WESTERN SYDNEY UNIVERSITY

PENRITH CITY COUNCIL

BENCHMARKING SUMMER HEAT ACROSS PENRITH, NEW SOUTH WALES

AUGUST 2020

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With respect for Aboriginal cultural protocol and out of recognition that the campuses of Western Sydney University occupy their traditional lands, the Darug, Tharawal (also historically referred to as Dharawal), Gandangara and Wiradjuri people are acknowledged and thanked for permitting this work in their lands (Greater Western Sydney and beyond).

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> **There are seven major categories of threat: sea level rise and storm surges, river flooding, extreme rain events, life-threatening heat, drought, wildfire, and food shortages.**
>
> **These forces will affect all urban design decisions, about where to build, when to build, and what to build.**
>
> JONATHAN BARNETT (JOURNAL OF URBAN DESIGN, 2020)

KEY FINDINGS

The aim of the current project was to document summer temperatures across the Local Government Area (LGA) of Penrith City where record-breaking heat has been measured frequently during the past years. These measurements come from a single weather station that is located outside the urban centres and neighbourhoods of Penrith City. It therefore remains unknown what air temperatures the local communities experience.

It is well known that urban microclimates vary depending on the composition of surface space. To capture this variation, air temperatures were continuously recorded at 120 locations across the LGA from 14 December 2019 to 30 March 2020, resulting in more than 1.4 million individual temperature measurements.

The number of days with air temperatures at or above 35°C was far greater across the LGA (39 days) compared to the measurements from the official weather station (24 days)

Maximum air temperatures of more than 50°C were recorded at six locations

Nighttime air temperatures were warmer in suburbs with high cover of hard surfaces (typical Urban Heat Island effect)

Emu Plains was the warmest, Mulgoa the coolest suburb

Individual locations in **Agnes Banks**, **Badgerys Creek**, **Berkshire Park**, **Castlereagh**, **Emu Plains**, **Glenmore Park**, **Orchard Hills** and **Penrith** had mean summer daytime (10:00-18:00) temperatures above 29°C

The urban core of **St Marys** remained up to 2.4°C warmer during the night compared to surrounding residential areas (typical Urban Heat Island effect)

This project provides the first empirical evidence about the variation of summer air temperature across the hottest region in the Sydney Basin. The results should be used to increase the resilience of local communities, economies, infrastructure and the environment against increasing summer heat.

Current models predict a synchronous increase in population and extreme heat for the region. Risks and consequences created by inevitable changes in air temperature can no longer be marginalised. Mitigating Urban Heat Island effects and increasing resilience of local communities against extreme heat must become a central goal for urban planning.

Regional development and building regulations across Western Sydney, and especially Penrith City must address the permanent implications of Urban Heat Islands and be prepared to respond to the acute shocks of extreme heat. 12 recommendations are provided at the end of this report that will assist in reaching this goal.

RECOMMENDED ACTIONS

- Formulate separate policies and guidelines that address (a) mitigation of Urban Heat Island effects and (b) strategies for days of extreme heat.
- Establish a monitoring network for continuous measurement of air temperature.
- Implement cooling initiatives for those suburbs that have the highest Heat Vulnerability Index.
- Reduce the area of hard surfaces in the central section of the LGA.
- Introduce trees for shading carpark surfaces.
- Limit the area of hard surfaces in new development.
- Generate clear policies to implement recommendations 4-6.
- Concentrate cooling efforts in St Marys on the hottest areas.
- Form a multidisciplinary Heat Task Force.
- Develop a comprehensive Community and Infrastructure Heat Emergency Plan.
- Continue to deliver actions and initiatives listed in the Cooling the City Strategy.
- Work with Western Sydney University to generate evidence for threshold-size effects.

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1. BACKGROUND

About 55 km west of the entrance to Sydney Harbour lies the Local Government Area (LGA) of Penrith. It covers 405 km^2 of urban, peri-urban and rural land in the western section of the Sydney Basin, where the Nepean River forms the natural border between alluvial plains in the east and the foothills of the Blue Mountains in the west.

In 2019, the 37 suburbs and localities (29 suburbs for census data collection) of Penrith were home to 213,000 people. Estimates of the NSW State Government predict that the local population will increase more than 60% by 2036, adding 140,000 new residents to the LGA. This anticipated growth has its origin in a range of factors, including lower than average land prices, high rates of greenfield development, the construction of Sydney's second international airport, urban expansion around the South Creek catchment, the growth of Penrith's health and education precinct and the rising importance of Penrith as a metropolitan hub in the envisioned Western Parkland City (Greater Sydney Commission, 2019).

While these developments are expected to result in economic and social change in the region, it cannot be ignored that the area around Penrith is the hottest part of Western Sydney (Figure 1). The high summer temperatures are the result of several contributing factors. These factors include:

- Lack of cooling sea breezes
- Low annual precipitation and consequential limited cooling from evapotranspiration
- Presence of alluvial soils with substantial clay lenses that store heat
- A north-south ridgeline from Glenorie to Mt Annan that obstructs near-surface air flows

While these factors have their origin in natural causes, several additional factors contribute to increasing heat throughout the region that are man-made. These factors include:

- Global warming
- Urbanisation
- Generation of anthropogenic heat
- Low tree canopy cover
- Location of several suburbs of Penrith City in the lowest part of the Hawkesbury-Nepean Valley where hot air is easily trapped

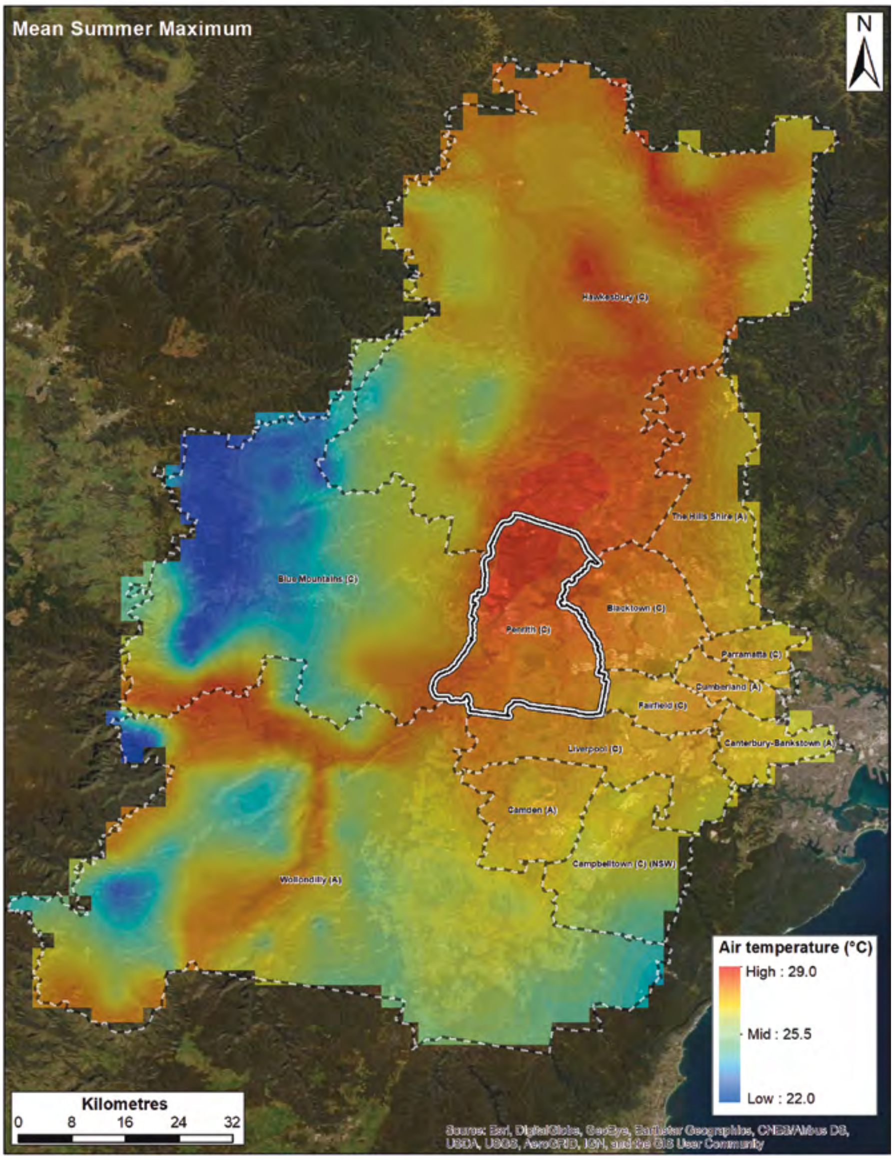


FIGURE 1: Mean summer (December-February) maximum air temperatures across Greater Western Sydney. The boundary of the Local Government Area (LGA) of Penrith is highlighted by a solid double line. Council boundaries of the other 12 LGAs that together make up Greater Western Sydney are shown by dashed lines. Mean maximum summer air temperatures of 29°C or higher occur in the LGA of Penrith and Hawkesbury. The map is based on data for the past 30 years which was retrieved from the Australian Bureau of Meteorology.

The cumulative effects of natural and man-made factors on summer heat are evident. Since 1910, mean surface temperature across Australia has increased by 1°C, with an accelerating trend in past decades. This widespread trend of warming leads to a higher frequency of heatwaves, extreme summer heat and also less nighttime cooling (Bureau of Meteorology, 2018). Long-term temperature analyses show that extreme monthly maximum air temperatures across Australia increased from 2% (1951-1980) to 12% (2003-2017)[1]. The same trend can be observed for unusually warm monthly minimum temperatures (i.e. high nighttime temperatures).

Meteorological records for Western Sydney show a stronger increase in the number of days where maximum air temperatures exceed 35°C or even 40°C (defined as 'hot' and 'extreme' according to the Bureau of Meteorology), compared to locations further east, like Parramatta in the geographical centre of the Sydney Basin or Observatory Hill near the harbour in the east (Greater

1. According to the Bureau of Meteorology, days of extreme heat are those outside each monthly 99th percentile calculated for the interval 1910-2017.

Sydney Commission 2019). The trend of accelerated warming in Western Sydney has also been documented for the area around Campbelltown (Pfautsch and Rouillard 2019a) where the pace of urbanisation and associated greenfield development is comparable to development around the LGA of Penrith.

The phenomenon of rising air temperature in metropolitan regions is not limited to cities in Western Sydney. As many cities around the world rapidly increased in size during the economic and agriculture boom in the post-WWII era, meteorologists noticed that air temperatures in city centres, and especially during the night, were significantly higher than those in adjacent rural land (Sundborg 1950, Kratzer 1956, Mitchell 1961). This phenomenon was termed 'Urban Heat Island' (UHI). Today's understanding of UHI is grounded in the seminal work of Timothy R. Oke (1973, 1982), and UHI effects have been described for cities and towns across the Sydney Basin (e.g., Pfautsch and Rouillard 2019a-c; Santamouris et al. 2017), Australia (Santamouris 2015), and indeed around the world (e.g., Peng et al. 2012; Ramamurthy and Sangobanwo 2016).

With increasing urbanisation and continued global warming, it is predicted that the intensity of UHI effects will further increase (Bowler et al. 2010, Santamouris et al. 2017). Higher air temperatures during summer as a result of continued urban development have also been forecasted for the area around Penrith (Adams et al. 2015). In addition to the processes of global warming and the conversion of greenfield to grey infrastructure, summer temperatures are further increased by urban densification and the associated loss of established vegetation together with an increased output of heat from traffic and buildings (Lin et al. 2015; Duan et al. 2019; Lima et al. 2019).

The dangerous effect of these processes that take place at global, regional and local scales is captured by studies that show a strong and increasing relationship between summer heat and rates of morbidity and mortality in urban populations (Li et al. 2018, Limaye et al. 2018). The detrimental effect of heat on urban communities has been scientifically documented as early as 1930 (Shattuck and Hilferty 1932). The work analysed the "officially reported deaths related to heat" in the United States between 1900 and 1929. The results clearly showed that heat-related mortality was far greater in urban compared to rural populations. One hundred years later, these observations remain absolutely relevant.

Extreme heat is responsible for more deaths in Australia than all other natural disasters combined (Zander et al. 2015) and heatwaves have been identified as the biggest risk to public health in the Sydney Basin (Resilient Sydney, 2018). Yet, nearly 100 years after the important findings by George Shattuck and Margaret Hilferty, communities in Penrith and other parts of Western Sydney experience more extreme summer temperatures than ever before.

As reported by the Greater Sydney Commission (2019), extreme heat in January 2013 caused power outages in Penrith and more than 260 people needed medical treatment. New heat records were broken in the summer 2016/17 where 1,100 people required medical treatment at Nepean Hospital with symptoms like heat exhaustion, dehydration and heat shock. Climate forecasts indicate that the trend of increasing urban heat will worsen for several decades (Dahl et al. 2019). The question arises: What can be done to slow or better yet reverse this perilous development?

Answers to this question are urgently needed. The latest climate predictions from the World Meteorological Organisation for the time between now and 2024 predict further warming and below average annual rainfall for Australia (World Meteorological Organisation 2019). The assessment was produced with contributions from Australia's Commonwealth Science and Industry Research Organisation (CSIRO), and it underlines that the necessary environmental preconditions for the development of extreme summer temperatures and heatwaves across Western Sydney will be rife for many summers in the near future.

All residents of Western Sydney, from Camden and Campbelltown in the south, to Liverpool and Penrith in the centre, and Blacktown and Hawkesbury in the north will be impacted by these conditions. Summer heat that exceeds already extreme conditions poses not only a real threat to the well-being of local populations. It adds pressure on economic development and the supply networks for electricity and transport, and urban infrastructure in Western Sydney more broadly.

An assessment of UHI effects and the exposure of local populations to the impacts of heat helps us to understand the status quo of heat across Western Sydney. During the summer of 2015/16, sections in the central region of the LGA of Penrith were identified to experience high and very high UHI effects, where average land surface temperatures were up to 12°C higher compared to reference sites, such as nearby forested land (Devereux and Caccetta 2017). These UHI effects were severe in the CBD of Penrith, but also in Glenmore Park, Erskine Park and North St Marys (Figure 2).

The assessment of land surface temperatures is helpful to understand the impact of vegetation cover on urban climate. The casual link between increasing urban heat and the absence of vegetation was established more than half a century ago (Duckworth and Sandberg 1954). However, assessing how land surface temperatures impact urban climate ignores the human component. To overcome this limitation, the NSW Government developed the Heat Vulnerability Index (HVI). The HVI is estimated by combining three indicators (SEED, NSW Government):

1. Exposure to heat – using temperature classes
2. Sensitivity to heat – using vegetation area, road area, population density, and the number of elderly, very young and persons needing care
3. Adaptivity to heat – using data from the Australian Bureau of Statistics (Socio-economic Indexes for Areas (SEIFA) – Index of Relative Socio-Economic Disadvantage (IRSD) and Index of Employment and Education (IEO)

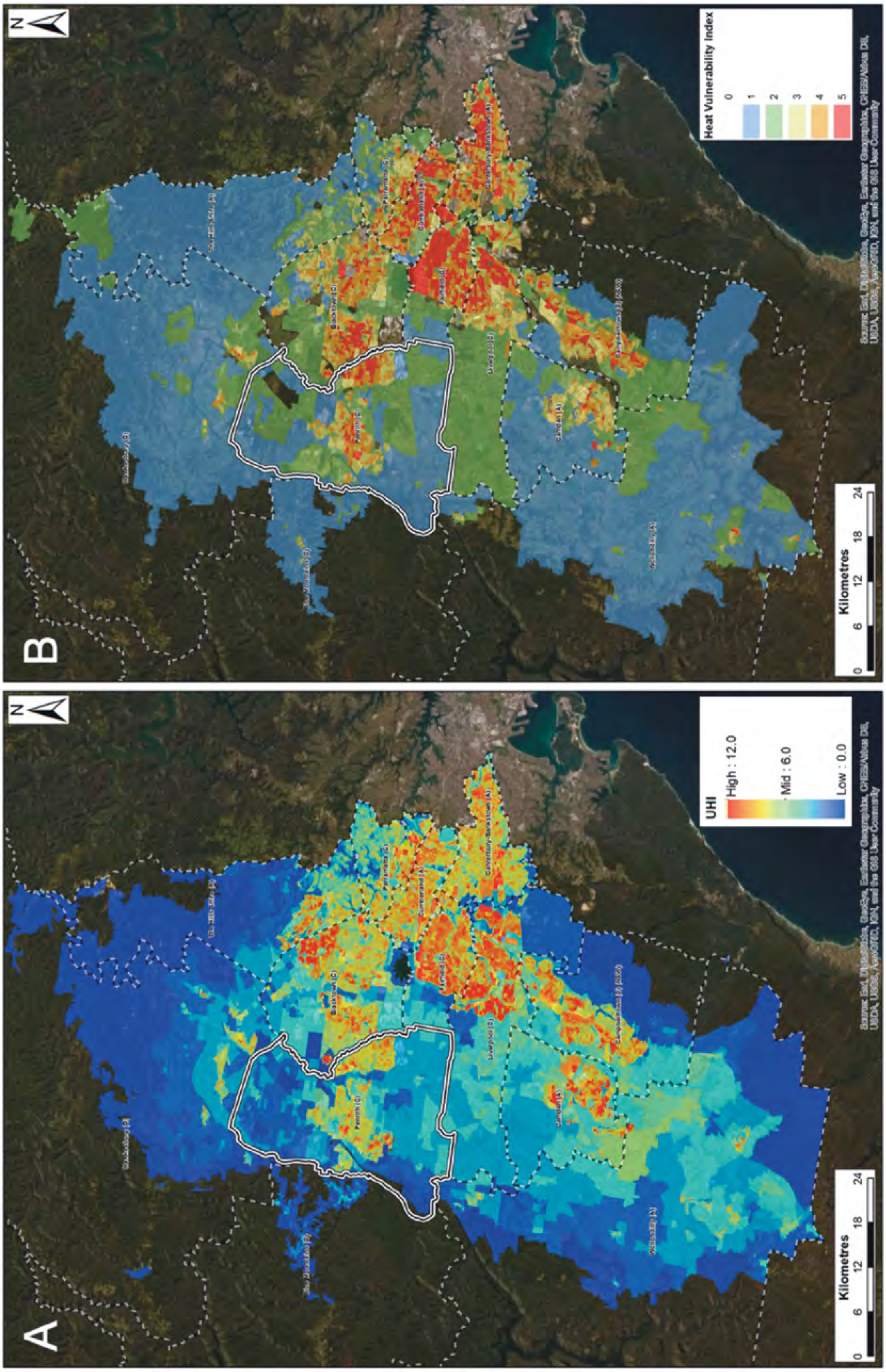


FIGURE 2: Maps depicting the Urban Heat Island (UHI) effect (left) and the Heat Vulnerability Index (HVI) scores (right) for Greater Western Sydney during the summer of 2015/16. The boundary of the Local Government Area (LGA) of Penrith is highlighted by a solid double line. Council boundaries of the other 12 LGAs that together make up Greater Western Sydney are shown by dashed lines. The UHI is a phenomenon related to differences in land surface temperatures and measured in °C. The HVI represents an indicator that merges three indices related to exposure, sensitivity and adaptivity of local populations to heat. For more information of UHI and HVI, please see text. Data source: seed.nsw.gov.au.

The resulting HVI score was estimated for every Level 1 area of the Australian Bureau of Statistics. Level 1 areas contain a minimum of 200 and a maximum of 800 people. The score assigns values from 1 to 5, where an HVI of 5 indicates high exposure, high sensitivity and low adaptive capacity to heat. A score of 1 indicates the opposite.

