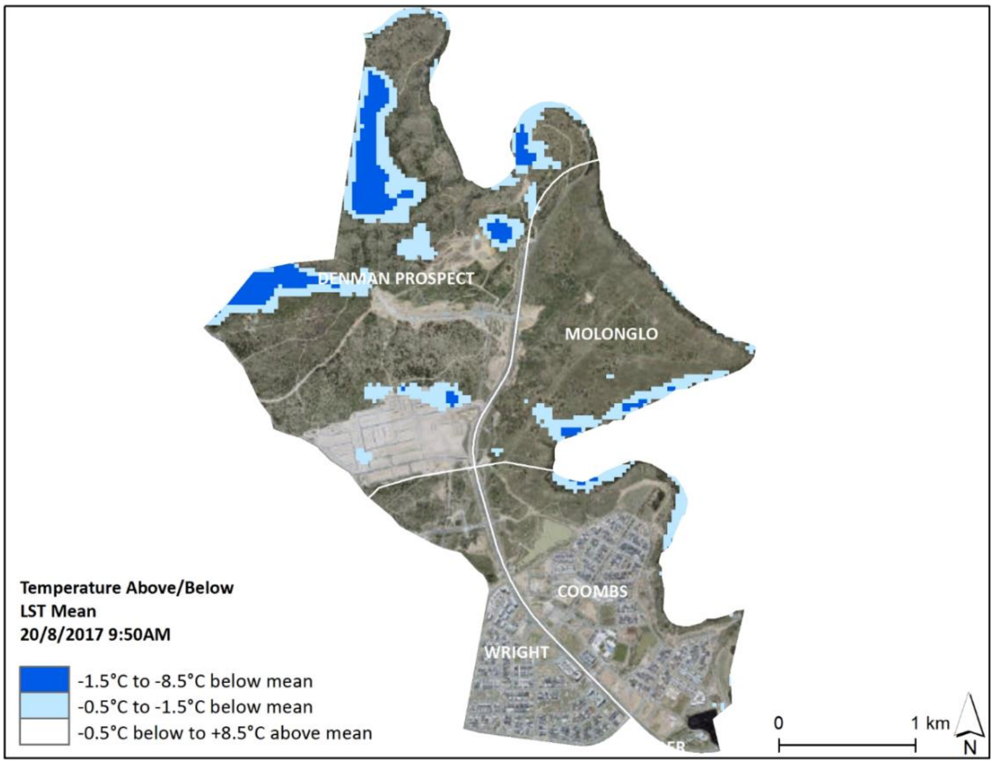
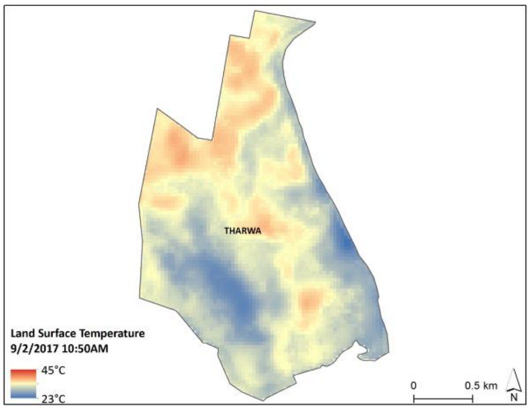


Figure W2: Cool spots; departure from the mean land surface temperature of 11.4 °C.
ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

Tharwa

Summer Land Surface Temperature, 9-2-2017 10.50AM



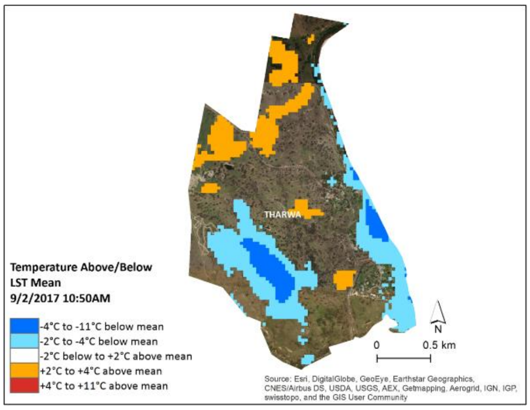
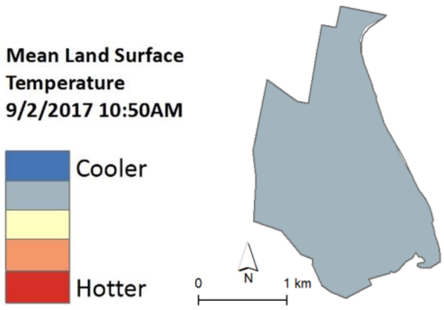


Figure S1 (left): Land surface temperatures for 9-2-2017, 10.50 AM DST derived using Landsat 8 thermal data.
Figure S2 (right): Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

Summer Neighbourhood Heat Exposure and Vulnerability



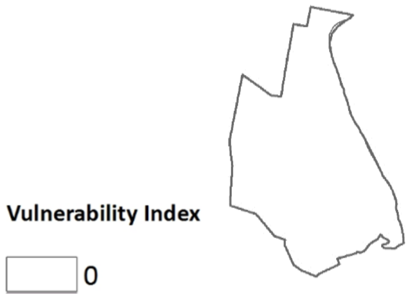
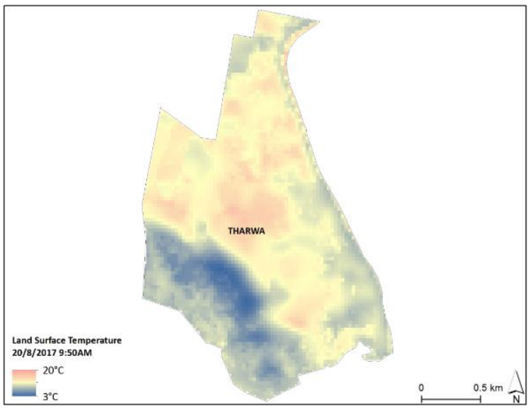


Figure S3 (left): Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.
Figure S4 (right): Vulnerability score; based on Mesh Blocks with the highest 20% for each of three vulnerability factors, the number of people over 65 years, or under 5 years, or the number of low-income households.

Winter Land Surface Temperature, 20-8-2017 9.50AM



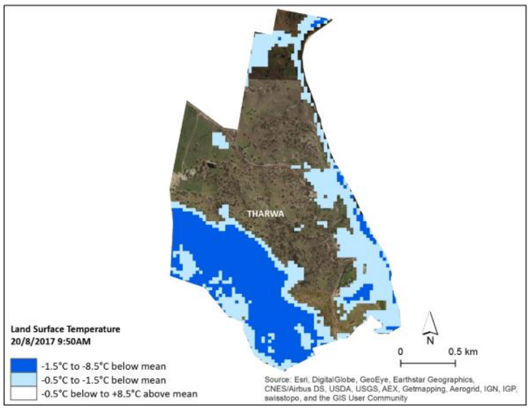


Figure W1 (left): Land surface temperatures for 20-8-2017, 9.50 AM EST derived using Landsat 8 thermal data.
Figure W2 (right): Cool spots; departure from the mean land surface temperature of 11.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

Tuggeranong

Summer Land Surface Temperature, 9-2-2017 10.50AM

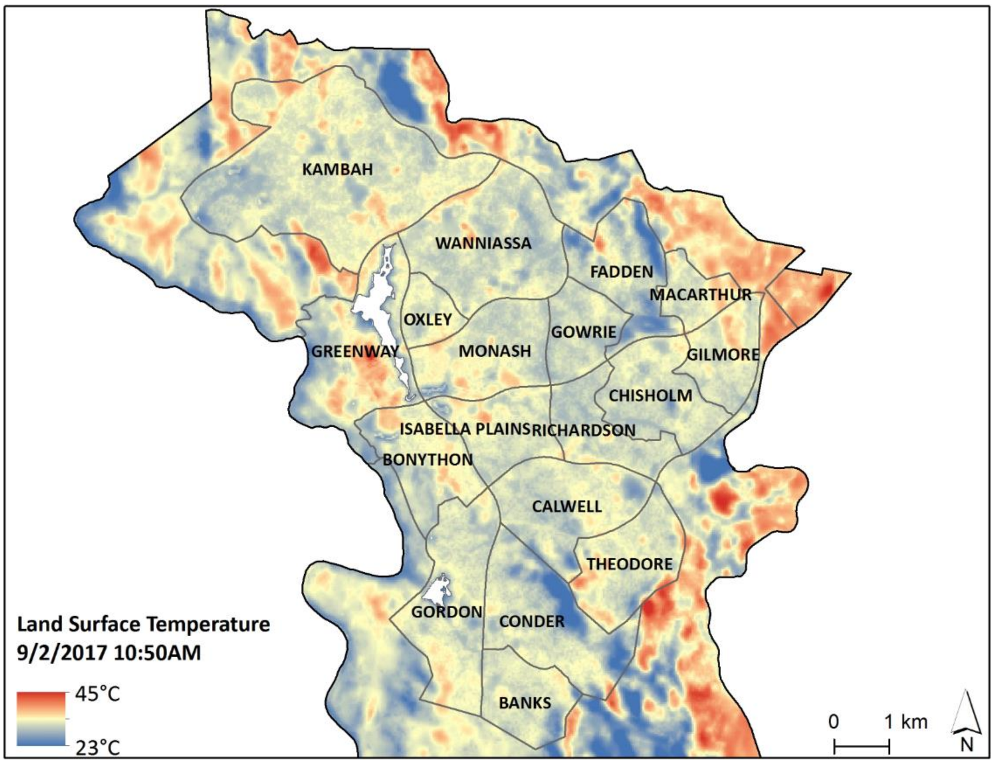


Figure S1: Land surface temperatures for 9 February 2017 (10.50 AM DST) derived using Landsat 8 thermal data.

