WESTERN SYDNEY UNIVERSITY

BENCHMARKING HEAT ACROSS CAMPBELLTOWN, NEW SOUTH WALES

CAMPBELLTOWN CITY COUNCIL

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With respect for Aboriginal cultural protocol and out of recognition that its campuses occupy their traditional lands, Western Sydney University acknowledges the Darug, Tharawal (also historically referred to as Dharawal), Gandangara and Wiradjuri peoples and thanks them for their support of its work in their lands (Greater Western Sydney and beyond).

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EXECUTIVE SUMMARY

The compounding effects of climate change and rapid urbanisation cause cities to heat up. Metropolitan Sydney is no exception to this trend. Today, the communities of Campbelltown in the southern region of the Greater Sydney Basin already experience extreme summer temperatures and heatwave conditions on an annual basis. Climate predictions point toward amplification of summer heat. Already today these conditions represent a serious threat to the quality of life, public health and economic prosperity in the region.

Near-surface air temperature in complex urban terrain can vary. A large proportion of this variation originates from differences in thermal characteristics of materials that together make up the terrain. While roads and buildings can lead to higher temperatures in urban landscapes, trees and other green urban infrastructure can provide cooling. Hence, depending on the kind, make and proportion of urban infrastructure types (e.g. grey, green, blue), air temperatures will vary. Until now, the magnitude of air temperature variation among suburbs within the Campbelltown Local Government Area (LGA) remained unknown.

Here, we report apparent microclimatic variation across this LGA. During the summer of 2018/19, more than 1.46 million individual air temperature measurements were recorded at 102 locations in and around the LGA. These measurements were used to:

1. assess the spatio-temporal dynamics of microclimate and heatwaves in the area;
2. develop a temperature-based ranking matrix of suburbs;
3. assess thermal differences between rural, peri-urban and urban sections of the LGA, and
4. generate the first microclimate maps for Campbelltown Council.

Between 01 December 2018 and 15 March 2019, average air temperature across across the Campbelltown Local Government Area was 23.4°C. Absolute maximum temperatures among the 102 measurement locations ranged from 37.4°C (near Jingga Pools at Dharawal National Park) to 45.4°C at a ridge line in northern Holsworthy. The absolute lowest temperature was 7.5°C, also recorded in the Dharawal National Park.

Daytime air temperature (10:00 – 18:00) regularly varied around 6°C among the 102 measurement locations. This variation was less pronounced during the night. During days of extreme heat (greater than 35°C), the variation of air temperature among individual locations increased to more than 10°C. A cool change following a day of extreme heat on 31 January 2019 caused the largest variation of more than 17°C (17:40, 43.3°C at Korringa Reserve in St Andrews; 26°C at Hodgson Close in Wedderburn).

A significant warming trend from forested to urbanised locations was observed. On average, landscapes that were dominated by grey infrastructure were 1.5°C warmer compared to landscapes where grey infrastructure was absent. Due to the generally higher thermal mass of grey compared to green infrastructure, the former locations heated up slower during the morning, but cooled down less during the night.

A pronounced Urban Heat Island Effect, where urban centres remain warmer during the night compared to nearby rural areas, was documented for the Campbelltown LGA. This effect was most pronounced during periods of extreme heat (i.e. heatwaves), where temperatures around urban centres like Campbelltown CBD and Ingleburn were up to 5°C warmer compared to those measured in Wedderburn or Gilead in the south.

The Bureau of Meteorology does not operate an official weather station in the vicinity of any of the urban centres of Campbelltown. This markedly limits our understanding of suburb-specific temperature dynamics. During the summer of 2018/19, the nearest official weather station at Mt Annan Botanic Garden recorded maximum air temperatures >35°C during 23 days and >40°C during one single day. In contrast, our measurements documented that extreme summer heat occurred much more frequently across the LGA (i.e. 54 days >35°C, 22 days >40°C).

Our measurements document that people living across the LGA are exposed to more extreme heat than previously known. Based on these data, it becomes clear that vulnerability of local communities against heat is a critical issue already today, but can be expected to become increasingly critical with continued climate warming and urbanisation in the region.

This new understanding of heat across the Campbelltown LGA is based on empirical evidence, making results relevant and applicable. Analyses provided in this study offers real-world information to better plan, prepare and respond to increasing urban heat in the future.

Based on findings of this research and two similar studies (Pfautsch and Rouillard 2019a, b), the following actions are recommended:

» establishment of a cross-council *Heat Task Force* to jointly develop, implement and evaluate success of activities that aim to mitigate urban heat;

» develop mechanisms for stronger protection of existing tree canopy and expand canopy for urban cooling in anticipated growth centres;

» promote growth of young trees as expansion of their canopies will have the largest local cooling effect;

» use microclimate maps presented in this report to communicate the issue of urban heat within the communities of Campbelltown;

» calculate a *Heat Vulnerability Index* by merging microclimate data with census information about age of the population; communicate this Index to emergency services to reduce incident response times during heatwaves;

» establish and promote a network of *Cool Zones* (parks, playgrounds, reserves, etc.) across the urban centres of Campbelltown where the public can find relief from urban heat.

CONTENTS

1. BACKGROUND

The Campbelltown LGA is located in the south of the Greater Sydney Basin (GSB) on the eastern coastline of Australia (Fig. 1). The land upon which the suburbs of the city were built has been home to the Dharawal people for more than 50,000 years. Today, cities, towns and landscapes across the Greater Sydney Basin are transforming rapidly to become the *Metropolis of Three Cities* (Greater Sydney Commission, 2018). Campbelltown will be an integral part of the Western Parkland City (Greater Sydney Commission, 2018), being the gateway to the south and western residential and economic growth areas in this part of the GSB. The Campbelltown-Macarthur growth area is expected to become a metropolitan centre, due to its excellent access to public transport infrastructure, major traffic routes, and its close proximity to the new airport at Badgerys Creek. A new health and education precinct (Greater Sydney Commission, 2019) will further strengthen this role.

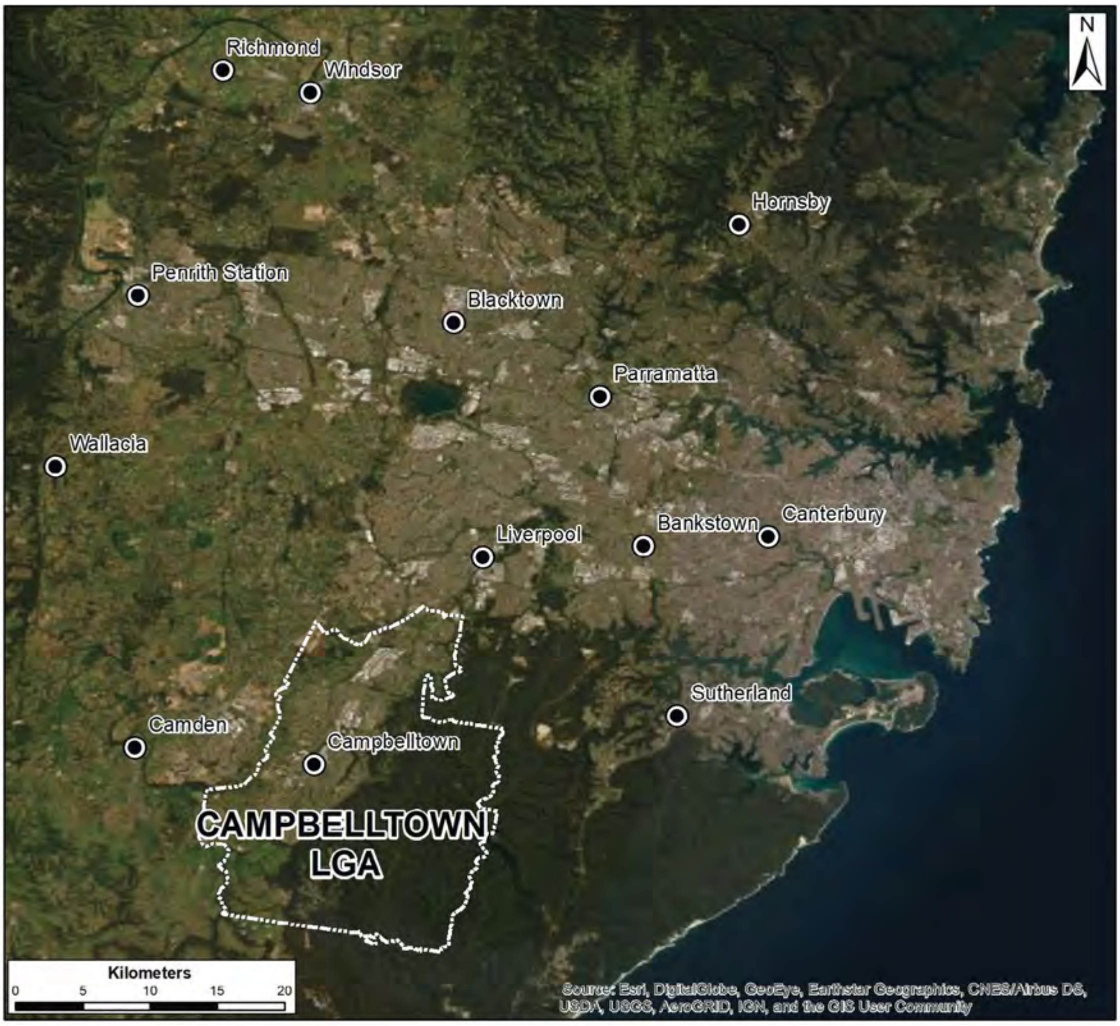


FIGURE 1: Location of the Campbelltown LGA in the south west of the Greater Sydney Basin.

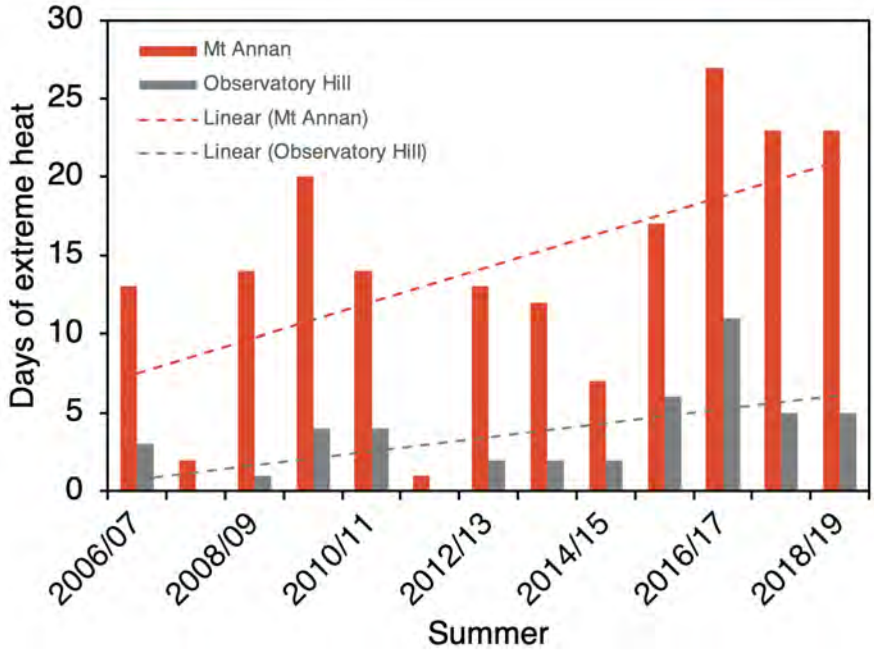


FIGURE 2: Number of days at Mt Annan (red) and Sydney Observatory Hill (grey) where air temperatures were equal or greater than 35°C. Only maximum daily temperatures between 15 November – 15 March were evaluated to represent summer conditions. Data were downloaded from the Bureau of Meteorology website. Dashed lines indicate trend predictions for each location.

The Sydney Basin is heating up. Two sources are responsible for this concerning trend: global warming and local, climatically-unbalanced urbanisation (United Nations 2016). Resulting Urban Heat Island Effects (UHIE) have been confirmed for metropolitan areas across the Sydney Basin (Santamouris *et al.*, 2017; Pfautsch and Rouillard, 2019a, b) and many other cities around the world (Peng *et al.*, 2012).

Since 1910, mean surface temperatures across Australia have increased 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 temperatures across Australia increased from 2% of the time in the past (1951-1980) to 12% in the recent past (2003-2017)[1]. The same trend can be observed for unusually warm monthly minimum temperatures (i.e. nighttime temperatures).

A comparison of recent data from Sydney's longest operating weather station at Observatory Hill at Sydney CBD, and the closest weather station to Campbelltown CBD operated by the Bureau of Meteorology (station # 068257 at Mt Annan Botanic Garden), shows how summer heat in the southern region is generally greater, but also increasing in the past decade (Fig. 2). Notably since the summer of 2006/07 (summer = 15 November to 15 March) the number of days with extreme heat (maximum daily temperature ≥35°C) has increased more strongly near Campbelltown compared to Sydney CBD. Between 2006/07 and 2018/19, the station at Observatory Hill recorded 45 days ≥35°C during summer seasons. At Mt Annan, such extreme temperatures were recorded during 186 days – four times more often. Similarly, the number of days with maximum temperatures ≥40°C was eight at Observatory Hill and 31 at Mt Annan.

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

The predominant reason for more intense heat in the southern, landlocked part of the GSB compared to eastern, coastal regions is the absence of cooling sea breezes. As recently documented by Sadhegi *et al.* (2018), the most beneficial wind direction for human thermal comfort in the Sydney Basin comes from East North East (ENE). These sea breezes regularly occur in summer (Batt, 1995). Sea breezes commence once air temperatures over land exceed those over the sea and the strength of air flow increases with rising heat during the early and late afternoon (Sadhegi *et al.*, 2018). Thus, eastern suburbs benefit proportionally more from these cooling winds during periods of extreme heat. Build infrastructure and topography in Sydney's coastal and inner west regions, together with generally stronger UHIE in the central and western region (Santamouris *et al.*, 2017), blocks progression of these cool airflows towards the west and south.

From 2011 to 2018 the population of Campbelltown increased by 17,000 residents to around 168,000. At the same time, the relative abundance of separate houses declined (-2.4%), while medium- (+1.4%) and high-density (+0.9%) housing increased slightly to accommodate the added portion of the population (online data from profile.id.com.au). In 2019, approximately 171,000 people called Campbelltown LGA their home and the local population is expected to increase by 61% to a total of around 276,000 by 2036 (forecast.id.com.au/campbelltown). To accommodate the expected increase in population, an additional 40,400 dwellings will be required across the LGA of Campbelltown.

The suburbs of Campbelltown will experience different rates of population increase and associated conversion of green to grey infrastructure and urban densification. The largest population growth between 2019 and 2036 is forecasted to take place at Menangle Park (+1,748%), Rural Residential (including Denham Court (excluding East Leppington small area), Gilead (excluding forthcoming release area of Mount Gilead), Holsworthy, Kentlyn, Long Point, part of Menangle Park (west of Hume Hwy), Minto Heights, Mount Annan, Varroville, Wedderburn, Wonora Dam) (+1,400%) and Mount Gilead (+1,039%). This remarkable increase in local populations equates to an absolute change in residents from 580 to 10,818 at Menangle Park, 2,560 to 38,380 across Rural Residential and 630 to 7,200 at Mount Gilead (based on data from the Australian Bureau of Statistics, published by forecast.id.com.au).

As indicated by the currently low population density, today these three high-growth areas are dominated by rural and semi-natural land uses that provide open, vegetated and thus pervious surfaces. While the anticipated trend of increasing urbanisation in the region is in accordance with global trends in urban population dynamics (Gerland *et al.*, 2014), its consequences on summer temperatures (day and night) and the number of days with extreme heat remain to be quantified.

It is well known that development of urban space increases regional heat. This is owed to transformation of green to grey infrastructure and increasing emissions of anthropogenic heat from energy use and traffic (Georgescu *et al.*, 2014; Hwang *et al.*, 2017; Li *et al.*, 2014). It is reasonable to speculate that urban transformation around the LGA of Campbelltown from rural and peri-urban to urban land uses with predominately impervious surfaces will change microclimate regimes, habitat quality, soil carbon stocks, quality and volume flows of water and other biogeochemical services and functions. Given the current trend of population increase in Campbelltown, it is not surprising that the LGA is experiencing a net loss of green infrastructure and net gain in hard surfaces (Amati *et al.*, 2017). Research from RMIT University indicated that the Campbelltown LGA had lost a noticeable proportion of green infrastructure (2009 to 2016: tree cover = -2%, shrub cover = -0.5%, grass cover = -1.5%), while hard surfaces over the same time increased statistically significantly by 4% (Amati, unpublished). The low proportion of 18% tree cover in urban areas of the city (Greater Sydney Commission 2019) renders its population very vulnerable to heat, causes poor public health, represents economic disadvantages and provides limited access to parks and gardens (Amati *et al.*, 2017).

Impacts of urban heat can be studied at different scales. Metropolitan regions like the Greater Sydney Basin (GSB) are embedded in a geographical landform with distinct attributes, such as mountain

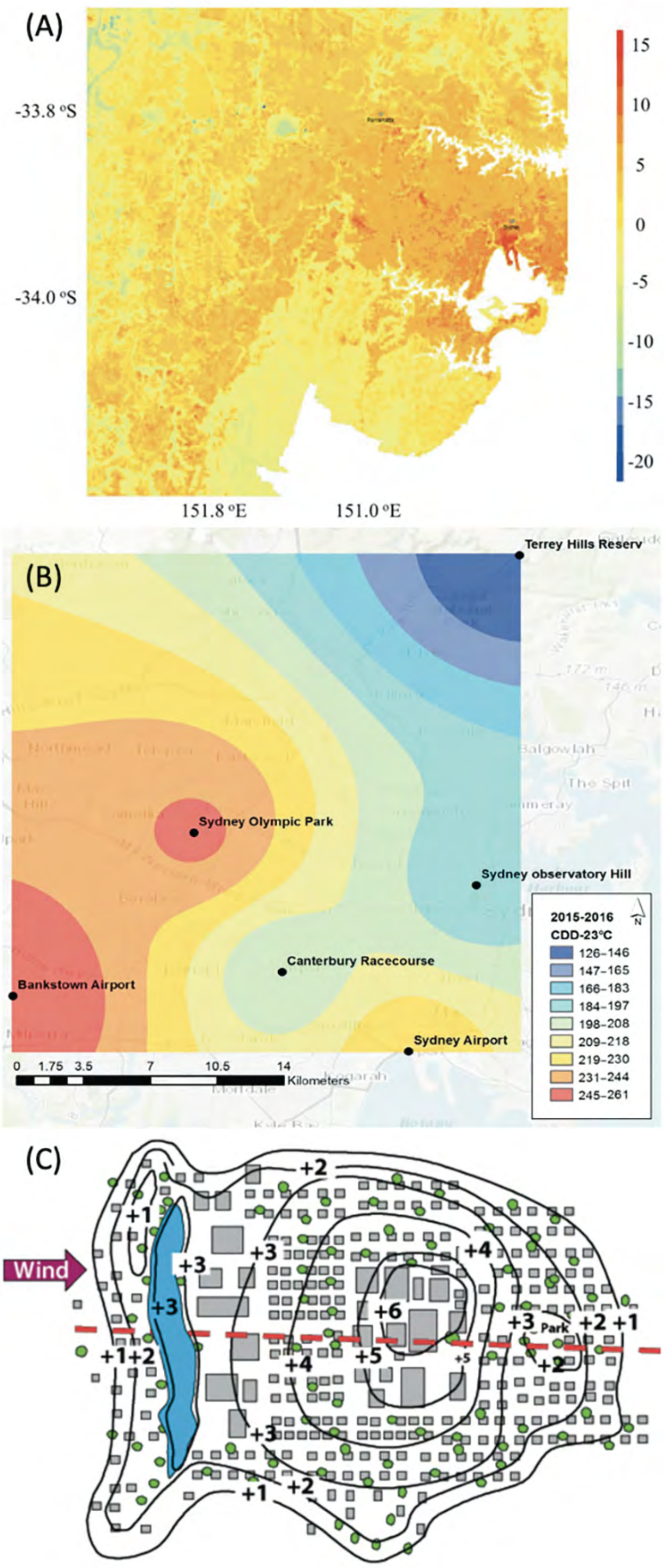


FIGURE 3: Studying urban heat at different scales. (A) Distribution of heat across the Greater Sydney Basin on 05 November 2013 9:45. The image was generated using satellite imagery (Sidiqui *et al.*, 2016). (B) Map depicting Cooling Degree Days (i.e. cooling energy demand index) for the period between November 2015 and October 2016 across eastern and central councils of Sydney (Santamouris *et al.*, 2017). (C) Conceptual map of a nighttime Urban Heat Island developed over a residential precinct using isotherms to depict air temperature differentials. The red line indicates a transect along which measurements were collected (online available at www.epa.gov/heat-islands).

ranges, coastlines, planes or river systems. Reducing scale, the urban landscape begins to break up into distinct grey, green and blue infrastructure components like residential, industrial or commercial zones, parklands, creeks, dams or lakes. Zooming in even further, individual components reveal a highly heterogenous mosaic of structures made from a wide range of materials that differ in surface, colour and thermal characteristics. Depending on the level of scale, the heterogeneity of objects and their influence on urban heat varies. Thus, urban heat and UHIE have several gradations that can be studied (Fig. 3):

1. macro scale – across the GSB, where air temperatures in peri-urban and rural zones are likely lower during the day, but more so during the night compared to densely populated spaces;
2. meso scale – differences in air temperatures among individual

suburbs; in the GSB, this applies to eastern (coastal), central and western (landlocked) suburbs;

3. micro scale – microclimatic variation of air temperatures over a small parcel of land, such as a precinct, a park or around a single building.

Since the first systematic documentation of UHIE in the 1950s (Duckworth and Sandberg, 1954; Sundborg, 1950), climate research has assessed effects of urban heat at these different scales (Oke, 1973; Oke, 1982; Akbari *et al*., 2009; Gunawardena *et al*., 2017). Macro-scale investigations generally rely on remotely sensed data and synoptic climate and landscape models (Heaviside *et al*., 2015; Duncan *et al*., 2019). While these investigations provide important information about cities and regional climate patterns and phenomena, they are rarely suitable to inform strategies and actions that aim to mitigate local heat.

In addition, assessments of urban heat using remotely sensed information (e.g. satellite-/drone-based infrared thermography) report findings based on surface temperature data. Resulting mapping products can be misleading, as they depict surface temperatures of objects and spaces that are not regularly frequented by the public, like roofs or road surfaces.

Meso- and micro-scale research can identify local heat patterns (Coutts *et al*., 2016; Ziter *et al*., 2019), optimise urban design (Gaitani *et al*., 2017), document human thermal comfort (Broadbent *et al*., 2018), and inform best-practice to reduce summer heat at the street level (Sanusi *et al*., 2017). However, as a result of financial or logistical constraints, these types of investigations are often spatially restricted to single locations. As a consequence, empirical knowledge about the variability of heat across complex urban topography remains limited.

The LGA of Campbelltown includes 36 suburbs, covers 310 km^2 and has a population density of 550 km^{-2}. Around 20% of that land is used for primary production, 9% for residential uses, 53% is located in National Parks and other permanently vegetated land and 20% has ‘other’ uses. Excluding the large area of bushland covered by the suburb of Holsworthy, which is mostly inaccessible to the public because of its military use, would substantially reduce the proportion of permanently vegetated land. It is for this reason that the canopy cover of the LGA was assessed as being between 30 and 40% (Jacobs *et al*., 2014). In reality, however, urban tree cover of the Campbelltown LGA is, according to the Greater Sydney Commission (2019), around 18%.