Places around the LGA of Penrith that scored a 5 during the summer of 2015/2016 include the CBD of Penrith, Kingswood, Jamisontown, St Marys, Oxley Park, Colyton and others (see geo.seed.nsw.gov.au for more details) (Figure 2). The majority of suburbs in the central region of the LGA had an HVI of 3 or higher, indicating that vulnerability to heat was a widespread issue in the area that summer. It is reasonable to expect that many Level 1 areas that scored 3 or 4 in the summer of 2015/16 'achieved' a higher score in 2018/19 and 2019/20, where cumulative summer heat loads were even greater.

Two important observations arise when comparing the maps in Figure 1 and 2. First, the area with the highest mean maximum summer air temperature (mostly vegetated, low population density) does not match the area of high and very high UHI effects and HVI scores (mostly unvegetated, high population density). This observation serves as a clear indicator that grey infrastructure has a large impact on the experience of summer heat by local populations. Second, the exposure to high UHI effects or HVI scores varies notably within and among the suburbs of the Penrith LGA. This variation is most likely the result of environmental and societal differences at a relatively small scale.

It is well known that urban climate can vary markedly at the micro scale (Muller et al. 2013). Yet, information about near-surface air temperatures across the LGA of Penrith comes from a single measurement point (Bureau of Meteorology station #067108). This makes it impossible to determine how environmental differences relate to microclimatic variation across the LGA. The networks of official weather stations are simply not designed to assess urban climates. A limited number of these stations usually covers a relatively large area (Muller et al. 2013). By regulation of the World Meteorological Organisation (2019), they must be positioned away from densely populated areas. These conditions limit the use of data recorded by these stations to document near-surface air temperatures that local commmunities experience during summer (Meier et al. 2017).

Sound knowledge about microclimatic variation across the LGA of Penrith represents several opportunities. These relate to (a) knowing the apparent level of heat exposure in local communities; (b) an enhanced capacity to develop strategies and guidelines for heat-smart urban planning and landscape design; (c) evidence to inform and improve policies; (d) improved effectiveness of interventions that aim to mitigate local heat; (e) better guidance to prioritise these cooling interventions; (f) more comprehensive information available to health and emergency services when preparing for the impacts of heatwaves; (g) new local knowledge about local hot and cool spots that can be used to provide guidance for communities.

Information generated in the present project addresses several of these opportunities by providing microclimate analyses based on empirical data collected across the entire LGA of Penrith. 120 instruments were systematically dispersed across more than 450 km^2 of residential, industrial, peri-urban and green terrain to record near-surface air temperatures during the summer of 2019/20. More than 1.4 million measurements were collected and analysed to document the variability of summer air temperatures in and around Penrith at unprecedented detail. Results of this work provide evidence that the residents of Penrith are exposed to more heat than previously known and report the highest air temperatures ever measured in Western Sydney.

2. AIMS

The objective of this project was to benchmark summer air temperatures across the entire LGA of Penrith and by doing so, identify patterns of variation in air temperature that have their origin in the form and cover of the land.

The project area was located in the western region of the Sydney Basin where the hottest summer temperatures across the Basin are regularly recorded. Hence, special emphasis was given to the analysis of extreme heat to generate evidence about hot spots and cool zones around the Penrith LGA with the aim to inform planning practices around heat mitigation.

The commercial centre of St Marys is of great importance to the local economy. However, the area is dominated by hard surfaces in the form of roads, carparks and buildings. Tree canopy cover to shade these mostly dark surfaces is minimal. A sub-project analysed variation of air temperature across this area to identify those locations with the warmest microclimate where additional canopy cover would generate the greatest cooling benefits.

While results are based on analyses using data from 120 locations dispersed across the LGA of Penrith, results of the project are relevant for heat-smart urban planning and development in Western Sydney and beyond.

3. METHODOLOGY

3.1 DESIGN OF LOCAL HEAT LOGGERS

This research project used a technique developed by Western Sydney University to continuously record near-surface air temperature throughout the entire area covered by the LGA of Penrith. The custom-made local heat loggers (from here on abbreviated as ***LHL***) consisted of two main components:

1. A commercially available temperature sensor with integrated logger (Figure 3A). The high accuracy (±0.5°C) and resolution (0.1°C) of the sensor (Tempmate®-S1 V2, Imtec Messtechnik, Heilbronn, Germany) has been certified by international standards (e.g., CE, EN 12830). The sensor was sealed in a waterproof plastic casing and programmed to record air temperature (T_{air}) at 10-minute intervals.

2. A protective shield to prevent exposure of the sensor to direct solar radiation (Figure 3B). The shield was made from thin aluminium to limit thermal mass and associated absorption and re-radiation of solar energy. To further reduce the potential risk of heat absorption, the outside of the shield was coated with white, high-gloss enamel paint. The base of the shield was open and three large holes were punched into the top of the shield to allow good internal circulation of air (Fig. 3C). Once mounted in the field to any support structure (in this study exclusively trees), the LHL was oriented perpendicular to the ground surface (Figure 3D).

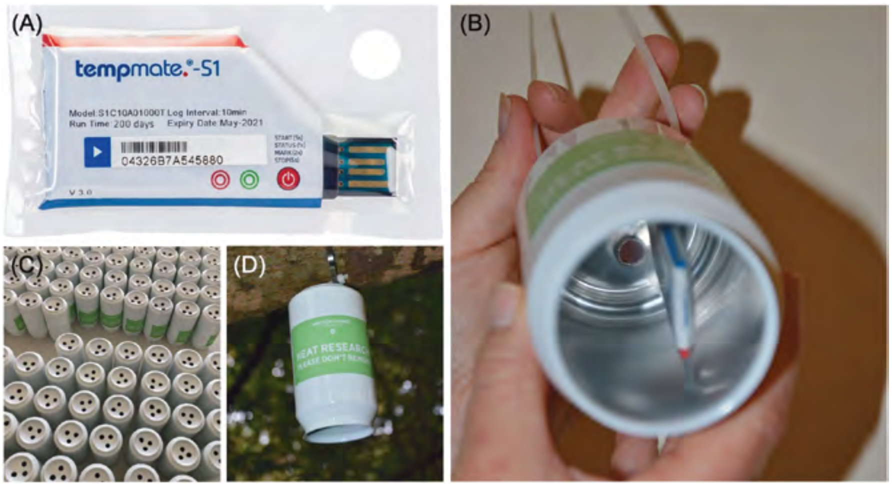


FIGURE 3: Details of the Local Heat Logger designed by Western Sydney University. (A) The sensor used to record near-surface air temperature. (B) The protective shield with sensor inside. (C) Detail of the shield showing the holes necessary for air flow inside the shield. (D) Installation of the Local Heat Logger in the field with the open bottom facing the surface.

3.2 CALIBRATION OF LOCAL HEAT LOGGERS

Several tests were conducted to validate the accuracy of the LHL. These tests involved experiments where the performance of the LHL was assessed against another commercially available temperature sensor and three official weather stations operated by the Commonwealth Bureau of Meteorology across Western Sydney (Sydney Olympic Park, Parramatta North, Mt Annan). Results of these tests were previously published in Pfautsch and Rouillard (2019). All tests yielded very high coefficients of determination (R^2 close to 1) and indicated a highly significant ($p < 0.001$) and linear relationship of the data recorded using the LHL with the data from the commercial logger and the weather stations.

To ensure high quality of the recorded data for this project, an additional calibration was done using available minimum and maximum air temperature measurements from the official weather station operated by the Bureau of Meteorology in the vicinity of the International Regatta Stadium north of the CBD of Penrith (Station #067108, latitude: 33°53'49"S, longitude: 150°43'41"E). Data from the weather station and three LHLs recorded between 14 December 2019 and 30 March 2020 were used for the calibration (Figure 4). The three LHL locations were at:

1. 153-233 Old Castlereagh Road, Castlereagh (in front of the Penrith Lakes Environment Education Centre)
2. Sydney International Regatta Centre (near the entrance to the White-Water Stadium)
3. Penrith Lakes, Penrith (in front of Hadley Park Homestead)

Similar to previous calibrations, the Penrith-specific calibrations yielded significant ($p < 0.001$) relationships and very high coefficients of determination (R^2 of up to 0.98) (Figure 4). It is worth noting that daily maximum air temperatures matched better between the LHLs and the weather station, compared to daily minimum temperatures. Daily minimum air temperatures are usually recorded during the early morning hours. Minimum daily air temperatures recorded with the LHLs were slightly higher compared to those recorded by the weather station. It is reasonable to attribute this additional warming to the environment surrounding the LHLs, which contained hard surfaces. These will store energy during the day and re-radiate this energy during the night which is likely to lead to the observed warmer air temperatures.

Additional calculations that assessed the quality of the temperature data, revealed that the differences between daily maximum and minimum air temperatures measured with the LHLs and the official weather station were very small (Table 1). These temperature differentials (denoted using the Greek capital letter ***Delta***, Δ) were positive for two and negative for one LHL yet always less than 0.5 °C.

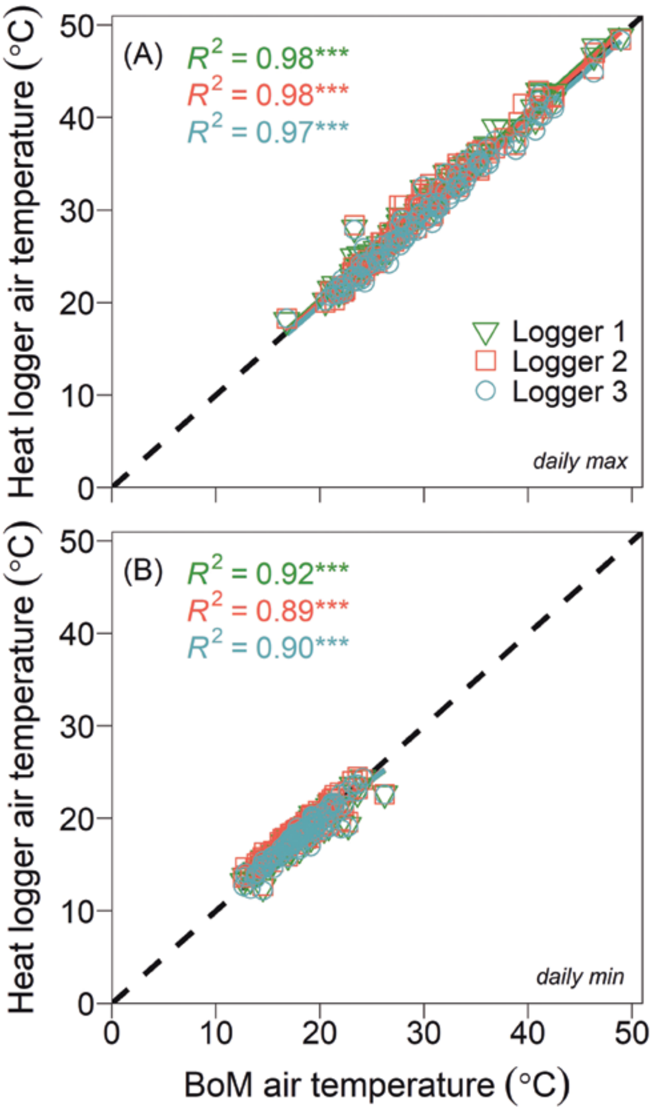


FIGURE 4: Calibrations of near-surface air temperatures measured with three custom-build Local Heat Loggers against data recorded by the Bureau of Meteorology weather station at Penrith Lakes. Daily measurements of (A) maximum and (B) minimum air temperatures for the interval of 14 December 2019 to 30 March 2020 were used in the calibrations. All calibrations yielded highly significant correlations ($p < 0.001$).

TABLE 1: Quality assessment of temperature measurements made with three Local Heat Loggers (LHL). The absolute minimum and maximum daily air temperatures recorded by the official weather station were subtracted from those recorded using the LHLs. The resulting differential (Δ) temperatures were averaged (Mean Δ) and the absolute minimum and maximum differentials for each data set are shown. SE indicates 1 standard error of the mean. Data were recorded on 107 days from 14 December 2019 to 30 March 2020.

COMPARISON	N	MEAN Δ	SE
Heat logger 1 *vs* BoM station			
$T_{air-min}$	108	0.04	0.08
$T_{air-max}$	108	0.46	0.08
Heat logger 2 *vs* BoM station			
$T_{air-min}$	108	0.38	0.09
$T_{air-max}$	108	0.19	0.1
Heat logger 3 *vs* BoM station			
$T_{air-min}$	108	-0.09	0.08
$T_{air-max}$	108	-0.38	0.1

3.3 MEASUREMENT NETWORKS

Three networks, containing a total of 120 local heat loggers (LHL) were deployed between 11 and 13 December 2019. Each LHL recorded near-surface air temperatures at 10-minute intervals until the beginning of April 2020, generating a total of nearly 1.7 million raw measurements. Each of the three networks was designed for a specific purpose. While Network 1 covered the entire LGA using 100 LHLs, Network 2 focussed on the retail centre in the heart of St Marys using 10 LHLs and another 10 LHLs were used for Network 3 that documented summer temperatures at strategically important locations throughout the LGA. These locations included the CBD of Penrith and St Marys, the Nepean River, Badgerys Creek and others.

The process from inception to installation of Network 1 involved several steps. First, a spatial x-y grid with 100 cells was projected onto the area covered by the LGA. As the population density of Penrith is much higher in the central area from St Marys in the east to Penrith in the west, this area was covered with a larger number of grid cells (n= 60) compared to the grid used to cover the northern (n = 20 cells) and southern (n = 20 cells) section of the LGA. A 2 km buffer zone outside the boundary of the LGA was included to ensure complete coverage of the LGA during the production of temperature maps.

The centre of each of the 100 cells represented the idealised location for each LHL (Figure 5). In the next step, a combination of aerial imagery and Google Maps was used to identify accessible trees that could be used to install the LHLs. Once physical locations of trees were selected, locations were grouped into 10 clusters and the most efficient driving routes that connected all locations in individual clusters were generated. Using these directions supported the distribution of 100 LHLs between 11 and 13 December 2019.

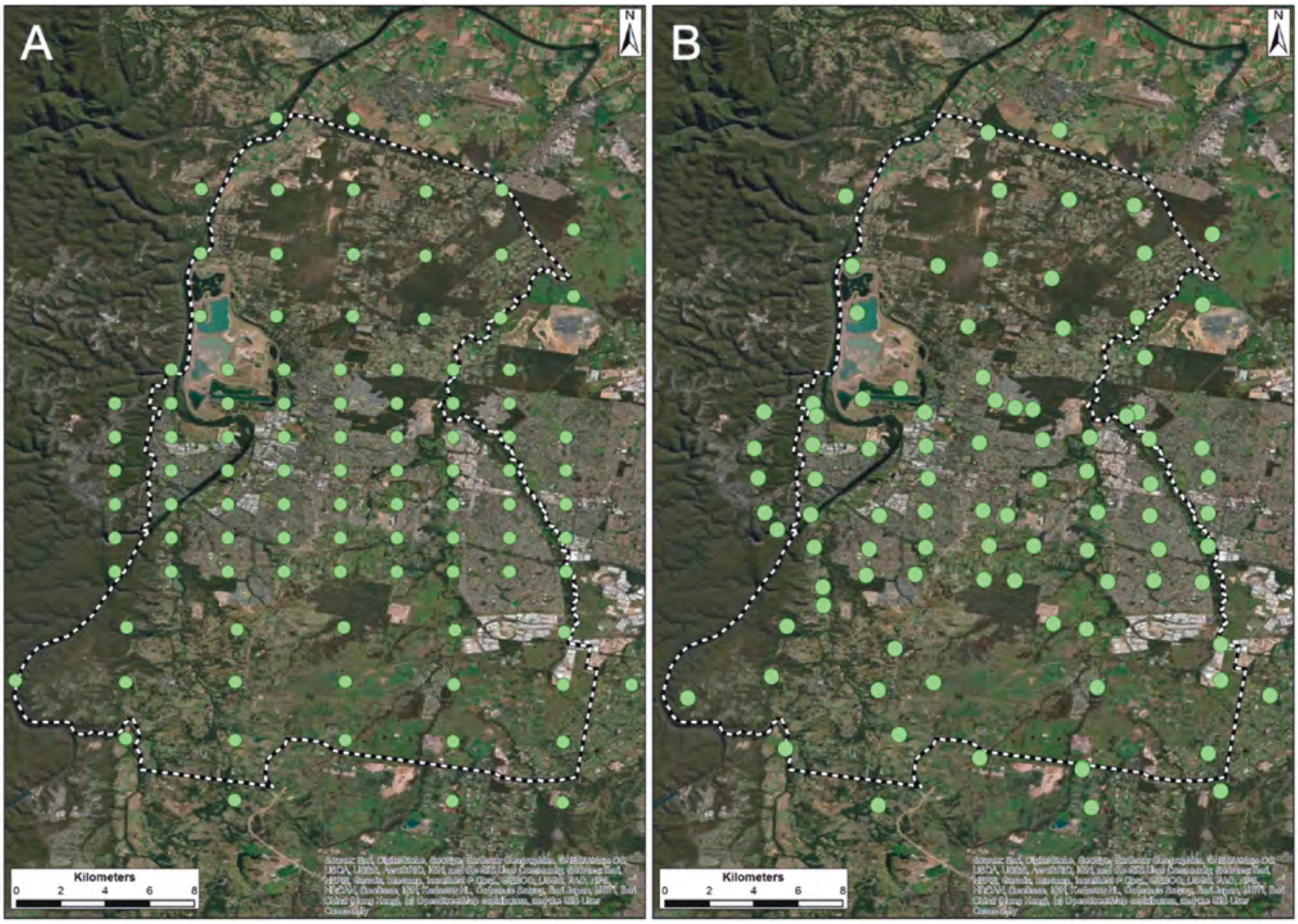


FIGURE 5: Maps of the idealised (A) and actual network (B) of Local Heat Loggers across the Local Government Area of Penrith. Both networks consist of 100 measurement points. The boundary of the LGA of Penrith is shown as dashed line.

At each location, a step ladder was used to access the canopy of the tree. The LHL was mounted to a branch at the base of the canopy 2.5-3 m above ground level. The space between the branch and the ground surface was free of other branches. The geographical position of each tree was recorded using coordinates from Global Positioning System (GPS) satellites.

All locations were revisited to collect the LHLs on 31 March and 1 April 2020. A total of 94 LHLs were retrieved, while 6 LHLs were either lost or not activated correctly. Some sensors showed signs of electrical and/or physical damage (Figure 6). However, it was possible to download data from all 94 sensors. For unknown reasons, the LHL at Sanctuary Drive in Windsor Downs stopped recording data on 21 January 2020. Quality of the data was assessed in an initial screening process before truncating to gain continuous data from 14 December 2019 until 30 March 2020. This data set contained 1,451,847 individual measurement of near-surface air temperatures.

FIGURE 6: Sensors that showed signs of electrical and/or physical damage after being deployed in the field for several months. Data from all damaged loggers were retrieved without problems.

The 10 locations for LHLs in Network 2 were selected to provide good spatial coverage of the urban core (i.e., Queen Street and adjacent carparks) of St Marys (Figure 7). All locations contained a tree to install the LHL. Installation commenced on 11 December 2019 and all 10 LHLs were collected in the first week of April 2020. Following the identical procedure described for data treatment of Network 1, a failure was detected for a single sensor located at the carpark at 34-50 Gidley Street (black dot in Figure 7). This sensor stopped operating during the early afternoon of 4 January 2020, a day of extreme heat and was excluded from the analysis. After truncating data, Network 2 produced a total of 145,077 individual measurements of near-surface air temperature.

FIGURE 7: Map showing the location of 10 Local Heat Loggers around Queen Street and adjacent carparks in the urban core of St Marys. Colours of each location match with those used in Figures 15 and 16 in Section 4.5.