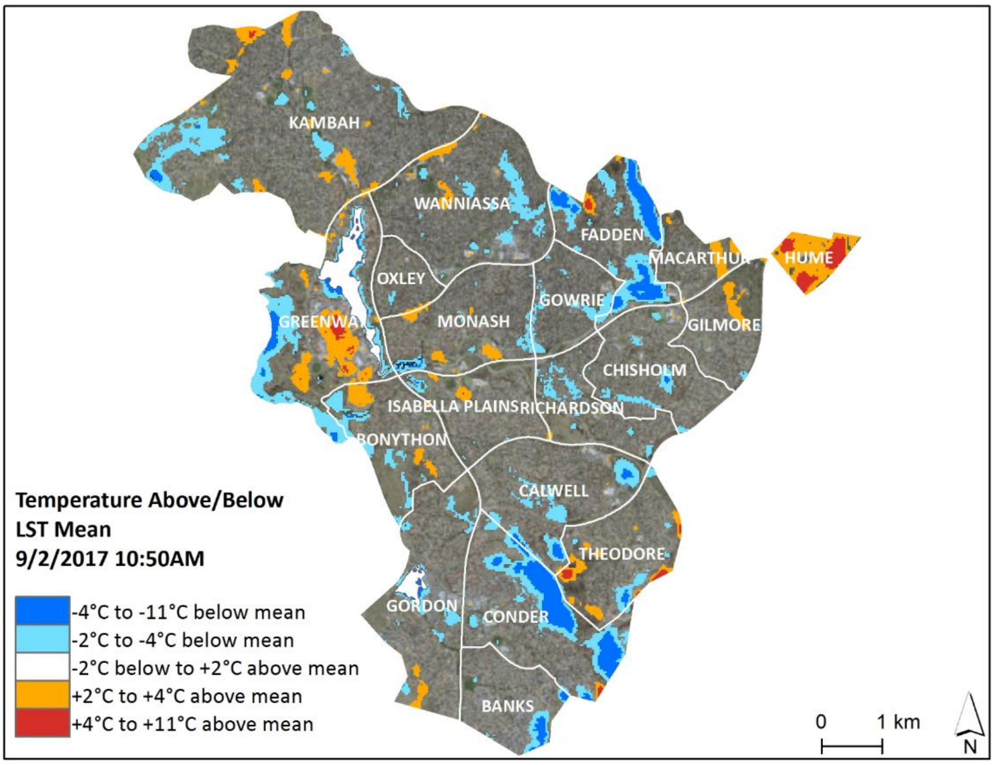


Figure S2: Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

Summer Neighbourhood Heat Exposure and Vulnerability

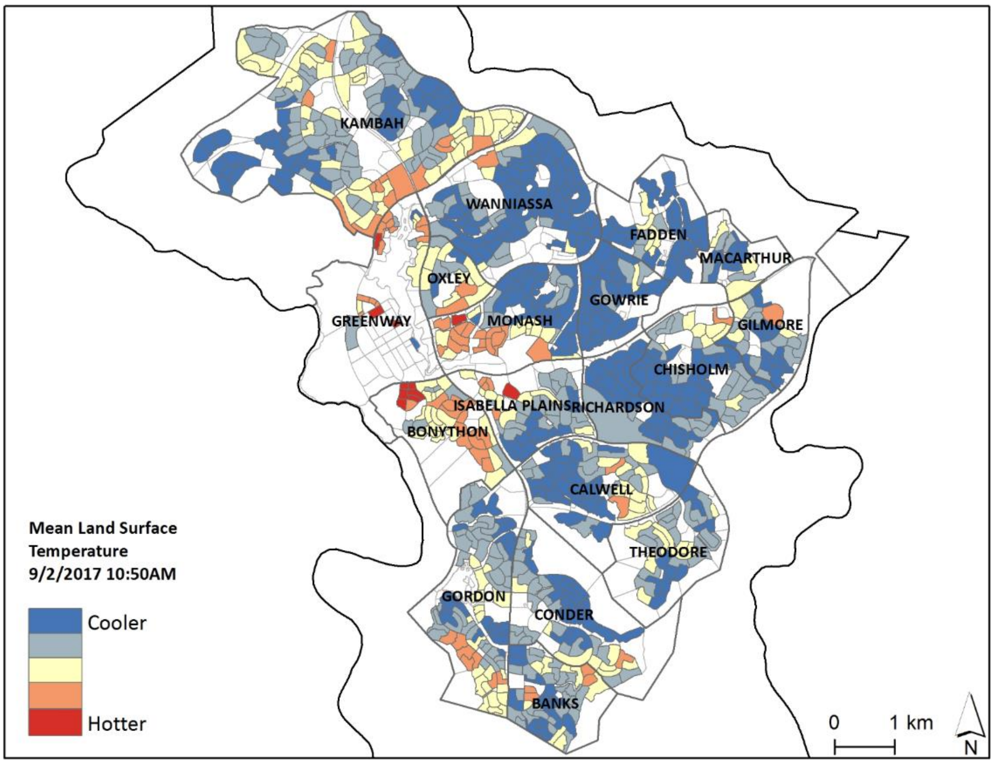


Figure S3: Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.

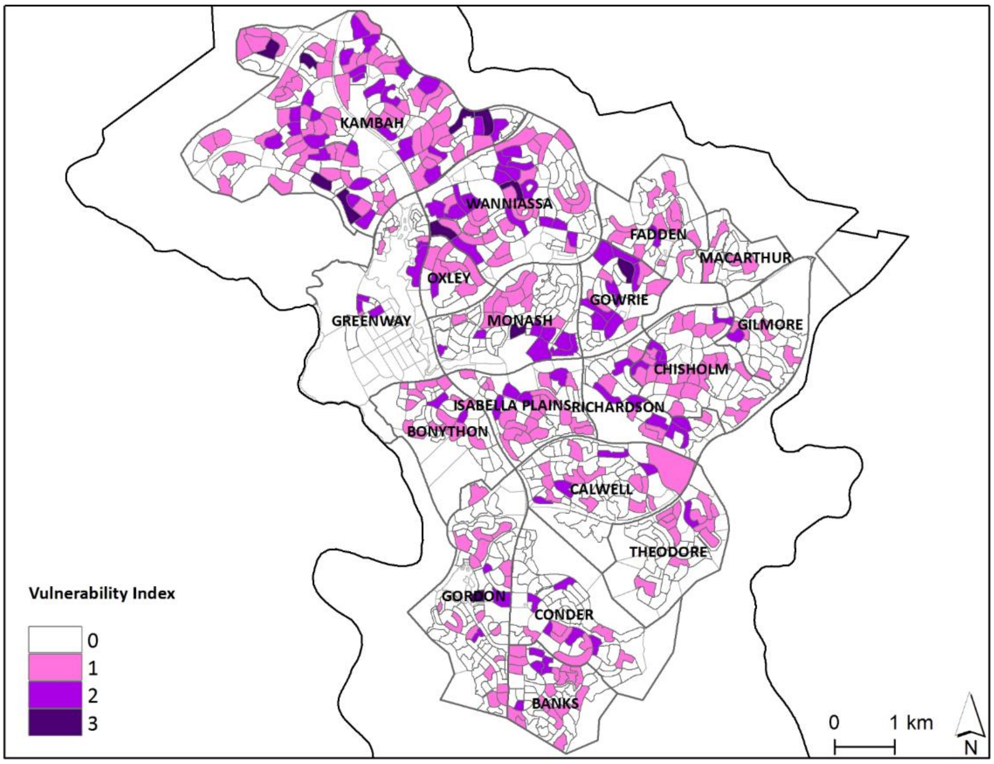


Figure S4: Vulnerability score; based on the cumulative score for Mesh Blocks with the highest 20% for each of three heat vulnerability factors; the number of people over 65 years, or under 5 years, or the number of low-income households.

Summer Neighbourhood Heat Exposure and Vulnerability Combined

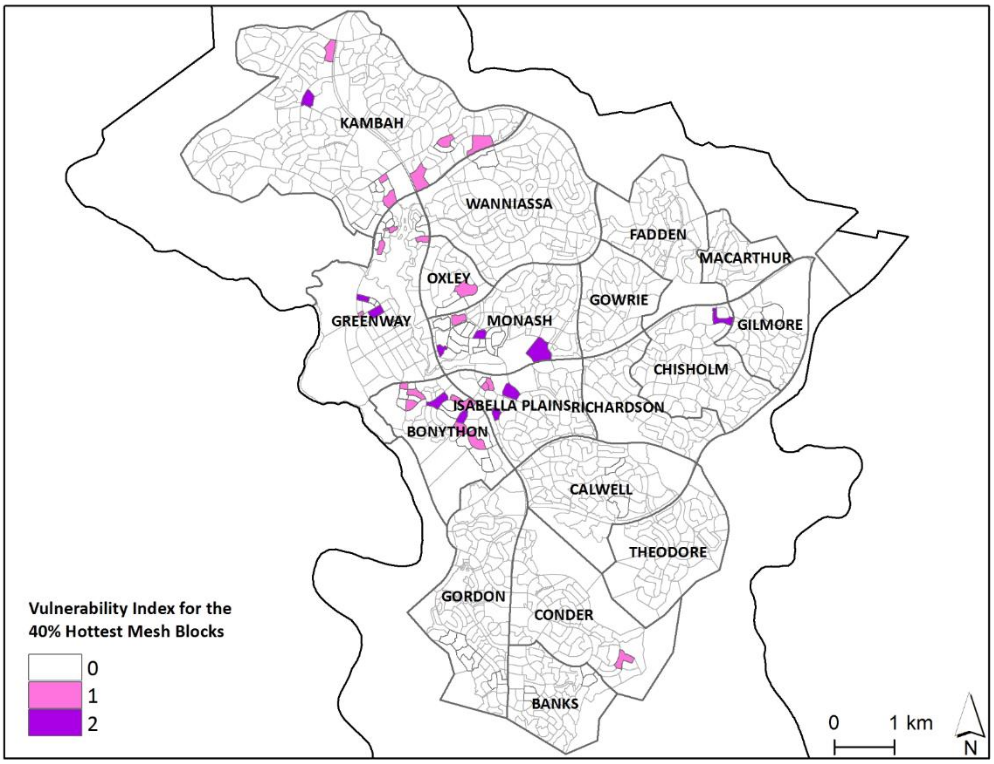


Figure S5: Vulnerability scores within the hottest 40% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