To date, there is only one permanently-operated weather station from the Bureau of Meteorology (BoM) within the boundaries of the LGA. This station is located 8 km to the east of Campbelltown CBD (Station #068263 in Holsworthy), where it is surrounded by bushland. A second station, 4 km from the CBD yet outside the LGA boundary, is located at Mt Annan Botanic Garden (Station #068257). Local climate information for suburbs within the LGA is not available. Using available climate data from the stations at Mt Annan and Holsworthy to gauge temperatures of suburbs and communities across the Campbelltown LGA is problematic, because these stations are not surrounded by grey infrastructure which can have an enormous effect on urban microclimates (Wong and Yu, 2008; Erell *et al*., 2011). Not knowing suburb-specific variation of air temperature represents several disadvantages. These relate to: (a) unknown exposure of citizens to extreme heat; (b) preparation of health and emergency services in the wake of heatwaves; (c) advising citizens about local hot and cool spots; (d) prioritising cooling interventions; (e) restricted capacity in urban planning and landscape design; and (f) unknown effectiveness of interventions that aim to mitigate local heat.

Information generated in the current project addresses several of these disadvantages by providing microclimate analyses based on empirical data collected across the entire LGA of Campbelltown. Development of a set of novel instruments and techniques allowed assessing urban heat at unprecedented scale. Results of this project traverse the boundary between micro- and macro-scales, and provide an enriched understanding of summer heat between Glenfield (north) and Wedderburn (south).

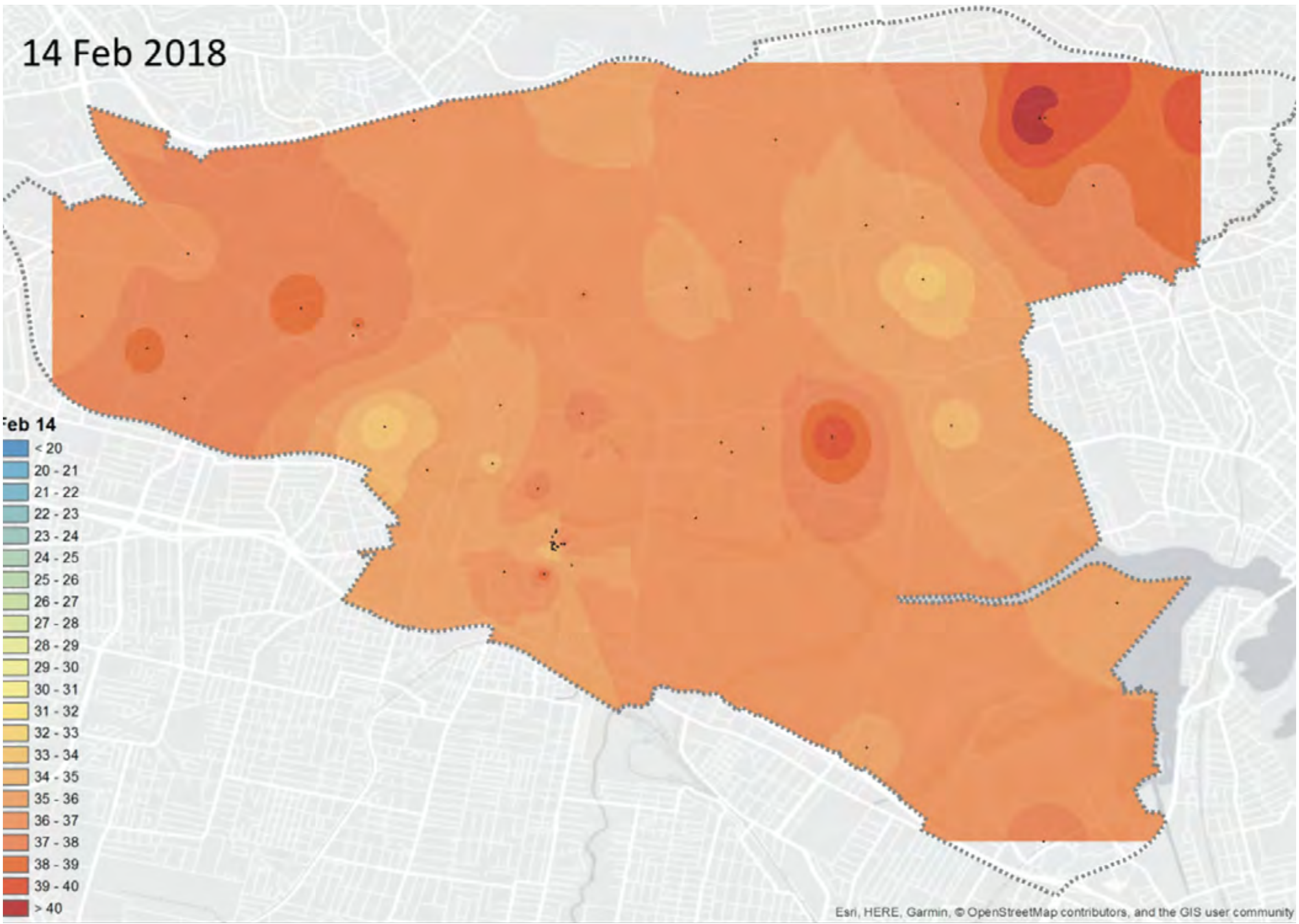
2. PROJECT HISTORY

The technical basis for the current project was developed and trialled during summer 2017/18, where Western Sydney University and the Future City Team of Parramatta City Council collected data of urban air temperatures using 80 data loggers. Results of the pilot provided proof of concept and allowed generation of initial microclimate maps (Fig. 4). Results were presented to the project team on 28 May 2018. Based on analysis of the pilot data and discussion among the team, several aspects of the work were refined. These included:

- optimised design of temperature recording equipment;
- refined documentation of measurement locations;
- optimised coverage of the LGA;
- inclusion of suburb names and boundaries in maps;
- improved strategy for selection of measurement locations; and
- expanded manpower to accelerate field deployment of loggers.

The resultant improvements were used to design and implement the current, full-scale research project.

FIGURE 4: Mean daytime microclimate map (10:00 – 17:00) generated with data collected during the pilot project. The map shows mean daytime air temperatures across most parts of the LGA during a day of extreme heat in February 2018. Variation of air temperature of more than 7°C is discernible among 62 locations included in the visualisation.



3. METHODOLOGY

3.1 THE HEAT LOGGER

Western Sydney University custom-built a low-cost device for continuous measurements of air temperature (hereafter called 'heat logger' for simplicity). The heat logger consisted of a commercially available temperature sensor (Tempmate.®-S1 V2, Imec Messtechnik, Heilbronn, Germany) (Fig. 5A). The sensor was mounted inside an inverted, white aluminium can to protect the sensor from direct solar radiation (Fig. 5B). Holes were drilled into the top of the shield to allow ventilation of the heat logger. The waterproof sensor was programmed to record air temperature at 10-minute intervals for 110 days with an accuracy of ±0.5°C (-20°C / +40°C) at a resolution of 0.1°C. Measurement quality was certified through international standards (e.g. CE, EN 12830).

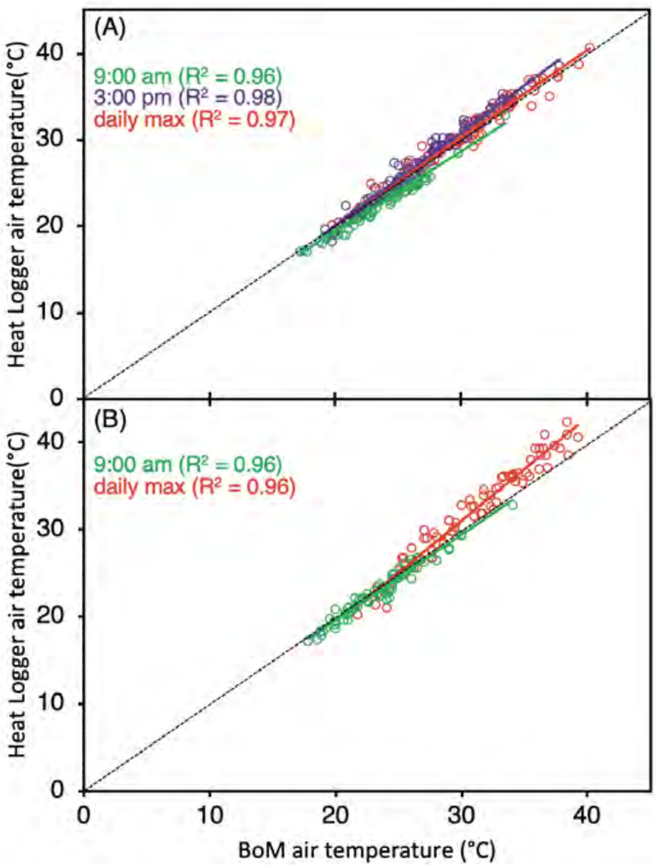
Three methods were used to evaluate the accuracy of the custom-built device prior to their use in the study. In a first test, data from heat loggers that were placed in the vicinity of meteorological stations operated by the Bureau of Meteorology (BoM). Air temperatures recorded between 28 November 2018 and 10 March 2019 from the heat loggers were compared to data (available online) recorded by the stations in North Parramatta and Sydney Olympic Park.

FIGURE 5: : Sensor (A) and shield (B) used for construction of the heat logger.

The second and third tests assessed performance of the individual sensor, as well as the heat logger, against a widely used air temperature logger (TGP 4500, TinyTag, Gemini Data Loggers, Chichester, United Kingdom) housed in a white Stevenson's Type Screen (ACS-5050, Hastings Data Loggers, Port Macquarie, Australia). To assess the accuracy of the sensor, one Tempmate.®-S1 V2 was placed next to the TinyTag logger inside the screen. A complete heat logger was hung next to the shield in a sunlit area of a residential garden in Sydney, Australia. These loggers recorded air temperatures at 10-minute intervals from 16 October 2018 until 02 February 2019, collecting a total of 47,520 individual measurements.

Results of the calibration analyses indicated high accuracy of the heat logger. Correlations between data from heat loggers and BoM weather stations at North Parramatta (station #066124) and Sydney Olympic Park (station #066212) yielded very high coefficients of determination (i.e. close to 1) (Fig. 6).

FIGURE 6: Relationship between air temperature measurements recorded by two weather stations operated by the Bureau of Meteorology (A: North Parramatta; B: Sydney Olympic Park) and the custom-built heat logger from Western Sydney University. Data for 09:00, 15:00 and maximum daily temperatures, recorded between 28 November 2018 and 10 March 2019, were used. A 1:1 line (black, dotted) as well as linear correlations of air temperature data (colours, solid), as well as coefficients of determination (R^2) for each data set are shown.



With permission of adjacent local governments, heat loggers were also placed outside the boundary of the Campbelltown LGA for technical reasons. This allowed placement of heat loggers near the weather station at Mt Annan Botanic Garden. Data from two loggers in the suburb of Mt Annan (#79 and #80, see Appendix 1) were compared to publicly available data from the station for additional quality control. One logger recorded data in William Howe Regional Park (surrounded by green infrastructure). The other logger was placed in a residential street near the botanic garden (surrounded by grey infrastructure). Linear correlations indicated that maximum daily temperatures measured at the station matched extremely well with those measured using the loggers (R^2 = 0.97-0.98) (Fig. 7).

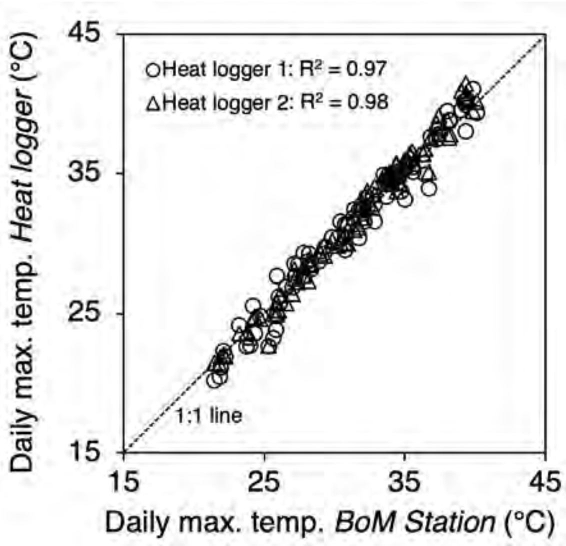


FIGURE 7: Relationship between maximum air temperature measurements recorded by an official weather station operated by the Bureau of Meteorology (#068257) and two WSU heat loggers in close proximity to the station. Heat logger 1 was at Solander Place, Mt Annan; heat logger 2 was at William Howe Regional Park, Mt Annan. The dashed 1:1 line indicates where x and y data are identical. Coefficients of determination for each data set are shown.

Temperature differentials (ΔT; difference between air temperature at the same point in time measured with the sensor/heat logger and the TinyTag) were calculated to assess the difference between measurements collected with the sensor or heat logger and the TinyTag logger. Negative ΔT indicated sensor/heat logger recording lower air temperatures, positive ΔT indicated higher air temperatures compared to the TinyTag logger. These analyses revealed that the sensor and heat logger deviated between -0.2°C and +0.3°C from the measurements collected with the TinyTag logger (Table 1). Differentials for maximum and minimum deviations were in a tolerable range, indicating that heat loggers capture accurate and reliable data.

COMPARISON	n	mean	SE	min	max
TEMPMATE SENSOR vs TINYTAG					
9am*	110	-0.15	0.01	-0.43	0.24
3pm*	110	-0.19	0.01	-0.60	0.08
Daily T_{max}	110	-0.13	0.02	-0.68	0.29
HEAT LOGGER vs TINYTAG					
9am	110	0.17	0.02	-0.46	0.77
3pm	110	-0.19	0.02	-0.90	0.26
Daily T_{max}	110	0.33	0.03	-0.41	1.38

TABLE 1: Qualitative analyses of air temperature differentials (ΔT) for the Tempmate.®-S1 V2 sensors, heat logger and the TinyTag logger. Abbreviations: n = number of measurements; SE = standard error of mean.

3.2 DEPLOYMENT AND RETURN OF HEAT LOGGERS

Field deployment of heat loggers by a team from Campbelltown Council commenced on 27 November 2018. By 01 December, 61 (55%) of 110 loggers were in position and recorded temperature data. The last heat logger was activated on 23 December 2018. Locations of loggers were pre-determined to increase time efficiency during deployment. At each location, the serial number of a sensor was noted before activating and assembling the heat logger. Each logger was mounted to a tree branch (approx. 2.5-3 m above ground) using a step ladder and cable ties. Using trees as support structures for the heat loggers offered several advantages, including their omnipresence in public space, being managed by Council, being accessible and providing additional protection. In newly built suburbs where mature trees were absent (Bardia, Macarthur Heights, Willowdale), heat loggers were mounted to light poles using a council-operated hydraulic platform (Fig. 8).

Besides light poles, heat loggers were placed in street and park trees, as well as in nature strips, green verges, reserves, native forest and other localities (Fig. 8). A complete list of locations is provided in Appendix 1. Care was taken that loggers were installed vertically with the open base pointing toward the ground. Once installed, the physical address, GPS location and tree species were noted.

Heat loggers were collected in mid-March 2019. Of the 110 logger that were deployed, eight were lost, representing a return rate of 93%. Although some of the heat sensors were severely damaged by animals (Fig. 9), complete data sets could be downloaded from 102 heat loggers. Figure 10 showing the resulting final network coverage of heat loggers across the LGA of Campbelltown.
The 102 loggers recorded a total of 1,462,095 individual measurements of air temperature. These data were truncated to yield a data set spanning from 01 December 2018 to 15 March 2019, leaving 1,447,911 measurements for analyses. We note that data coverage for the first two weeks in December 2018 is incomplete. Importantly, full data coverage was available for the first major heatwave event between 26 and 31 December 2018. In addition, we note that results shown for March only represent the interval of 01-15 March 2019.

FIGURE 8: Examples of the diverse urban and rural locations and tree species used for installing heat loggers. (A) *Eucalyptus tereticornis* tree along Moreton Park Road, Douglas Park. (B) *Angophora costata* near Georges River, Holsworthy. (C) Light pole at Macarthur Heights. (D) *Corymbia punctata* at a playground in Macarthur Heights. (E) *Eucalyptus tereticornis* along Camden Valley Road, Edmondson Park. (F) *Ulmus parvifolia* in the CBD of Ingleburn. Visible heat loggers are highlighted inside yellow circles.

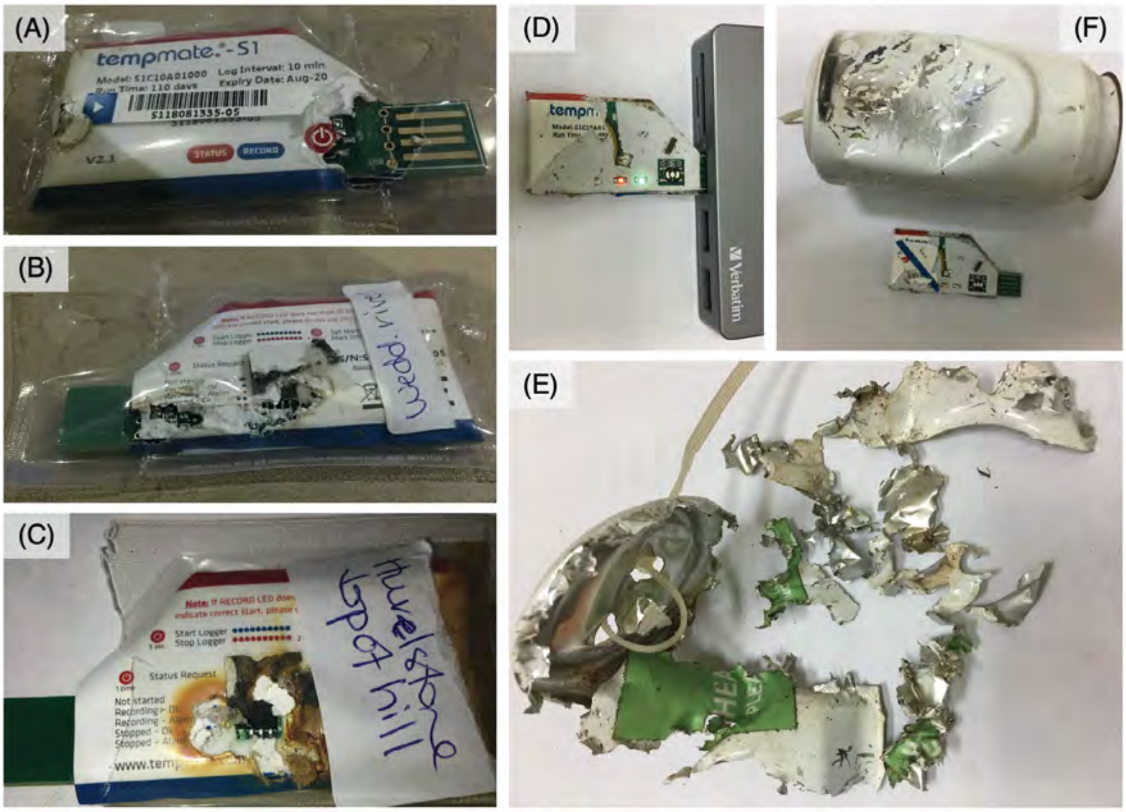


FIGURE 9: Damage of sensors and protective shields in the field. (A-C) Chewing marks and burn traces on sensors. (D) Damaged logger during data download. (E, F) Examples of vandalism. Data from all sensors shown were retrieved without complications, underlining the robustness of the sensor and its effectiveness in urban research.

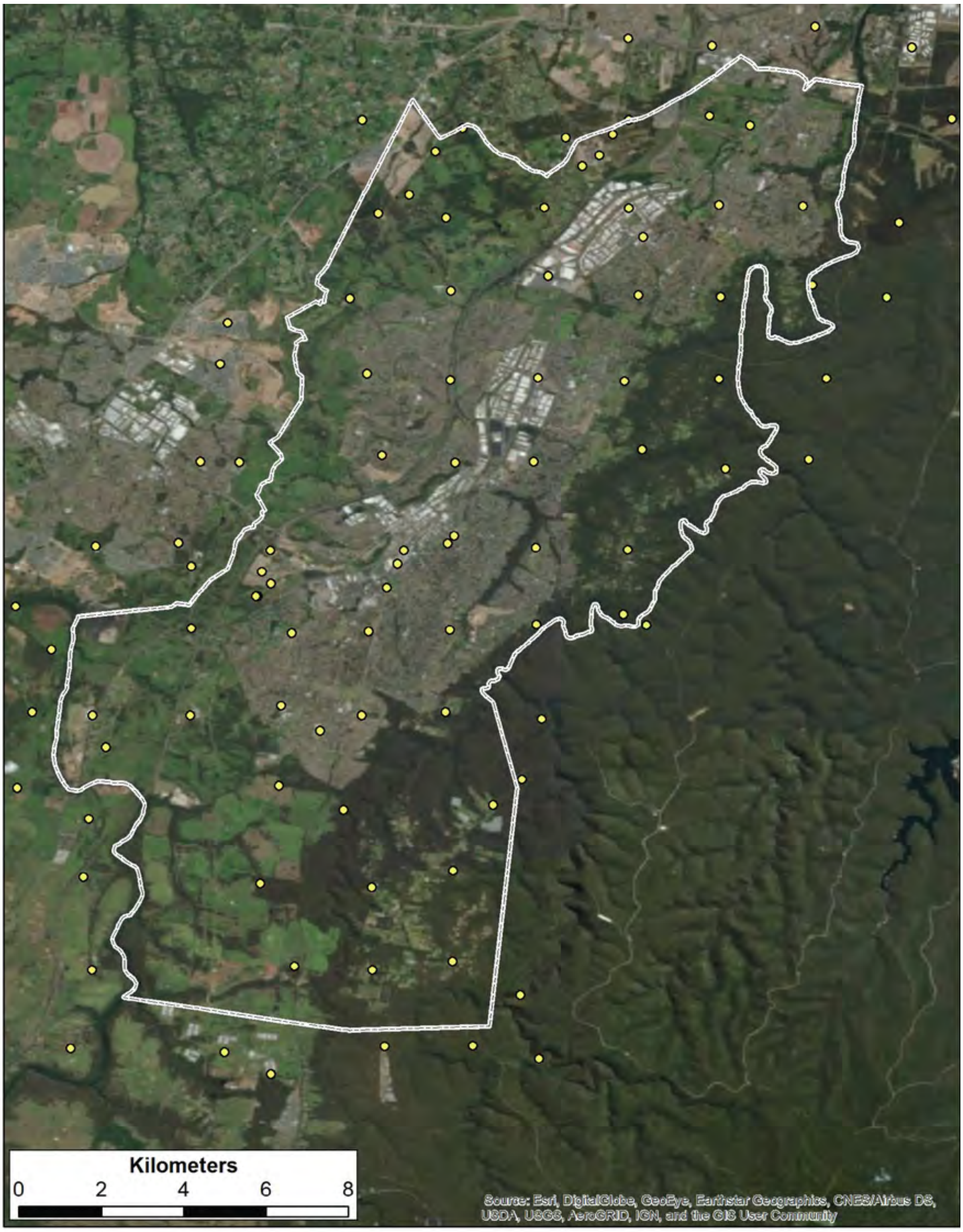


FIGURE 10: Location of heat loggers across the LGA of Campbelltown. The white line delineates the area of investigation, excluding a large proportion of the native bushland to the east. This bushland is part of the Campbelltown LGA but is closed for public access due to military use. Yellow dots indicate locations from which loggers were retrieved. Clearly visible is the coverage of urban, peri-urban, rural and forested landscapes. Loggers were also placed in well-established and newly developed and developing suburbs. A relatively higher concentration of heat loggers is visible around the CBD of Campbelltown (central), Macarthur Heights (west) and Bardia (north). Locations outside of the boundaries of the LGA were included to reconstruct climate within the boundaries of the LGA accurately.