An additional 10 LHLs were installed at location in the CBD of Penrith, in a park near the Nepean River, as well as in Agnes Banks, Jordan Springs, St Marys, Badgerys Creek and Mulgoa. These LHLs represented Network 3 (see Figure S1 at the end of the report). Nine LHLs were collected from the field in mid-January, resulting in 34,279 individual measurements. One of the ten loggers was not switched on during the installation and consequently did not record any data. Available measurements were analysed and preliminary trends of summer heat across the LGA were provided before and during the Cooling the City Masterclass event held by Penrith City Council in early February 2020.

In the present analyses, data from Network 3 was included in Network 1, except for three locations where data were recorded in duplicate. These locations were at (1) Agnes Banks Nature Reserve, Rickards Rd, Agnes Banks; (2) Tench Reserve, Jamison Rd, Penrith; (3) Northern Road, Jordan Springs. After including the remaining seven data sets in the data base for Network 1, analyses of summer heat across the LGA was based on a total of 1,481,223 measurements from 100 locations. These locations were mapped using their GPS coordinates (Figure 6), representing the final network of measurement points used for the analysis and visualisation of summer heat across the LGA.

3.4 **GENERATING MICROCLIMATE MAPS**

Direct measurements of near-surface air temperature and derivatives of these measurements were used to develop geo-referenced maps that cover the LGA of Penrith. To produce these maps, the geographic positions of 100 LHLs were imported into ArcGIS 10.6 to create shapefiles. A procedure based on Inverse Distance Weighted (IDW) interpolation was used to estimate continuous raster temperature maps. For these maps, an algorithm was used that was able to estimate the value of each pixel based on measured or derived temperature values of the 12 nearest locations in the shapefile. The influence of measured or derived temperatures at individual locations on the temperature value of each pixel declined with distance to the pixel. Raster maps produced from IDW interpolations were clipped at the boundary of the LGA. Finally, to display air temperature variation it was necessary to optimise a graduated colour scheme for each map. Each shade of the gradual changes represents a fixed temperature value interval, which is specified in the caption of the map.

The following map types were produced:

1. ***Overview Maps*** – showing the mean temperature environment across the LGA of Penrith for time intervals, such as the entire summer season, daytime or nighttime conditions
2. ***Absolute-Temperature Maps*** – depicting absolute maximum and absolute minimum air temperatures measured at a single location
3. ***Heatwave Maps*** – providing a visualisation of near-surface air temperatures during the day and night of heatwaves.

4. PROJECT RESULTS

4.1 GENERAL PATTERNS

The summer of 2019/20 was unusual in several respects. Until the beginning of February 2020, the entire state of New South Wales endured 10 consecutive months below average rainfall. December 2019 was the state's second driest December on record. The low availability of moisture resulted in a very early beginning of the fire season. Catastrophic bush fires in the Blue Mountains burned for months, leaving the communities of Penrith City and beyond engulfed in smoke. The drought was broken by very heavy rainfalls between 7 and 10 February, where Penrith received 269 mm precipitation. Further, the otherwise typical build-up of extreme heat in Western Sydney was recorded only once. In the past decade, every summer had several repetitions of a temperature pattern, where maximum daily air temperature steadily climbs above 40°C, remains at these extreme levels for several days before the arrival of a cool change brings relief. Although the summer of 2019/20 was one of the warmest on record, the absence of 'typical heatwave patterns' was noticed by many.

The mean summer air temperature across the LGA between 14 December 2019 and 29 February 2020 was 23.9°C (±5.6; ±1 Standard Deviation). January was the hottest month with a mean temperature of 24.7°C (±5.6), followed by the second half of December (24.2°C ±6.5) and February (22.7°C ±4.7). Air temperatures in March 2020 were much cooler with an average of 19.8 °C (±4.4). The absolute lowest air temperature was 9.8°C measured on 13 March at 06:10 near the Agnes Banks Nature Reserve in the northwest of the LGA. The absolute highest air temperature was 52.0°C, recorded on 4 January at 13:40 along Llandilo Road in Berkshire Park in the central north of the LGA.

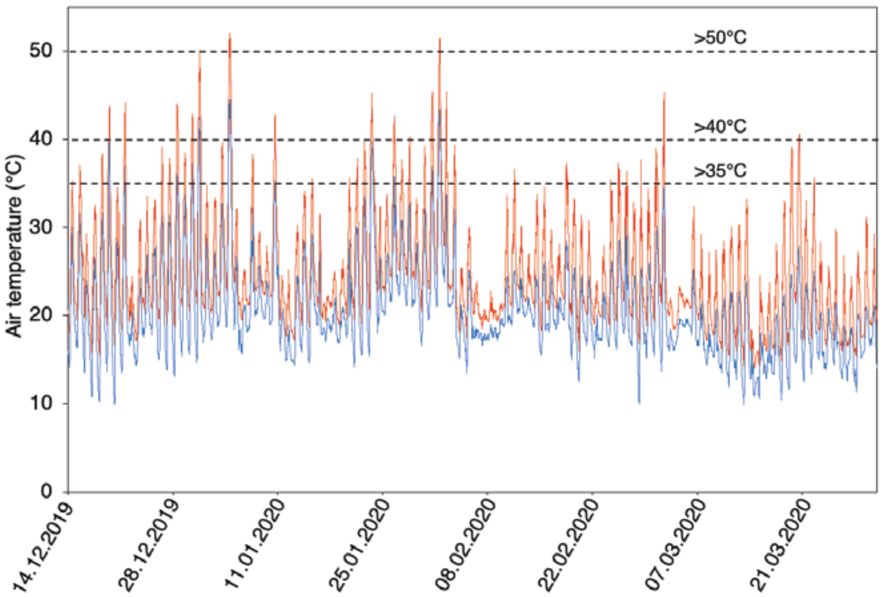


FIGURE 8: Absolute maximum (red line) and absolute minimum (blue line) near-surface air temperatures measured between 14 December 2019 and 30 March 2020 at 100 locations across the LGA of Penrith. Dashed lines indicate thresholds of 35°C, 40°C and 50°C. These thresholds are meant to help gauge the periods of high and extreme heat throughout the measurement period of 107 days. Air temperatures above 50°C were recorded on 31 December 2019, 4 January and 1 February 2020.

Of the 100 measurement locations used to record summer air temperatures for this project, 75 were located inside the LGA of Penrith. Among these locations mean summer air temperatures ranged from 24.7°C at Emu Plains to 22.7°C at a site in Mulgoa. The second warmest location was in Derby Street in Penrith's CBD where mean summer air temperatures were 24.6°C. Among the 20 warmest locations during summer 2019/20 were four locations at Penrith CBD, three locations at Castlereagh, two at Emu Plains, Emu Heights, Jordan Springs, Glenmore Park and Berkshire Park (Table 2). The range in mean summer air temperatures among the 30 warmest locations was just 0.7°C, indicating very similar heat loads across some suburbs of Penrith. Locations in the north and central north dominated the top 30 list of the warmest locations, which is in perfect agreement with long-term temperature modelling shown in Figure 1.

TABLE 2: Ranking of the 30 warmest locations according to their mean summer air temperature (T_{mean}, °C) calculated for the period between 14 December 2019 and 29 February 2020.

RANK	LOCATION	SUBURB	T_{mean}
1	Mackellar Street	Emu Plains	24.7
2	Derby Street	Penrith	24.6
3	Old Castlereagh Road	Castlereagh	24.6
4	William Howell Drive	Glenmore Park	24.6
5	Victoria Street	Werrington	24.5
6	Sydney Int. Regatta Centre	Castlereagh	24.4
7	Smith Road	Castlereagh	24.4
8	Brougham Street	Emu Plains	24.4
9	South Street	Glenmore Park	24.3
10	Wedmore Road	Emu Heights	24.3
11	Tench Reserve	Penrith	24.2
12	Watergum Drive	Jordan Springs	24.2
13	Llandilo Road	Berkshire Park	24.2
14	Penrith Lakes	Penrith	24.2
15	Coreen Avenue	Penrith	24.2
16	Solander Drive	St Clair	24.1
17	Bromley Road	Emu Heights	24.1
18	Warburton Crescent	Werrington County	24.1
19	Richmond Road	Berkshire Park	24.1
20	The Northern Road	Jordan Springs	24.1
21	Richmond Road	Cambridge Park	24.1
22	The Haven	Orchard Hills	24.1
23	Mallee Street	North St Marys	24.1
24	Wianamatta Parkway	Llandilo	24.0
25	Princess Street	Werrington	24.0
26	Barnes Road	Llandilo	24.0
27	Shepherd Street	Colyton	24.0
28	Darvill Road	Orchard Hills	24.0
29	Frogmore Road	Orchard Hills	24.0
30	Marrett Way	Cranebrook	24.0

The coolest locations were predominately in the southern section of the LGA. The lowest mean summer air temperature of 22.7 was recorded along Park River Close in Mulgoa (Table 3). This mean air temperature was 2°C lower compared to the warmest location at Emu Plains less than 20 km to the north. The exceptionally cool microclimate of the secluded area around Park River Close in Mulgoa is demonstrated by the difference between the site and the second coolest location at Fairlight Road, which is also located in Mulgoa, approximately 3 km to the north east. The difference in mean summer air temperature between the two sites was 0.6°C. A similar difference in mean summer air temperature was detected between the 2nd and 30th coolest sites. Sites throughout Mulgoa, but also Luddenham, Mt Vernon, Orchard Hills and Kemps Creek featured among the top 20 coolest sites.

TABLE 3: Ranking of the 30 coolest locations according to their mean summer air temperature (T_{mean}, °C) calculated for the period between 14 December 2019 and 29 February 2020.

RANK	LOCATION	SUBURB	T_{mean}
1	Park River Close	Mulgoa	22.7
2	Fairlight Road	Mulgoa	23.3
3	Littlefields Road	Mulgoa	23.3
4	Medinah Avenue	Luddenham	23.4
5	Mulgoa Road	Mulgoa	23.4
6	Mulgoa Road	Mulgoa	23.4
7	Mayfair Road	Mulgoa	23.5
8	Kerrs Road	Mt Vernon	23.5
9	Defence Establishment	Orchard Hills	23.6
10	Andrews Road	Penrith	23.6
11	Adams Road	Luddenham	23.6
12	River Road	Leonay	23.6
13	Galaxy Road	Luddenham	23.6
14	Peppermint Crescent	Kingswood	23.6
15	Willowdene Avenue	Luddenham	23.6
16	Thornbill Crescent	Glenmore Park	23.7
17	Elizabeth Drive	Kemps Creek	23.7
18	O'Connell Street	Claremont Meadows	23.7
19	Gates Road	Luddenham	23.7
20	Putland Street	St Marys	23.7
21	Timesweep Drive	St Clair	23.7
22	Luddenham Road	Orchard Hills	23.8
23	Nutt Road	Londonderry	23.8
24	The Northern Road	Cranebrook	23.8
25	Mulgoa Road	Mulgoa	23.8
26	Lakeside Parade	Jordan Springs	23.8
27	Fourth Avenue	Llandilo	23.8
28	Glengarry Drive	Glenmore Park	23.8
29	Links Road	St Marys	23.8
30	Warbler Street	Erskine Park	23.9

Using mean summer air temperatures allowed a ranking of suburbs that were included in the present study. This ranking is shown in Table 4 and confirms the observations for the warmest and coolest locations. Emu Plains and nearby Emu Heights ranked among the warmest suburbs, together with Castlereagh, Werrington and Penrith. The mean summer air temperature for each of these suburbs is based on more than one measurement point, which reassures their status as generally warmer places.

Many suburbs in the 'mid-range' of the ranking had very similar mean summer air temperatures. With a difference of just 0.2°C among them are 17 suburbs, from Emu Heights at 24.1°C mean summer air temperature to Londonderry with 23.9°C mean summer air temperature. Similar to the ranking of individual locations, it confirms that warm summer air temperatures are widespread across the region in Western Sydney. The three coolest suburbs were Mulgoa, Mt Vernon and Luddenham. These suburbs were all in the south of the LGA and had mean summer air temperatures of 23.4°C, 23.5°C and 23.6°C, respectively.

TABLE 4: Mean summer air temperature (T_{mean}, °C) for the suburbs in the LGA of Penrith. Suburbs are listed from highest to lowest T_{mean}. Means were calculated for the period between 14 December 2019 and 29 February 2020 using data from 75 locations. The number of Local Heat Loggers (LHL) located in each suburb is shown.

SUBURB	LHL	T_{mean}
Emu Plains	2	24.6
Castlereagh	4	24.4
Werrington	2	24.3
Penrith	5	24.2
Emu Heights	3	24.1
Cambridge Park	1	24.1
Glenmore Park	4	24.1
North St Marys	1	24.1
Werrington County	1	24.1
Berkshire Park	3	24.1
Jordan Springs	3	24.0
Agnes Banks	1	24.0
Badgerys Creek	1	24.0
South Penrith	1	24.0
Colyton	2	24.0
Llandilo	3	23.9
Orchard Hills	7	23.9
Cranebrook	2	23.9
Erskine Park	1	23.9
Jamisontown	1	23.9
St Clair	2	23.9
Londonderry	3	23.9
St Marys	3	23.8
Kemps Creek	2	23.8
Claremont Meadows	1	23.7
Kingswood	1	23.6
Leonay	1	23.6
Luddenham	5	23.6
Mt Vernon	1	23.5
Mulgoa	8	23.4

The analyses of mean summer air temperatures at individual locations and whole suburbs indicates that differences in local microclimates do exist, even though their absolute range was relatively small. These differences are important to understand as they provide information about the general heterogeneity of microclimate in Western Sydney. Among the 100 locations across the LGA of Penrith, summer air temperatures varied on average 4.3°C (summer mean: 23.9°C). Variation of air temperatures ≥10°C occurred on 25 days. Most of these large variations were recorded during the early and late afternoon of days where extremely hot air was replaced by cooler air masses. This is a typical weather pattern in Western Sydney where the arrival of a cold front from the south (known as a 'Southerly Buster') signifies the end of extreme heat. While these extreme temperature changes were complete in 2-3 hours (i.e., fast moving cold air replaced hot air quickly) during hot days in December, January and February, they lasted 6-7 hours towards the end of March. These observations were similar in magnitude and duration for the studies documenting air temperatures in three other LGAs in the summer of 2018/19 (Pfautsch and Rouillard 2019a-c) and capture broader weather and climate patterns of Western Sydney.

4.2 DAYTIME AND NIGHTTIME AIR TEMPERATURES

In the summer 2019/20 mean daytime air temperature was 28.5°C and nighttime air temperature was 20.5°C across the LGA of Penrith. Daytime and nighttime temperature was calculated as mean of the 8-hour period between 10:00 and 18:00 (day) and 21:00 and 5:00 (night). In January, mean daytime air temperature was 29.1°C (±6.1) and in February it was 26.4°C (±5.2). Mean daytime air temperature in December 2019, recorded between 14 and 31 December, was 30.9°C (±5.8), which was strongly influenced by the hot weather in the last two weeks of that month. Mean nighttime temperatures were 21.6°C (±3.0) and 20.2°C (±2.5) in January and February, respectively.

At individual locations, daytime temperatures during the entire summer 2019/20, ranged from 29.5°C (±6.4) at a location in Agnes Banks to 27.4°C (±6.0) at a location in Mulgoa. Locations with mean daytime temperatures warmer than 29°C were found in Castlereagh, Penrith, Berkshire Park, Badgerys Creek, Orchard Hills, Glenmore Park and Emu Plains. Locations where mean daytime air temperatures were below 28°C were located in Claremont Meadows, Kingswood, St Clair, Emu Heights, Leonay and Mulgoa.

When calculated per suburb, Agnes Banks had the warmest daytime temperatures (Figure 9). The second warmest suburb was Badgerys Creek with a mean daytime temperature of 29.2°C (±6.2). Air temperatures in both suburbs were recorded at one measurement location only. However, the next five warmest suburbs were all covered with multiple measurement locations and their daytime mean temperatures varied by only 0.4°C and had very similar standard deviations (Castlereagh: 29.1°C (±6.1), Berkshire Park: 29.1°C (±6.2), Emu Plains: 28.9°C (±5.9), Glenmore Park and Orchard Hills: 28.7°C (±6.0)).

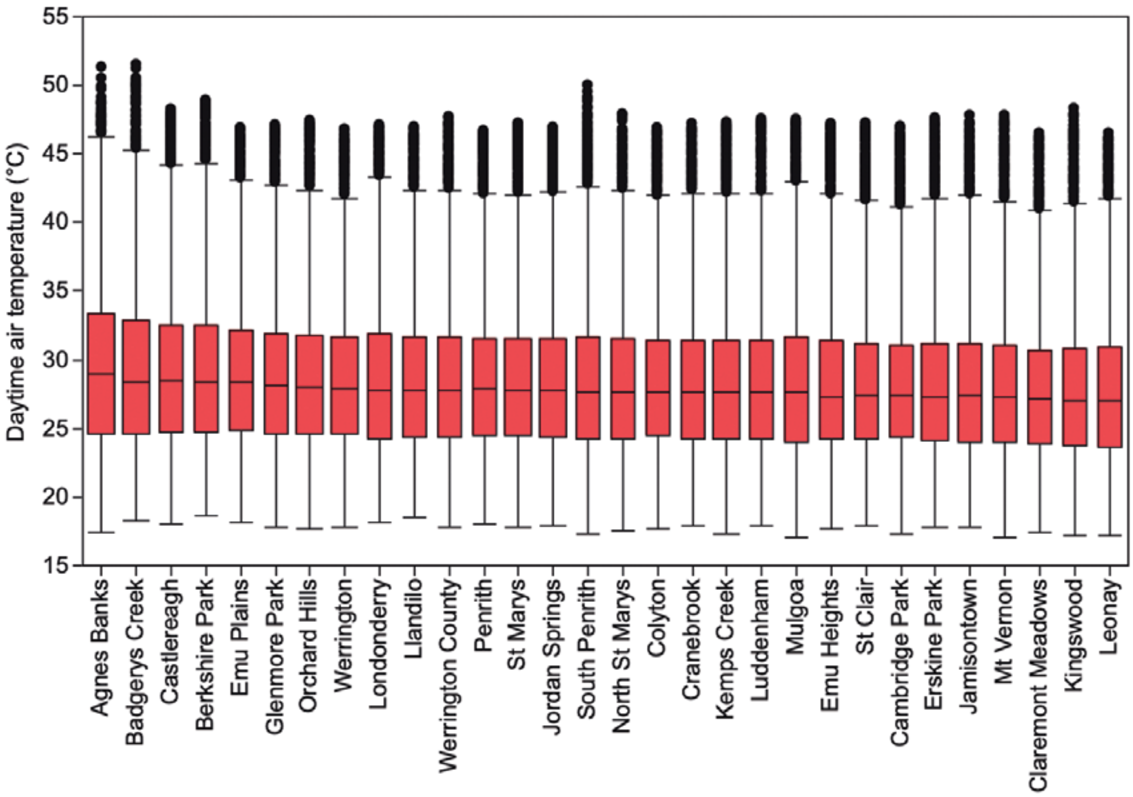


FIGURE 9: Variation of daytime (10:00-18:00) air temperatures across all suburbs of Penrith included in this study. Daytime air temperatures are calculated for the time between 14 December 2019 and 29 February 2020. Suburbs are listed from the warmest mean daytime to the coolest mean daytime temperature. The upper and lower end of the box shows the 75th and 25th percentiles, the line inside the box shows the median and the whiskers indicate minimum and maximum values; dots show outliers.