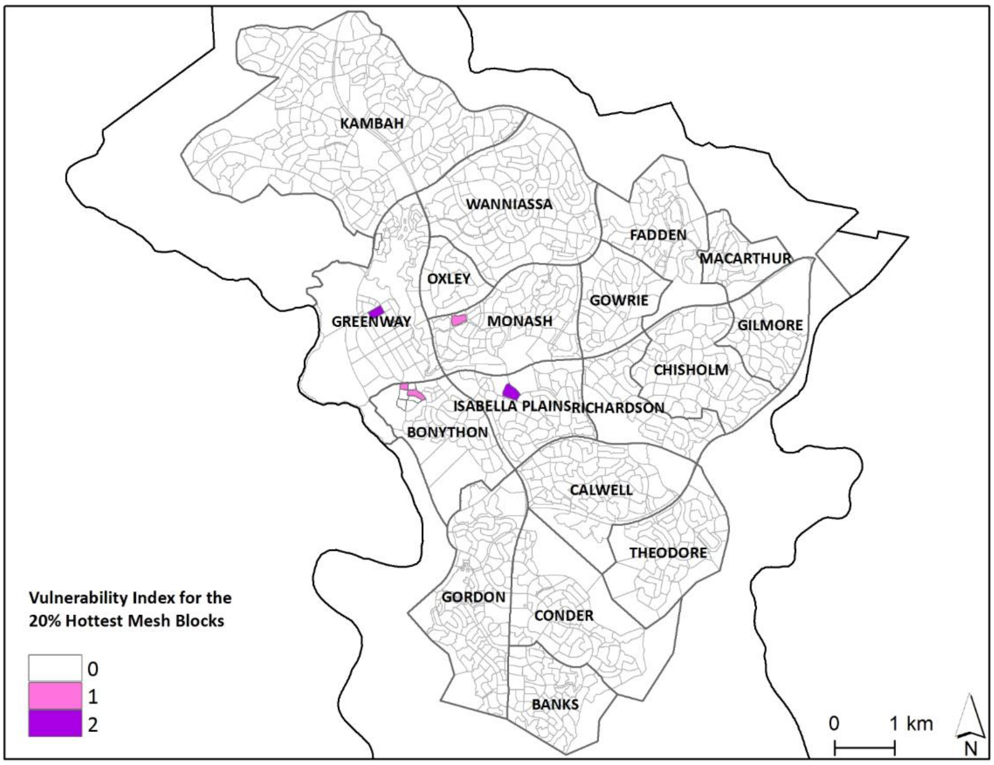


Figure S6: Vulnerability scores within the hottest 20% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

Winter Land Surface Temperature, 20-8-2017 9.50AM

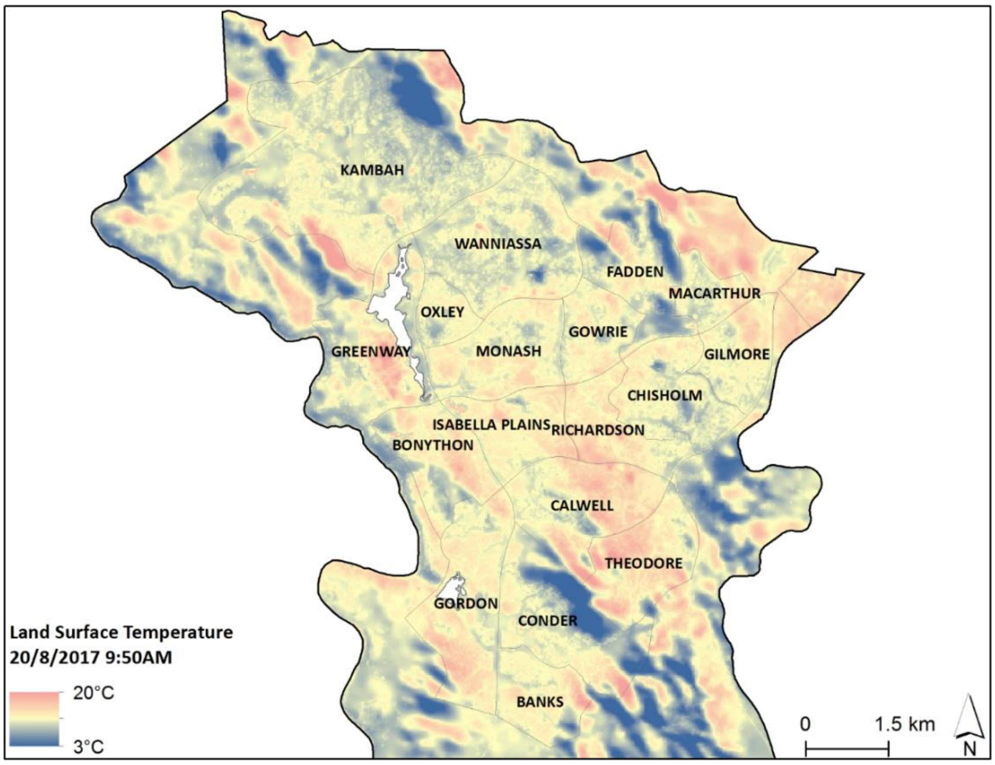


Figure W1: Land surface temperatures for 20-8-2017 (9.50 AM EST) derived using Landsat 8 thermal data.

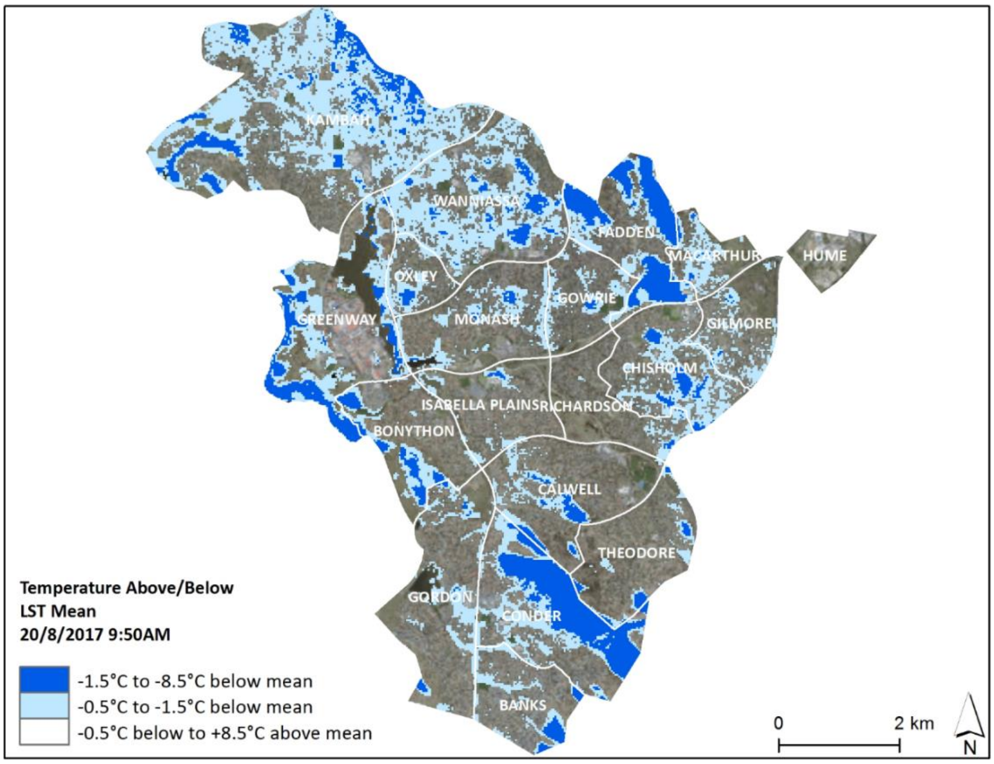
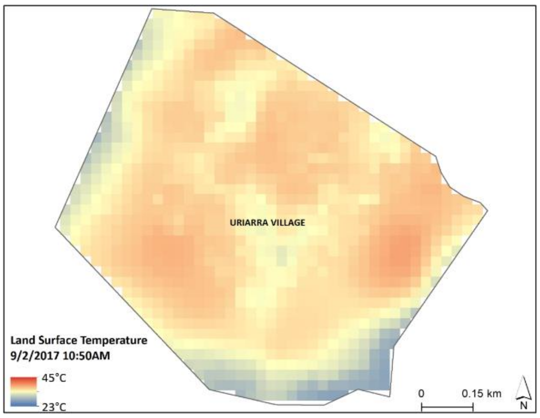