4. PROJECT FINDINGS

4.1 OVERVIEW

Average summer temperature between 01 December 2018 and 15 March 2019 across the 102 measurement locations was 23.4 °C (±5.4; ±1 standard deviation of the mean) (Fig. 11). Three heatwave periods were captured in December 2018 (25 December 2018 to 02 January 2019) and January 2019 (15-18 January 2019 and 25-27 January 2019). Here, heatwaves are defined as events where maximum daily air temperature was above 38°C for at least three consecutive days.

The absolute hottest temperature was 45.4°C, measured on 28 December at 14:10 and on 29 December between 14:20-14:50 in open Grey Gum Forest on a ridge in the northwest of Holsworthy. The coolest temperatures were generally measured in the southern section of the LGA, namely in Appin, Wedderburn and Menangle, where they fell below 10°C. The absolute coldest temperature in summer 2018/19 was 7.5°C, recorded in the early morning hours (5:50 – 6:10) on 24 December at the Dharawal National Park (Appin). Mean nighttime temperatures during January were with 21.7°C, particularly high compared to all other months where they were below 20°C.

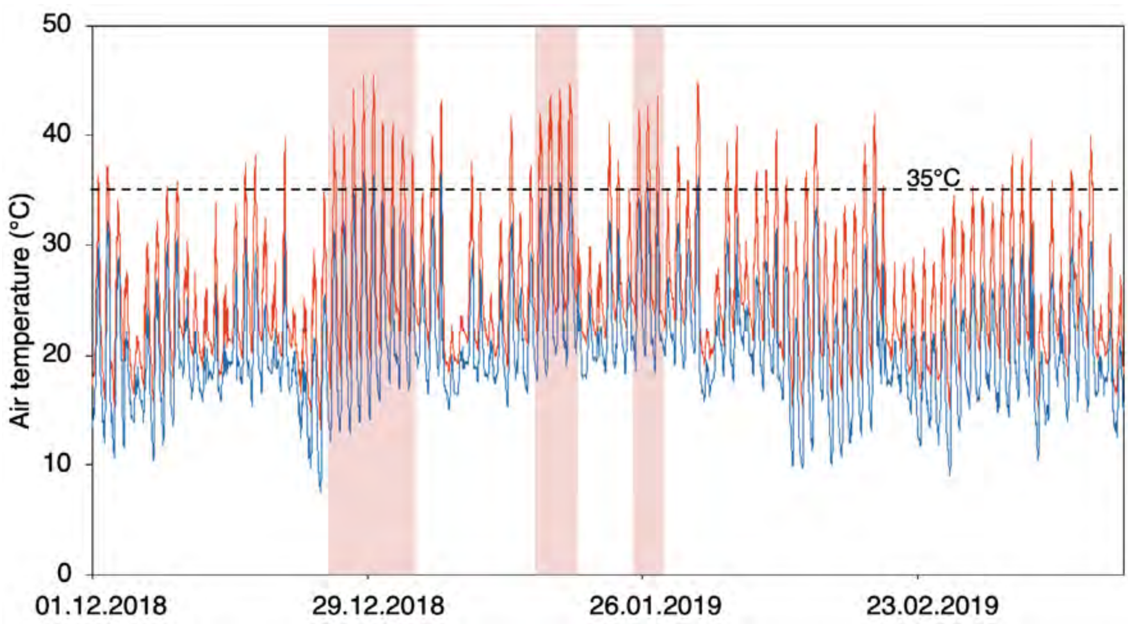


FIGURE 11: Overview of absolute maximum (red) and minimum (blue) air temperatures recorded at 102 locations across the LGA of Campbelltown. The dashed line indicates 35°C, a threshold temperature, above which heat becomes extreme. Areas marked in red indicate heatwave periods (25 December 2018 – 02 January 2019; 15-18 January 2019; 25-27 January 2019). See text for a definition for heatwave conditions.

Heat loggers collected information in 40 suburbs in and around the LGA of Campbelltown. Among these 40 suburbs, most measurement locations were in Holsworthy (n = 11), Wedderburn (n = 6), Ingleburn and Macarthur Heights (both n = 5). The remaining suburbs contained four or less measurement locations.

Loggers were predominately mounted to *Eucalyptus* (n = 53), *Corymbia* (n = 11) and *Angophora* (n = 7) trees, reflecting the large presence of native tree vegetation present across the LGA. Within these three genera, *E. tereticornis* was by far the single most species present (n = 16), followed by *E. microcorys* and *E. mollucana* (both n = 7). *Corymbia maculata* (n = 4) and *A. floribunda* (n = 4) were the most frequently used species within the other two genera. Of the total of 38 species, heat loggers were affixed to a single representative of 23 species (Appendix 1).

4.2 AIR TEMPERATURES ACROSS CAMPBELLTOWN

January 2019 was the hottest month (mean: 25.2°C ±5.2). Mean temperature in December 2018, February and March 2019 was slightly lower with 22.6 °C. Mean daily temperatures were most variable in December 2018 (±5.7) and least variable in March 2019 (±4.7). The warmest mean summer temperatures were measured in Campbelltown CBD, followed by Raby and Edmondson Park (Table 2). Three newly developed suburbs, Gregory Hills, Bardia and Willowdale, were among the top 10 hottest suburbs. The lowest mean summer temperatures were measured in Appin and Wedderburn in the southern, largely rural part of the LGA.

The ranking of suburbs according to mean summer temperatures could potentially be influenced by differences in the number of measurement points within each suburb. For this reason, a more detailed analysis is provided based on individual locations further below. However, the 'hottest' and 'coolest' suburbs had four or six measurement locations each within their boundaries. This makes a compelling argument that these suburbs have indeed very juxtaposing microclimates. Structure of these suburbs, with Campbelltown dominated by hard surfaces and build environment, and Wedderburn with mostly open, natural surfaces and high coverage of green infrastructure, certainly plays a supreme role in generating a difference in mean summer temperature of 2.1°C (Table 2). Distance between these two suburbs is only 8 km.

Rank	Suburb	Measurement locations	Mean temperature (°C)
1	Campbelltown	4	24.5
2	Raby	1	24.2
3	Edmondson Park	2	24.1
4	Ambervale	1	24.0
5	Casula	2	24.0
6	Gregory Hills	1	24.0
7	Bardia	4	23.9
8	Willowdale	3	23.9
9	Woodbine	1	23.9
10	Ingleburn	5	23.9
11	Gledswood Hills	1	23.8
12	Glen Alpine	1	23.8
13	Bradbury	2	23.7
14	Denham Court	2	23.7
15	Claymore	1	23.6
16	Currans Hill	2	23.6
17	Leumeah Park	1	23.6
18	Macarthur Heights	5	23.6
19	Glenfield	2	23.6
20	Macquarie Fields	2	23.6
21	Menangle Park	3	23.5
22	Minto	3	23.5
23	Mt Annan	4	23.5
24	Varroville	4	23.5
25	Eschol Park	1	23.5
26	Ruse	1	23.5
27	Leppington	1	23.4
28	Holsworthy	11	23.4
29	St Helens Park	1	23.2
30	Menangle	4	23.2
31	Kentlyn	4	23.1
32	Camden Park	2	23.1
33	Gilead	4	23.1
34	Rosemeadow	2	23.0
35	Lynwood	1	22.9
36	Airds	1	22.7
37	Douglas Park	1	22.7
38	Spring Farm	1	22.6
39	Appin	4	22.4
40	Wedderburn	6	22.4

TABLE 2: Ranking of suburbs according to mean air temperature measured between 01 December 2018 and 15 March 2019.

Using absolute maximum temperatures measured within and across suburbs, results in a similar ranking. Campbelltown and Wedderburn once more are among the hottest and coolest suburbs (Table 3). While Holsworthy was ranked #28 when using mean temperatures, the area was #4 when using maximum temperatures as ranking criterion. Clearly, a maximum temperature of 42.8°C as an average of 11 measurement locations indicates that Holsworthy is a very hot place during heatwaves. Yet, the significant difference between mean and absolute maximum temperatures indicates that while the area is hot during the day, it also cools down well during the night. This in an important thermal characteristic that natural environments have and build environments lack, most prominently documented by UHIE. It is no surprise that the measurement location at Spring Farm had the lowest absolute maximum temperature. This location was inside a riparian forest alongside the Napean River, where the water body of the river and plant-available soil water generate evaporative cooling. This cooling effect is especially beneficial during periods of extreme heat.

Rank	Suburb	Measurement locations	Absolute max. temperature (°C)
1	Raby	1	43.8
2	Campbelltown	4	43.1
3	Woodbine	1	42.9
4	Holsworthy	11	42.8
5	Kentlyn	4	42.8
6	Bradbury	2	42.7
7	Leumeah Park	1	42.6
8	Macarthur Heights	5	42.4
9	Gledswood Hills	1	42.3
10	Ambervale	1	42.2
11	Eschol Park	1	42.2
12	Ruse	1	42.2
13	Menangle	4	42.1
14	Minto	3	42.0
15	Menangle Park	3	42.0
16	Mt Annan	4	42.0
17	Ingleburn	5	41.9
18	Currans Hill	2	41.9
19	Leppington	1	41.8
20	Edmondson Park	2	41.8
21	Bardia	4	41.7
22	Varroville	4	41.7
23	Casula	2	41.5
24	Willowdale	3	41.4
25	Airds	1	41.4
26	Gregory Hills	1	41.4
27	Appin	4	41.1
28	Camden Park	2	41.1
29	Glen Alpine	1	40.9
30	Gilead	4	40.8
31	Claymore	1	40.7
32	Macquarie Fields	2	40.7
33	St Helens Park	1	40.7
34	Rosemeadow	2	40.7
35	Wedderburn	6	40.7
36	Denham Court	2	40.5
37	Douglas Park	1	40.2
38	Glenfield	2	40.1
39	Lynwood	1	40.1
40	Spring Farm	1	38.5

TABLE 3: Ranking of suburbs according to absolute maximum air temperature measured between 01 December 2018 and 15 March 2019. If more than one heat logger was present in a suburb, absolute max. temperature was calculated as average of the loggers.

Observations from individual sites mirror those described above for suburbs. Mean summer temperature varied 2.6°C among the 102 measurement sites, with the top three warmest sites in Campbelltown (Table 4). The 10 sites with the lowest minimum temperatures were all in Appin and Wedderburn. Minimum, as well as mean and maximum temperatures from individual sites indicated that placing heat loggers on light poles, where they could have been exposed to more solar radiation compared to loggers placed under tree canopies, had no effect on recorded data. The warmest 'light pole site' was in Bardia, where mean summer temperatures were 0.4°C lower compared to the warmest site in Campbelltown. Light pole sites at Willowdale and Macarthur Heights had even lower mean summer temperatures. No systematic influence of the structure supporting the heat loggers was detected at Bardia and Macarthur Heights where temperature data were collected using light poles and trees (Appendix 1).

Sites that were generally warm throughout summer also tended to have higher minimum temperatures. Site-specific data on mean and absolute minimum temperatures showed a significant positive correlation ($p < 0.0001$) (Fig. 12). This is an important finding, as it points towards UHIE influencing urban microclimate at night across the Campbelltown LGA. Minimum temperatures are regularly recorded during early morning hours. Stored energy in hard surfaces and other build infrastructure emits heat throughout the night, leading to less nighttime cooling and subsequent higher minimum temperatures. In contrast, greater cooling is usually found in areas where vegetation dominates large open spaces (e.g. sports fields, golf courses). Less energy is stored in such places during the day, and any residual energy is lost quickly into the surrounding atmosphere in the early night. Data from Campbelltown clearly show that *warm places stay warm*. The relationship between mean and absolute maximum temperatures was also positive and statistically significant ($p < 0.0001$), yet considerably weaker ($R^2 = 0.15$, data not shown).

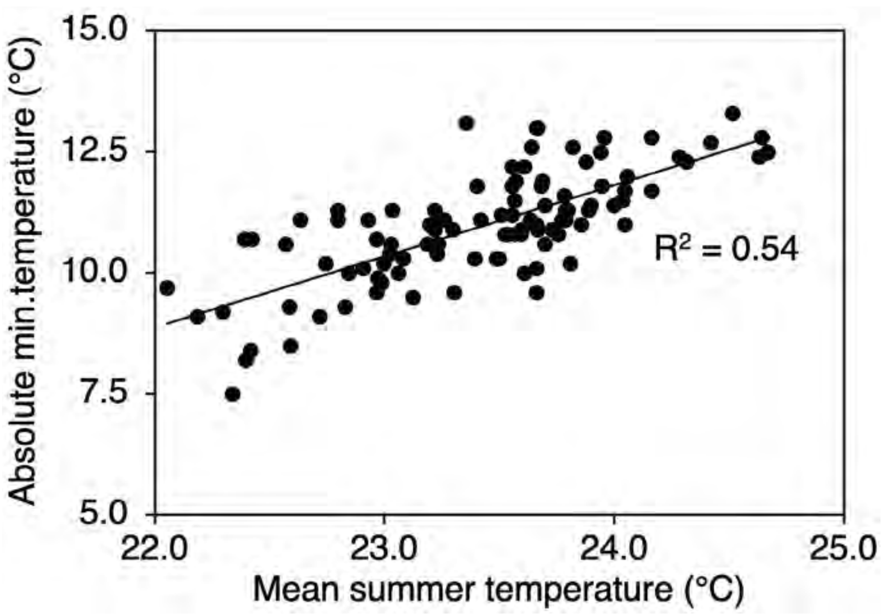


FIGURE 12: Relationship between mean summer temperatures and absolute minimum temperatures across 102 measurement locations in and around the LGA of Campbelltown. Solid line indicates linear correlation. Coefficient of determination is shown.

4.3 DAY AND NIGHT TEMPERATURES

Between 01 December 2018 and 15 March 2019, mean daytime (10:00-18:00) temperature across the LGA was 28.1°C (±5.0). Mean nighttime (21:00-05:00) temperature during the same time interval was 19.9°C (±2.9). January 2019 was the warmest month, with a mean temperature of 29.9°C during days and 21.7°C during nights.

During summer 2018/19, the warmest daytime temperatures were recorded at the end of Newman Road in Kentlyn (29.5°C), followed by a location in the bushland of Holsworthy parallel to Macquarie Fields (29.2°C). Among the top 10 warmest mean daytime temperatures were eight locations at Holsworthy and three locations each in Campbelltown, Ingleburn and Mt Annan (Table 4). Appendix 2 provides a complete list of mean, maximum and minimum daytime temperatures.

Similar to the coolest overall temperatures during the entire summer (section 4.2), also the coolest daytime temperatures were recorded in the Dharawal National Park near O'Hares Creek (26.3°C). Here it was more than 3°C cooler during daytime compared to Kentlyn. The absolute lowest daytime temperature during the summer 2018/19 was 16.5°C, measured at Victoria Road in Wedderburn and along a fire trail in Dharawal National Park (Appin). At Wedderburn, 16.5°C was recorded at midday on 05 December 2018, while at Dharawal National Park, this temperature was measured on 23 February 2019.

Rank	Mean summer daytime temp. (°C)	Suburb
1	29.5	Kentlyn
2	29.2	Holsworthy
3	29.1	Bardia, Campbelltown (twice), Holsworthy
4	29.0	Campbelltown, Menangle Park
5	28.9	Holsworthy (twice), Raby
6	28.8	Holsworthy, Ingleburn, Macarthur Heights, Varroville, Willowdale, Woodbine
7	28.7	Appin, Minto
8	28.6	Edmondson Park, Eschol Park, Gledswood Hills, Ingleburn (twice), Menangle Park, Mt Annan, Willowdale
9	28.5	Gregory Hills, Holsworthy, Macarthur Heights, Mt Annan
10	28.4	Ambervale, Appin, Bradbury, Casula, Edmondson Park, Holsworthy (twice), Mt Annan, Ruse, Verroville

TABLE 4: Top 10 warmest mean daytime temperatures and the respective suburbs where they were measured. "Twice" means that two locations in that suburb were represented.

Mean nighttime temperatures ranged from 17.7°C at Appin to 21.4-21.5°C around Campbelltown and 21.6°C at Ingleburn. The warmest nighttime temperatures were measured at Campbelltown (31.7-32.6°C) and Ingleburn (31.8-32.0°C) during the second heatwave in mid-January 2019 (18 January, 22:00).

Regression analyses revealed trends in general thermal performance of measurement locations. There was a significant and positive relationship between mean daytime and absolute maximum daytime (R^2 = 0.66, p <0.0001) (Fig. 13). This relationship indicates that sites that are generally warmer during the day tended to also get very hot during heatwaves. Similarly, sites that remained generally cool during nighttime were also the sites that cooled down the most during cold nights. Mean nighttime temperatures correlated stronger with absolute minimum temperatures (R^2 = 0.82, p <0.0001). Taken together, these results point towards the importance of site-specific characteristics related to absorption, storage and emission of solar energy and their impact on microclimate. Understanding the direction and magnitude of influence of these characteristics should be subjects of further research.

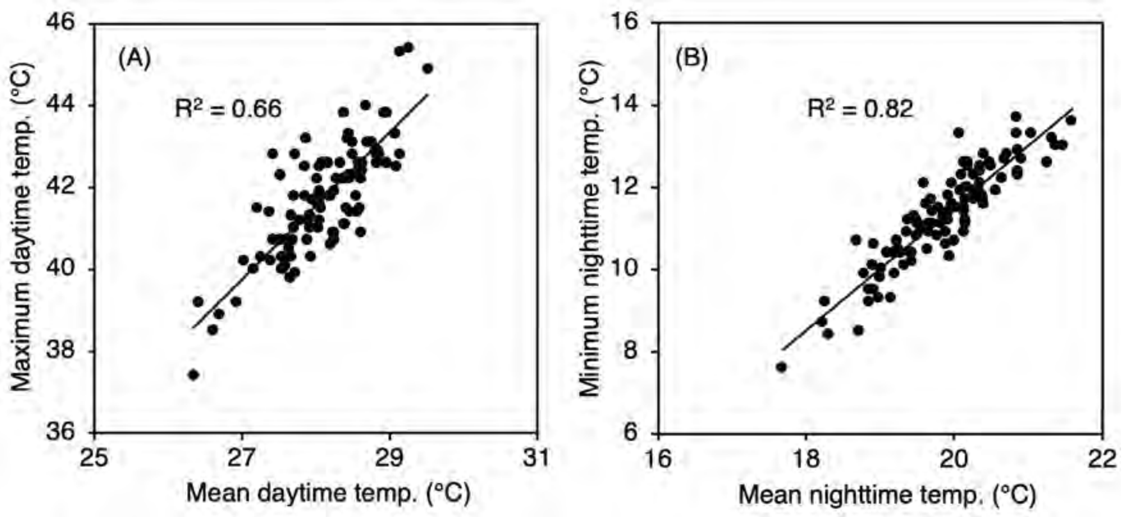


FIGURE 13: Relationship between (A) mean and maximum daytime temperatures and (B) mean and minimum nighttime temperatures of 102 measurement locations in and around Campbelltown. Solid lines indicate linear regressions and coefficients of correlation are shown.

It is well known that dense urban space retains heat more than peri-urban and rural landscapes during nighttime, resulting in UHIE. Air temperature data collected during this project confirm a pronounced UHIE for the LGA of Campbelltown. To better understand the thermal effect of UHIE across the LGA, each measurement location was assigned a land use, being urban (n = 45), rural (n = 35) or forest (n = 22). General linear modelling was used to assess the effect of land use on nighttime temperatures. Mean, maximum and minimum nighttime temperatures were significantly higher in urban compared to rural and forest locations ($p < 0.0001$).

Maximum and minimum nighttime temperatures were on average 1.5°C warmer in urban compared to forest sites (Fig. 14). Two sites of the ‘forest’ category located in Wedderburn and Appin had a particularly strong influence on this large temperature decline. In absolute terms, these two sites were nearly 6°C cooler compared to urban locations in Bardia and Willowdale (both newly built suburbs) where minimum nighttime temperatures were 13.7°C.

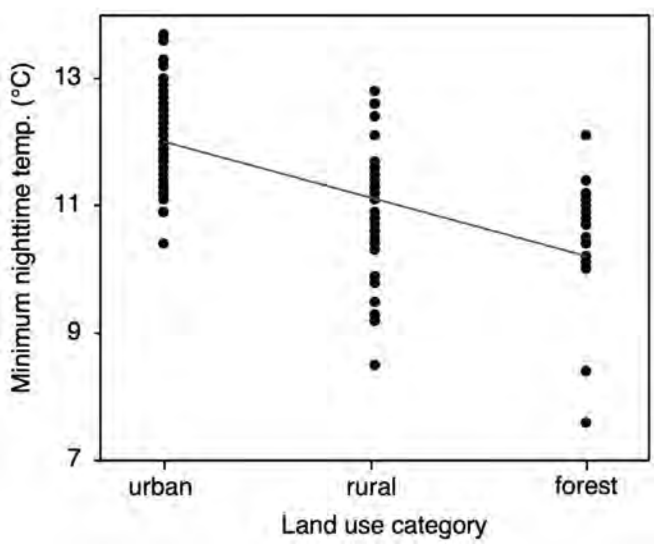


FIGURE 14: Effect of land use on mean minimum nighttime (21:00-05:00, 01 December 2018 – 15 March 2019) temperatures across the LGA of Campbelltown. Data from 102 measurement locations are shown. Solid line indicates linear fit.

Furthermore, the area covered by heat loggers was divided into nine zones. The zones were (1) north west, (2) north central, (3) north east, (4) central west, (5) central, (6) central weast, (7) south west, (8) south central and (9) south east. The M7 motorway in the west and the rapid change from urban space to native bushland in the east of the LGA were used to separate western and eastern from central regions in the north, centre and south (Fig. 15). Urban land use was absent from all three southern zones where land use was predominately rural and forest.

The largest temperature decline from urban to rural land use was observed in the central west zone, followed by central and central north zones. Surprisingly, the highest mean daytime and also the highest maximum daytime temperatures were calculated for the north eastern zone, which is dominated by native bushland. However, the central zone around Campbelltown CBD produced the second highest mean and maximum daytime temperatures. The south central and south east zones where the urban category was absent generally had the coolest daytime and nighttime temperatures, including absolute maximum and minimum measurements. Analysis of temperatures by zones clearly identified the central and north central zones as the hottest during the night (Fig. 15). These two zones were dominated by dense urban land use where maximum nighttime temperatures remained high, providing a typical example of UHIE.