Nighttime temperatures across suburbs have a different distribution compared to daytime temperatures. Suburbs with high daytime temperatures had large areas of open space and green infrastructure. Yet, these were the suburbs with the lowest absolute and mean nighttime temperatures (Figure 10). Namely Agnes Banks, Badgerys Creek, Berkshire Park and Orchard Hills where suburbs with the largest difference between mean and maximum daytime temperatures compared to their mean and minimum nighttime temperatures. This amplitude between mean daytime and mean nighttime temperature was 9.6°C in Agnes Banks, 8.9°C in Badgerys Creek and 8.8°C in Orchard Hills, all suburbs with large proportions of open space. The overall largest range between the absolute maximum and absolute minimum air temperature was 40.9°C in Berkshire Park.

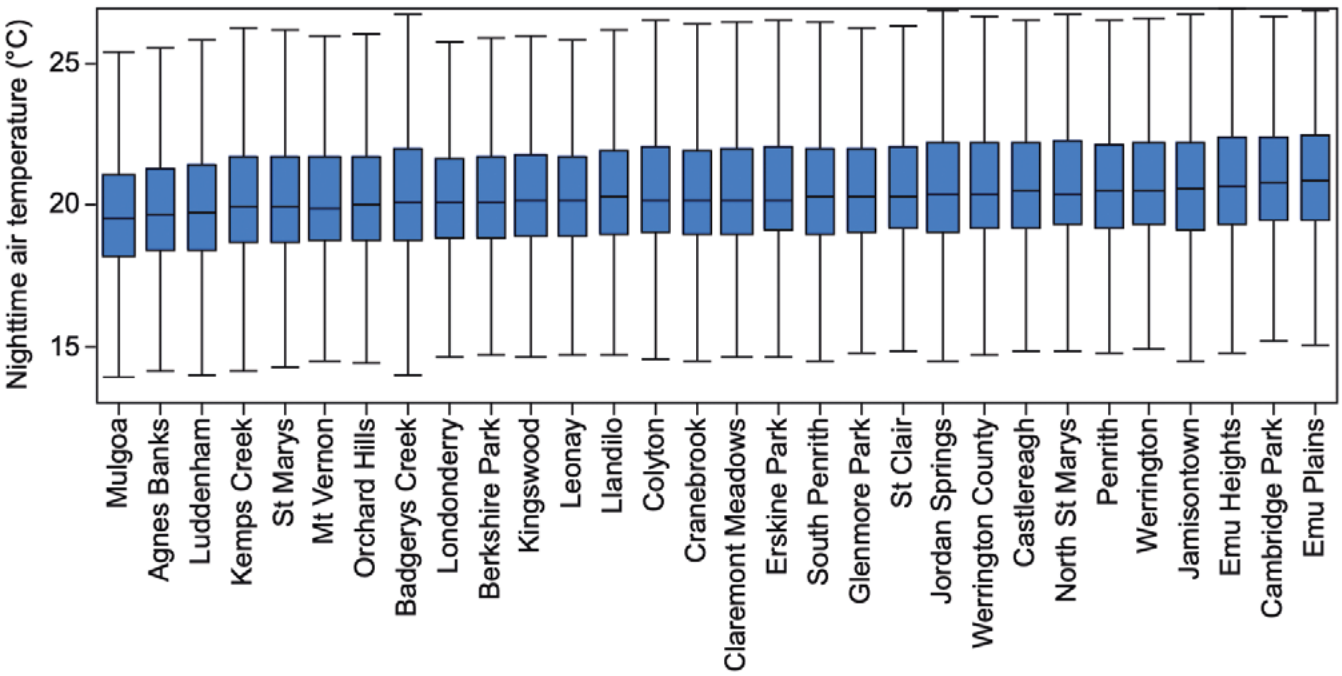


FIGURE 10: Variation of nighttime (21:00-5:00) air temperatures across all suburbs of Penrith included in this study. Data is shown for the time between 14 December 2019 and 29 February 2020. Suburbs are listed from the coolest mean to the warmest mean nighttime temperature. The upper and lower end of the box shows the 75th and 25th percentiles, the line inside the box shows the median and the whiskers indicate minimum and maximum values.

It is a common observation in Western Sydney that maximum air temperatures during the day are recorded in landscapes where natural elements dominate. The low thermal mass within these landscapes combined with 'environmental priming' for heat events (loss of soil moisture for cooling and high clay content that holds heat) accelerates heating of air temperatures during the morning hours. Air temperatures in landscapes with higher thermal mass, like those where buildings and roads dominate, require longer to heat up during the morning. The reverse is observed during the evening and early night where air temperatures in landscapes with low thermal mass cool down quickly, while air temperatures in landscapes with higher thermal mass cool down slower or even remain warmer. This phenomenon is a typical effect of the UHI. The consequence of generally higher maximum air temperatures (day) in combination with lower minimum temperatures (night) is captured well in the data set of this project, especially for times during very hot daytime air temperatures at the end of December 2019 and early January 2020 (Figure 11).

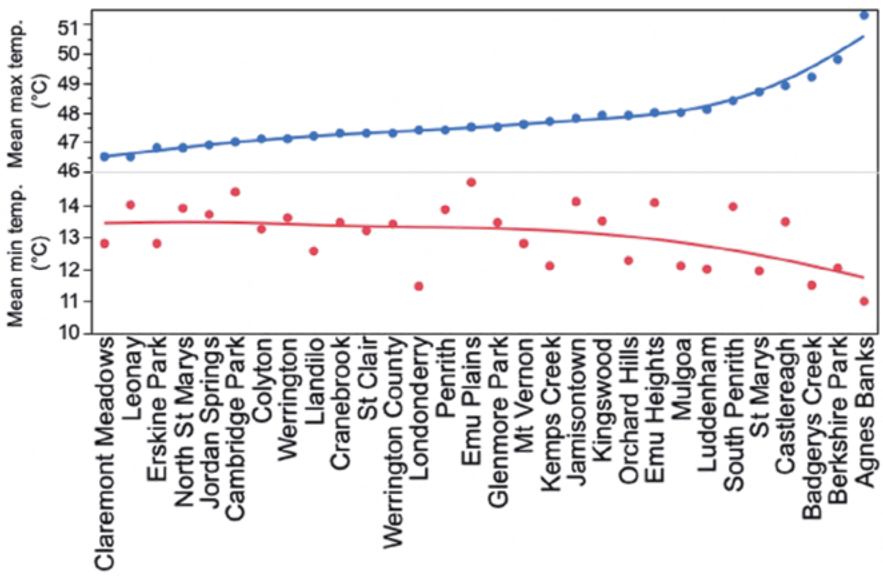


FIGURE 11: Mean maximum (top) and mean minimum (bottom) air temperatures between 17 December 2019 and 10 January 2020. This time interval represents the hottest period during the summer 2019/20. Data were calculated for each suburb of the Penrith LGA that was included in this project. Lines represent smoothed trends, indicating a 'scissor-effect', where those suburbs with the highest maximum air temperatures tend to also have the coolest nighttime air temperatures.

A similar trend can be observed when assessing the absolute minimum and maximum air temperatures recorded between 3:00 and 5:00 in the morning (Figure 12). At this time, just before dawn, near-surface air temperature is usually at its coolest point. Figure 11 clearly shows that, when ranked from the warmest to the coolest suburb, suburbs with high cover of buildings and roads (i.e., grey infrastructure) tend to display higher nighttime air temperatures compared to suburbs where the cover of grey infrastructure is lower. This trend holds for both, the highest and lowest nighttime air temperatures measured in the early morning hours of each of the 77 days between 14 December 2019 and 29 February 2020, providing additional evidence that this is not a random occurrence, but a systematic effect of grey infrastructure.

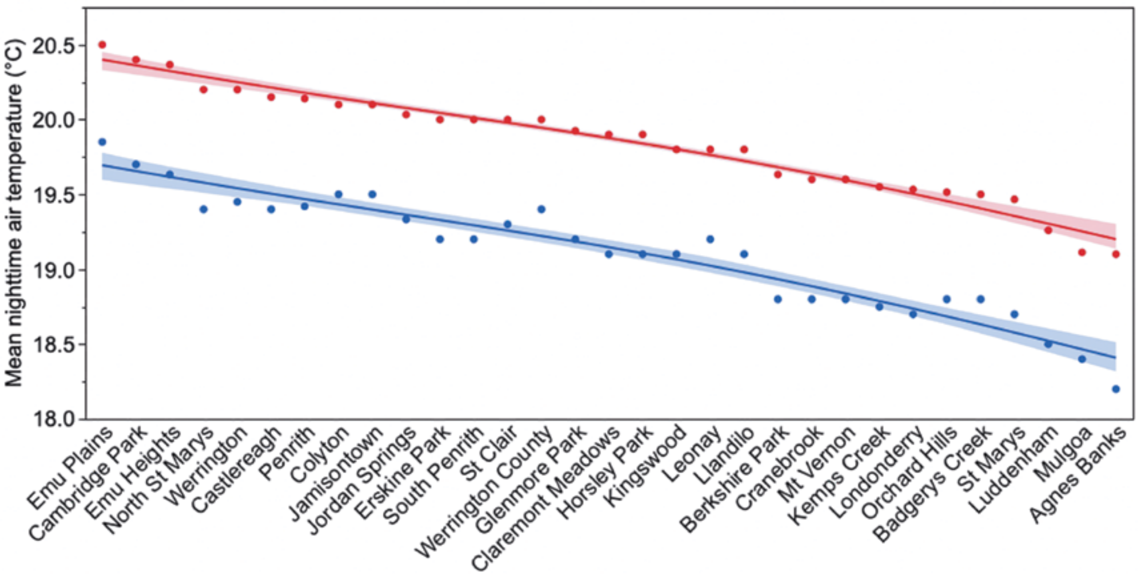


FIGURE 12: Mean maximum and minimum nighttime air temperatures across the suburbs of Penrith. Data were calculated based on measurements between 3:00 and 5:00 in the morning of each day between 14 December 2019 and 29 February 2020. Lines show curve-linear fits and coloured bands show 95% confidence intervals.

Lastly, an example of the effect of predominant land surface cover on air temperatures is presented. To demonstrate this effect the mean daytime and nighttime temperatures were calculated for the period between 17 December 2019 and 10 January 2020. During this time, heat loads were generally high and several days with extreme heat were recorded. Air temperatures for the following sites were compared:

1. Agnes Banks Nature Reserve – 15 km north of Penrith Station
2. Tench Reserve – 2.5 km west of Penrith Station
3. Union Road – 1 km south of Penrith Station
4. Collins Street Park – 8 km east of Penrith Station

The area at Agnes Banks Nature Reserve was dominated by a unique woodland patch on sand deposits with an open canopy structure. The Tench Reserve is a 2 km long park on the eastern banks of the Nepean River, where grass-covered lawns are shaded by mature tree canopies and riparian forest. The location at Union Road in the urban core of Penrith was covered by a large, flat, asphalt-covered carpark with a few trees around its perimeter. At Collins Street in St Marys a small park contained a group of trees and a lawn area, surrounded by residential neighbourhoods and a few roads.

During the hot period at the turn of the year, the highest mean maximum daytime temperatures were measured at Agnes Banks (34.0°C) (Figure 13). Mean maximum daytime air temperatures were very similar at the neighbourhood park in St Marys (33.3°C) and the carpark in the CBD of Penrith (33.2°C). By far the coolest place during the day was near the Nepean River where mean maximum air temperatures were only 32.1°C. During the night, mean air temperatures were the warmest in the CBD of Penrith, followed by the Tench Reserve, Collins Street park and Agnes Banks (Figure 13).

The near opposite ranking of mean maximum daytime and mean nighttime temperatures demonstrates the effect of dominant land surface cover on local microclimate. While the large water body of the Nepean River was likely cooling the air around the riverbanks, it also kept air warmer during the night. The high nighttime temperatures at the CBD of Penrith are entirely attributable to the local UHI effect. This effect was much less pronounced in the residential neighbourhoods of St Marys where air temperatures cooled down more during the night. The largest amplitude of temperature variation was consistently observed in the landscapes where the presence of buildings, roads and other grey infrastructure was low.

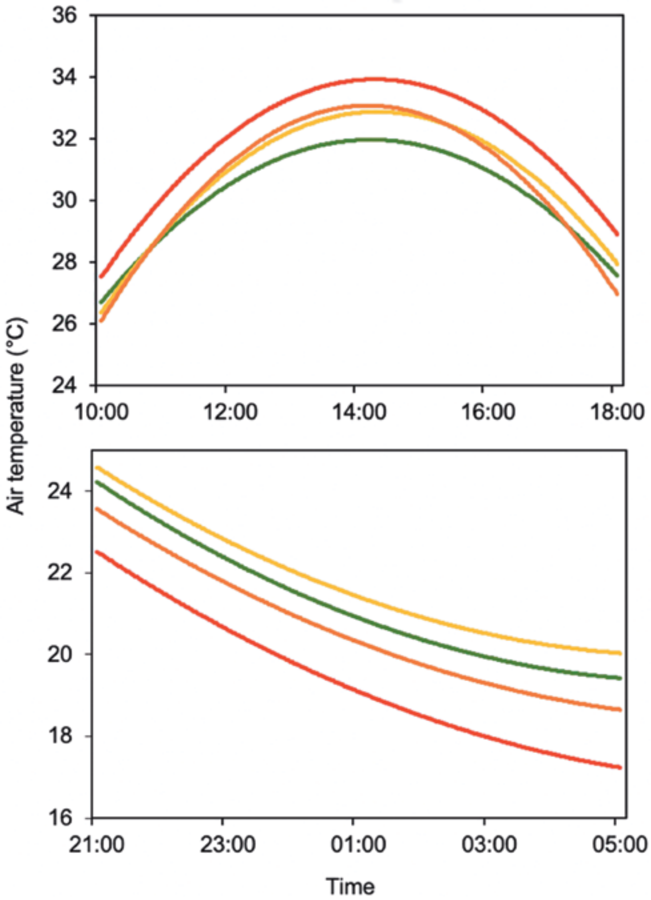


FIGURE 13: Mean daytime and nighttime air temperatures at four locations that differed in their dominant surface cover. Red line: Agnes Banks Nature Reserve; green line: Tench Reserve, Penrith; yellow line: Union Road, Penrith CBD; orange line: Collins Street Park, St Marys. Data was averaged for the period between 17 December 2019 and 10 January 2020. Lines show idealised temperature trends with an R^2 of 0.99 or 1 for all trend predictions.

4.3 HEAT ASSESSMENT

Penrith is located in the hottest part of Western Sydney. Hence, documenting local patterns of high and extreme summer heat was an central aspect of the present research. Most importantly, this research captured data showing that local communities are experiencing previously unknown levels of extreme heat. The absolute highest recorded air temperature was 52.0°C. It is the highest near-surface air temperature ever measured in the Sydney Basin.

Assessments of heat across the Sydney Basin use the increasing number of days where maximum air temperatures are at or above 35°C and at or above 40°C to demonstrate that Western Sydney is heating up faster than Eastern Sydney (e.g., Greater Sydney Commission 2019). These assessments are usually based on data available for relevant weather stations. During the 107 days of field measurements from 14 December 2019 to 30 March 2020, the weather station at Observatory Hill in Sydney's east recorded 6 days at or above 35°C and 31 days at or above 40°C. During the same time, the weather station at the International Regatta Centre in Sydney's west recorded 24 days at or above 35°C and 11 days at or above 40°C, confirming the general trend of warmer summers in Western Sydney.

Although these measurements confirm that the local summer climate around Penrith is hotter, they may still underrepresent the level of heat that residents around Penrith experience. Reasons for this issue were explained at the beginning of this report. Indeed, data collected using the network of LHLs across the entire LGA of Penrith indicate a greater number of hot or extreme days across the 100 network locations than those recorded by the local weather station (Table 5). The total number of days where air temperatures were hot or extreme across the LGA of Penrith during the entire summer of 2019/20 is likely greater than Table 5 suggests. Reason is that the LHLs did not record data for the first two weeks of December where the local weather station already recorded an additional 3 days above 35°C and 1 day above 40°C.

TABLE 5: Number of days with hot or extreme air temperatures across the LGA of Penrith during 14 December 2019 to 30 March 2020.

	TOTAL	DECEMBER	JANUARY	FEBRUARY	MARCH
≥35°C	39	11	14	9	5
≥40°C	15	5	6	2	2
≥45°C	7	1	3	2	1
≥50°C	3	1	1	1	0

As depicted in Figure 8, extreme air temperatures (defined by the Bureau of Meteorology as being equal to or above 40°C) occurred during nine intervals. Extreme air temperatures were reached first on 19 December 2019 and last on 20 March 2020. During this time and across the 100 measurement locations air temperatures of 35°C and above were measured during a minimum of 9 and the maximum of 34 days at individual sites. Similar variation among the individual sites was detected for the number of days where maximum air temperatures were equal of greater 40°C (4-14 days), 45°C (1-5 days) and 50°C (1-3 days). When summarised by suburbs, those with the highest number of days at or above 35°C were Berkshire Park, Badgerys Creek and Agnes Banks and while those with the lowest number of days above 35°C were Kingswood, Erskine Park and Leonay (Figure 14A). A similar, albeit lower in total numbers, was observed for days at or above 40°C (Figure 14B).

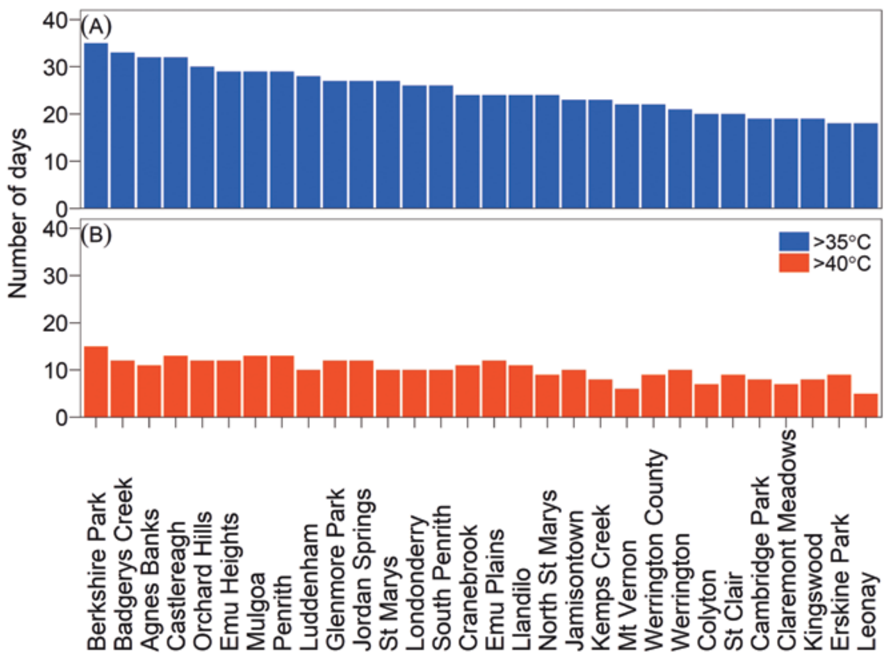


FIGURE 14: Ranking of suburbs across the LGA of Penrith according to the number of days where maximum air temperatures were at or above 35°C (A). Panel B depicts the number of days for these suburbs where air temperatures were at or above 40°C.

The two days that stand out during the summer of 2019/20 are 4 January and 1 February 2020 where air temperatures at half a dozen locations soared above 50.0°C. In the following, a chronology of 4 January 2019 is provided to illustrate the duration and magnitude of this new type of super-heated conditions in Western Sydney.

At 13:30 on 31 December 2019 a maximum air temperature 0f 50.1°C was measured for the first time in the LGA and only at a single location along Llandilo Road in Berkshire Park. During the following three days, maximum air temperatures across the LGA did not exceed 40°C. This changed on 4 January 2020.