Figure W2: Cool spots; departure from the mean land surface temperature of 11.4 °C.
ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

Uriarra Village

Summer Land Surface Temperature, 9-2-2017 10.50AM



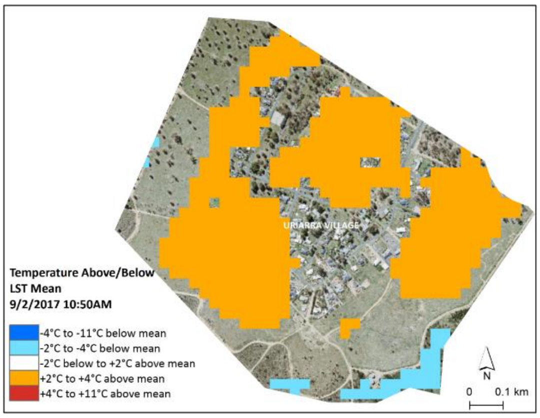


Figure S1 (left): Land surface temperatures for 9-2- 2017 (10.50 AM DST) derived using Landsat 8 thermal data.
Figure S2 (right): Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C.
ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

Summer Neighbourhood Heat Exposure and Vulnerability

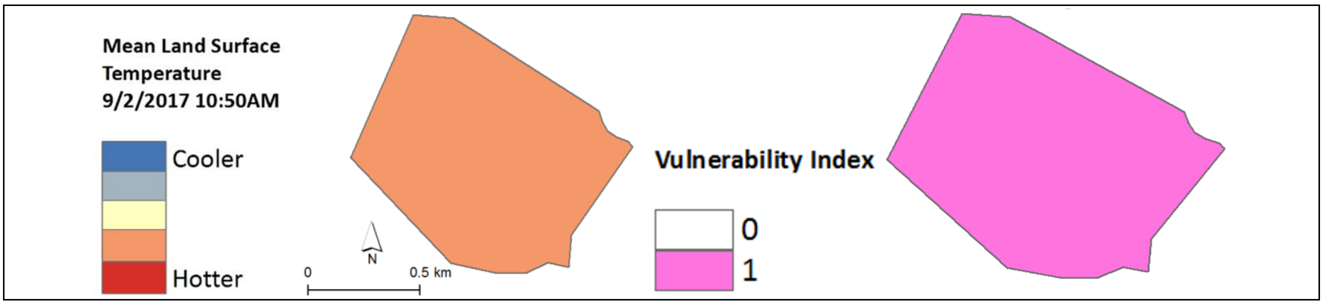
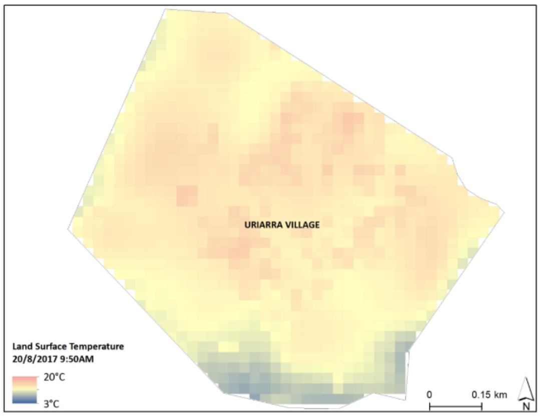


Figure S3 (left): Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.
Figure S4 (right): Vulnerability score; based on Mesh Blocks with the highest 20% for each of three vulnerability factors, the number of people over 65 years, or under 5 years, or the number of low-income households.

Winter Land Surface Temperature, 20-8-2017 9.50AM



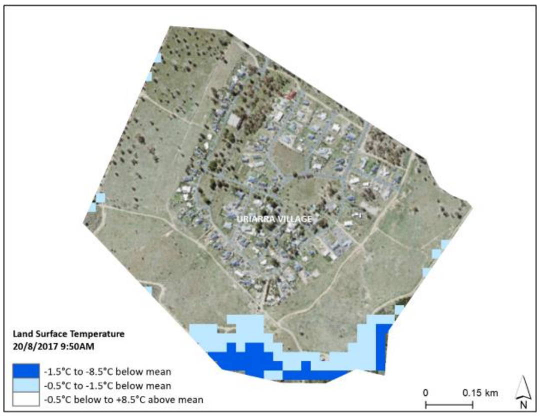


Figure W1 (left): Land surface temperature for 20-8-2017 (9.50 AM EST) derived using Landsat 8 thermal data.
Figure W2 (right): Cool spots; departure from the mean land surface temperature of 11.4 °C.
ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

Weston Creek

Summer Land Surface Temperature, 9-2-2017 10.50AM

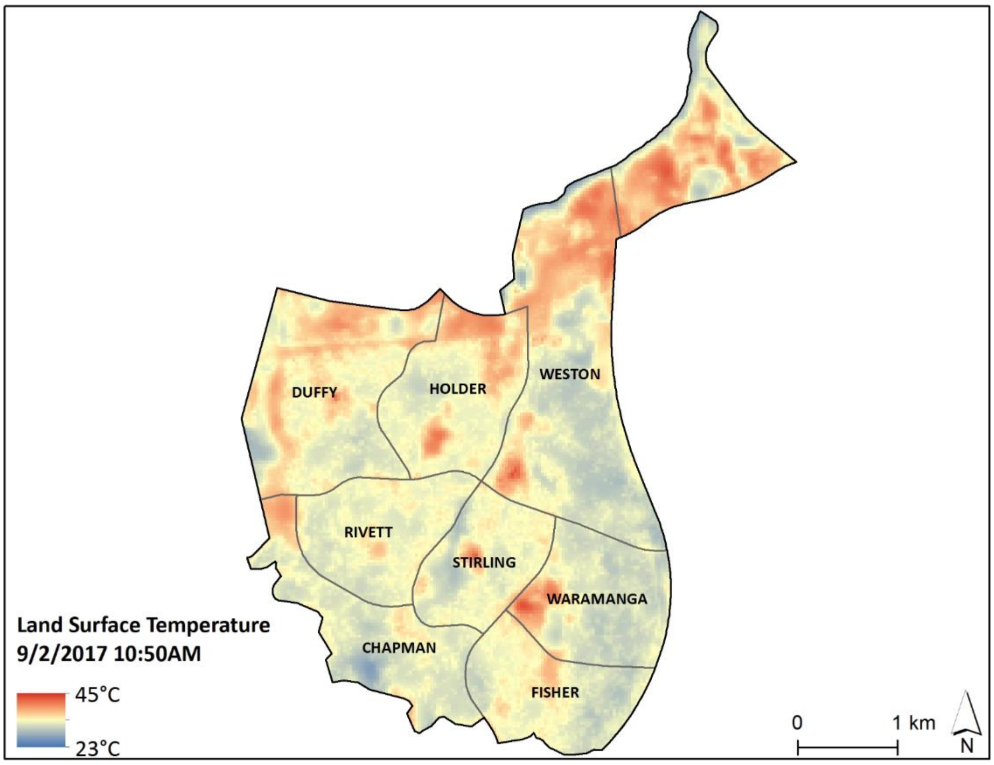


Figure S1: Land surface temperature for 9 February 2017 (10.50 AM DST) derived using Landsat 8 thermal data.