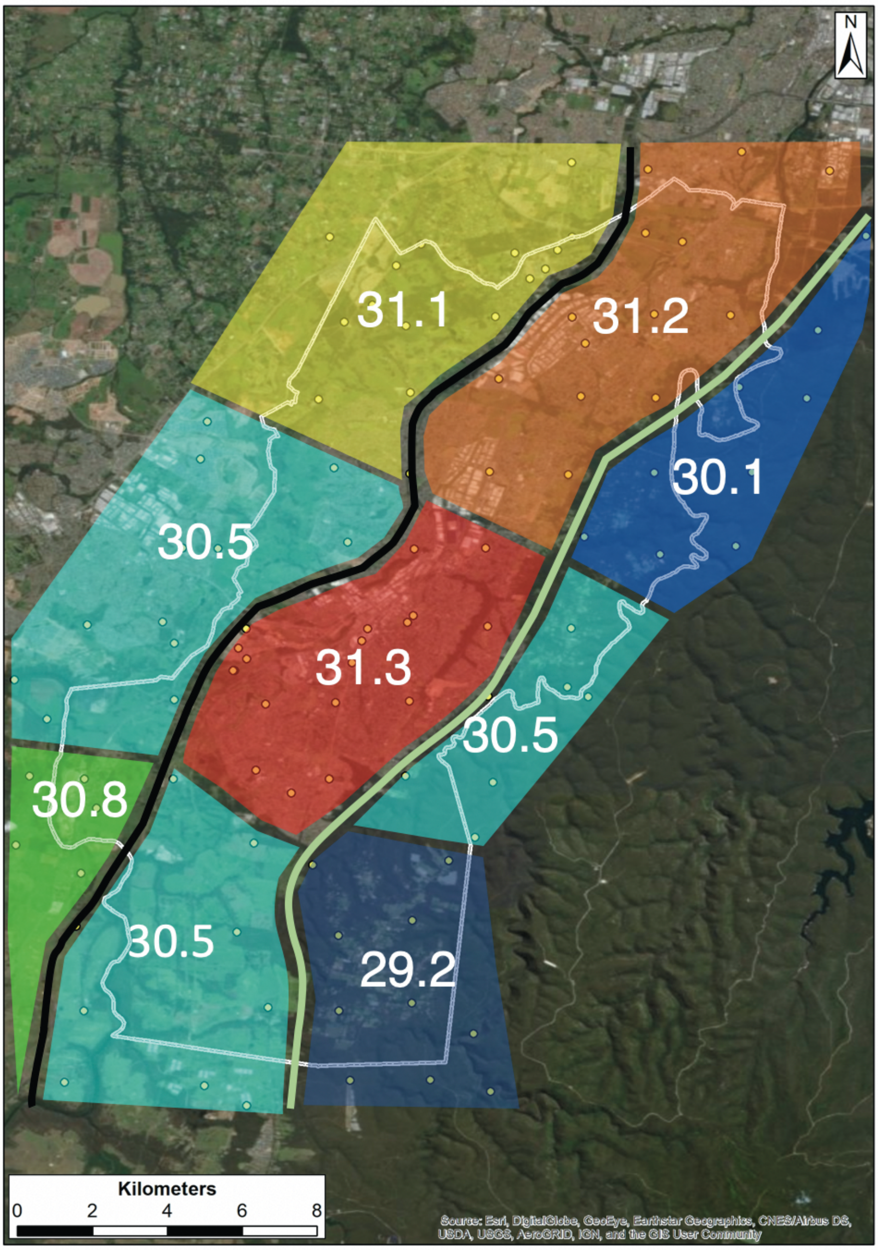


FIGURE 15: Example of the Urban Heat Island Effect. Mean maximum nighttime temperatures according to nine zones across the LGA of Campbelltown. Data was recorded during the warm night of 18/19 January 2019 and averaged across measurement locations inside each zone. The black line traces the M7 motorway; the green line separates the eastern forested lands from predominately urban (north central and central zones) and rural (south central zone) land uses.

4.4 TEMPERATURE VARIATION

It is important to understand the variation among air temperatures measured at any point in time and space. For this purpose, temperature differentials (ΔT) were calculated. These ΔT represent the difference between absolute minimum and absolute maximum air temperature among the 102 locations at each single time point. It is acknowledged that microclimates at each location will be influenced by a range of factors, including albedo (a proxi for the reflectiveness of a surface) and thermal mass of surrounding structures, canopy density of trees, proximity of sources of anthropogenic heat, and others. The present analyses do not attempt to determine the potential extent of these influencing factors, but treat measurements from each location equally. Across all locations and time points, ΔT varied on average by 5.1°C and was lowest during a rainy night (1.2-1.6°C on 13/14 December 2018) (Fig. 9).

Daytime (10:00 – 18:00) ΔT varied on average by 5.9°C among all locations. A visual representation of this type of variation and its spatial distribution across the LGA is depicted for a regular summer day in Fig. 23. ΔT generally increased during periods of extreme heat. For example, during the heatwave between 15 and 18 January 2019, ΔT regularly exceeded 9-10°C during the day. On 16 January at 17:50, these high ΔT originated from high temperatures at Menangle Park (41.2°C) and low temperatures at Holsworthy (30.1 °C).

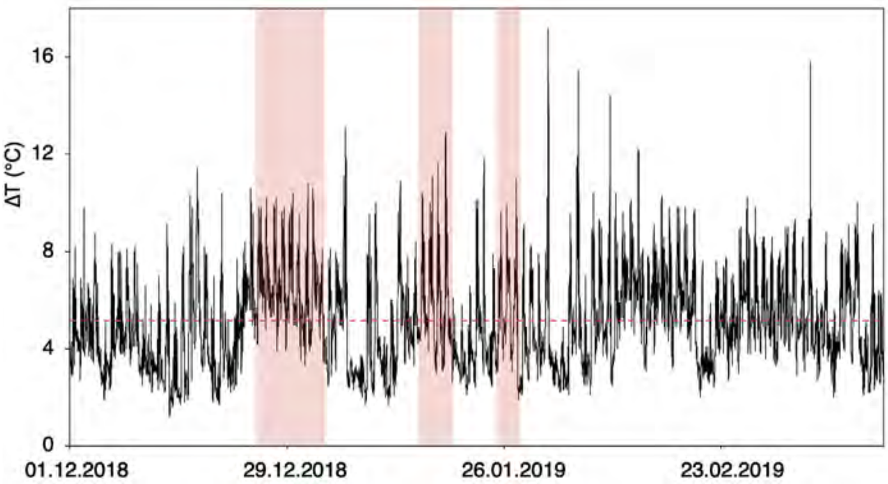


FIGURE 16: Temperature differentials (ΔT) calculated for each time point across 102 measurement locations between 01 December 2018 and 15 March 2019. ΔT indicates the variability of air temperature across the LGA of Campbelltown Areas marked in red indicate heatwave periods (25 December 2018 – 02 January 2019; 15-18 January 2019; 25-27 January 2019). The red dashed line indicates mean ΔT of 5.1°C.

ΔT of nighttime temperatures was slightly lower (4.3°C) compared to daytime ΔT. Yet, similar to daytime ΔT, during intervals of extreme heat, also nighttime ΔT increased well above 4°C, reaching as high as 7.4°C on 28 December 2018 at 23:30 (25.2°C at Denham Court, 17.8°C at Camden Park).

The largest ΔT was regularly observed during the time when extreme heat was pushed out of the LGA by a cold front (Fig. 17 and Fig. 28). These synoptic conditions were characteristic in signifying the end of heatwaves. Following the build-up of heat over several consecutive days, the cool changes swiftly replaced the hot with notably cooler air masses. The greatest ΔT was detected at 17:40 on 31 January 2019, where after a day of extreme heat, a cold front approached from the south. The rapid replacement of heat by much cooler air resulted in a ΔT of 17.2°C (43.3°C at Korringa Reserve in St Andrews; 26.0°C at Hodgson Close in Wedderburn). Similar rapid changes in air temperature due to fast moving cold fronts have been documented here for 08 February 2019 (max. ΔT 14.7 °C at 16:50) and 06 March 2019 (max. ΔT 15.8°C at 13:30) (Fig. 17). Notably, once a cool change had passed, ΔT across the LGA was much smaller compared to the time before the cool change, indicating that heat stored in structures and surfaces had dissipated quickly.

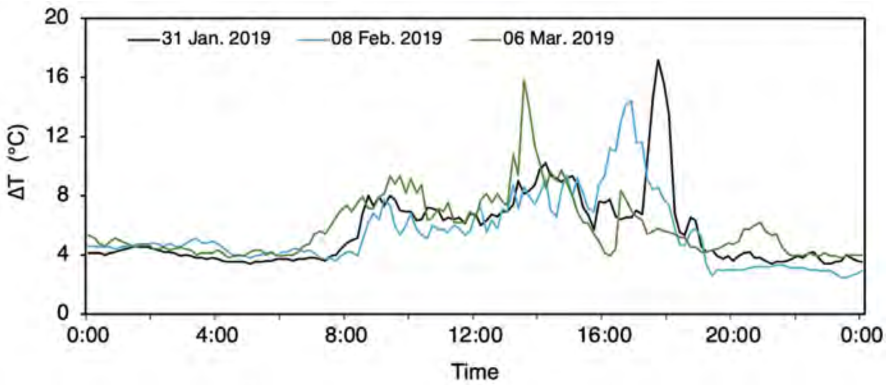


FIGURE 17: Daily course of temperature differentials (ΔT) across the LGA of Campbelltown. Air temperatures during 31 January and 08 February 2019 reached extreme levels above 40°C. In the late afternoon of both days, a cool change caused air temperatures to drop rapidly. Timing of cooling at each geographic location across the LGA depended on direction of the cool change, resulting in large ΔT among measurement locations.

4.5 HEAT DAYS

This project recorded detailed information of microclimatic variability during three heatwaves and also a large number of very hot days. As mentioned before, the hottest temperature in the Campbelltown LGA was 45.4°C, measured during the afternoon of 31 December 2018 in native bushland at Holsworthy. At the same time that day, the BoM stations at Mt Annan and Holsworthy recorded maximum temperatures of 40.1°C and 40.9°C, respectively. Between 01 December 2018 and 15 March 2019, heat loggers recorded extremely hot air temperatures (i.e. above 35°C) during 54 days. At Mt Annan such temperatures were measured during 23 days and at Holsworthy during 22 days.

Even more extreme, air temperatures >40°C were recorded during 22 days across the LGA, whereas these dangerous levels of heat were only recorded during five days at Holsworthy, and just once (05 January 2019) at Mt Annan. On a technical level, the larger number of days above 40°C recorded at the BoM station at Holsworthy compared to Mt Annan confirms the trend of greater heat in the north east of the LGA documented by heat loggers. Taken together, the significantly higher number of extremely hot days documented with heat loggers around the LGA indicates that communities of Campbelltown are exposed to very high levels of heat more frequently than previously known. It is reasonable to expect that similar microclimatic conditions can be found across other LGAs of the central Sydney Basin. This finding should have far-reaching implications of how heat resilience of urban space and its populations is assessed and valued.

There were 17 days where extreme hot temperatures (>35°C) were recorded at 90 locations or more. Extreme heat was most widespread during the first summer heatwave (27-29 December 2018), the second heatwave (15-18 January 2019) and three days in January 2019 (05, 26, 31 January) where all 102 heat loggers recorded maximum temperatures at or above 35°C. The Campbelltown LGA experienced the highest and most widespread levels of heat at 15:10 on 29 December 2018, where temperatures >40°C were recorded at 65 measurement locations.

The 10 hottest locations throughout summer were at Kentlyn, Holsworthy, Appin, Minto, Campbelltown, Bardia and Menangle Park (Table 5). These locations had the largest number of days between 01 December 2018 and 15 March 2019 where daily maximum air temperature was at or above 35°C. The top 4 hottest locations were in the north east of the LGA. These sites were dominated by native bushland. While these sites also showed high numbers of days above 40°C, there were seven sites that never experienced such high temperatures. These 'cool' locations were all situated in the south central or south east section of the LGA.

Rank	Suburb	Lat. (°)	Long. (°)	No. of days >35°C	No. of days >40°C	Absolute max. temp. (°C)
1	Kentlyn	-34.0442	150.8653	50	17	44.9
2	Holsworthy	-33.9946	150.9213	46	21	45.4
3	Holsworthy	-34.0287	150.9055	44	16	43.8
4	Holsworthy	-33.9720	150.9329	42	12	45.3
5	Appin	-34.1745	150.8283	40	12	44.0
6	Minto	-34.0288	150.8820	39	11	43.1
7	Campbelltown	-34.0662	150.8132	39	10	43.8
8	Bardia	-33.9799	150.8559	38	12	42.5
9	Campbelltown	-34.0647	150.8228	38	8	42.8
10	Menangle Park	-34.1022	150.7666	38	10	42.6
11	Willowdale	-33.9791	150.8201	37	11	42.8
12	Woodbine	-34.0471	150.8244	37	7	42.9
13	Holsworthy	-34.0825	150.8662	37	10	42.8
14	Mt Annan	-34.0832	150.7668	37	10	43.1
15	Holsworthy	-34.1163	150.8390	37	9	43.3
16	Campbelltown	-34.0691	150.8119	37	11	43.3
17	Holsworthy	-34.0464	150.9017	37	10	43.8
18	Varroville	-34.0095	150.8235	36	8	43.2
19	Varroville	-34.0112	150.8015	36	10	42.6
20	Eschol Park	-34.0276	150.8052	36	10	42.2
21	Ruse	-34.0656	150.8421	36	11	42.2
22	Appin	-34.1773	150.8427	36	9	42.2
23	Mt Annan	-34.0697	150.7669	35	10	42.3
24	Wedderburn	-34.1560	150.8239	35	10	42.8
25	Raby	-34.0290	150.8234	34	11	43.8
26	Bradbury	-34.0836	150.8233	34	10	43.8
27	Menangle Park	-34.1023	150.7453	34	12	42.6
28	Wedderburn	-34.1746	150.8091	34	9	42.8
29	Macarthur Heights	-34.0735	150.7842	34	10	42.6
30	Holsworthy	-33.9564	150.9241	33	7	41.8
31	Kentlyn	-34.0802	150.8612	33	9	43.2
32	Holsworthy	-34.1031	150.8433	33	10	42.2
33	Gregory Hills	-34.0255	150.7731	32	6	41.4
34	Campbelltown	-34.0631	150.8242	32	7	42.6
35	Gilead	-34.1390	150.7819	32	7	41.3
36	Menangle	-34.1579	150.7451	32	9	42.5
37	Macarthur Heights	-34.0662	150.7841	32	11	43.1
38	Macarthur Heights	-34.0763	150.7813	32	7	42.8
39	Macarthur Heights	-34.0763	150.7810	32	9	42.2
40	Willowdale	-33.9739	150.8152	31	7	41.5
41	Ingleburn	-34.0105	150.8644	31	6	41.9

TABLE 5: Complete list of measurement locations ranked by the number of days where maximum daily air temperatures were at or above 35°C. Also shown are the number of days where maximum daily air temperatures were at or above 40°C, as well as absolute maximum temperature. The ranking used air temperature measurements recorded between 20 December 2018 and 28 February 2019.

Rank	Suburb	Lat. (°)	Long. (°)	No. of days >35°C	No. of days >40°C	Absolute max. temp. (°C)
42	Gledswood Hills	-34.0165	150.7748	31	8	42.3
43	Minto	-34.0292	150.8614	31	6	41.2
44	Edmondson Park	-33.9544	150.8622	30	6	42.4
45	Edmondson Park	-33.9761	150.8486	30	7	41.1
46	Ingleburn	-33.9915	150.8623	30	6	42.6
47	Ingleburn	-34.0063	150.8447	30	7	42.9
48	Currans Hill	-34.0468	150.7688	30	7	41.8
49	Airds	-34.0824	150.8422	30	5	41.4
50	Menangle	-34.1249	150.7444	30	7	42.5
51	Macarthur Heights	-34.0709	150.7822	30	6	41.5
52	Casula	-33.9518	150.9030	29	5	41.8
53	Leppington	-33.9722	150.8042	29	4	41.8
54	Ingleburn	-33.9978	150.8655	29	6	40.9
55	Holsworthy	-34.0083	150.9025	29	5	41.5
56	Leumeah Park	-34.0469	150.8416	29	6	42.6
57	Kentlyn	-34.0661	150.8621	29	5	42.3
58	Glen Alpine	-34.0843	150.7888	29	5	40.9
59	Camden Park	-34.1015	150.7321	29	6	40.9
60	Casula	-33.9560	150.8805	28	5	41.1
61	Holsworthy	-34.0109	150.9187	28	5	41.0
62	Mt Annan	-34.0646	150.7641	28	7	41.4
63	Ambervale	-34.0839	150.8055	28	7	42.2
64	Bardia	-33.9823	150.8522	27	6	42.6
65	Ingleburn	-34.0108	150.8824	27	7	41.0
66	Minto	-34.0285	150.8425	27	6	41.8
67	Menangle	-34.1376	150.7433	27	9	41.7
68	Kentlyn	-34.0484	150.8835	26	4	40.7
69	Wedderburn	-34.1362	150.8240	26	7	41.5
70	Gilead	-34.1176	150.7860	26	3	40.7
71	Claymore	-34.0454	150.8085	25	2	40.7
72	Currans Hill	-34.0470	150.7773	25	4	41.9
73	Gilead	-34.1229	150.8001	25	6	41.2
74	Denham Court	-33.9740	150.8261	24	6	40.6
75	Lynwood	-34.1016	150.8224	24	3	40.1
76	Wedderburn	-34.1398	150.8063	24	4	40.2
77	Bradbury	-34.0744	150.8095	24	4	41.6
78	Menangle Park	-34.1092	150.7482	24	3	40.7
79	Menangle	-34.1181	150.7288	24	3	41.6
80	Bardia	-33.9754	150.8589	23	4	41.8
81	Varroville	-33.9936	150.8225	23	4	40.3
82	Mt Annan	-34.0652	150.7459	23	4	41.0
83	St Helens Park	-34.1023	150.8040	23	5	40.7

Rank	Suburb	Lat. (°)	Long. (°)	No. of days >35°C	No. of days >40°C	Absolute max. temp. (°C)
84	Bardia	-33.9722	150.8624	22	4	40.0
85	Willowdale	-33.9886	150.8144	22	4	40.0
86	Varroville	-33.9926	150.8076	22	5	40.5
87	Macquarie Fields	-33.9908	150.8820	22	3	40.7
88	Macquarie Fields	-33.9910	150.9004	22	4	40.7
89	Gilead	-34.1571	150.7894	22	0	39.8
90	Glenfield	-33.9734	150.8888	21	0	39.9
91	Glenfield	-33.9713	150.8799	21	5	40.3
92	Denham Court	-33.9914	150.8439	21	3	40.3
93	Holsworthy	-34.1219	150.8327	21	3	40.3
94	Douglas Park	-34.1750	150.7405	21	3	40.2
95	Rosemeadow	-34.1056	150.7950	21	2	40.0
96	Appin	-34.1806	150.7842	19	0	38.9
97	Camden Park	-34.0879	150.7363	18	2	41.2
98	Wedderburn	-34.1579	150.8064	18	0	39.2
99	Rosemeadow	-34.1002	150.7864	17	6	41.3
100	Appin	-34.1758	150.7741	17	0	39.2
101	Spring Farm	-34.0785	150.7285	16	0	38.5
102	Wedderburn	-34.1634	150.8387	10	0	37.4

4.6 HEAT MAPPING

This project used data from 102 locations to generate 15 geo-referenced maps that illustrate variation of air temperature across the LGA of Campbelltown. For each map, we imported location-specific data, including latitude and longitude of measurement positions into ArcGIS 10.6. This data allowed us to create shapefiles using the GPS coordinates. Inverse Distance Weighted (IDW) interpolation was used to estimate continuous raster temperature maps from temperature values recorded at the location of each heat logger. The resulting temperature value of each pixel in raster maps was estimated according to values of the 12 nearest locations in the shapefile. The influence of each location on the temperature value of each pixel declined with distance to the pixel.

Raster maps produced from IDW interpolations were clipped to include only the suburbs within the boundary of the LGA and a 2 km buffer zone around it, which included measurement points outside the LGA of Campbelltown. Finally, to display varying ranges of 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 maps excluded the large eastern part of the LGA where native forests and woodlands dominate the landscape.

The following map types were produced:

- Overview Maps show absolute maximum and minimum temperatures recorded during the study at each of 102 measurement locations (Figs. 18, 19), variation of air temperature among measurement points throughout the entire summer (Fig. 20), variation of air temperature during daytime (10:00 – 18:00) and nighttime (21:00 – 05:00) for February 2019 (Figs. 21, 22) or a single day/night representative for common summer conditions across the LGA (Figs. 23, 24).

- » Snapshot Maps depict microclimatic conditions at specific points in time (e.g. during the peak of a heatwave or during a cool change) (Figs. 25, 26, 27, 28).
- » Process Maps capture the dynamic course of warming during the morning and cooling during the evening (Figs. 29, 30). For these maps, we calculated ΔT for each day and measurement position as the difference between air temperature between 07:00 and 11:00 (warming) and from 20:00 to 00:00 (cooling) for each day in January and February 2019. The extent of temperature difference can be interpreted as an indicator of how quickly a location heated up or cooled down.
- » Deviation Maps provide a graphical representation of the additional number of days where heat loggers recorded maximum temperatures above 35°C and above 40°C, relative to the number of days where these maximum temperatures were recorded at the BoM station at Mt Annan Botanic Garden (Figs. 31, 32). For these maps, the 'Mt Annan baseline' was 23 days above 35°C and one day above 40°C.

Key observations:

1. The central section from Ambervale in the south to Edmondson Park in the north had the warmest mean summer temperatures. Urban density in this part of the LGA is much higher compared to surrounding suburbs.
2. Clear nighttime UHIE are documented for urban centres around Campbelltown, Ingleburn, Bardia and Edmondson Park.
3. This trend is confirmed in Overview, Snapshot and Process Maps.
4. The coolest part of the LGA during the entire summer (individual months, days, nights, and even heatwaves) is the southern region of the LGA, including the suburbs of Wedderburn, Gilead and Appin.
5. Much larger differences between minimum and maximum temperatures were observed in the eastern part of the LGA dominated by native vegetation, compared to urban centres where temperature variation was less pronounced.
6. Effects of thermal mass of objects that dominate a certain zone of the LGA were visible. Areas with low abundance or absence of grey infrastructure heated up quickly, y*et al*so cooled down faster compared to those areas that had a greater spatial abundance of grey infrastructure (buildings, roads, etc.).