- 04:50 – average air temperature across 100 measurement locations was 20.6°C
- 10:10 – air temperature at Windsor Downs and Berkshire Park exceeded 40°C
- 10:50 – average air temperature across the LGA was 40.9°C
- 11:10 – all 100 locations record air temperatures exceeding 40.0°C
- 11:10 – air temperature at Berkshire Park was greater than 45.0°C
- 12:40 – 50.1°C was reached at Berkshire Park
- 13:40 – 52.0°C measured in Berkshire Park
- 13:40 to 16:30 - above 49.0°C at 10 locations, above 50.0° at 6 locations
- 18:10 – for the first time the lowest air temperature across the LGA was below 40.0°C
- 19:50 – the last of 100 locations measured more than 40.0°C
- 23:50 – maximum and minimum air temperatures were 27.4°C and 24.0°C

The highest temperature of 52.0°C at Berkshire Park was measured 3 times, and the second highest temperature of 51.5°C was measured twice at Badgerys Creek and once at Agnes Banks (for additional information see Figure S2 at the end of this report). Temperatures above 50.0°C were also measured 5 times at Luddenham and 4 times at Castlereagh. The fact that such extreme air temperatures were measured during different days at several locations and at these locations during more than one timepoint provides high confidence that these measurements of super-heated air temperatures are not an artefact but a true representation of previously undocumented levels of extreme heat in Western Sydney.

At individual locations air temperatures climbed from under 45.0°C to more than 49.0°C within just 30 minutes in the early afternoon of 4 January. While air temperatures varied between 44.0° and 46.5°C throughout the afternoon at many measurement locations, some locations experienced extended periods of extreme heat. The following seven locations stand out with the longest consecutive time where air temperatures remained above 47°C (maximum air temperature is also provided in parentheses):

1. Mulgoa Road, Mulgoa: 330 consecutive minutes (49.7°C)
2. Darville Road, Orchard Hills: 280 consecutive minutes (49.5°C)
3. Llandilo Road, Berkshire Park: 230 consecutive minutes (52.0°C)
4. Solander Drive, St Clair: 230 consecutive minutes (48.2°C)
5. Smith Road, Castlereagh: 210 consecutive minutes (50.8°C)
6. The Northern Road, Berkshire Park: 200 consecutive minutes (49.3°C)
7. Martin Road, Badgerys Creek: 170 consecutive minutes (50.1°C)

A consistent trend was identified for mean summer air temperatures across the LGA, where the northern section appeared warmer and the southern section appeared cooler (Tables 2 and 3, but also see Figure 1). No such trend could be identified when ranking locations according to maximum air temperature (Table 6). While maximum air temperatures during late December 2019 and early 2020 were greater than 48.0°C at the warmest 30 sites, their locations spread across the LGA, from Mulgoa, Badgerys Creek and Orchard Hills in the south, to Penrith, St Marys and Emu Plains in the centre and Agnes Banks and Berkshire Park in the north.

TABLE 6: Ranking of the 30 hottest locations according to the absolute maximum air temperature (T_{max}, °C) measured between 17 December 2019 and 10 January 2020.

RANK	LOCATION	SUBURB	T_{max}
1	Llandilo Road	Berkshire Park	52.0
2	Collins Street	St Marys	51.5
3	Agnes Banks Nature Reserve	Agnes Banks	51.3
4	Smith Road	Castlereagh	50.8
5	Martin Road	Badgerys Creek	50.1
6	Hillview Avenue	South Penrith	50.0
7	Mulgoa Road	Mulgoa	49.7
8	Wedmore Road	Emu Heights	49.6
9	Darvill Road	Orchard Hills	49.5
10	The Northern Road	Berkshire Park	49.3
11	Links Road	St Marys	48.8
12	Old Castlereagh Road	Castlereagh	48.8
13	Brown Street	Penrith	48.8
14	Willowdene Avenue	Luddenham	48.6
15	Gates Road	Luddenham	48.6
16	The Northern Road	Mulgoa	48.6
17	Mulgoa Road	Mulgoa	48.4
18	Sydney Int. Regatta Centre	Castlereagh	48.4
19	Penrith Lakes	Penrith	48.4
20	South Street	Glenmore Park	48.3
21	Brougham Street	Emu Plains	48.3
22	Derby Street	Penrith	48.3
23	Solander Drive	St Clair	48.2
24	The Haven	Orchard Hills	48.2
25	Frogmore Road	Orchard Hills	48.2
26	Richmond Road	Berkshire Park	48.2
27	Mulgoa Road	Mulgoa	48.2
28	Elizabeth Drive	Badgerys Creek	48.2
29	Littlefields Road (Gow Park)	Mulgoa	48.2
30	Barnes Road	Llandilo	48.1

The observation that no consistent geographical pattern can be identified for peak heatwave conditions is also reflected in the ranking of all suburbs included in the current study (Table 7). The top 3 hottest suburbs in late December 2019 and early January 2020 were Agnes Banks and Berkshire Park in the northern section of the LGA and Badgerys Creek in the south. Most suburbs that had high mean summer air temperatures (e.g., Penrith, Emu Plains, Werrington) were not the places where also peak maximum air temperatures were recorded. Seven of the top 10 suburbs with the highest maximum air temperatures were suburbs where open space, woodlands and pastures dominated the landscape.

TABLE 7: Maximum air temperatures (T_{max}, °C) in the suburbs of Penrith City. Suburbs are listed from highest to lowest T_{max}. Measurements were calculated for the period between 17 December 2019 and 10 January 2020 using data from 81 locations. The number of Local Heat Loggers (LHL) located in each suburb is shown. Built-up areas like St Marys experienced equally hot air temperatures compared to more rural suburbs like Castlereagh.

SUBURB	LHL	T_{max}
Agnes Banks	1	51.3
Berkshire Park	3	49.8
Badgerys Creek	2	49.2
Castlereagh	4	48.9
St Marys	4	48.7
South Penrith	2	48.4
Luddenham	5	48.1
Mulgoa	9	48.0
Emu Heights	3	48.0
Orchard Hills	7	47.9
Kingswood	1	47.9
Jamisontown	1	47.8
Kemps Creek	2	47.7
Mt Vernon	1	47.6
Emu Plains	2	47.5
Glenmore Park	4	47.5
Penrith	7	47.4
Londonderry	3	47.4
Werrington County	1	47.3
Cranebrook	2	47.3
St Clair	2	47.3
Llandilo	3	47.2
Colyton	2	47.1
Werrington	2	47.1
Cambridge Park	1	47.0
Jordan Springs	3	46.9
Erskine Park	1	46.8
North St Marys	1	46.8
Claremont Meadows	1	46.5
Leonay	1	46.5

As explained previously, maximum daytime temperatures were recorded in landscapes with lower thermal mass. However, maximum nighttime temperatures, especially during heatwaves were recorded predominately in landscapes with higher thermal mass. When focussing on those very warm nights, where air temperatures were greater than 30°C at least at one single measurement location, it becomes clear that residential and industrial sites remained much warmer compared to rural and wooded sites. During these very hot nights, nine of the ten hottest locations were in densely populated areas of Emu Plains, Glenmore Park, Penrith and others (Figure 15). In contrast, nine of the ten locations with the lowest mean air temperatures during these nights were in Mulgoa and Luddenham where the landscape is open with low cover of roads and houses.

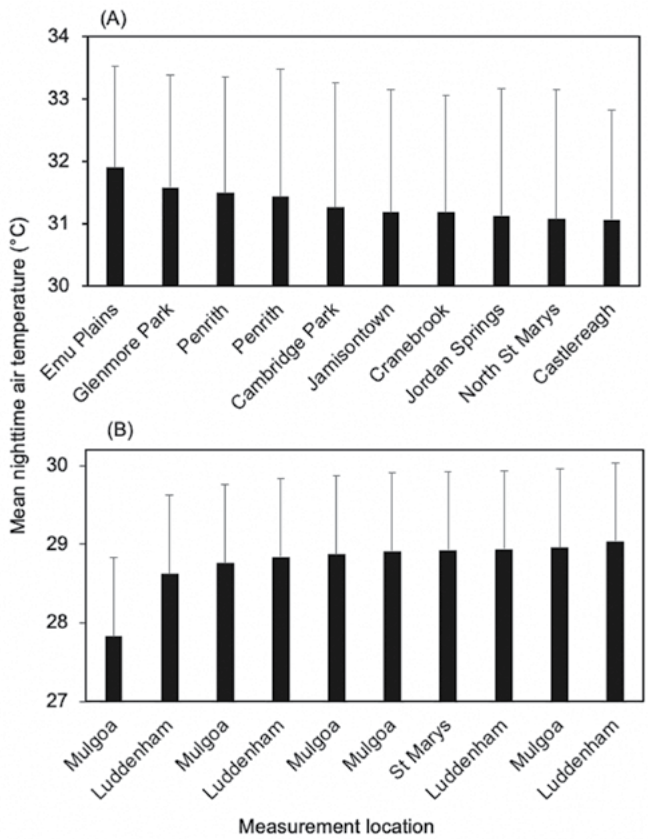


FIGURE 15: Mean nighttime air temperatures for the 10 hottest (A) and 10 coolest (B) measurement locations during heatwave nights. Heatwave nights were defined as those where air temperature between 21:00 and 5:00 was greater than 30°C at least at a single measurement location throughout the Penrith LGA. These conditions applied to the nights of 4, 10, 23, 24 and 31 January as well as 1 and 2 February 2020. Note the different scale on the y-axis in panel A and B.

4.4 MICROCLIMATE MAPS

Novel, evidence-based temperature maps were created to visualise a range of conditions and phenomena related to near-surface air temperatures across the LGA of Penrith. These maps reveal:

- Higher mean summer air temperatures in the central region of the LGA, especially around the commercial centre of Penrith (Figure 16)
- Very high daytime and very low nighttime air temperatures in the northern section of the LGA (Figures 17 and 18)
- A clear UHI effect for the commercial centre of Penrith, but also for Emu Plains, South Penrith and Glenmore Park, as well as St Marys (Figure 18 and 20)
- Absence of extreme heat (>50°C) from the central, densely populated central region of the LGA (Figure 19)
- Very large temperature fluctuations between maximum and minimum air temperatures in the south and north of the LGA (Figure 19 and 20)
- Cool zones along Mulgoa Creek and South Creek (Figure 20)
- Large temperature variations (more than 7°C) can exist during periods of extreme heat (Figure 21 and 22)
- The suburbs of Penrith, Emu Plains, Jamisontown, South Penrith and St Marys experience the warmest nighttime temperatures during heatwaves (Figure 23)

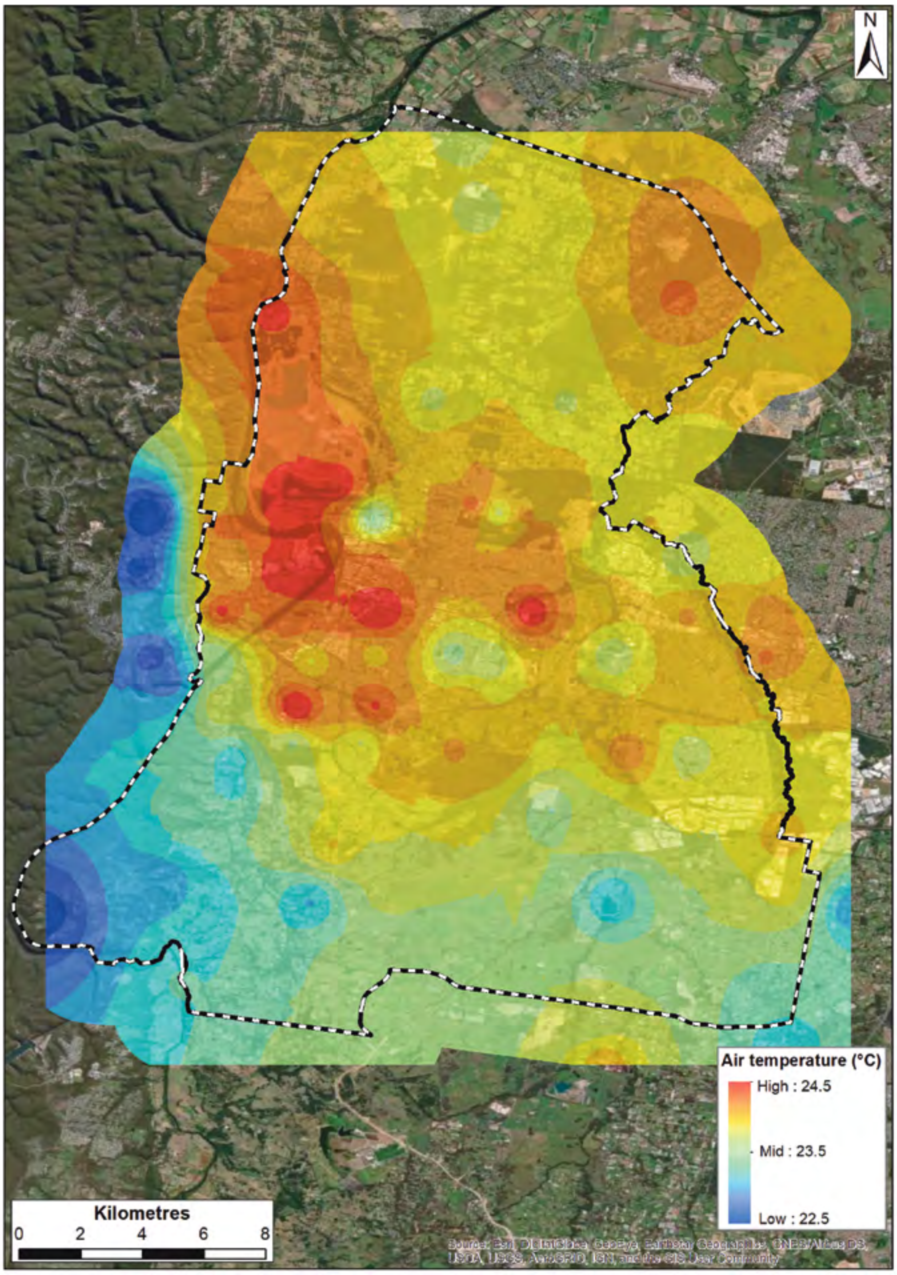


FIGURE 16: Mean summer air temperature in the summer of 2019/20 across the LGA of Penrith. Data were collected at 94 measurement locations and averaged for the period from 14 December 2019 to 29 February 2020. The boundary of the LGA is shown as dashed line.

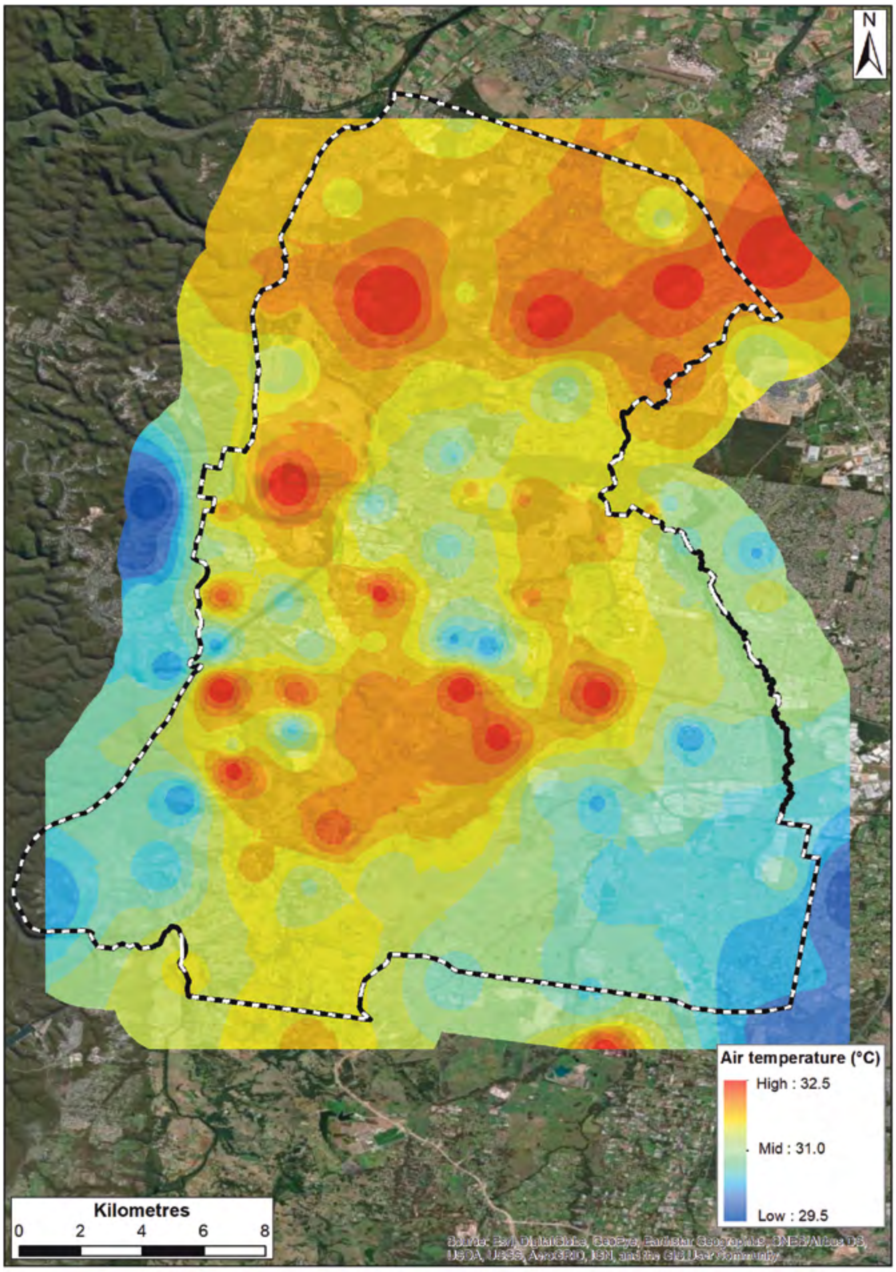
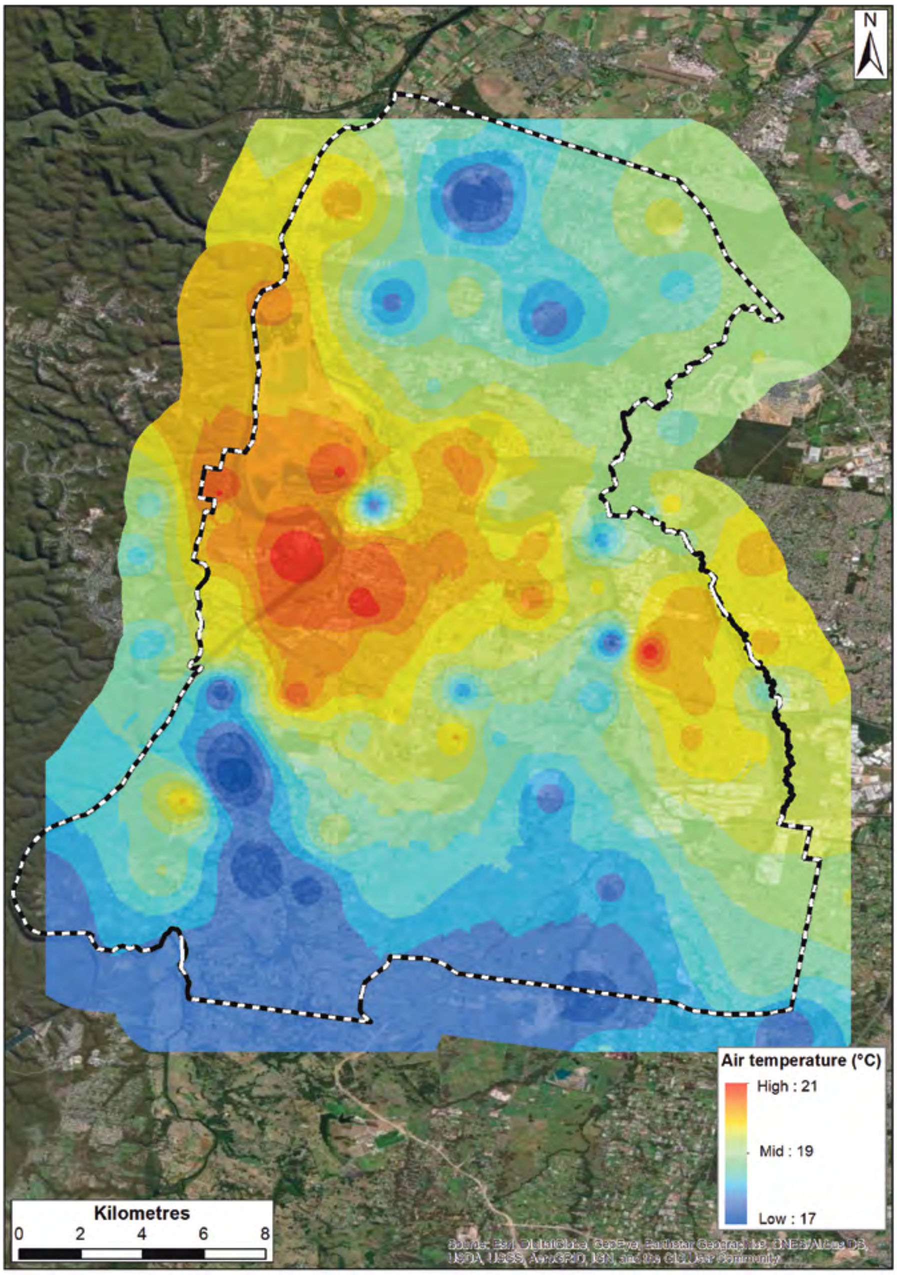


FIGURE 17: Mean daytime (10:00 to 18:00) air temperatures across the LGA of Penrith during a warm fortnight at the end of 2019 (17 to 31 December 2019). Data from 100 measurement locations were used. The boundary of the LGA is shown as dashed line.