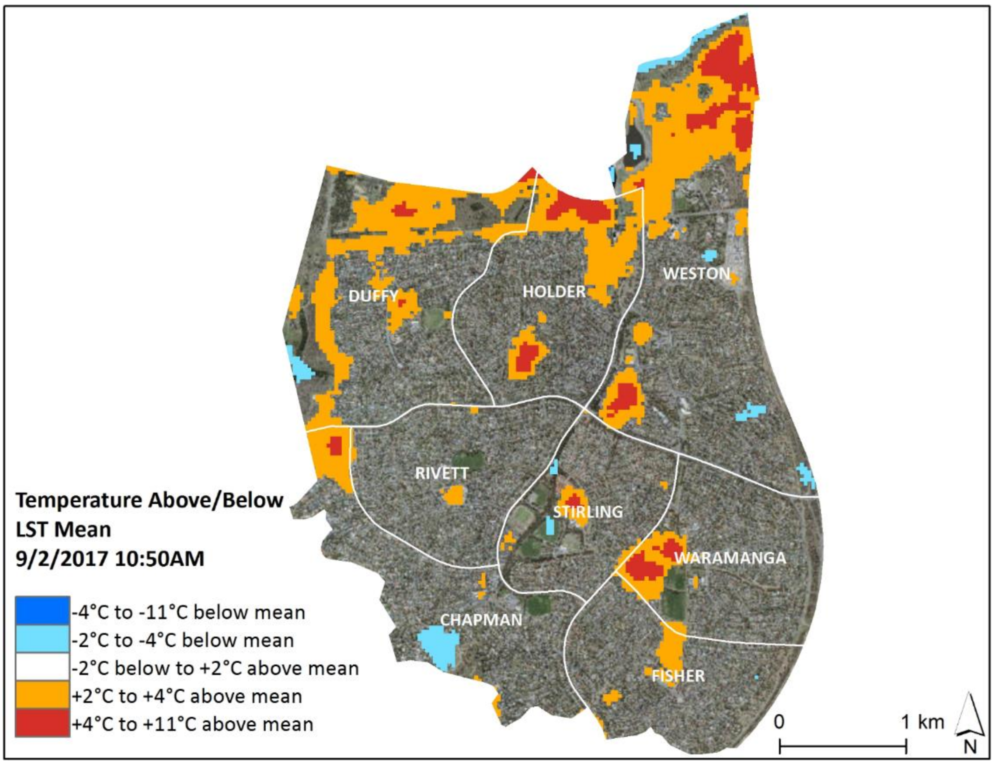


Figure S2: Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

Summer Neighbourhood Heat Exposure and Vulnerability

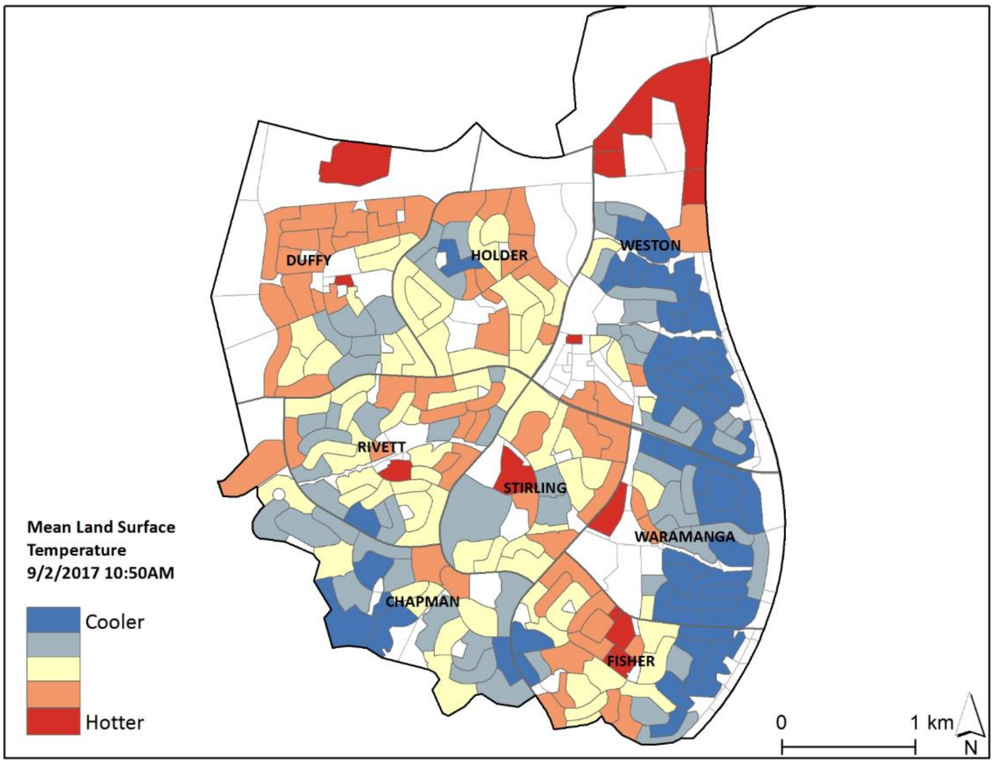


Figure S3: Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.

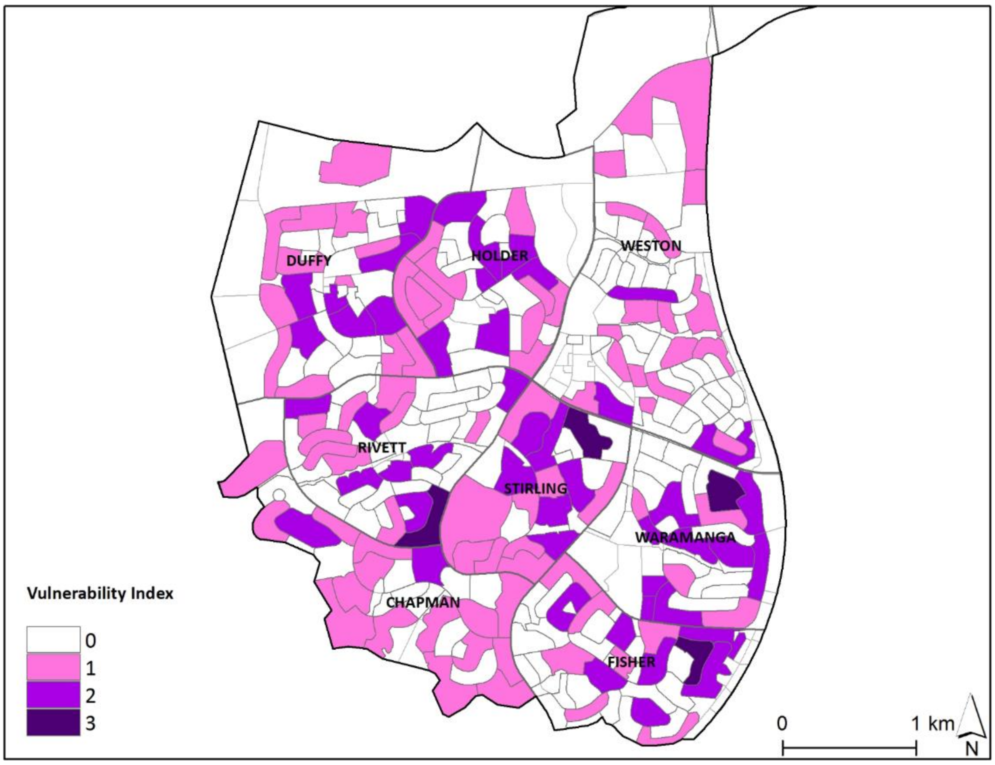


Figure S4: Vulnerability score; based on the cumulative score for Mesh Blocks with the highest 20% for each of three heat vulnerability factors; the number of people over 65 years, or under 5 years, or the number of low-income households.

Summer Neighbourhood Heat Exposure and Vulnerability Combined

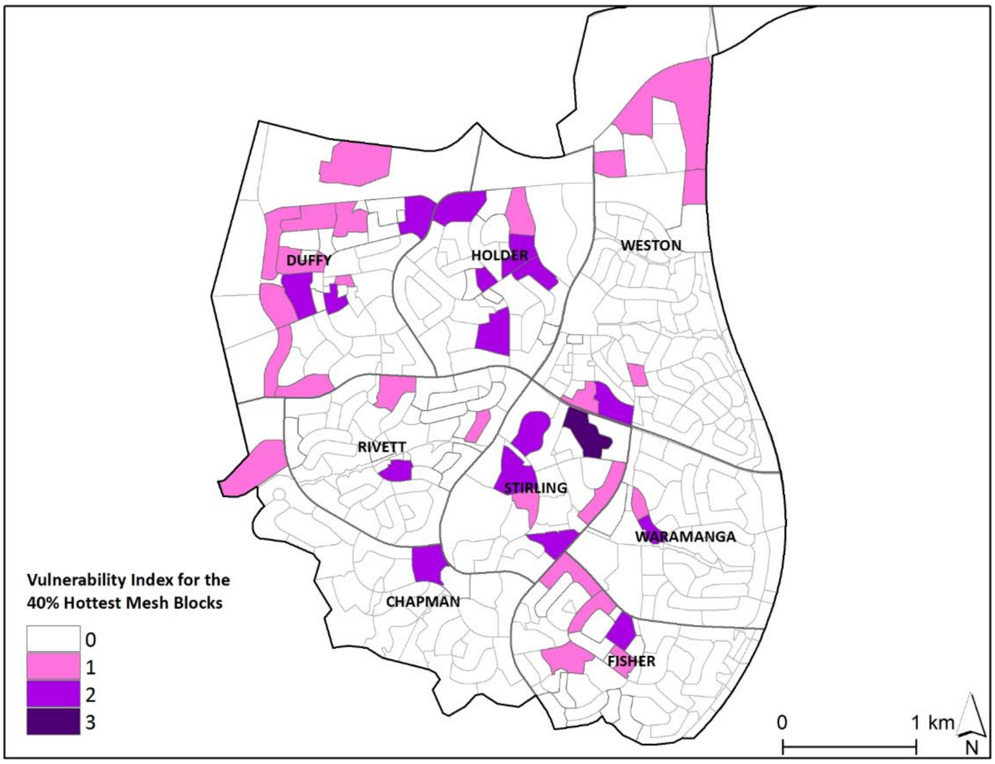


Figure S5: Vulnerability scores within the hottest 40% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

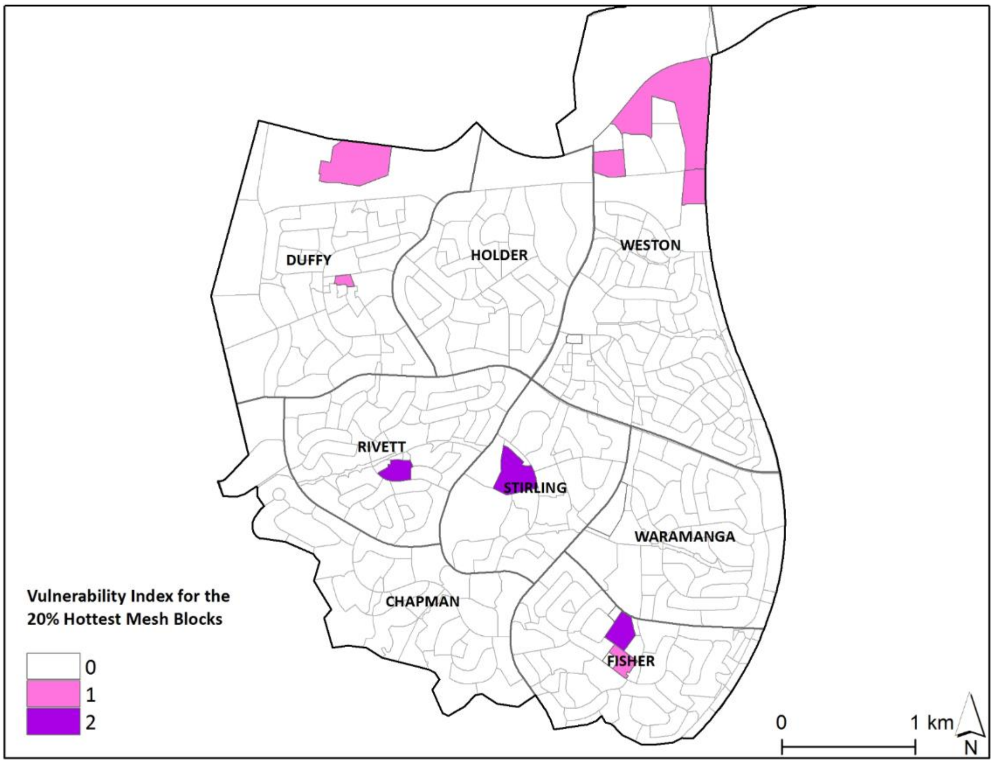


Figure S6: Vulnerability scores within the hottest 20% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