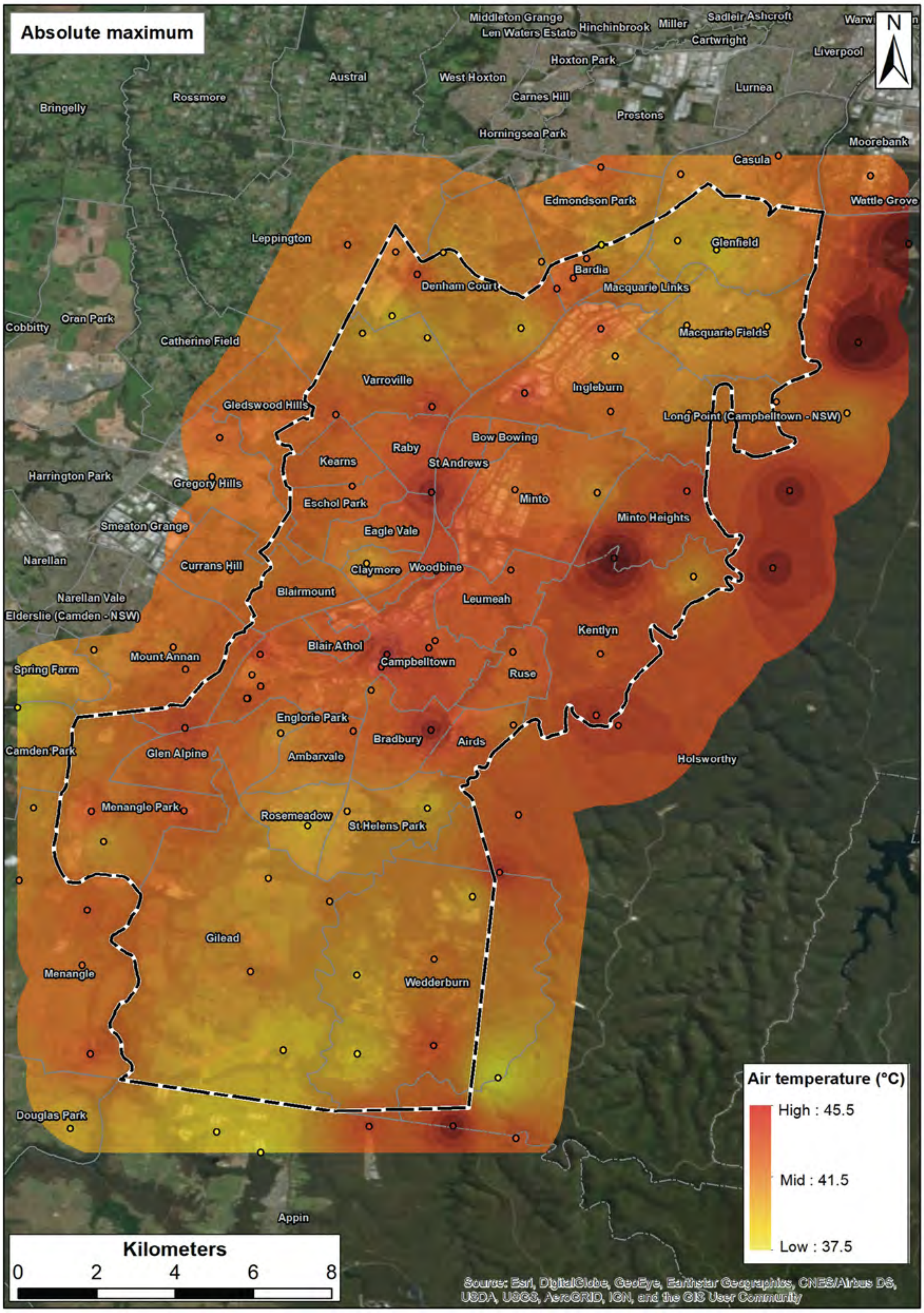


FIGURE 18: Absolute maximum air temperature at each of 102 measurement locations during summer 2019 (01 December 2018 – 28 February 2019). Colour gradations represent 0.5°C increments.

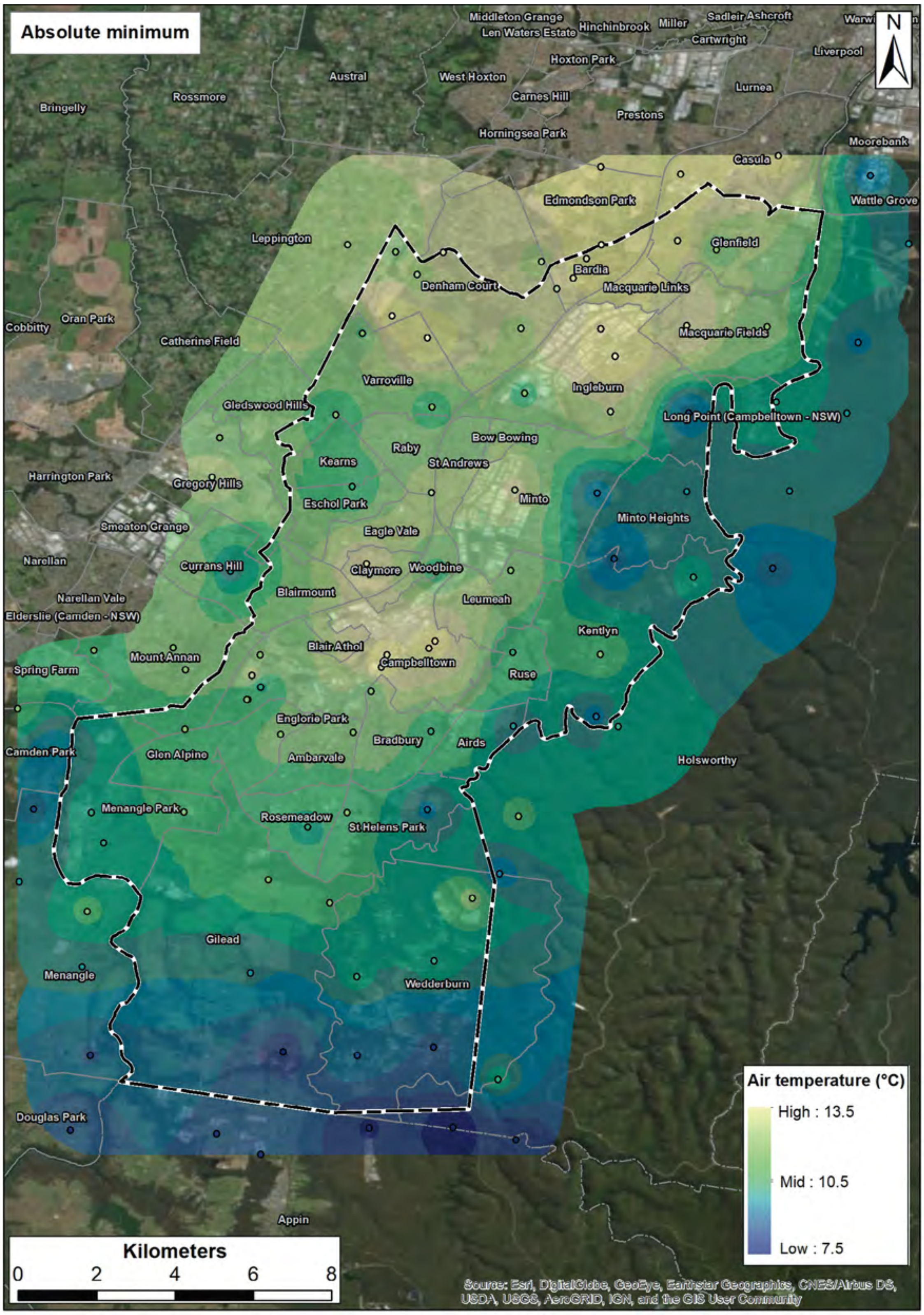


FIGURE 19: Absolute minimum air temperature at each of 102 measurement locations during summer 2019 (01 December 2018 – 28 February 2019). Colour gradations represent 0.5°C increments.

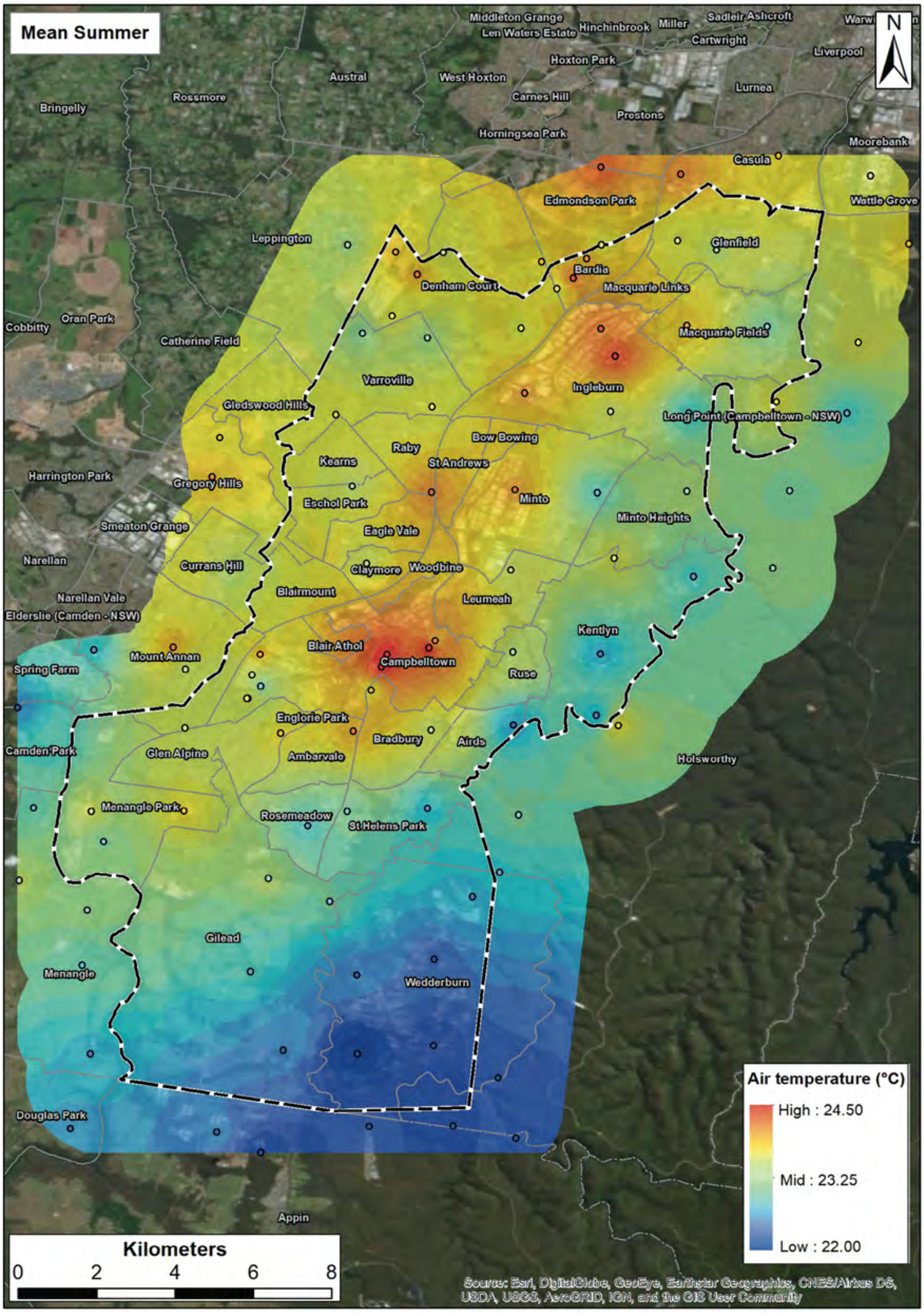


FIGURE 20: Mean air temperature during summer 2019 (01 December 2018 – 28 February 2019). Colour gradations represent 0.1°C increments.

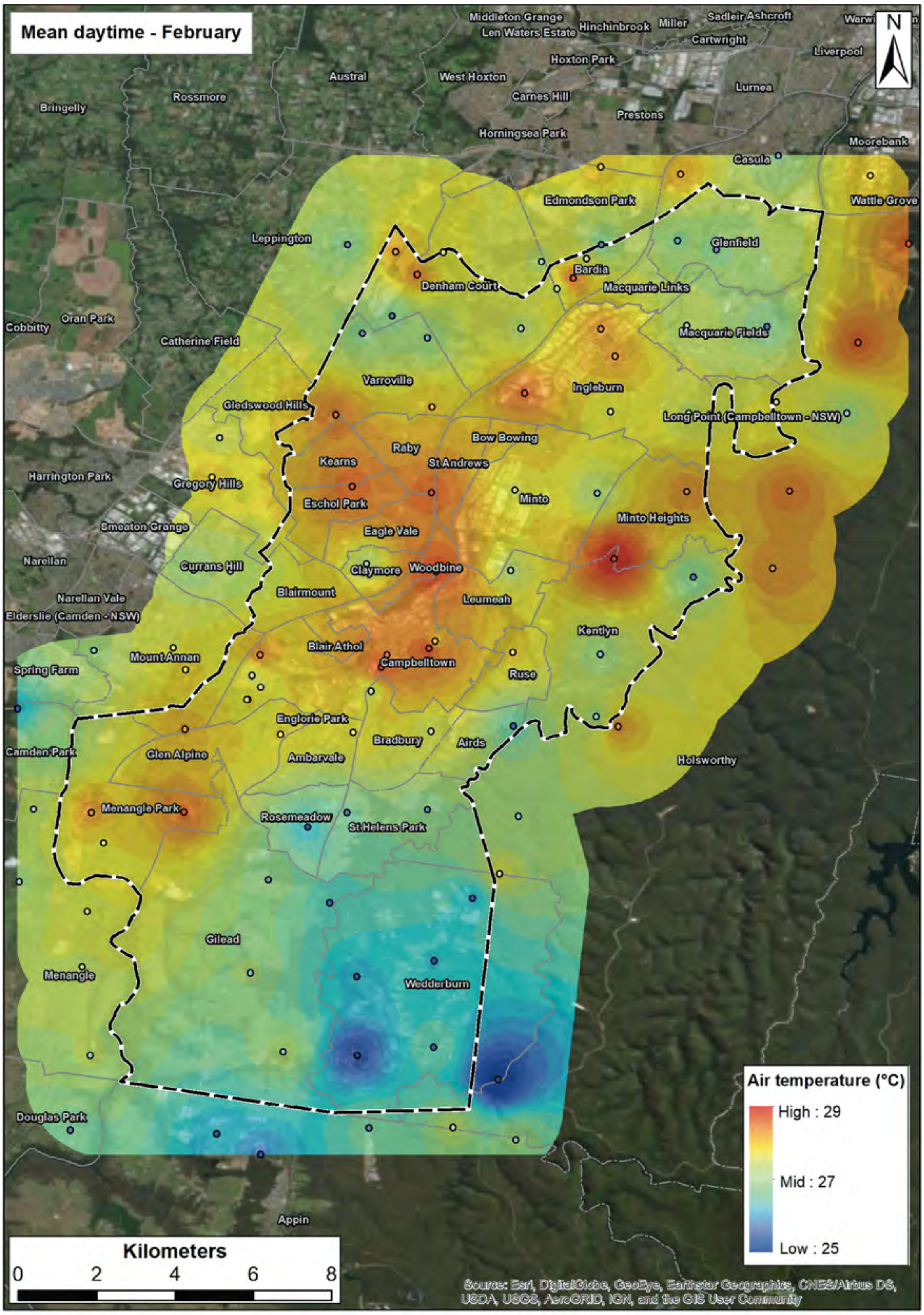


FIGURE 21: Mean daytime (10:00 – 18:00) air temperature in February 2019. Colour gradations represent 0.2°C increments.

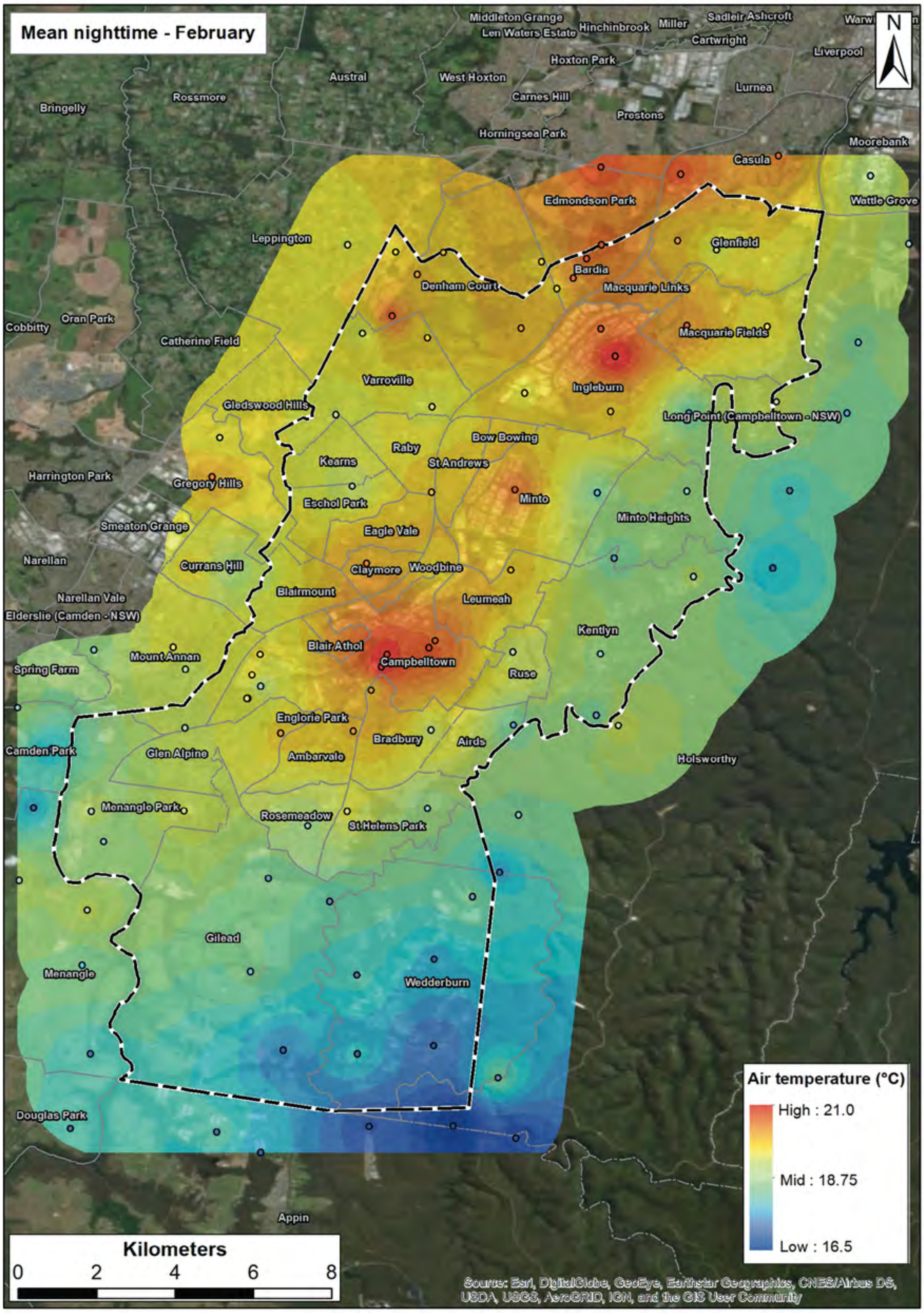


FIGURE 22:
Mean nighttime (21:00 – 05:00) air temperature in February 2019. Colour gradations represent 0.2°C increments.

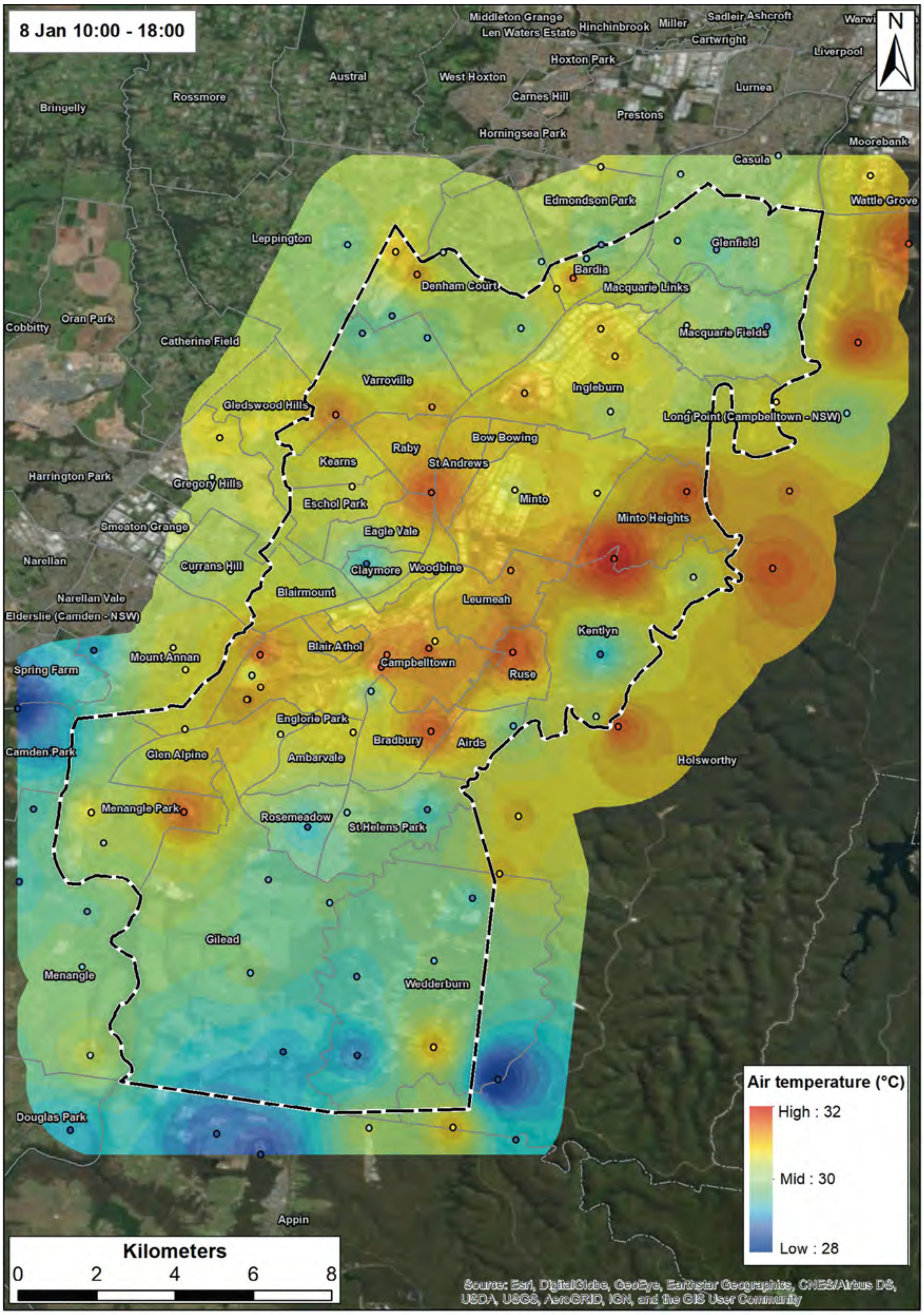


FIGURE 23: Variation of air temperature during a regular summer day (10:00 – 18:00, 08 January 2019). Colour gradations represent 0.2°C increments.