FIGURE 18: Mean nighttime (21:00 to 5:00) air temperatures across the LGA of Penrith during a warm fortnight at the end of 2019 (17 to 31 December 2019). Data from 100 measurement locations were used. The boundary of the LGA is shown as dashed line.



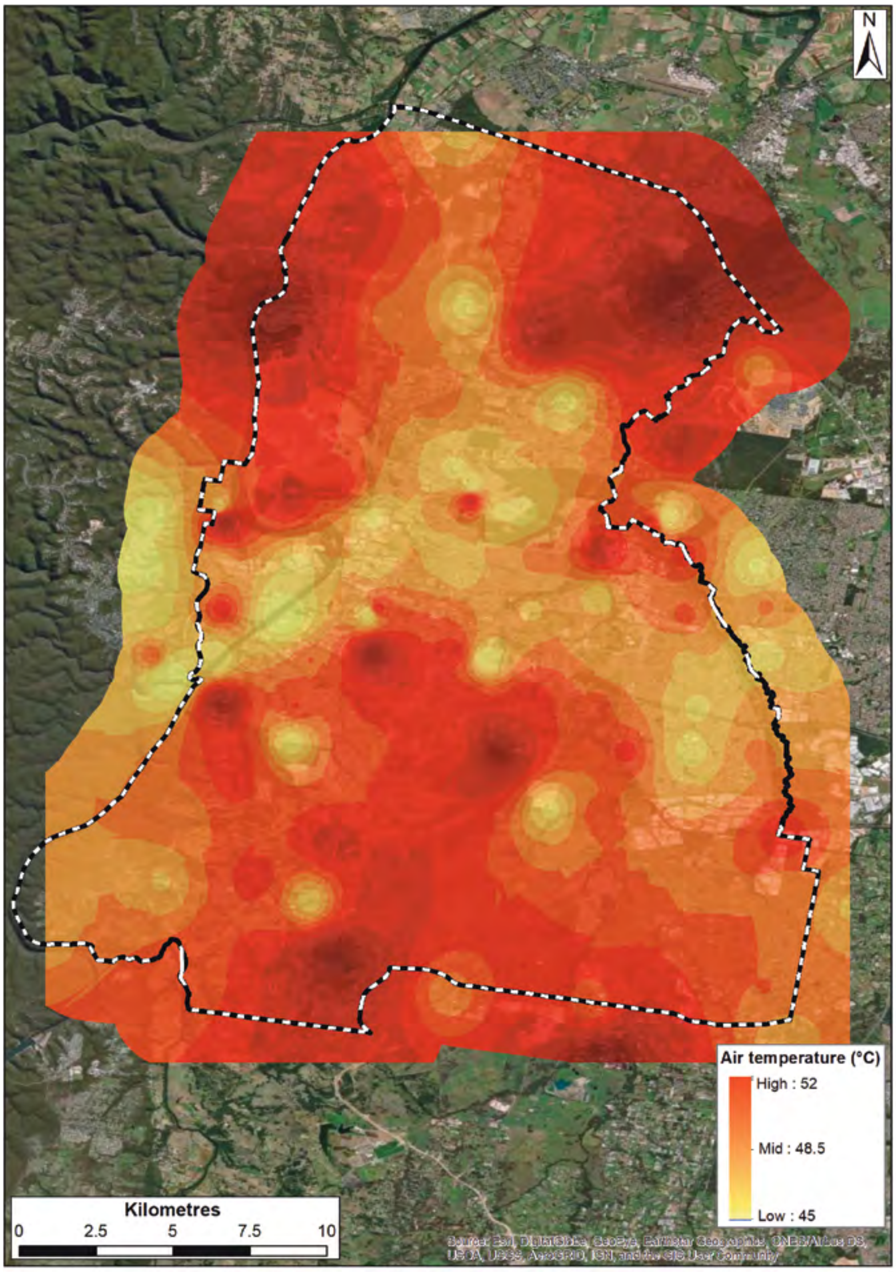
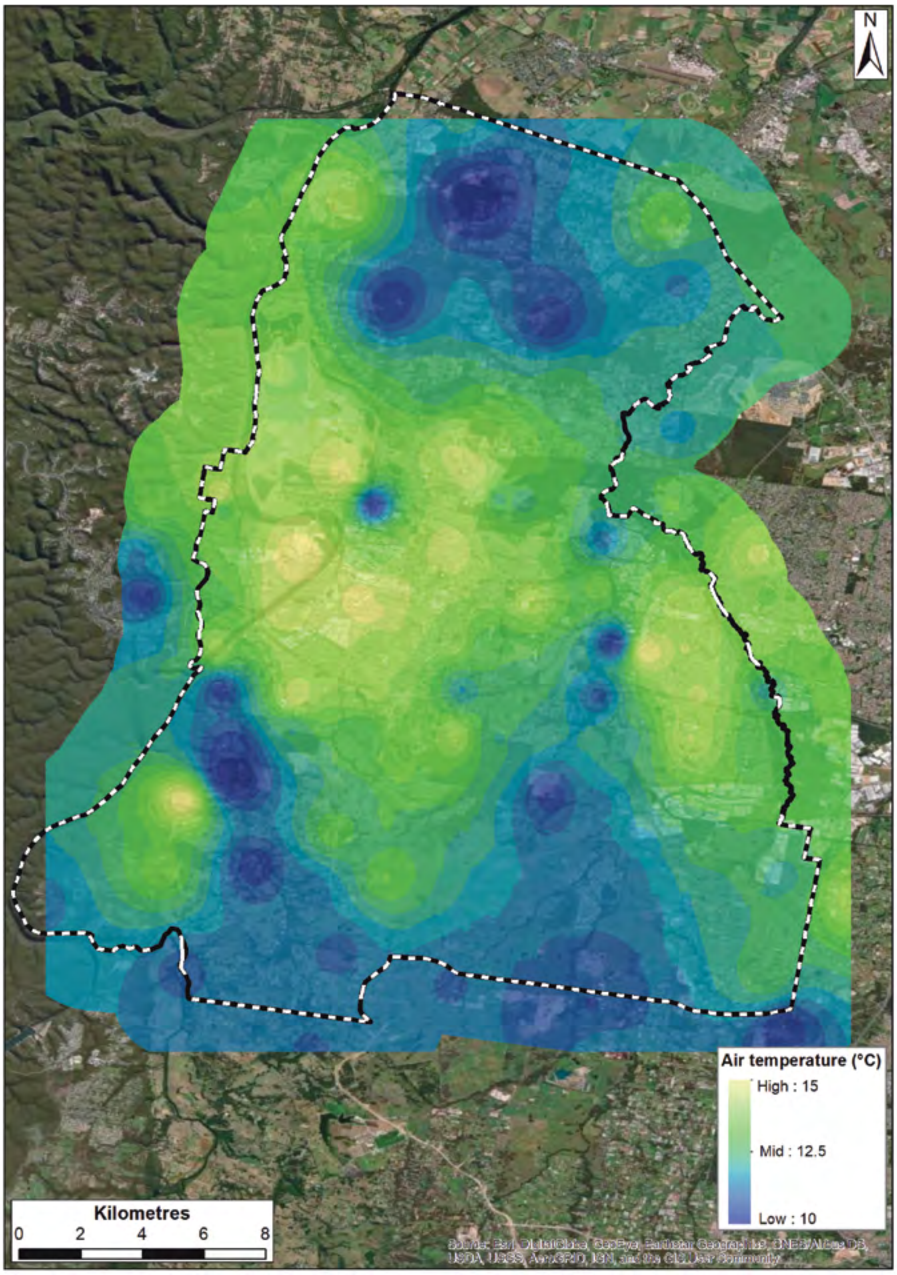


FIGURE 19: Absolute maximum air temperature measured between 14 December 2019 and 29 February 2020 at any of 100 measurement locations across the LGA of Penrith. The boundary of the LGA is shown as dashed line.

FIGURE 20: Absolute minimum air temperature measured between 14 December 2019 and 29 February 2020 at any of 100 measurement locations across the LGA of Penrith. The boundary of the LGA is shown as dashed line.



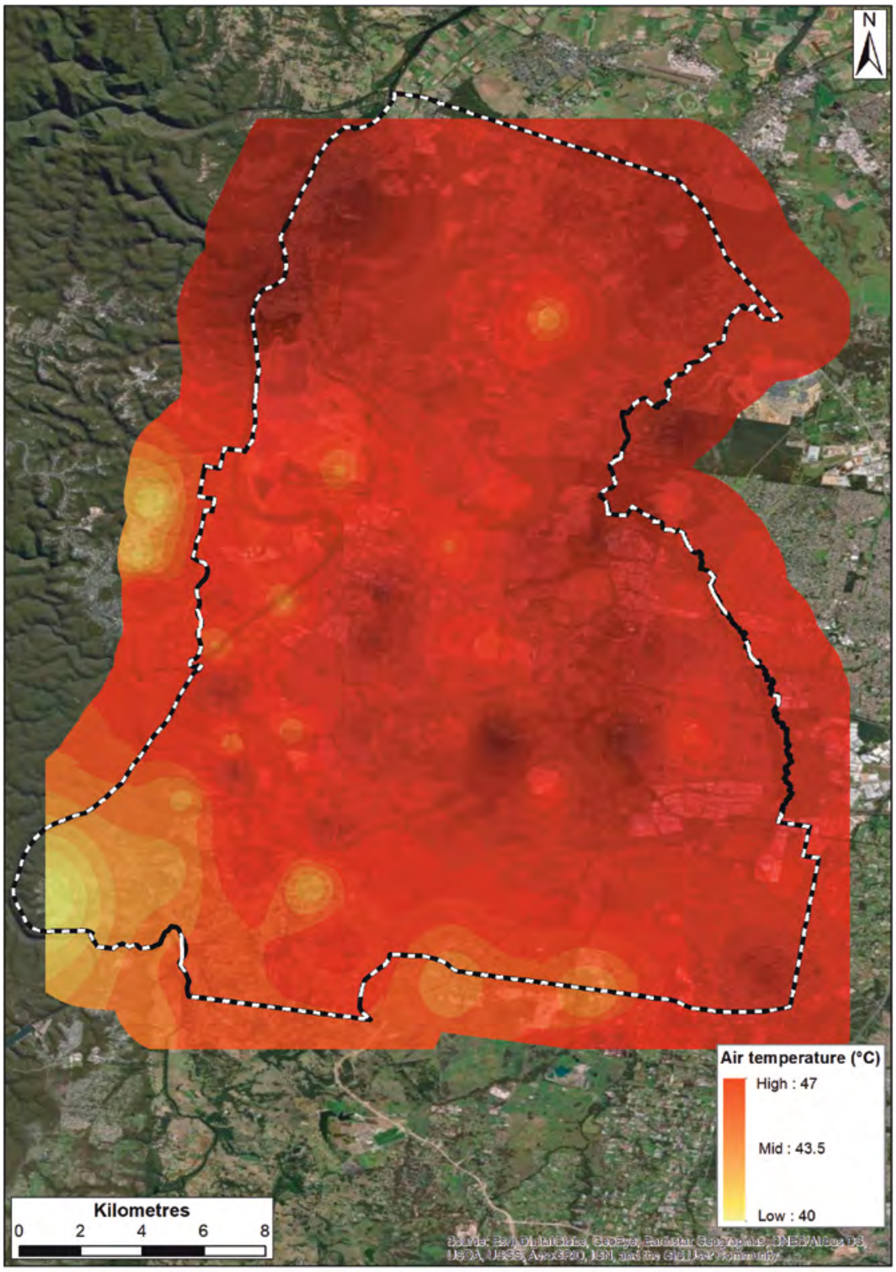
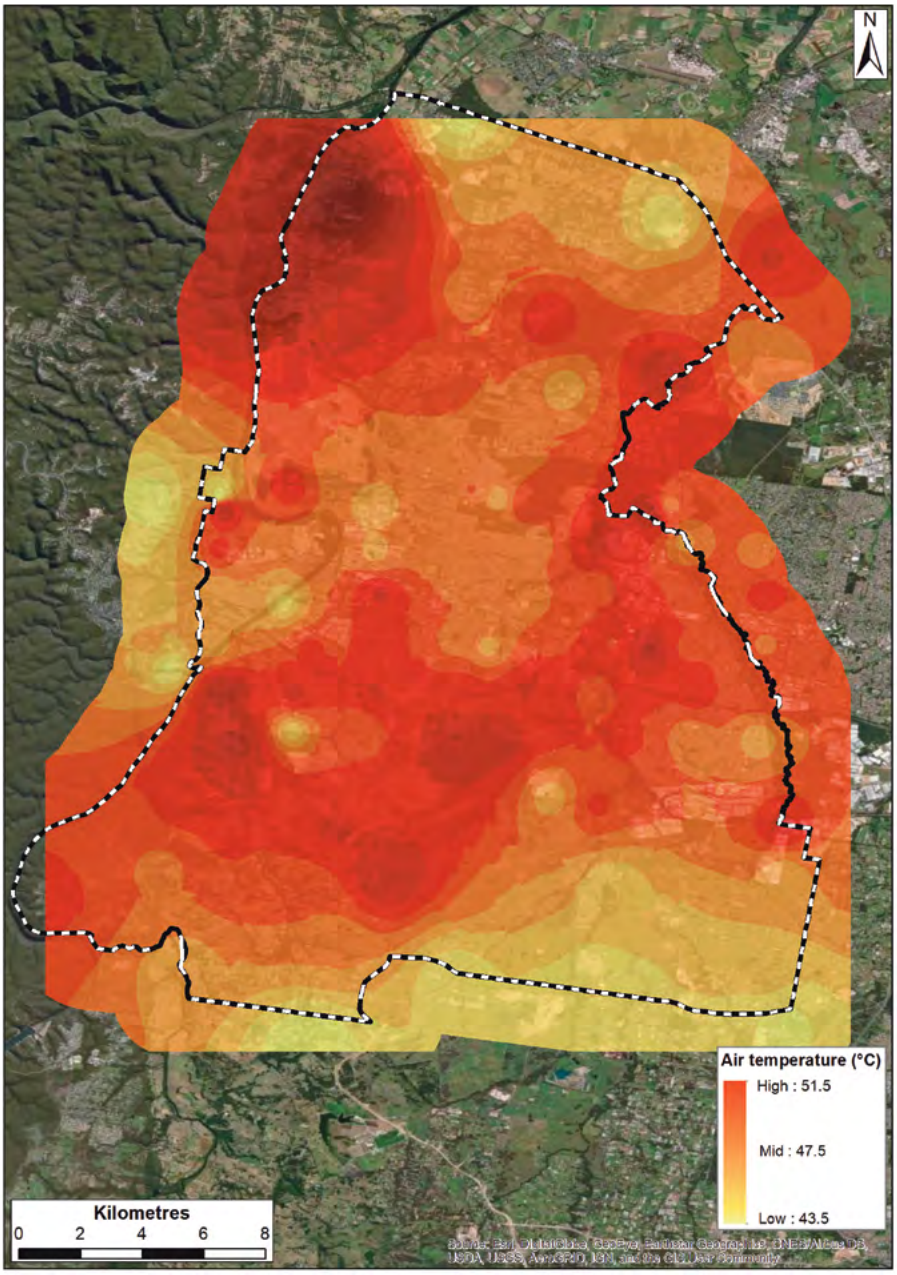


FIGURE 21: Variation of air temperature on 31 December 2019, a day of extreme heat. Data recorded at 14:30 across 100 locations were used to generate the map. At this time, absolute maximum air temperatures were measured at 12 of the 100 locations, indicating widespread extreme heat conditions. The boundary of the LGA is shown as dashed line.

FIGURE 22: Variation of air temperature on 4 January 2020, the hottest day during the summer 2019/20 in Western Sydney. Data recorded at 16:30 across 100 locations were used to generate the map. At this time, air temperatures showed 8.3°C across the LGA of Penrith. The boundary of the LGA is shown as dashed line.