<u>Winter</u> Land Surface Temperature, 20-8-2017 9.50AM

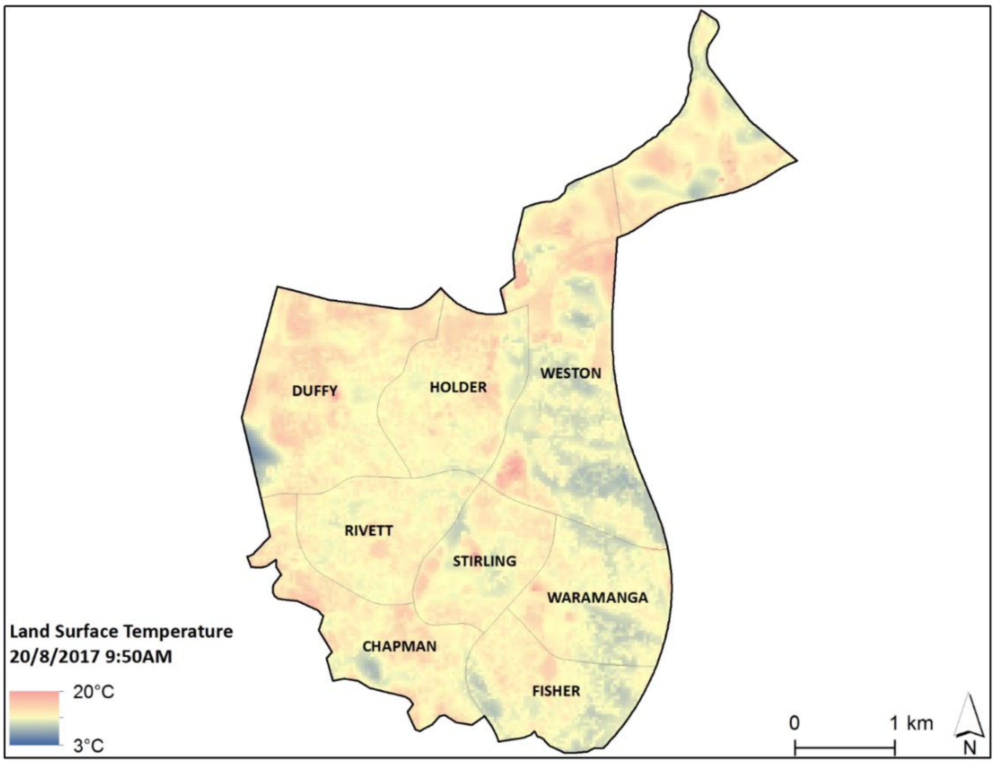


Figure W1: Land surface temperature for 20-8-2017 (9.50 AM EST) derived using Landsat 8 thermal data.

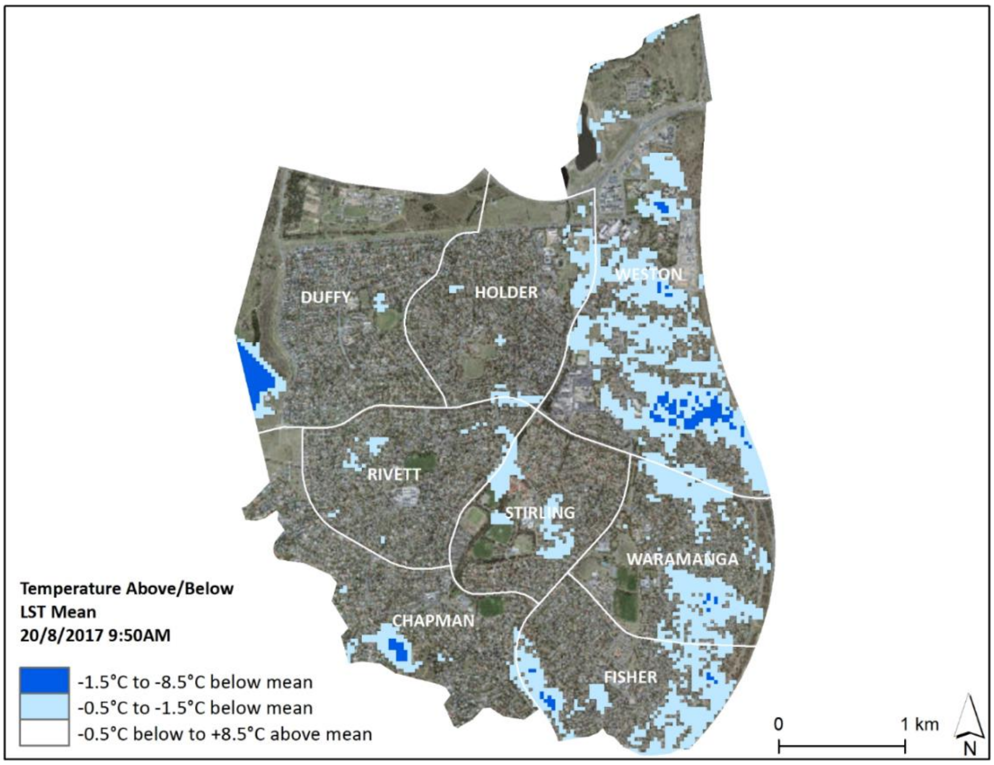


Figure W2: Cool spots; departure from the mean land surface temperature of 11.4 °C.
ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

Woden Valley

Summer Land Surface Temperature, 9-2-2017 10.50AM

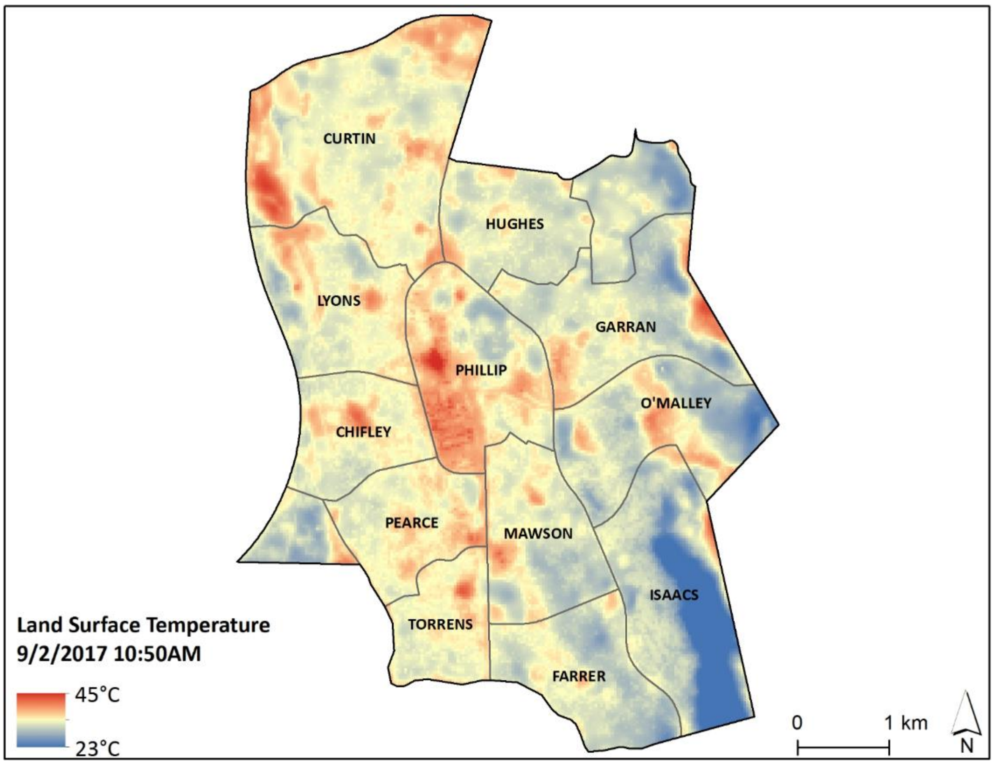


Figure S1: Land surface temperature for 9 February 2017 (10.50 AM DST) derived using Landsat 8 thermal data.