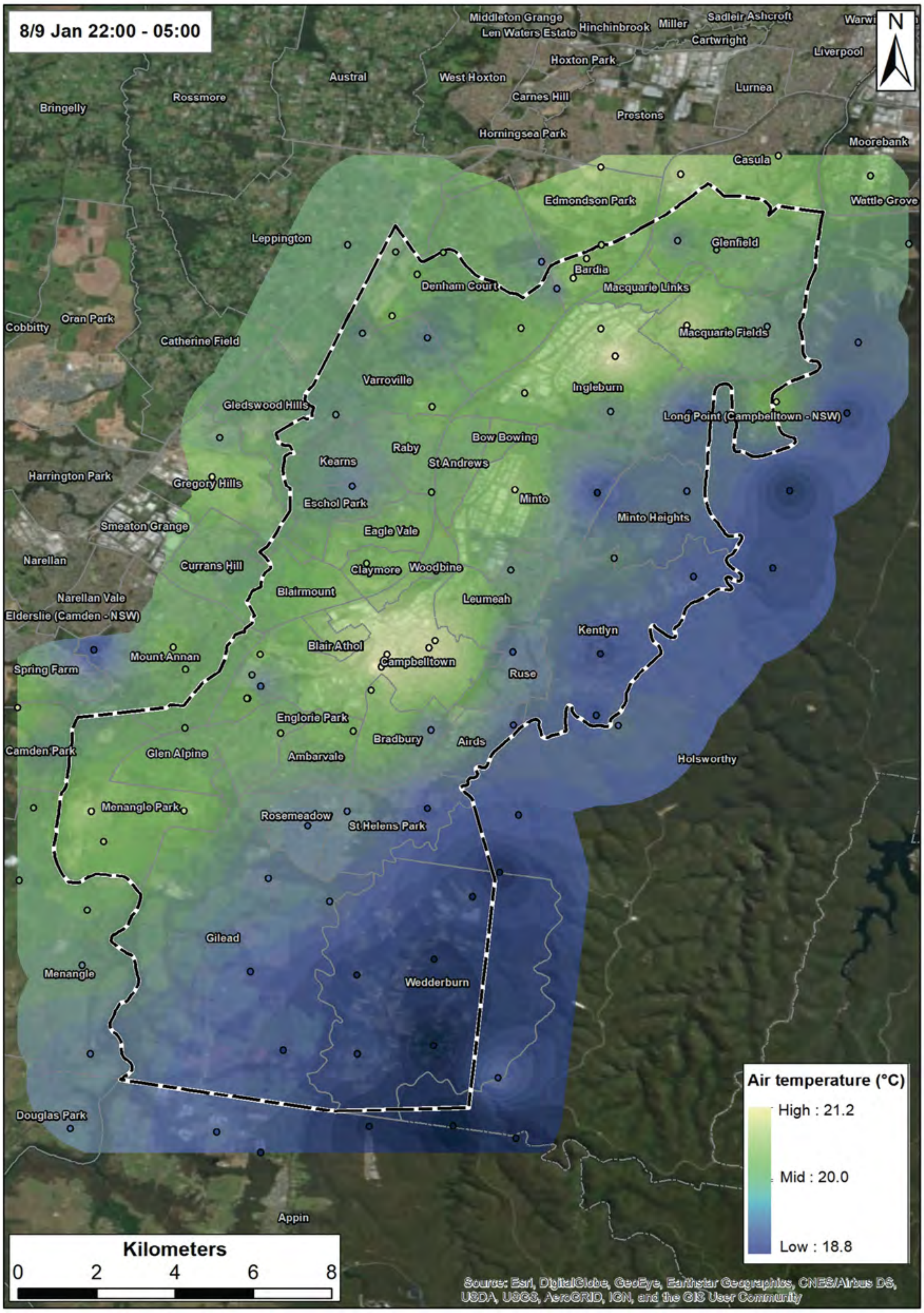


FIGURE 24: Variation of air temperature during a regular summer night (22:00 – 05:00, 25 January 2019). Colour gradations represent 0.1°C increments.

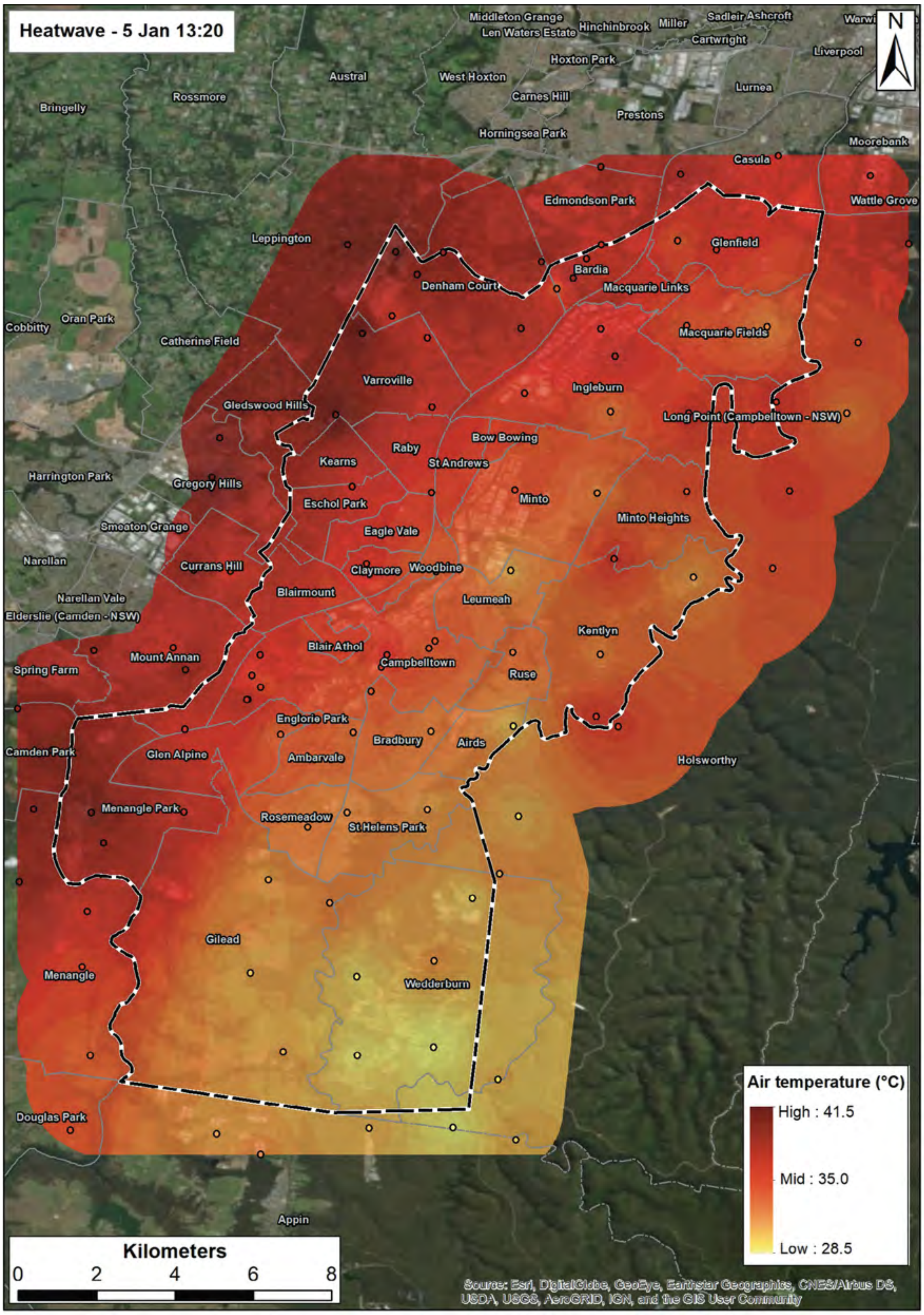


FIGURE 25: Variation of air temperature during a heatwave (13:20, 05 January 2019). Colour gradations represent 0.5°C increments.

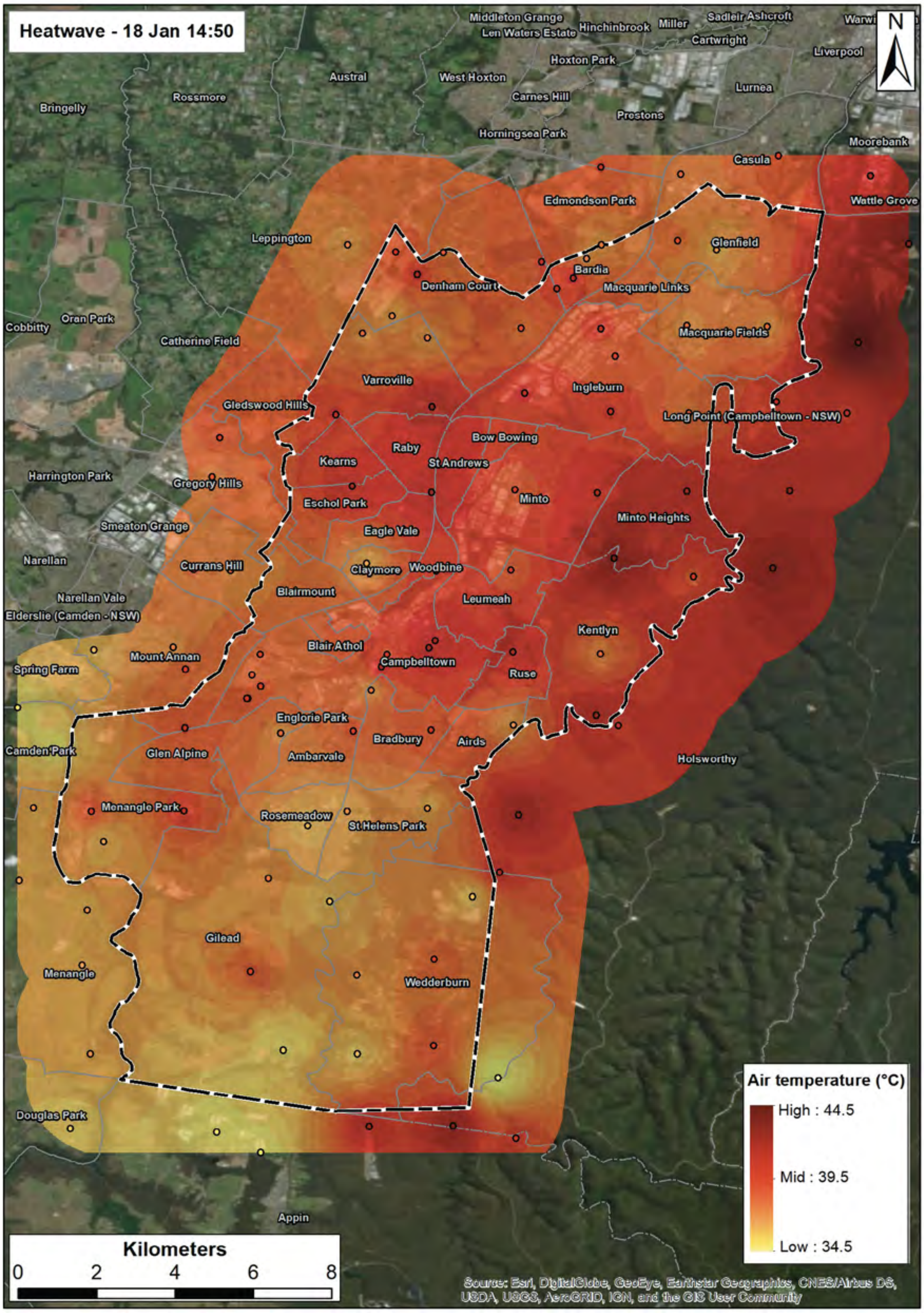


FIGURE 26: Variation of air temperature during a heatwave (14:50, 18 January 2019). Colour gradations represent 0.5°C increments.

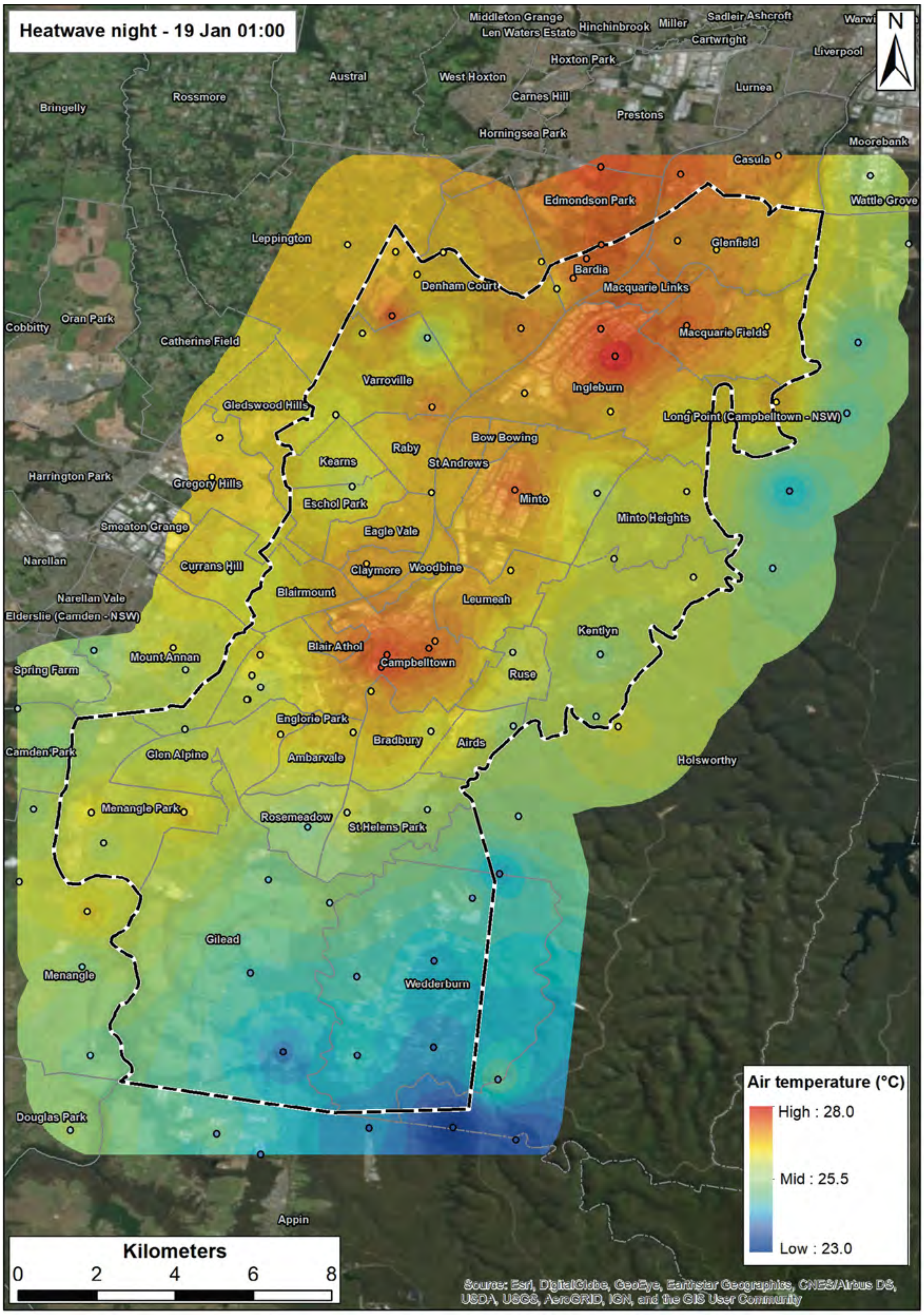


FIGURE 27: Variation of air temperature during a very warm night (01:00, 19 January 2019). Colour gradations represent 0.2°C increments.

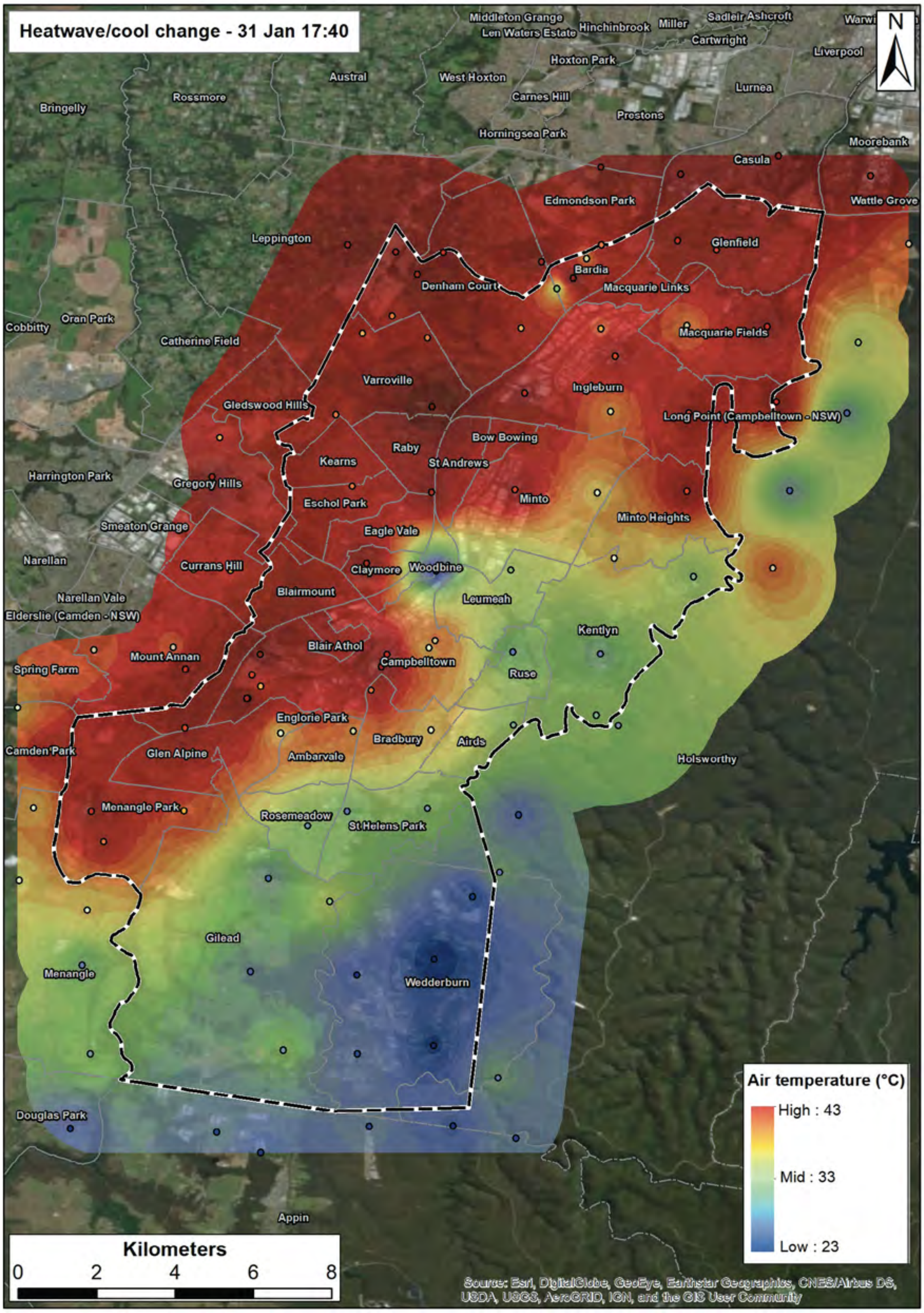


FIGURE 28: Variation of air temperature at the end of a day with extreme heat (17:40, 31 January 2019). The map shows 20°C temperature difference as a result of a southerly cool change. Colour gradations represent 0.5°C increments.

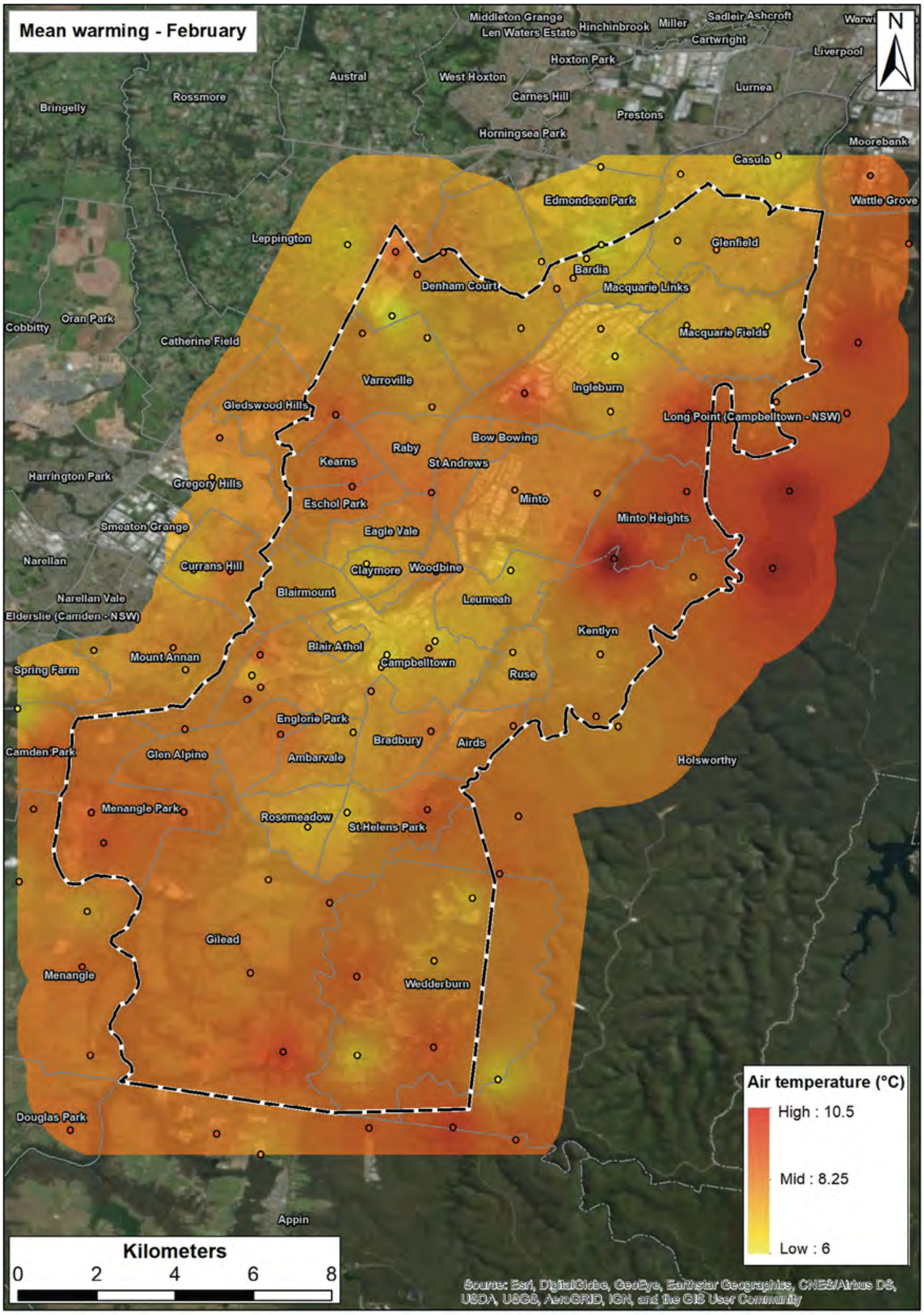


FIGURE 29: Relative warming (i.e. temperature increase from 07:00 – 11:00) during February 2019. Colour gradations represent 0.5°C increments.