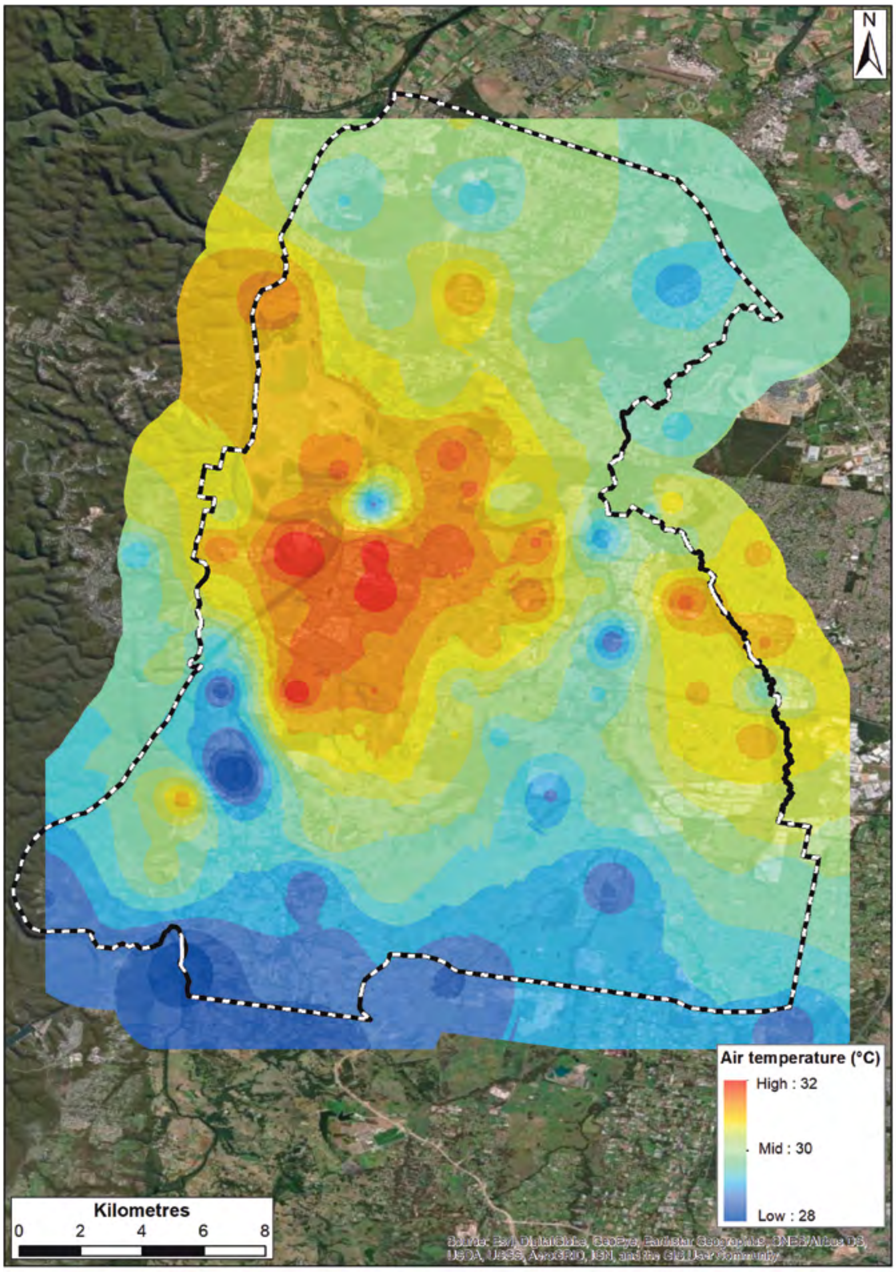


FIGURE 23: Mean nighttime air temperatures across the LGA of Penrith during 'heatwave nights' in the summer of 2019/20. Heatwave nights are defined as nights where at least one of the 93 measurement locations recorded air temperatures greater than 30°C. Data recorded between 14 December 2019 and 29 February 2020 were analysed for such conditions and were identified for 7 nights in January and February 2020. The boundary of the LGA is shown as dashed line.

4.5 **HEAT AROUND ST MARYS**

Air temperatures across the urban core of St Marys varied considerably during summer. The warmest area was around the train station where mean summer air temperatures were 23.6°C at the crosswalk in front of the station, 23.5°C at the carpark east of the station (45 Station St) and 23.7°C at the measurement location on upper Queen Street (Figure 24). The highest air temperature of all LHLs in Network 2 was 49.1C, recorded on 4 January 2020 in front of the train station. The highest air temperature in December 2019 (46.2°C) was also measured in front of the train station. At the intersection of Queen Street and Belar Street, south of the train station, mean monthly air temperatures were consistently high during January (mean: 25.6°C) and February (mean: 23.8°C). Mean summer air temperatures in the west of Queen Street were considerably cooler than those measured in the east and north.

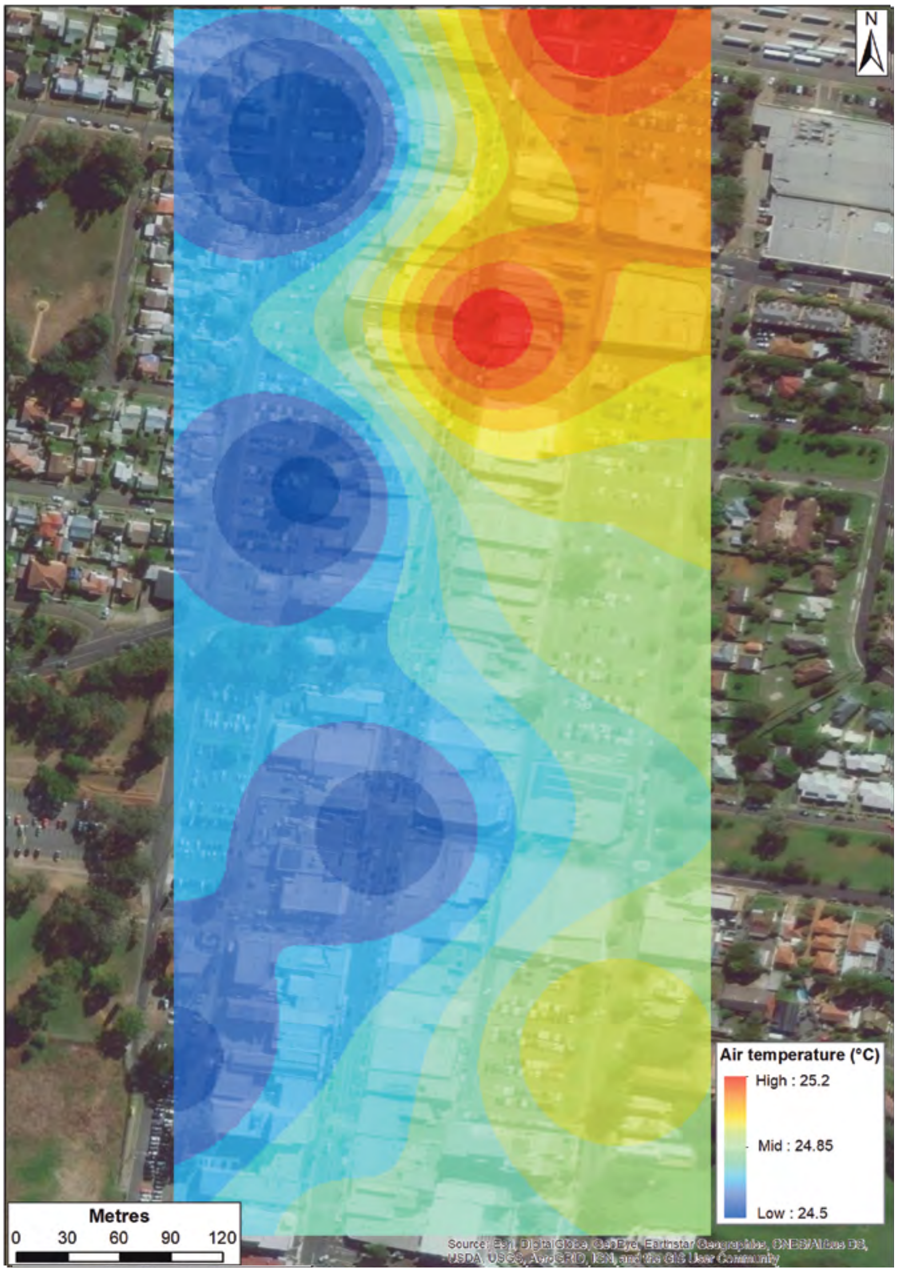


FIGURE 24: Mean summer air temperatures across the town centre of St Marys. Data to produce the map was recorded between 14 December 2019 and 3 February 2020.

Generally low mean and maximum air temperatures were recorded at the central location in queen Street, opposite the Post Office. Here, maximum air temperatures were 3°C lower during a hot spell in February compared to the measurement location at the lower end of Queen Street near the intersections with King Street. This remarkable temperature difference during peak heat events was consistent in all three months of summer.

A ranking of increasing mean and maximum daytime air temperatures was established for nine measurement locations that covered the entire summer period between 14 December 2019 and 29 February 2020 (Figure 25). The ranking reveals that the four coolest locations during the day are near the Post Office in Queen Street (28.1°C) and along West Lane (average 28.2°C), whereas the warmer locations were along East Lane (average 28.8°C), the upper section of Queen Street (29.7 °C) and the train station (29.3°C).

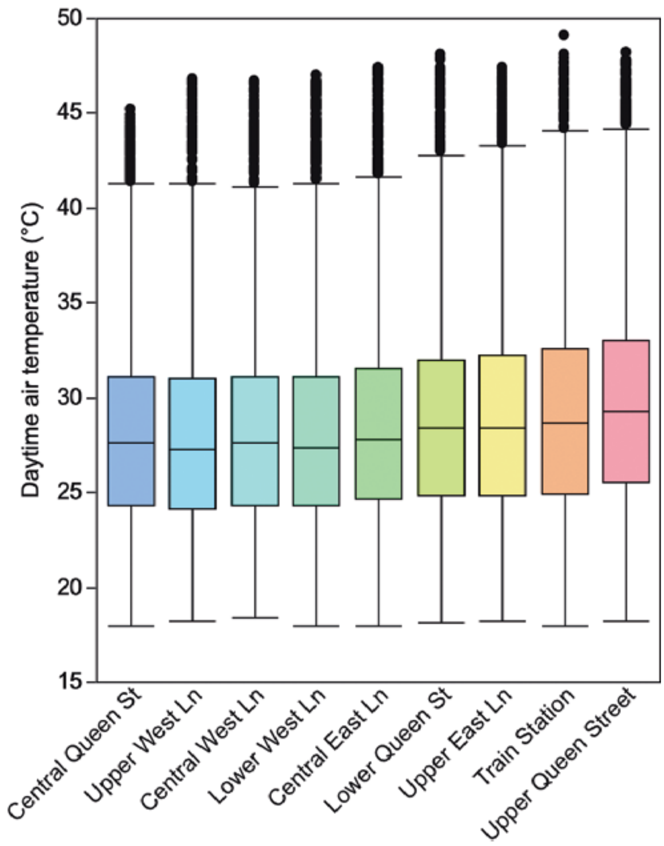


FIGURE 25: Variation of daytime temperatures across 9 measurement locations in the centre of St Marys. Data is shown for the time between 14 December 2019 and 29 February 2020. Daytime is represented by data spanning from 10:00 to 18:00. Locations are listed from the lowest to the highest mean daytime temperature. The upper and lower end of the box shows the 75th and 25th percentiles, the line inside the box shows the median and the whiskers indicate minimum and maximum values; dots show outliers. Colours inside each box match with locations indicated in Figure 7.

Across summer, nighttime air temperatures only varied between 21.6°C and 21.7°C for mean and 11.9°C and 12.1°C for minimum temperatures among the nine measurement locations. The hottest nighttime temperatures across St Marys CBD were recorded on 4 January, where at 21:00 air temperatures remained above 36°C. By midnight of that extraordinarily hot day, air temperatures had cooled to around 30°C at all measurement locations. Other nights, where air temperatures were above 30°C included 10, 23, 24 and 31 January as well as 1 and 2 February 2020. Particularly during the night of 1 February, LHLs at all measurement locations recorded more than 30°C for three consecutive hours between 21:00 and midnight.

Similar to other suburbs, the centre of St Marys also experienced periods of high and extreme heat. During these periods, maximum air temperatures may have differed slightly among the 9 measurement locations, yet minimum air temperatures were again very similar. To visualise these conditions, the heatwave at the end of December 2019 is depicted in Figure 26. During this time, heat was building up from Christmas Eve, where maximum air temperatures were in the high 20s, reaching 40°C on 28 December for the first time.

Extreme heat was again reached on 30 December where peak heat was 42.3°C at the location on upper Queen Street. On the following day, air temperatures were 19°C around 5:00 from where they climbed swiftly at all measurement locations to reach more than 40°C by 10:30. Peak heat of 46.2°C was reached in front of the St Marys train station at 16:00. In the following two hours a typical 'Southerly Buster' swept hot air to the north, leading to a drop of air temperatures by 20°C. The rapid decline of air temperatures is visible in Figure 26 where individual measurements are so far apart that the usual line-patterns of the 10-minute intervals is interrupted in the afternoon of 31 December. This slow build-up of extreme air temperatures over several days ending in an abrupt decline in air temperature by 20°C or more is a typical heatwave pattern in Western Sydney, now documented for the first time at St Marys.

An additional analysis of air temperature around the centre of St Marys and surrounding suburbs revealed a pronounced local UHI effect in the urban core of this suburb. For this analysis, all measurements collected at the nine locations of Network 2 were compared to those collected at the four nearest measurement locations. These locations were at Cutler Avenue and Putland Street in St Marys, Mallee Street in North St Marys and Princess Street in Werrington. LHLs at these locations were positioned in trees of small neighbourhood parks and along open space adjacent to South Creek. Data were grouped and averaged for daytime (10:00-18:00) and nighttime (21:00-5:00) to represent air temperature conditions 'inside' and 'outside' the urban core of St Marys.

The results show that the urban core of St Marys remains warmer compared to the surrounding residential and open areas (Table 8). While the effect was small during the day, it was highly notable during the night, and particularly obvious during periods of high nighttime temperatures. Across the entire summer, nighttime air temperatures in the centre of St Marys were 0.9C warmer compared to the surrounding suburban landscapes. Between 14 and 31 December, where maximum air temperatures exceeded 40°C during several days, this difference increased to 1.4°C. During individual nights, these temperature differences grew to more than 2.0°C. Extreme temperature differentials of up to 2.4°C were measured during the nights of 19 December 2019 and 22 January 2020. Daytime temperatures preceding both nights were above 40°C, which demonstrates the importance of parks and open spaces to provide local communities with cool nighttime temperatures after days of extreme heat.

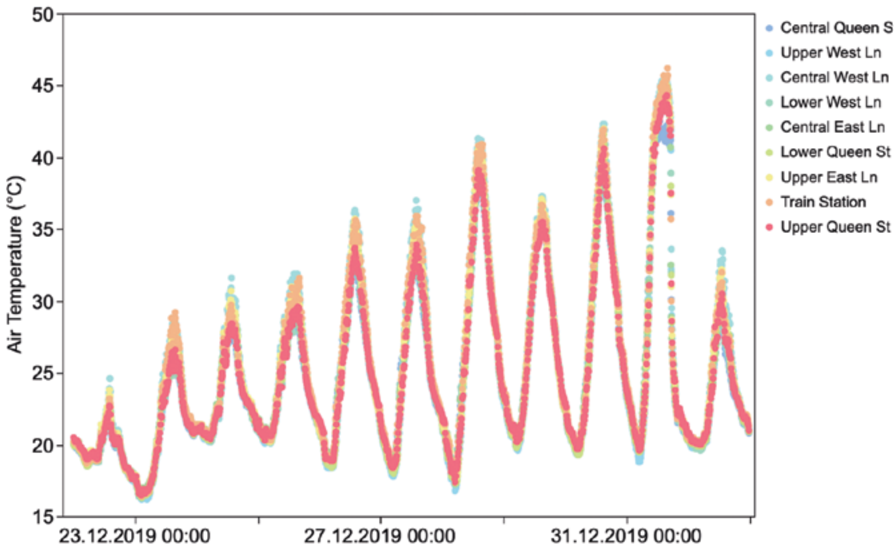


FIGURE 26: Development of a heatwave at the end of 2019 in St Marys. All nine measurement locations in the urban core of St Marys are shown. Data spans the interval from 22 December 2019 to 1 January 2020. Colours correspond to locations as shown in Figure 7 and 27.

TABLE 8: Daytime and nighttime air temperatures measured inside (n = 9) and outside (n = 4) the urban core of St Marys. Data were averaged for the entire summer (14 December 2019 to 29 February 2020), and also for individual months. The mean temperatures for December 2019 were calculated for the period from 14 to 31 December only. Numbers in parenthesis show 1 standard deviation.

	DAYTIME		NIGHTTIME	
	inside core	*outside core*	*inside core*	*outside core*
Mean Summer	28.6 (5.8)	28.3 (5.9)	21.4 (2.8)	20.5 (2.9)
Mean December 2019	30.8 (5.7)	30.6 (5.9)	20.5 (2.4)	19.1 (2.6)
Mean January 2020	29.2 (6.0)	29.0 (6.0)	22.4 (3.0)	21.5 (3.0)
Mean February 2020	26.7 (5.1)	26.2 (5.0)	21.0 (2.6)	20.2 (2.5)
Mean March 2020	23.9 (4.2)	23.5 (4.6)	18.1 (2.3)	17.2 (2.3)

5. IMPLICATIONS AND RECOMMENDATIONS

This project documented the variation of near-surface air temperatures across the LGA of Penrith City during the summer of 2019/20. Data, collected at more than 100 locations were analysed for a range of time intervals to assess patterns in seasonal, monthly, as well as daytime and nighttime air temperatures. Results of these analyses reveal that local communities are exposed to significantly more hot and extreme summer temperatures than previously known. Clear geographic patterns of microclimatic variation were detected, which confirmed long-term climate modelling for Western Sydney. Using empirical data revealed the existence of local UHIs, especially in the central section of the LGA where the majority of residents live between Emu Plains in the west and St Marys in the east.

Summer temperatures in Western Sydney are naturally higher compared to Eastern Sydney. The origin of this phenomenon lies in the combined effects of geomorphologic processes and synoptic climate across the Sydney Basin. However, the reason for faster warming in Western Sydney during the past decade is largely the result of human activities. Given the current projections of population growth and the plans to develop large tracts of land in the southern region of the LGA, it is reasonable to expect that an increasing proportion of the local population will be exposed to dangerous levels of extreme heat.

Based on available climate projections, it is highly unlikely that summer air temperatures will remain at current levels or even decrease. Increasing mean summer temperatures and more frequent extreme heat days - those with air temperatures above 40°C - are the reality of today and the coming decades (Bureau of Meteorology 2018, Ogge et al. 2018). The causal relationships among global warming, increasing extreme heat and rising rates of heat-related morbidity and mortality are well documented (e.g., Huang et al. 2011, Mills et al. 2015, Sanderson et al. 2017).

This study documented air temperatures above 50°C for the first time in the Sydney Basin at six different locations and three individual days in December, January and February. These observations are evidence for a situation where super-heated air impacts not a single location or suburb, but a wider section of Western Sydney. Hence, planning and development across the region must aim to build the greatest possible resilience against heat. Landscape and building design, supply infrastructure for water and energy, transport infrastructure and greening strategies must be approached with the clear intention to provide best functionality under extreme summer temperatures and wherever possible additional cooling. Applying these principles anywhere across the LGA and Western Sydney more broadly will be paramount because measurements indicate that air temperatures between 45°C and 50°C already occur at many locations.

Currently the risk of heat on public health is greatest around two clusters in the central section of the LGA where population density is high (Figure 27). These clusters are in the west around the CBD of Penrith towards Kingswood and in the east around Colyton and Oxley Park. When compared with temperature data recorded during very hot nights in the summer 2019/20, it becomes obvious that the areas with high vulnerability to heat are also those that have the highest nighttime temperatures. High nighttime temperatures and the associated lack of recovery from daytime heat have been shown to further increase heat-related risks to public health (Murage et al. 2017, Roye 2017). Hence, interventions to reduce surface heat, decrease the UHI effects and improve urban microclimate should be concentrated in these areas. Related benefits to public health can be expected to be substantially greater in these areas compared to suburbs where the Heat Vulnerability Index is lower.