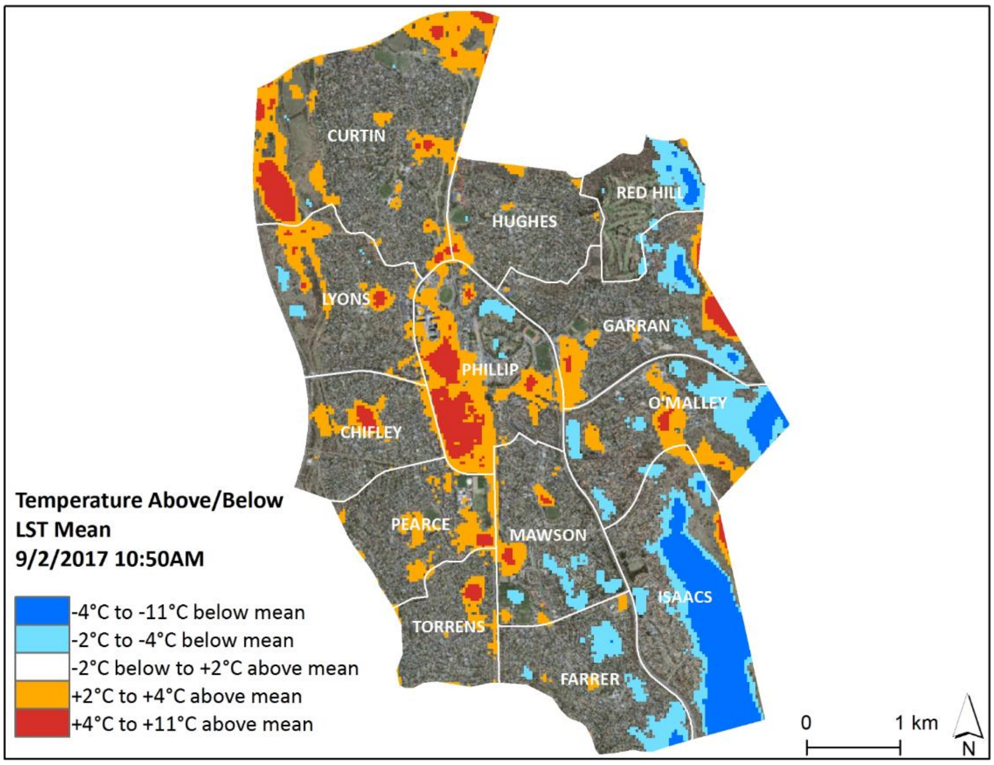


Figure S2: Hot spots and cool spots; departure from the mean land surface temperature of 34.4 °C. ACTmapi 2016 10 cm aerial photography is shown where temperatures are '-2 °C below to +2 °C above mean'.

Summer Neighbourhood Heat Exposure and Vulnerability

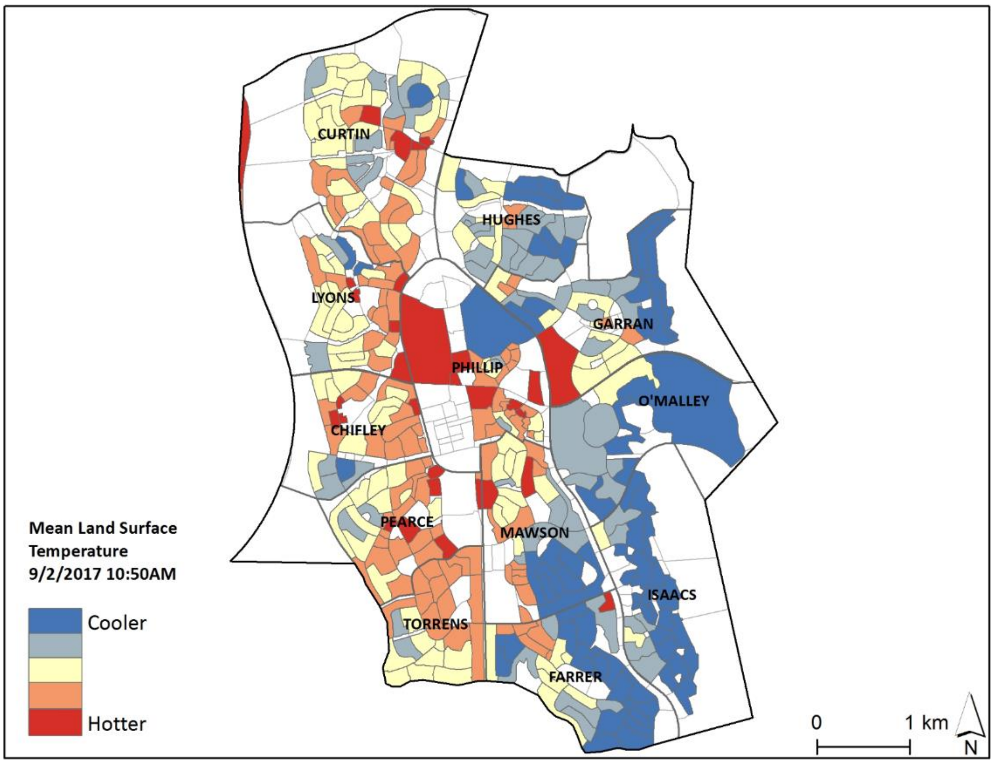


Figure S3: Mean land surface temperatures (9-2-2017, 10.50 AM DST) shown in 20% classes, for suburban ABS Mesh Blocks where people were living at the time of the ABS 2016 Census of Population and Housing.

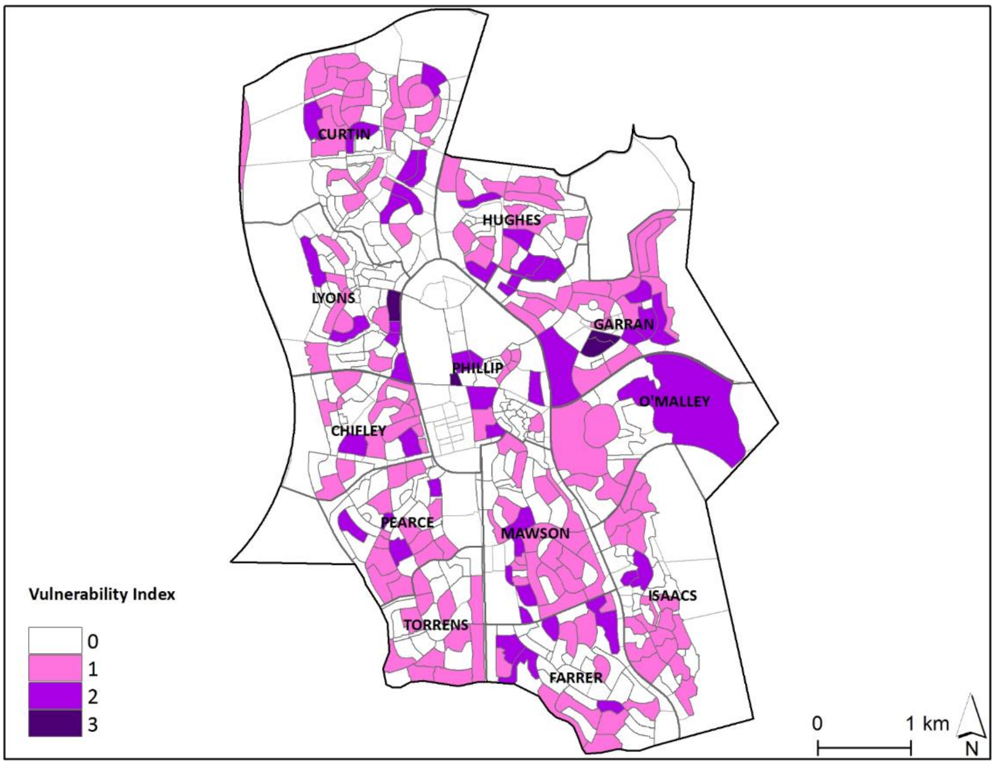


Figure S4: Vulnerability score; based on the cumulative score for Mesh Blocks with the highest 20% for each of three heat vulnerability factors; the number of people over 65 years, or under 5 years, or the number of low-income households.

<u>Summer</u> Neighbourhood Heat Exposure and Vulnerability Combined

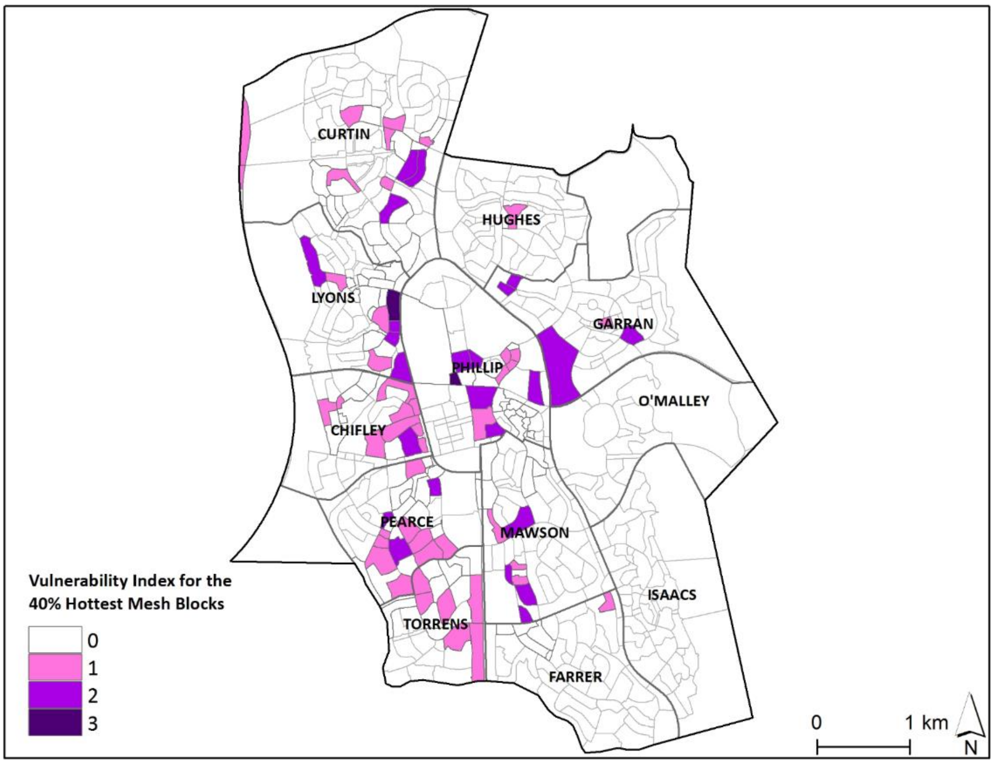


Figure S5: Vulnerability scores within the hottest 40% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