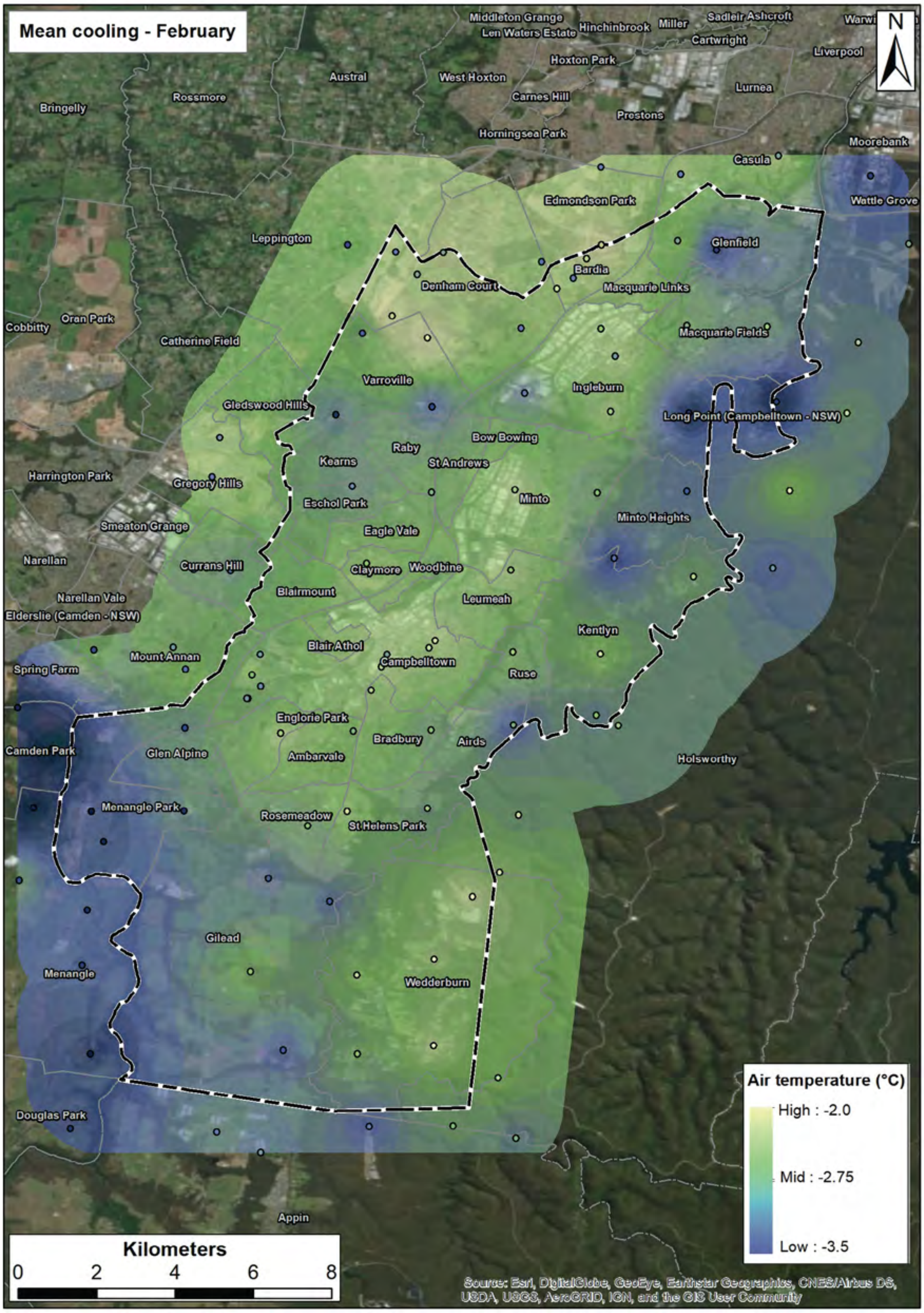


FIGURE 30: Relative cooling (i.e. temperature decrease from 20:00 – 00:00) during February 2019. Colour gradations represent 0.1°C increments.

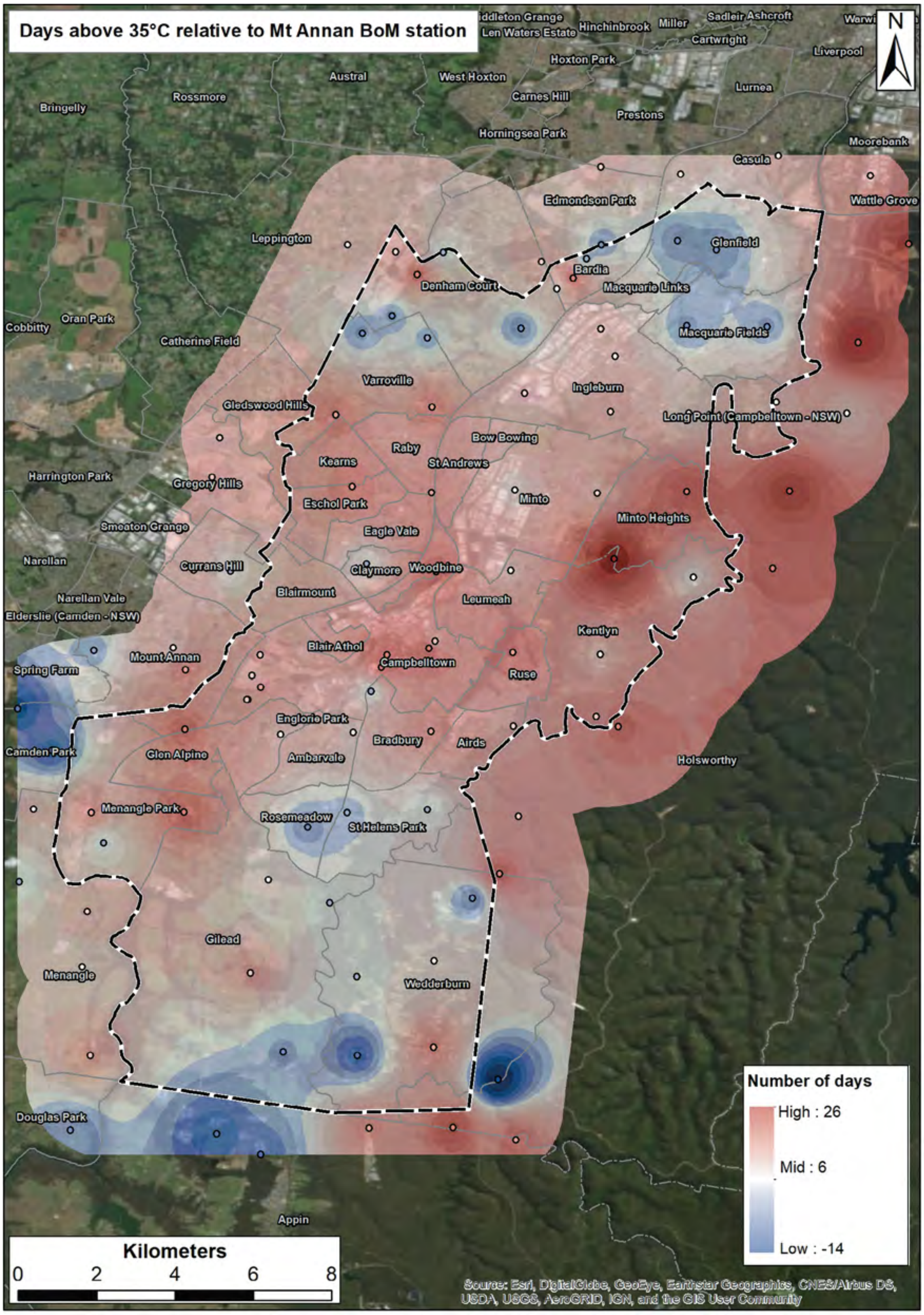


FIGURE 31: This map depicts if heat loggers either recorded more (red colouring) or fewer (blue colouring) days where maximum air temperature was >35°C, relative to the BoM station at Mt Annan Botanic Garden. At that location, maximum temperature of >35°C was recorded during 23 days in summer 2019 (01 December – 28 February 2019), represented as white colouring.

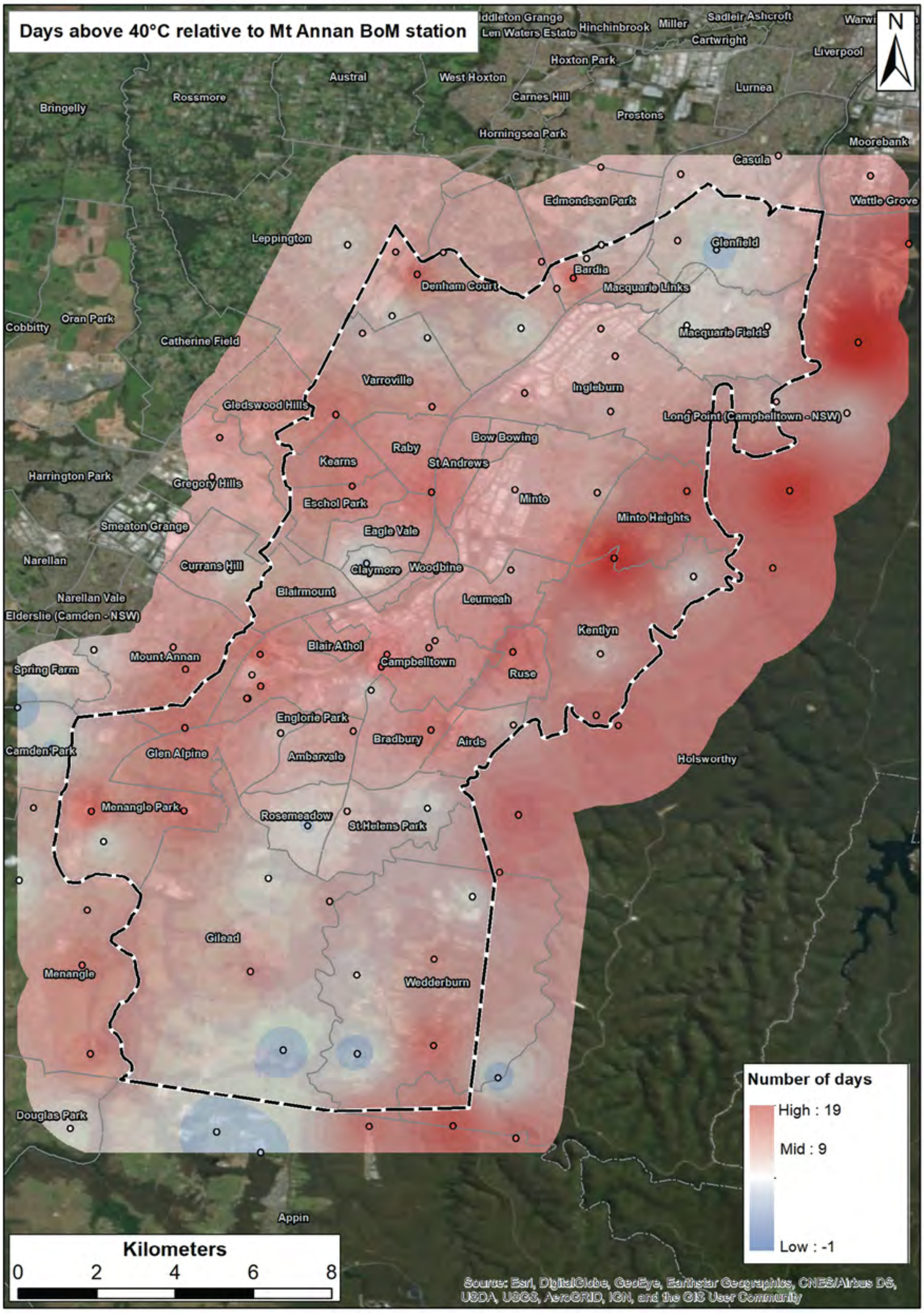


FIGURE 32: This map depicts if heat loggers either recorded more (red colouring) or fewer (blue colouring) days where maximum air temperature was >40°C, relative to the BoM station at Mt Annan Botanic Garden. At that location, maximum temperature of >40°C was recorded during one day in summer 2019 (01 December – 28 February 2019), represented as white colouring.

4.7 CAMPBELLTOWN CBD

To assess patterns of urban heat and the UHIE across Campbelltown CBD, heat loggers were placed around this area at strategic locations. These included a median strip in Moore Street and the Tyler Street Apartments in the east, in the mall area of Queen Street and the Milgate Arcade car park in the centre. Generally, temperature regimes across day and night were very similar at these locations. The absolute highest temperature was measured at the central locations, with 43.8°C in the Milgate Arcade car park and 43.3°C in Queen Street. Mean summer temperature at both locations was 24.6°C 1°C warmer than a site in Leumeah just 3 km to the north and 1.4°C lower than a location in Macarthur Heights 3 km to the south west.

The UHIE was most prominent during the night where temperatures around the city centre remained higher compared to surrounding suburbs. Especially large temperature differences between the CBD locations and nearby Macarthur Heights were present during heatwave nights, demonstrating the effect of heat emission from impervious surfaces and buildings in the CBD. During the heatwave at the end of December 2018, nighttime temperatures remained 4-5°C higher in the CBD (Fig. 33).

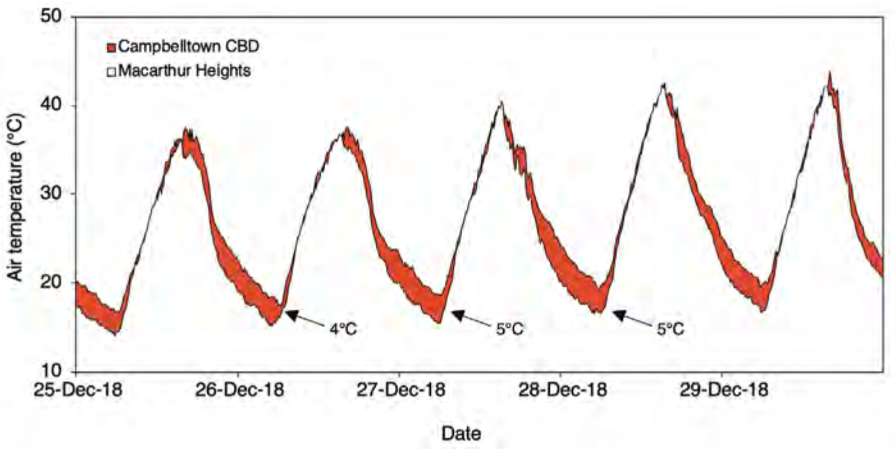


FIGURE 33: Heat Island Effect of Campbelltown CBD. Data was recorded during the heatwave between 25 and 29 December 2018. The area marked in red indicates when air temperature is warmer in the CBD (pedestrian walkway outside the Queen Street Mall) compared to a location at Macarthur Heights (nature strip along Goldsmith Street). Both heat loggers were positioned in eucalypt trees. The date-stamp on the x-axis indicates midnight, thus the gradual increase of temperature difference between the two sites shows more rapid cooling at Macarthur Heights. Maximum difference is reached in the early morning hours before sunrise, from whereon the CBD also heats up faster.

5. CONCLUSIONS AND RECOMMENDATIONS

For the first time, empirical data was used to document trends of microclimatic variation across the LGA of Campbelltown. The spatio-temporal resolution of results is unmatched. Instruments to record air temperatures across the LGA were calibrated against measurements from three official weather stations. These calibrations yielded very robust coefficients of correlation, providing high confidence in the accuracy of outcomes presented in the current study.

Based on more than 1.46 million measurements from 102 locations inside and around the Campbelltown LGA, we conclude that local communities are exposed to more summer heat than previously known. Suburbs especially in the densely populated central and northern zone of the LGA experience more than twice the number of days where temperatures exceed 35°C compared to the area around Mt Annan Botanic Garden at the western edge of the LGA. Here the official BoM weather station recorded temperatures above 35°C on 23 days, while 3 km to the east near the train station of Campbelltown such temperatures were measured during 39 days.

Even more concerning is the fact that in the summer 2018/19 extreme heat (>40°C) was documented only on a single day at the official weather station at Mt Annan, yet was measured at 25 locations during 10 or more days across the LGA, including Campbelltown CBD.

Realising that exposure to extreme summer heat is far greater than previously known should encourage Campbelltown Council to develop firm strategies for urban cooling. To ensure feasibility, implementation and evaluation of such strategies will require cross-organisational coordination.
We recommend establishing a *Heat Task Force* that works across Council units and teams with the purpose to develop and implement effective actions that reduce vulnerability of Campbelltown to summer heat.

This work found strong empirical evidence for a pronounced UHIE over the central and north central zone of the LGA. During hot nights, the city centre of Campbelltown remained significantly warmer (up to 5°C) compared to surrounding suburbs. During such periods, the local population will be disadvantaged as it cannot recover well from heat stress during the day. **We recommend** that Council establishes and advertises a network of *Cool Zones* across the urban centres of Ambervale, Campbelltown, Leumeah, Minto, Ingleburn, Bardia and Edmondson Park. *Cool Zones* can be parks, playgrounds, sports fields, local reserves and other assets with minimal presence of grey infrastructure. Pop-up events can be used to attract local communities to gather in *Cool Zones* during evenings, activating otherwise unused spaces and increasing social cohesion. Extending operational hours of splash parks and public pools during heatwaves can also be communicated under the banner of *Cool Zones*.

Reduction of tree canopy cover will impact local and regional climate (Duncan *et al*., 2019). In light of anticipated high population growth in areas of the LGA that are currently dominated by pervious surfaces with high vegetation cover, it is reasonable to expect these areas to heat up as result of urban growth. It is widely accepted that trees can help to cool cities and increase human thermal comfort (Armson *et al*., 2012; Estoque *et al*., 2017; Livesley *et al*., 2016). Thus, preventing any loss of green infrastructure, especially in the western and south western growth centres of the LGA should become a priority for planners and developers. **We recommend** to raise legal barriers to remove existing tree canopy, while at the same time commence tree plantings in these areas today, with the long-term goal of establishing 40-45% tree canopy cover by 2040. This 'provident approach' will deliver effective cooling benefits for the inhabitants of the new suburbs.

A valuable example of how species selection and planting arrangement of urban trees can reduce local heat comes from the Cool Streets and Cool Parks studies we have completed for the City of Parramatta (Pfautsch and Rouillard, 2019a). More than twice as many days of >40°C were recorded along a street in North Parramatta, where canopy cover was only 10%, compared to a nearby street where canopy cover was 30%. Air temperatures under trees with very dense canopies were more than 7°C lower during a heatwave compared to trees with open canopies.

We also showed that promoting growth of trees that are less than 10 m tall has the largest cooling effect on local microclimate (Pfautsch and Rouillard, 2019b). **We recommend** that this knowledge is used to inform urban planners to incorporate structures for storm water harvesting when designing the new suburbs. Storm water can be used to irrigate newly planted and existing trees. In established suburbs, programs for irrigation and fertilisation of younger trees could be implemented to accelerate height growth of trees, and thus canopy expansion and cooling. Techniques other than tree plantings could be used to cool Campbelltown. A range of documents provide valuable information about these techniques (OEH, 2015; Government Architect New South Wales, 2017; Osmond and Sharifi, 2017).

We acknowledge that the surrounding urban fabric could have influenced data recorded during this research project. While this can potentially be a limiting factor for interpretation of observations reported here, it is important to recognise that confidence in the accuracy of data, illustrations and heat maps can be drawn from a range of sources. First, measurements collected using heat loggers correlated very strongly with those recorded by three official weather stations and a widely used temperature sensor. Second, we used large amounts of data to calculate location- and suburb-specific trends and produce microclimate maps. Third, microclimatic differences due to selection of tree species used to support the heat loggers is negligible (Pfautsch and Rouillard 2019b). Lastly, the uneven distribution of urban heat in space and time is well known (Oke, 2006; Wong and Yu, 2008), particularly once measurements are collected at small scales (Erell *et al*., 2011). Hence, data presented here reflect this phenomenon for the LGA of Campbelltown.

Based on information provided here, it is now possible to overcome several disadvantages mentioned at the beginning of this report. **We recommend** that Council develops strategies and products to communicate heat in suburbs of the LGA. An excellent example to communicate heat visually are our maps. Moreover, **we recommend** that cooling interventions are focused on suburbs with high daytime and high nighttime temperatures, such as Campbelltown CBD, Bardia and Ingleburn.

The positive relationship between heat-related illnesses and people's age is well documented. **We recommend** that Council estimates a precinct-specific *Heat Vulnerability Index*. This index should combine information about temperatures during heatwave conditions with information on age of citizens from census data. It can be expected that the number of incidences during heatwaves will be greater where the index is high. Results of this work should be communicated to emergency services to improve response times to heat-related incidents. Thus, the *Heat Vulnerability Index* could save lives.

Additional recommendations, actions, targets and strategies to cool down the Campbelltown LGA can be drawn from the WSROC *Turn Down the Heat - Strategy and Action Plan* and the *Guide to Urban Cooling Strategies* developed by the Corporate Research Centre for Low Carbon Living. Both documents provide valuable information that go beyond the scope of the present report.

Heat has been identified as major shock to public life, health, infrastructure and economic development in the Sydney Basin (Resilient Sydney, 2018; WSROC, 2018). Benchmarking summer heat has value beyond the LGA of Campbelltown. In the state of New South Wales, 90% of the population lives in cities or towns. Climate change is affecting this urban lifestyle. Creating liveable, or more importantly lovable and sustainable cities that supply their inhabitants with the necessary resources and services is a shared duty among local governments. As predicted by the International Committee for Climate Change six years ago (IPCC, 2013), heatwaves are now more frequent, more severe and longer lasting. Exposure of humans to dangerous levels of heat stress is expected to increase by a factor of 5-10 by 2080 (Coffel *et al.*, 2018). The current state of summer heat, alarming forecasts of additional heat stress and rapid urban development in the Campbelltown-Macarthur region make responsible urban planning with a focus on reducing heat inevitable.

Prioritising heat interventions and associated decision-making processes can now be supported by evidence provided by the present report. We established a microclimate baseline, against which the success of cooling actions can now be measured. New strategies are necessary to adapt to increasing summer heat, and, where possible, reduce any negative impacts on local communities. Here we demonstrated how vulnerability to heat varies from suburb to suburb. It is at this level that operative actions against heat can and should take place across the Campbelltown LGA, the Greater Sydney Basin and beyond.