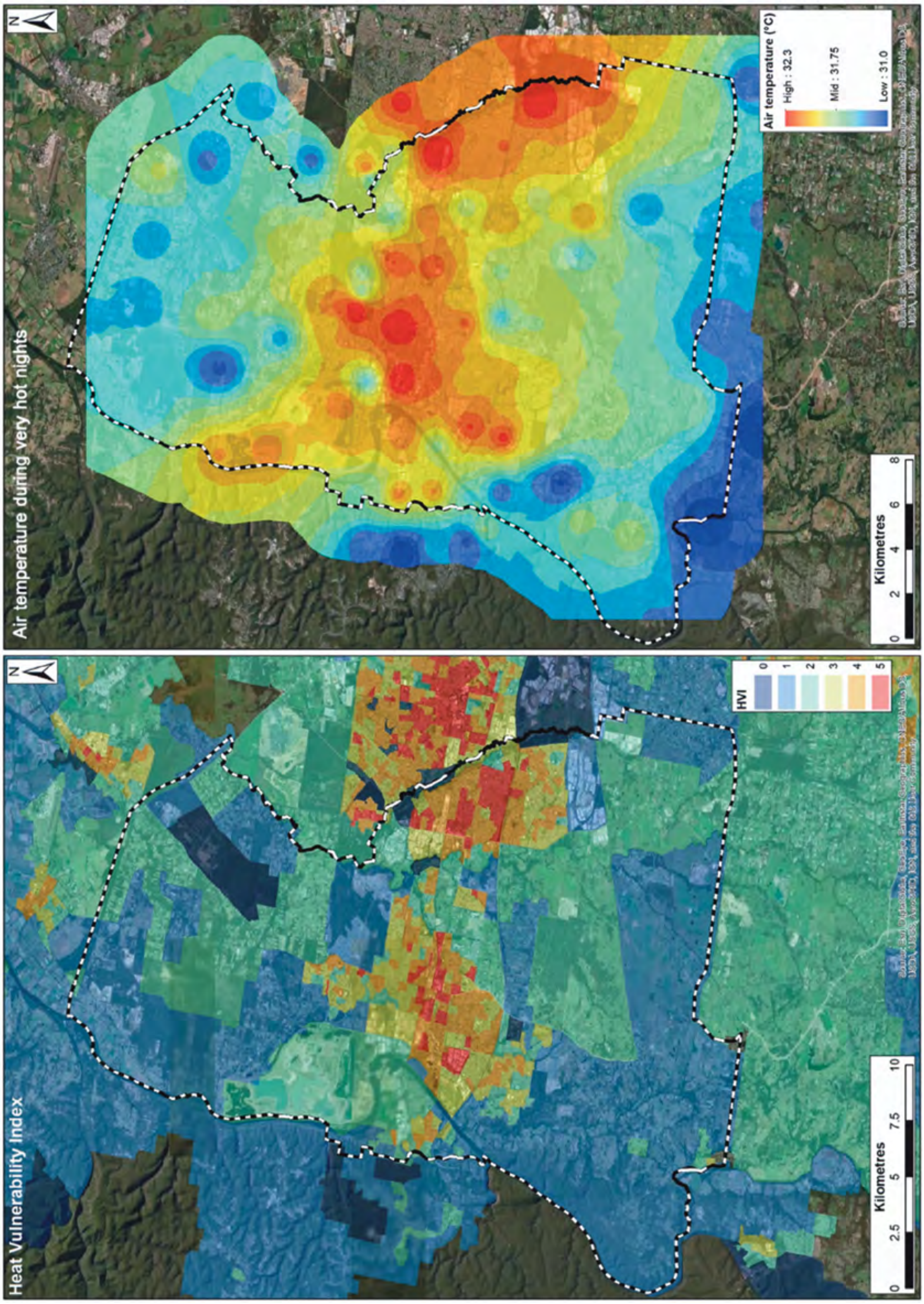


FIGURE 27: Side-by-side view of the Heat Vulnerability Index (HVI) and air temperatures during hot nights across the LGA of Penrith. The HVI was calculated for summer 2015/16 and data is available at seed.nsw.gov.au. Air temperatures were calculated as means of timepoints between 21:00 and 5:00 where temperatures across all locations were greater than 30°C.

One vital strategy to reduce surface temperatures and improve microclimate is to increase urban green infrastructure. The political will to increase urban green infrastructure across the Sydney Basin has never been greater. The cooling effect from vegetation, especially by trees has been assessed in countless studies (see reviews by Bowler et al. 2010, Santamouris et al. 2018). Today it is clear that tree canopies reduce air temperature in cities through transpirative cooling and shading of hard surfaces (Ziter et al. 2019). However, the magnitude of this cooling effect varies, and empirical work has shown that while the reduction of surface heat and 'feels like' temperature can be substantial (see Figure S3 for an example around these different temperatures), the cooling of air temperature may at best reach 1.0-1.5°C.

Increasing tree canopy cover will be an important strategy to reduce the impacts of surface heat throughout the central region of the LGA and especially in the suburbs and precincts of those areas with high vulnerability to heat. Currently the canopy cover across greater Penrith is a low 14%, compared to the average 21% canopy cover throughout the towns and suburbs of the Sydney Basin (Greater Sydney Commission, 2019). Between 2009 and 2016, tree cover declined by 2.5% and grass cover declined by 2.2% across the LGA, while at the same time the area covered by hard surfaces and buildings increased 3.4% (Amati et al. 2017).

Less canopy and vegetation cover and more land surfaces covered by hard, impervious materials will result in more pronounced UHI effects and further increase nighttime air temperature, the exact opposite of what should be aimed for to provide living conditions with high resilience against heat. The relative limited capacity of tree canopies to reduce air temperatures paired with the increasing area of hard surfaces across the LGA highlights the importance to look at other mitigation strategies to limit increasing urban heat, especially during the night. For these strategies to be effective, options to replace or reduce the area covered by hard surfaces will be vital (Ziter et al. 2019).

Another important aspect is the threshold-size that will influence how effective the strategies to deliver anticipated cooling will be. The point of maximum cooling efficiency can be determined for blue-green infrastructure and anticipated cooling effects (Yu et al. 2020) yet similar estimations should also be applied to determine how additions of hard surface cover and loss of green infrastructure will warm urban microclimates. Determining threshold-size for successful urban cooling strategies and initiatives can be difficult due to the complex interactions of climate and the configuration of the land. However, empirical studies that accompany urban development around the LGA of Penrith can be used to define threshold-sizes.

An undeniable asset to the City of Penrith and local cooling is the presence of several large water bodies in the form of the Nepean River and the Penrith Lakes. Air temperature data collected during this project showed that the Tench Reserve along the eastern riverbank was cooler during hot days compared to areas where water bodies were absent. However, the same data also showed that the area remained warmer during the night. This effect of large water bodies is well known (Gross 2017, Steenveld et al. 2014). It follows that large water bodies can actually contribute to local UHI effects, especially during late summer when water temperatures are high (Jacobs et al. 2020). This may especially apply to the lakes in the north of Penrith CBD, which are relatively shallow water bodies with negligible flows. The potential impact on nighttime air temperatures in the area around the lakes should be further investigated to inform upcoming urban development at Penrith Lakes.

In August 2015, Penrith City released its ***Cooling the City Strategy***. This strategy lists a large number of actions to reduce the UHI effect and provide more liveable conditions during summer to the local community. The strategy sits under a framework of 1-year (Operational Plan), 4-year (Delivery Program) and 10-year (Community Plan) plans. Having a dedicated planning framework that aims to reduce heat-related problems is not the current norm. A recent analysis of planning frameworks across participating cities in the 100 Resilient Cities Initiative has found that around the world local governments fail to either acknowledge the existence of the UHI effect or provide no defined strategies to combat it (Elgendawy et al. 2020).

However, Penrith's ***Cooling the City Strategy*** (Penrith City 2015) shares a number of common problems with similar strategies of local governments in Australia, Europe and North America. First, it does not provide fix targets for heat reduction. Second, many actions to reduce heat are not supported by thresholds and hard evidence about effectiveness. Third, issues related to UHI effects and heatwaves are intermingled, when ideally, they should be dealt with separately. Separate strategies are necessary to address (a) issues related to surface temperatures and mitigation of UHI effects and (b) management of air temperature and thermal comfort of local communities during heat and heatwaves. The latter should be further refined to also include actionable plans for those members of the community that are most vulnerable to heat – namely the elderly, the sick, the immobile, very young and those that cannot afford to pay for air conditioning. Such refinements are particularly important as the proportion of elderly residents has increased notably in the recent past (+63% people aged 65 and older between 2006 and 2016) and is expected to increase further in the future (Penrith City 2020).

The documentation of local summer air temperatures by the present research has provided an important benchmark for evidence-based strategy development and planning. It provides important information to inform the review of the ***Cooling the City Strategy***. Even though the work is based solely on measurements of air temperatures, it does present separate analyses of UHI effects (e.g., via novel nighttime air temperature maps) and extreme heat. For the first time across Penrith, data is available to show that the places where UHI effects are most pronounced are not the same places where the most extreme daytime air temperatures are measured. These and other findings of the research support a more sophisticated understanding of heat-related issues in the region of Western Sydney that is experiencing the highest summer air temperatures today and in the foreseeable future.

Based on the patterns and trends around summer air temperatures measured across the LGA of Penrith, and an intensive study of current state-of-the-science and related literature, the following actions are recommended:

1. **Formulate separate policies and guidelines that address (a) mitigation of Urban Heat Island effects and (b) strategies for days of extreme heat**. The former is permanent while the latter is episodic, and each requires different approaches to reduce urban heat (continuous stress) and increase community resilience against extreme heat (acute shock).
2. **Establish a monitoring network for continuous measurement of air temperature**. Currently, information on air temperature is based on a single weather station operated near the Penrith Lakes, which is not designed to document air temperatures experienced by the majority of residents across the LGA.
3. **Implement cooling initiatives for those suburbs that have the highest Heat Vulnerability Index**. The present research has shown that these areas experience the highest nighttime air temperatures during episodes of extreme heat. Cooling these neighbourhoods will provide marked benefits for the health and well-being of local populations.
4. **Reduce the area of hard surfaces in the central section of the LGA**. This applies especially to the urban cores of Penrith and St Marys. Substantial Urban Heat Island effects have been identified for both commercial hubs.
5. If replacing hard surfaces is not possible, **introduce trees for shading carpark surfaces**. Research by Western Sydney University has documented that collectively the LGA of Penrith contains 900,000 m^2 of flat, blacktop carparks of which only 1% is shaded. This type of infrastructure contributes to Urban Heat Island effects and should be transformed (shaded, change in surface type or colour, etc.) to reduce local heat.
6. **Limit the area of hard surfaces in new development** to an absolute minimum.
7. **Generate clear policies to implement recommendations 4-6**. Inclusion of objectives and controls in DCP/LEP for carparks including shading and light coloured surfaces.
8. **Concentrate cooling efforts in St Marys on the hottest areas**. These are the area in front of the train station and the carparks between Queen Street and East Lane.
9. **Form a multidisciplinary *Heat Task Force*** made up of staff from across all relevant Council departments/units. Due to the enormous impact of increasing heat and the documented current levels of exposure to heat by the residents of the region a concerted effort is necessary to ensure that all sectors of local government work collaboratively towards the shared goal of increasing heat resilience.
10. **Develop a comprehensive *Community and Infrastructure Heat Emergency Plan***. This plan should provide strategies and actions for government personnel, emergency services, service providers and the public in case of heat emergencies. Clear guidance during times of heat emergencies will be essential to reduce negative impacts on people, the local economy and environment.
11. **Continue to deliver actions and initiatives listed in the *Cooling the City Strategy***.
12. **Work with Western Sydney University to generate evidence for threshold-size effects** from interventions that lead to urban cooling or warming. This information will be essential when formulating best-practice requirements of heat-smart urban development in the coming decades.

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7. ADDITIONAL RESOURCES

FIGURE S1: Map showing the locations of 10 Local Heat Loggers (LHLs) for Network 3. This network of LHLs was used to inform participants of the ***Cooling the City Masterclass*** event about the project and present preliminary results. These LHLs were collected in mid-January and their data were incorporated into Network 1.

FIGURE S2: Map presented at the ***Cooling the City Masterclass*** event indicating the maximum air temperatures measured on 4 January 2020 at seven locations of Network 3. The boundary of the LGA of Penrith is shown as a white dotted line.

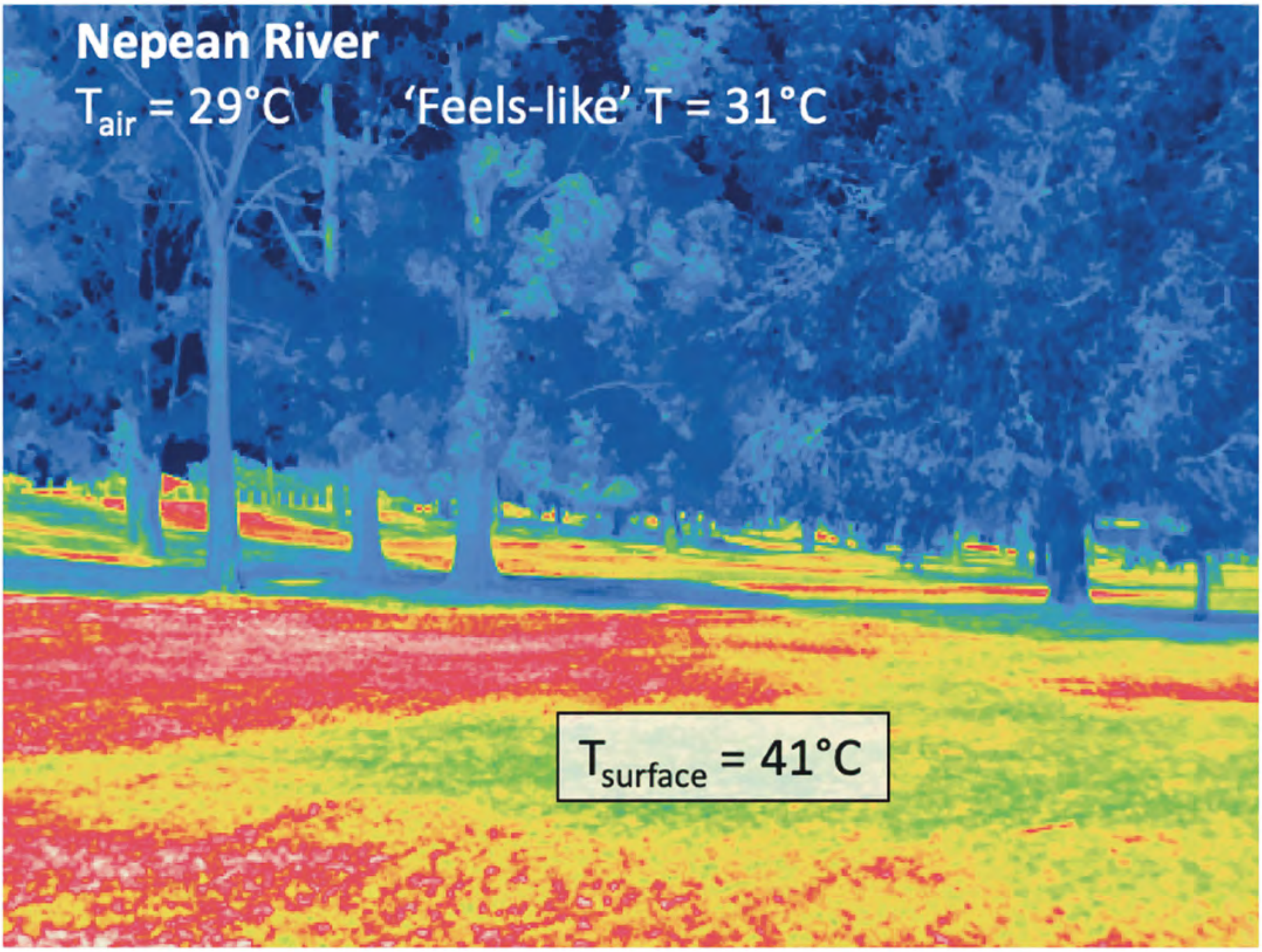
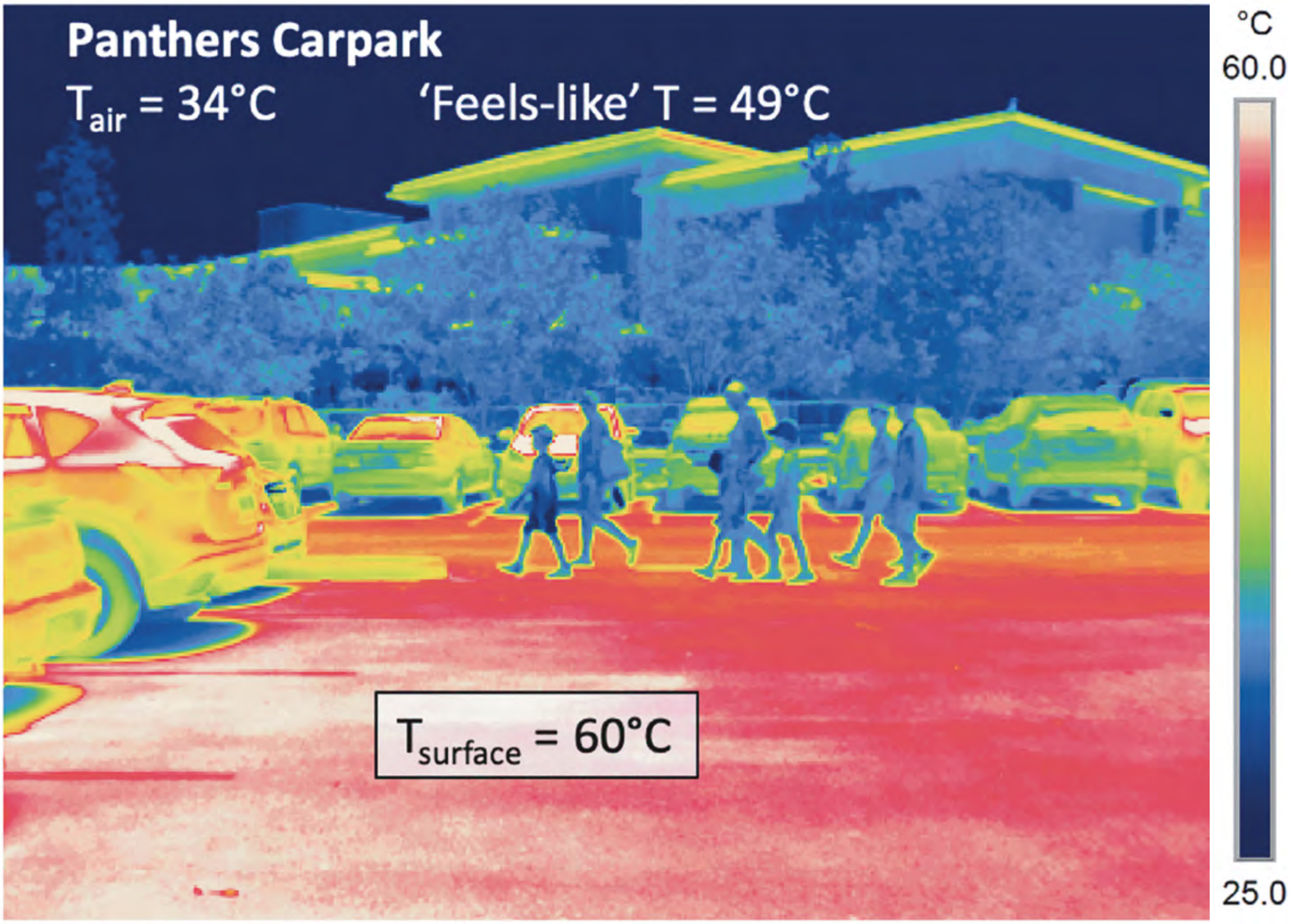


FIGURE S3: Thermal images of surface temperatures and added information on each location's air and black globe or 'feels like' temperature. Data were recorded simultaneously on 10 January 2020 around noon in the Tench Reserve near the Nepean River and the Penrith Panthers Carpark off Mulgoa Road in Penrith. The combined effects of clear differences in surface and air temperatures lead to a very different human thermal experience, represented by nearly 20°C difference in 'feels like' temperature.



Panthers Carpark
Tair = 34°C
'Feels-like' T = 49°C
Tsurface = 60°C
°C
60.0
25.0

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