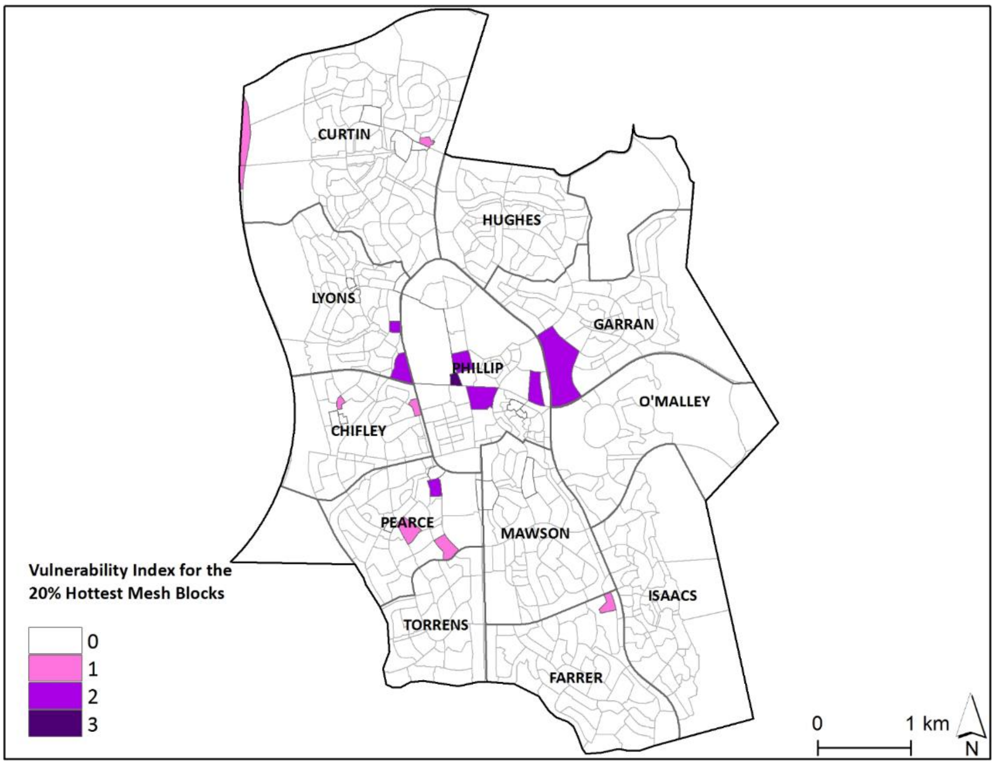


Figure S6: Vulnerability scores within the hottest 20% of Mesh Blocks, based on a combination of data shown in Figures S3 and S4.

Winter Land Surface Temperature, 20-8-2017 9.50AM

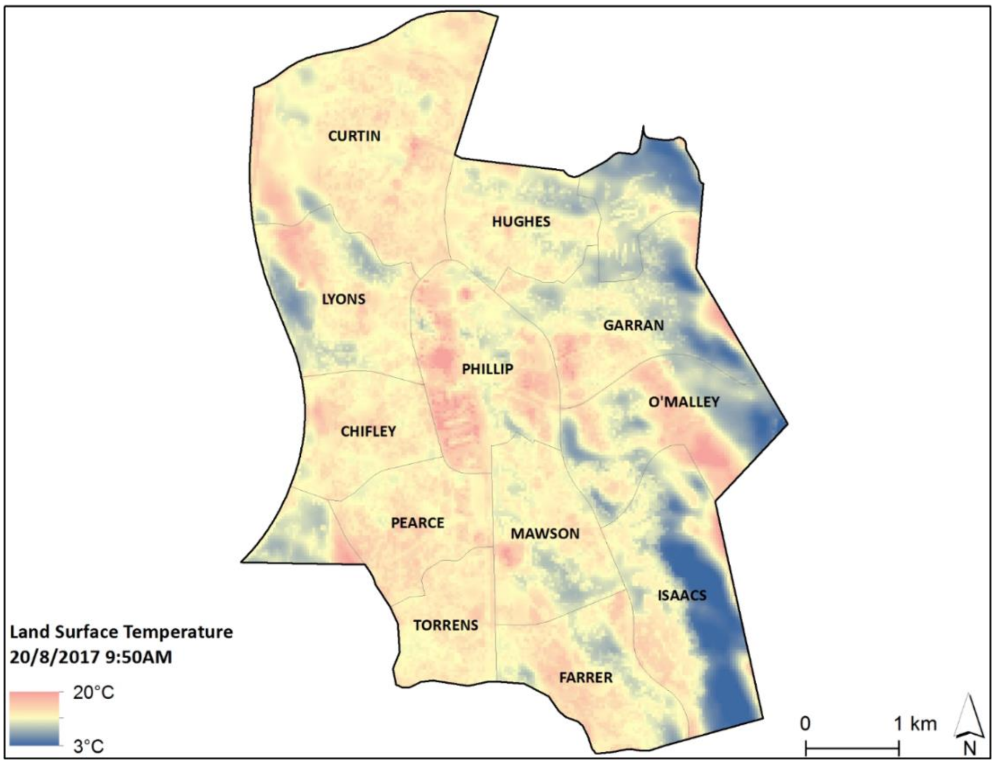


Figure W1: Land surface temperature for 20-8-2017 (9.50 AM EST) derived using Landsat 8 thermal data.

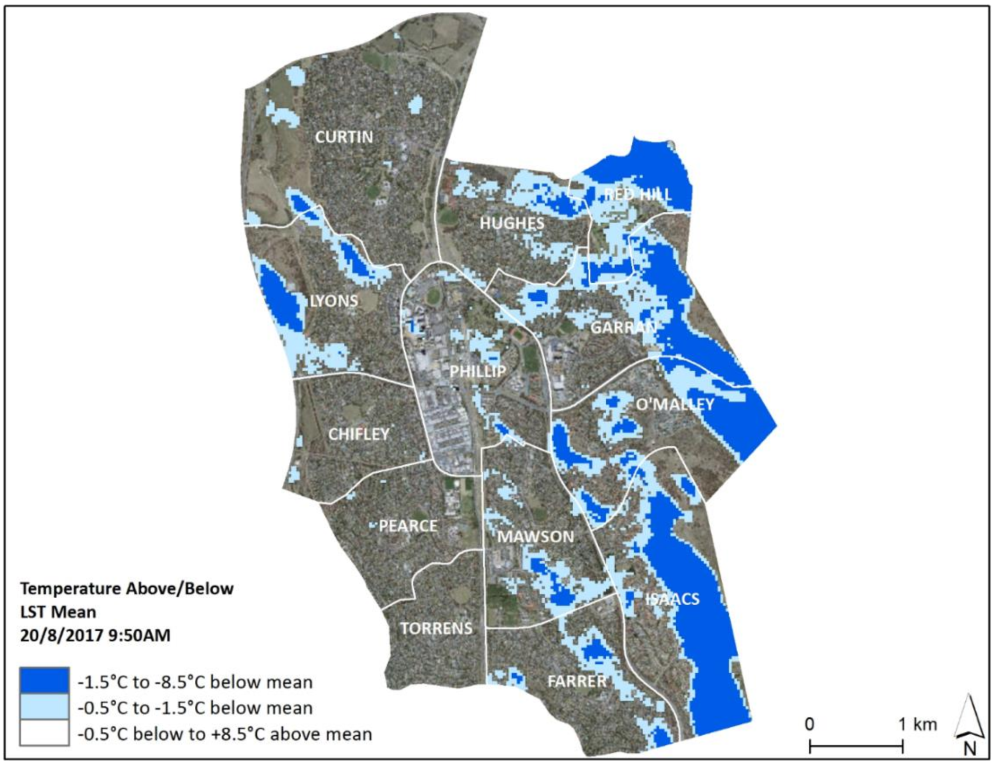


Figure W2: Cool spots; departure from the mean land surface temperature of 11.4 °C.
ACTmapi 2016 10 cm aerial photography is shown where temperatures are higher than –0.5 °C below the mean.

CONTACT US

t 1300 363 400
+61 3 9545 2176
e csiroenquiries@csiro.au
w www.csiro.au

AT CSIRO, WE DO THE
EXTRAORDINARY EVERY DAY

We innovate for tomorrow and help improve today – for our customers, all Australians and the world.

Our innovations contribute billions of dollars to the Australian economy every year. As the largest patent holder in the nation, our vast wealth of intellectual property has led to more than 150 spin-off companies.

With more than 5,000 experts and a burning desire to get things done, we are Australia’s catalyst for innovation.

CSIRO. WE IMAGINE. WE COLLABORATE.
WE INNOVATE.

FOR FURTHER INFORMATION

CSIRO Land and Water
Jacqui Meyers
t +61 2 62464384
e jacqui.meyers@csiro.au
w www.csiro.au/landandwater

Guy Barnett
t +61 2 62464380
e guy.barnett@csiro.au
w www.csiro.au/landandwater