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APPENDIX 1

Complete list of measurement locations, their geographic location and species information. Locations are listed alphabetically according to suburb. Light poles were used to mount heat loggers when trees were unavailable. Temperature data represent mean and absolute maximum and minimum values measured between 01 December 2018 and 15 March 2019

Location number	Suburb	Lat. (°)	Long. (°)	Genus	Tree species	Common name	Mean summer air temperature (°C)	Absolute max. air temperature (°C)	Absolute min. air temperature (°C)
1	Airds	-34.0824	150.8422	Angophora	*Angophora floribunda*	rough-barked apple	22.7	*41.4*	10.2
2	Ambervale	-34.0839	150.8055	Corymbia	*Corymbia citriodora*	lemon-scented gum	24.0	*42.2*	11.4
3	Appin	-34.1806	150.7842	Angophora	*Angophora floribunda*	rough-barked apple	22.2	*38.9*	9.1
4	Appin	-34.1745	150.8283	unknown	*unknown*	dead tree	22.3	*44.0*	7.5
5	Appin	-34.1773	150.8427	Banksia	*Banksia spinulosa var. cuninghamii*	banksia	22.4	*42.2*	8.4
6	Appin	-34.1758	150.7741	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	22.6	*39.2*	9.3
7	Bardia	-33.9722	150.8624	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	23.7	*40.0*	13.0
8	Bardia	-33.9799	150.8559	N/A	*N/A*	light pole	24.3	*42.5*	12.4
9	Bardia	-33.9823	150.8522	N/A	*N/A*	light pole	23.7	*42.6*	11.9
10	Bardia	-33.9754	150.8589	Lephostemon	*Lephostemon confertus*	Queensland brushbox	24.0	*41.8*	12.8
11	Bradbury	-34.0836	150.8233	Melaleuca	*Melaleuca bracteata*	black tea-tree	23.6	*43.8*	10.8
12	Bradbury	-34.0744	150.8095	Eucalyptus	*Eucalyptus amplifolia*	cabbage gum	23.8	*41.6*	11.1
13	Camden Park	-34.0879	150.7363	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	23.0	*41.2*	9.8
14	Camden Park	-34.1015	150.7321	Eucalyptus	*Eucalyptus baueriana*	round-leaved box	23.1	*40.9*	9.5
15	Campbelltown	-34.0647	150.8228	Eucalyptus	*Eucalyptus pilularis*	blackbutt	24.7	*42.8*	12.5
16	Campbelltown	-34.0631	150.8242	Melaleuca	*Melaleuca quinquinervia*	broad-leaved paperbark	23.9	*42.6*	12.5
17	Campbelltown	-34.0691	150.8119	Eucalyptus	*Eucalyptus microcorys*	tallowwood	24.6	*43.3*	12.8
18	Campbelltown	-34.0662	150.8132	Eucalyptus	*Eucalytpus sideroxylon*	red ironbark	24.6	*43.8*	12.4
19	Casula	-33.9560	150.8805	Eucalyptus	*Eucalyptus micorcorys*	tallowwood	24.2	*41.1*	12.8
20	Casula	-33.9518	150.9030	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	23.8	*41.8*	12.6
21	Claymore	-34.0454	150.8085	Corymbia	*Corymbia maculata*	spotted gum	23.6	*40.7*	12.2
22	Currans Hill	-34.0470	150.7773	Eucalyptus	*Eucalyptus punctata*	grey gum	23.5	*41.9*	10.3
23	Currans Hill	-34.0468	150.7688	Eucalyptus	*Eucalyptus microcorys*	tallowwood	23.7	*41.8*	11.4
24	Denham Court	-33.9740	150.8261	Eucalyptus	*Eucalyptus mollucana*	grey box	23.6	*40.6*	12.2
25	Denham Court	-33.9914	150.8439	Eucalyptus	*Eucalyptus eugenoides*	white stringybark	23.7	*40.3*	11.8
26	Douglas Park	-34.1750	150.7405	Corymbia	*Corymbia citriodora*	lemon-scented gum	22.7	*40.2*	9.1
27	Edmondson Park	-33.9544	150.8622	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	24.4	*42.4*	12.7
28	Edmondson Park	-33.9761	150.8486	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	23.8	*41.1*	11.6
29	Eschol Park	-34.0276	150.8052	Corymbia	*Corymbia citriodora*	lemon-scented gum	23.5	*42.2*	10.8
30	Gilead	-34.1390	150.7819	Eucalyptus	*Eucalyptus crebra*	narrow-leaved ironbark	23.0	*41.3*	10.2
31	Gilead	-34.1176	150.7860	Olea	*Olea europea subsp. cuspidata*	African olive	23.4	*40.7*	11.1
32	Gilead	-34.1571	150.7894	Angophora	*Angophora floribunda*	rough-barked apple	22.6	*39.8*	8.5
33	Gilead	-34.1229	150.8001	Acacia	*Acacia longifolia subsp. longifolia*	Sydney golden wattle	23.2	*41.2*	11.0
34	Gledswood Hills	-34.0165	150.7748	Eucalyptus	*Eucalyptus microcorys*	tallowwood	23.8	*42.3*	11.3
35	Glen Alpine	-34.0843	150.7888	Fraxinus	*Fraxinus angustifolia*	ash	23.8	*40.9*	11.3
36	Glenfield	-33.9734	150.8888	Casuarina	*Casuarina cunninghamiana*	she-oak	23.5	*39.9*	11.2

Location number	Suburb	Lat. (°)	Long. (°)	Genus	Tree species	Common name	Mean summer air temperature (°C)	Absolute max. air temperature (°C)	Absolute min. air temperature (°C)
37	Glenfield	-33.9713	150.8799	Olea	*Olea europea subsp. cuspidata*	African olive	23.6	*40.3*	12.6
38	Gregory Hills	-34.0255	150.7731	Eucalyptus	*Eucalyptus mollucana*	grey box	24.0	*41.4*	11.8
39	Holsworthy	-33.9564	150.9241	Eucalyptus	*Eucalyptus crebra*	narrow-leaved ironbark	23.6	*41.8*	10.0
40	Holsworthy	-33.9720	150.9329	Eucalyptus	*Eucalyptus punctata*	grey gum	23.8	*45.3*	10.2
41	Holsworthy	-33.9946	150.9213	Allocasuarina	*Allocasuarina littoralis*	black she-oak	23.7	*45.4*	10.1
42	Holsworthy	-34.0109	150.9187	Allocasuarina	*Allocasuarina littoralis*	black she-oak	23.0	*41.0*	10.4
43	Holsworthy	-34.0083	150.9025	Angophora	*Angophora costata*	Sydney red gum	23.7	*41.5*	10.6
44	Holsworthy	-34.0287	150.9055	Eucalyptus	*Eucalyptus sclerophylla*	scribbly gum	23.2	*43.8*	10.4
45	Holsworthy	-34.0825	150.8662	Angophora	*Angophora costata*	Sydney red gum	23.8	*42.8*	10.8
46	Holsworthy	-34.1031	150.8433	Allocasuarina	*Allocasuarina littoralis*	black she-oak	23.2	*42.2*	10.9
47	Holsworthy	-34.1163	150.8390	Corymbia	*Corymbia gummifera*	red bloodwood	23.0	*43.3*	9.9
48	Holsworthy	-34.1219	150.8327	Eucalyptus	*Eucalyptus punctata*	grey gum	22.8	*40.3*	11.3
49	Holsworthy	-34.0464	150.9017	unknown	*unknown*	unknown	23.3	*43.8*	9.6
50	Ingleburn	-33.9978	150.8655	Ulmus	*Ulmus parvifolia*	Chinese elm	24.5	*40.9*	13.3
51	Ingleburn	-33.9915	150.8623	Eucalyptus	*Eucalyptus nichollii*	narrow-leaved black peppermint	24.3	*42.6*	12.3
52	Ingleburn	-34.0108	150.8824	Eucalyptus	*Eucalyptus mollucana*	grey box	23.0	*41.0*	9.6
53	Ingleburn	-34.0105	150.8644	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	23.6	*41.9*	11.9
54	Ingleburn	-34.0063	150.8447	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	24.0	*42.9*	11.0
55	Kentlyn	-34.0484	150.8835	Acacia	*Acacia sp.*	wattle	23.0	*40.7*	10.6
56	Kentlyn	-34.0442	150.8653	Allocasuarina	*Allocasuarina littoralis*	black she-oak	23.7	*44.9*	9.6
57	Kentlyn	-34.0661	150.8621	Eucalyptus	*Eucalyptus oblonga*	narrow-leaved stringybark	22.8	*42.3*	11.1
58	Kentlyn	-34.0802	150.8612	Angophora	*Angophora costata*	Sydney red gum	22.8	*43.2*	10.0
59	Leppington	-33.9722	150.8042	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	23.4	*41.8*	11.8
60	Leumeah Park	-34.0469	150.8416	Grevillia	*Grevillea robusta*	silky oak	23.6	*42.6*	11.5
61	Lynwood	-34.1016	150.8224	Angophora	*Angophora floribunda*	rough-barked apple	22.9	*40.1*	10.1
62	Macarthur Heights	-34.0662	150.7841	N/A	*N/A*	light pole	23.9	*43.1*	11.4
63	Macarthur Heights	-34.0709	150.7822	N/A	*N/A*	light pole	23.6	*41.5*	11.8
64	Macarthur Heights	-34.0763	150.7813	N/A	*N/A*	light pole	23.6	*42.8*	11.1
65	Macarthur Heights	-34.0763	150.7810	N/A	*N/A*	light pole	23.7	*42.2*	11.0
66	Macarthur Heights	-34.0735	150.7842	Eucalyptus	*Eucalyptus spp.*	gum tree	23.2	*42.6*	10.6
67	Macquarie Fields	-33.9908	150.8820	Eucalyptus	*Eucalyptus robusta*	swamp mahogany	23.9	*40.7*	12.3
68	Macquarie Fields	-33.9910	150.9004	Eucalyptus	*Eucalyptus fibrosa*	broad-leaved red ironbark	23.2	*40.7*	11.3
69	Menangle	-34.1249	150.7444	Eucalyptus	*Eucalyptus tereticornis*	Forest red gum	23.3	*42.5*	10.9
70	Menangle	-34.1376	150.7433	Eucalyptus	*Eucalyptus microcorys*	tallowwood	23.1	*41.7*	10.3
71	Menangle	-34.1579	150.7451	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	22.8	*42.5*	9.3
72	Menangle	-34.1181	150.7288	Eucalyptus	*Eucalyptus mollucana*	grey box	23.5	*41.6*	10.3
73	Menangle Park	-34.1023	150.7453	Eucalyptus	*Eucalyptus microcorys*	tallowwood	23.6	*42.6*	10.8

Location number	Suburb	Lat. (°)	Long. (°)	Genus	Tree species	Common name	Mean summer air temperature (°C)	Absolute max. air temperature (°C)	Absolute min. air temperature (°C)
74	Menangle Park	-34.1022	150.7666	Corymbia	*Corymbia maculata*	spotted gum	23.8	*42.6*	11.1
75	Menangle Park	-34.1092	150.7482	Eucalyptus	*Eucalyptus mollucana*	grey box	23.2	*40.7*	10.6
76	Minto	-34.0285	150.8425	Melaleuca	*Melaleuca styphelioides*	prickly-leaved paperbark	24.1	*41.8*	12.0
77	Minto	-34.0292	150.8614	Corymbia	*Corymbia torreliana*	cadaghi gum	23.1	*41.2*	10.0
78	Minto	-34.0288	150.8820	Eucalyptus	*Eucalyptus crebra*	narrow-leaved ironbark	23.4	*43.1*	10.3
79	Mt Annan	-34.0652	150.7459	Olea	*Olea europea subsp. cuspidata*	African olive	22.9	*41.0*	11.1
80	Mt Annan	-34.0646	150.7641	Corymbia	*Corymbia maculata*	spotted gum	24.0	*41.4*	11.5
81	Mt Annan	-34.0832	150.7668	Eucalyptus	*Eucalyptus mollucana*	grey box	23.6	*43.1*	10.9
82	Mt Annan	-34.0697	150.7669	Eucalyptus	*Eucalyptus crebra*	narrow-leaved ironbark	23.6	*42.3*	11.2
83	Raby	-34.0290	150.8234	Eucalyptus	*Eucalyptus crebra*	narrow-leaved ironbark	24.2	*43.8*	11.7
84	Rosemeadow	-34.1002	150.7864	Eucalyptus	Eucalyptus tereticornis	forest red gum	23.0	41.3	11.3
85	Rosemeadow	-34.1056	150.7950	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	23.0	*40.0*	10.7
86	Ruse	-34.0656	150.8421	Callistemon	*Callistemon spp.*	bottlebrush	23.5	*42.2*	10.8
87	Spring Farm	-34.0785	150.7285	Ligustrum	*Ligustrum ludicum*	broad-leaved privet	22.6	*38.5*	11.1
88	St Helens Park	-34.1023	150.8040	Eucalyptus	*Eucalyptus baueriana*	round-leaved box	23.2	*40.7*	11.0
89	Varroville	-33.9926	150.8076	Eucalyptus	*Eucalyptus mollucana*	grey box	23.3	*40.5*	11.1
90	Varroville	-33.9936	150.8225	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	23.4	*40.3*	13.1
91	Varroville	-34.0095	150.8235	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	23.7	*43.2*	10.9
92	Varroville	-34.0112	150.8015	Corymbia	*Corymbia maculata*	grey box	23.7	*42.6*	10.9
93	Wedderburn	-34.1398	150.8063	Eucalyptus	*Eucalyptus eugenoides*	thin-leaved stringybark	22.6	*40.2*	10.6
94	Wedderburn	-34.1362	150.8240	Corymbia	*Corymbia gummifera*	red bloodwood	22.4	*41.5*	10.7
95	Wedderburn	-34.1634	150.8387	Creatopetalum	*Ceratopetalum apetalum*	coachwood	22.4	*37.4*	10.7
96	Wedderburn	-34.1560	150.8239	Eucalyptus	*Eucalyptus sclerophylla*	scribbly gum	22.3	*42.8*	9.2
97	Wedderburn	-34.1579	150.8064	Eucalyptus	*Eucalyptus microcorys*	tallowwood	22.1	*39.2*	9.7
98	Wedderburn	-34.1746	150.8091	Eucalyptus	*Eucalyptus sclerophylla*	scribbly gum	22.4	*42.8*	8.2
99	Willowdale	-33.9739	150.8152	N/A	N/A	light pole	23.9	41.5	11.3
100	Willowdale	-33.9791	150.8201	N/A	*N/A*	light pole	24.1	*42.8*	11.7
101	Willowdale	-33.9886	150.8144	N/A	*N/A*	light pole	23.7	*40.0*	13.0
102	Woodbine	-34.0471	150.8244	Eucalyptus	*Eucalyptus tereticornis*	forest red gum	23.9	*42.9*	11.0

APPENDIX 2

Site-specific mean, absolute maximum and minimum temperatures measured during daytime (10:00-18:00) and nighttime (21:00-05:00). Data were collected during 01 December 2018 and 15 March 2019 at 102 measurement locations in and around Campbelltown LGA. All temperatures are in °C.

Suburb	Latitude (°)	Longitude (°)	Mean daytime temp.	Max. daytime temp.	Min daytime temp.	Mean nighttime temp.	Max nighttime temp.	Min nighttime temp.
Airds	-34.0824	150.8422	27.4	41.4	17.9	19.3	30.8	10.5
Ambervale	-34.0839	150.8055	28.4	42.2	17.9	20.6	31.4	11.9
Appin	-34.1806	150.7842	26.7	38.9	17.0	18.9	29.7	9.2
Appin	-34.1745	150.8283	28.7	44.0	16.5	17.7	28.0	7.6
Appin	-34.1773	150.8427	28.4	42.2	16.5	18.2	27.7	8.7
Appin	-34.1758	150.7741	26.9	39.2	17.3	19.2	30.4	9.3
Bardia	-33.9722	150.8624	27.5	40.0	17.8	20.9	31.5	13.7
Bardia	-33.9799	150.8559	29.1	42.5	18.1	20.7	31.5	12.8
Bardia	-33.9823	150.8522	28.1	42.6	17.3	20.2	31.0	12.5
Bardia	-33.9754	150.8589	28.0	41.8	17.9	20.9	31.5	13.3
Bradbury	-34.0836	150.8233	28.4	43.8	18.4	19.9	30.9	10.9
Bradbury	-34.0744	150.8095	28.0	41.6	18.6	20.4	31.5	11.6
Camden Park	-34.0879	150.7363	27.8	41.2	17.9	19.0	29.7	9.8
Camden Park	-34.1015	150.7321	28.2	40.9	17.9	18.9	30.2	9.5
Campbelltown	-34.0647	150.8228	29.1	42.8	18.7	21.3	32.3	12.6
Campbelltown	-34.0631	150.8242	28.3	42.6	18.3	20.9	31.7	12.7
Campbelltown	-34.0691	150.8119	29.1	43.3	18.4	21.4	32.3	13.0
Campbelltown	-34.0662	150.8132	29.0	43.8	18.4	21.5	32.6	13.0
Casula	-33.9560	150.8805	28.4	41.1	18.5	21.0	31.4	13.3
Casula	-33.9518	150.9030	27.8	41.8	18.0	20.9	31.1	12.9
Claymore	-34.0454	150.8085	27.7	40.7	17.9	20.5	31.4	12.5
Currans Hill	-34.0470	150.7773	28.2	41.9	18.1	19.8	30.7	10.8
Currans Hill	-34.0468	150.7688	28.2	41.8	17.5	20.4	31.1	11.7
Denham Court	-33.9740	150.8261	28.2	40.6	17.8	20.1	30.5	12.6
Denham Court	-33.9914	150.8439	27.9	40.3	17.7	20.4	31.3	12.4
Douglas Park	-34.1750	150.7405	27.4	40.2	17.2	19.0	30.7	9.3
Edmondson Park	-33.9544	150.8622	28.6	42.4	18.3	21.3	31.7	13.2
Edmondson Park	-33.9761	150.8486	28.4	41.1	16.8	20.4	30.8	12.8
Eschol Park	-34.0276	150.8052	28.6	42.2	18.4	19.7	30.5	11.1
Gilead	-34.1390	150.7819	27.9	41.3	17.8	19.4	30.3	10.2
Gilead	-34.1176	150.7860	28.2	40.7	18.1	19.7	31.0	11.7
Gilead	-34.1571	150.7894	27.6	39.8	17.7	18.7	29.7	8.5
Gilead	-34.1229	150.8001	28.0	41.2	17.4	19.6	30.7	12.1
Gledswood Hills	-34.0165	150.7748	28.6	42.3	17.4	20.3	30.7	11.7
Glen Alpine	-34.0843	150.7888	28.2	40.9	18.0	20.4	31.6	11.8
Glenfield	-33.9734	150.8888	27.7	39.9	18.3	20.1	30.9	11.5
Glenfield	-33.9713	150.8799	27.7	40.3	18.0	20.5	30.9	12.6
Gregory Hills	-34.0255	150.7731	28.5	41.4	17.6	20.6	31.3	12.2

Suburb	Latitude (°)	Longitude (°)	Mean daytime temp.	Max. daytime temp.	Min daytime temp.	Mean nighttime temp.	Max nighttime temp.	Min nighttime temp.
Holsworthy	-33.9564	150.9241	28.5	41.8	18.4	19.9	30.8	10.6
Holsworthy	-33.9720	150.9329	29.1	45.3	18.2	20.0	30.7	10.7
Holsworthy	-33.9946	150.9213	29.2	45.4	18.1	19.6	30.0	10.5
Holsworthy	-34.0109	150.9187	27.9	41.0	17.9	19.4	29.5	10.4
Holsworthy	-34.0083	150.9025	28.4	41.5	18.4	20.2	30.6	11.1
Holsworthy	-34.0287	150.9055	28.9	43.8	17.5	19.1	29.4	10.4
Holsworthy	-34.0825	150.8662	28.8	42.8	17.7	20.1	30.4	10.9
Holsworthy	-34.1031	150.8433	28.0	42.2	17.7	19.7	30.5	11.1
Holsworthy	-34.1163	150.8390	28.4	43.3	17.6	18.9	29.3	10.1
Holsworthy	-34.1219	150.8327	27.2	40.3	17.7	19.5	29.9	11.3
Holsworthy	-34.0464	150.9017	28.9	43.8	17.8	19.0	29.8	10.0
Ingleburn	-33.9978	150.8655	28.6	40.9	18.7	21.6	32.0	13.6
Ingleburn	-33.9915	150.8623	28.6	42.6	18.5	20.9	31.8	12.4
Ingleburn	-34.0108	150.8824	28.0	41.0	18.0	19.2	30.3	9.9
Ingleburn	-34.0105	150.8644	28.0	41.9	18.3	20.3	31.2	12.3
Ingleburn	-34.0063	150.8447	28.8	42.9	18.0	20.2	31.5	11.2
Kentlyn	-34.0484	150.8835	27.6	40.7	18.0	19.6	30.5	11.0
Kentlyn	-34.0442	150.8653	29.5	44.9	18.4	19.3	30.3	10.1
Kentlyn	-34.0661	150.8621	27.5	42.3	17.7	19.4	30.1	11.2
Kentlyn	-34.0802	150.8612	27.9	43.2	17.8	19.2	30.3	10.4
Leppington	-33.9722	150.8042	27.7	41.8	17.2	20.2	30.9	12.6
Leumeah Park	-34.0469	150.8416	28.1	42.6	18.1	20.3	31.3	11.9
Lynwood	-34.1016	150.8224	27.6	40.1	17.8	19.4	30.5	10.4
Macarthur Heights	-34.0662	150.7841	28.8	43.1	17.8	20.1	31.4	11.9
Macarthur Heights	-34.0709	150.7822	28.1	41.5	18.1	20.1	31.3	12.3
Macarthur Heights	-34.0763	150.7813	28.5	42.8	17.6	19.9	31.2	11.8
Macarthur Heights	-34.0763	150.7810	28.3	42.2	17.6	20.0	31.5	11.5
Macarthur Heights	-34.0735	150.7842	28.2	42.6	17.8	19.5	30.6	11.2
Macquarie Fields	-33.9908	150.8820	27.9	40.7	18.5	20.7	31.3	12.7
Macquarie Fields	-33.9910	150.9004	27.4	40.7	18.1	20.1	31.0	11.4
Menangle	-34.1249	150.7444	28.0	42.5	17.9	19.7	31.2	11.1
Menangle	-34.1376	150.7433	27.9	41.7	17.8	19.2	30.6	10.7
Menangle	-34.1579	150.7451	27.8	42.5	17.1	18.9	30.7	9.5
Menangle	-34.1181	150.7288	28.0	41.6	17.8	19.9	30.5	10.3
Menangle Park	-34.1023	150.7453	28.6	42.6	18.1	19.7	31.3	11.1
Menangle Park	-34.1022	150.7666	29.0	42.6	18.4	19.9	31.5	11.4
Menangle Park	-34.1092	150.7482	28.2	40.7	17.8	19.4	30.8	10.9
Minto	-34.0285	150.8425	28.2	41.8	18.5	20.9	31.7	12.3

Suburb	Latitude (°)	Longitude (°)	Mean daytime temp.	Max. daytime temp.	Min daytime temp.	Mean nighttime temp.	Max nighttime temp.	Min nighttime temp.
Minto	-34.0292	150.8614	27.9	41.2	17.5	19.3	30.4	10.4
Minto	-34.0288	150.8820	28.7	43.1	17.8	19.5	30.5	10.8
Mt Annan	-34.0652	150.7459	27.7	41.0	16.9	19.5	29.7	11.1
Mt Annan	-34.0646	150.7641	28.6	41.4	18.3	20.3	31.0	11.9
Mt Annan	-34.0832	150.7668	28.5	43.1	18.3	19.9	31.2	11.2
Mt Annan	-34.0697	150.7669	28.4	42.3	17.9	20.0	30.3	12.1
Raby	-34.0290	150.8234	28.9	43.8	17.4	20.4	31.5	12.1
Rosemeadow	-34.1002	150.7864	27.7	41.3	17.6	19.6	29.1	11.6
Rosemeadow	-34.1056	150.7950	27.1	40.0	17.2	19.7	30.9	10.9
Ruse	-34.0656	150.8421	28.4	42.2	17.8	19.8	30.9	11.1
Spring Farm	-34.0785	150.7285	26.6	38.5	17.4	19.7	28.9	11.4
St Helens Park	-34.1023	150.8040	27.5	40.7	17.9	19.9	31.2	11.3
Varroville	-33.9926	150.8076	27.6	40.5	17.3	19.9	30.6	11.3
Varroville	-33.9936	150.8225	27.5	40.3	17.6	20.1	30.6	13.3
Varroville	-34.0095	150.8235	28.4	43.2	17.9	20.0	31.5	11.6
Varroville	-34.0112	150.8015	28.8	42.6	18.0	19.8	30.5	11.5
Wedderburn	-34.1398	150.8063	27.0	40.2	17.0	18.9	30.2	10.6
Wedderburn	-34.1362	150.8240	27.2	41.5	17.2	18.7	29.6	10.7
Wedderburn	-34.1634	150.8387	26.3	37.4	17.3	19.5	28.4	11.2
Wedderburn	-34.1560	150.8239	27.4	42.8	16.5	18.3	29.4	9.2
Wedderburn	-34.1579	150.8064	26.4	39.2	16.8	18.8	29.9	9.9
Wedderburn	-34.1746	150.8091	27.7	42.8	17.0	18.3	29.4	8.4
Willowdale	-33.9739	150.8152	28.6	41.5	17.2	20.2	31.2	12.0
Willowdale	-33.9791	150.8201	28.8	42.8	17.7	20.4	31.5	12.5
Willowdale	-33.9886	150.8144	27.5	40.0	17.8	20.9	31.5	13.7
Woodbine	-34.0471	150.8244	28.8	42.9	18.4	20.2	31.5	11.7

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