ArborCarbon *Creating Sustainable Ecosystems*

Resilient South
Strengthening Southern Adelaide for changes in our climate

Airborne Thermal Imagery and Analysis 2016

Resilient South

Report No. 16-04 prepared for Resilient South 22 May 2016

Government of South Australia
Department of Environment, Water and Natural Resources

City of Holdfast Bay

City of Mitcham

City of Marion

City of Onkaparinga

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EXECUTIVE SUMMARY

ArborCarbon Pty Ltd was engaged by Resilient South (*the client*) to acquire and undertake analysis of high-resolution thermal infrared imagery over a 285 square kilometre region on 22 February to determine the baseline surface temperatures of the region. In addition, we have included the previous analysis of satellite-derived surface temperature and NDVI (Normalised Difference Vegetation Index) undertaken for members of the Resilient South Region, and the terrestrial thermal data captured concurrently with the high-resolution airborne thermal data.

The main findings of this study are as follows:

- A total of 285 square kilometres was analysed for surface temperature based upon high-resolution (2.0m pixels) thermal infra-red imagery acquired on 22 February 2016 where air temperatures exceeded 38°C in Adelaide
- A total of twelve distinct regions were analysed in this study
- In general surface temperatures based upon the analysis of this dataset increase with distance from the coast-line
- Aldinga Beach recorded the lowest minimum temperature (7.18°C) whilst Maslin Beach recorded the highest minimum temperature (17.86°C), slightly higher than Port Willunga (17.45°C).
- Onkaparinga recorded the highest maximum temperature (86.76°C) whilst Maslin Beach recorded the lowest maximum temperature (41.47°C).
- Maslin Beach had the smallest range in temperatures of all regions
- Aldinga Beach Esplanade had the lowest mean surface temperature (29.73°C) and McLaren Flat had the highest mean surface temperature (36.67°C), almost 7°C warmer than Aldinga Beach Esplanade.
- The surface temperature of the City of Holdfast Bay ranged from 7.18°C to 47.9°C, with a mean of 32.50°C
- Satellite-derived surface temperature showed Glenelg East to be the hottest suburb within the City of Holdfast Bay, Glenelg, Glenelg South and Kingston Park were the coolest suburbs.
- Mean satellite-derived NDVI values of Glenelg and Glenelg South were amongst the lowest of all suburbs, with Glenelg East amongst the highest in the City of Holdfast Bay
- In the City of Marion the surface temperature ranged from 15.37°C to 57.35°C, with a mean of 31.88°C
- Satellite-derived surface temperature showed the suburbs with the hottest mean surface temperatures were the inland suburbs of Ascot Park, Clovelly Park, Mitchell Park and O'Halloran Hill, and the coolest suburb, Marino, was found closest to the coast in the south-west.

- Mean satellite-derived NDVI values of Morphettville, Marion and Bedford Park were amongst the highest of all suburbs, with Ascot Park, Edwardstown, Clovelly Park, and interestingly, Marino amongst the highest.
- In the City of Mitcham the surface temperature ranged from 12.93°C to 69.78°C, with a mean of 33.37°C.
- Mean satellite-derived surface temperature showed the suburbs in the City of Mitcham with the hottest mean surface temperatures were the northern and western most suburbs of Netherby, Lower Mitcham, Westbourne Park, Clarence Gardens, Cumberland Park, Melrose Park, Daw Park, St Marys and Pasadena, and the coolest suburbs were Crafers West and Upper Sturt
- Mean satellite-derived NDVI values of Clarence Gardens, Cumberland Park, Melrose Park, Daw Park, and St Marys, were lowest and the suburbs highest in NDVI were Belair, Hawthorndene and Crafers West.
- In the City of Onkaparinga the airborne-derived surface temperature ranged from 7.18°C (Aldinga Beach) to 86.76°C (Onkaparinga).
- Aldinga Beach had the coolest mean surface temperature (29.73°C), whilst McLaren Flat had the highest mean surface temperature (36.67°C).
- The coolest sites across the study were comprised of golf courses, water-bodies, dense woody vegetation and irrigated turf, whilst the hottest areas were generally comprised of buildings, dry agricultural fields, dry/dead grass and vegetation, exposed soil and unshaded hard surfaces.
- The findings from the airborne thermal data were also supported by the terrestrial data collected concurrently, with apparent differences in surface temperature of up to 30°C observed.

This study has very clearly identified the heat and cool islands throughout the Resilient South Region based upon airborne-derived surface temperature data. We provide the following recommendations based upon the findings of this study:

- Acquire high-resolution multispectral height-stratified vegetation cover data for the Cities of Holdfast Bay, Mitcham and Marion as previously acquired for the City of Onkaparinga
- Following acquisition of the high-resolution multispectral height-stratified vegetation cover for the Cities of Holdfast Bay, Mitcham and Marion, undertaken further analysis to determine the precise relationships between vegetation cover types (i.e. canopy versus non-canopy) and surface temperature
- Undertake analysis of the high-resolution multispectral height-stratified vegetation cover data for the City of Onkaparinga to determine the relationship between canopy cover of specific areas (i.e. Suburbs, parks, residential, commercial, roads) and surface temperatures

- Undertake analysis of the high-resolution airborne surface temperature data to determine the relationship between different residential development zones (i.e. R-codes) and surface temperature
- Undertake analysis of the high-resolution airborne surface temperature data to determine the relationship between different impervious layers and their surface temperature
- Analyse the high-resolution multispectral height-stratified vegetation cover data to classify individual materials (i.e. vegetation, impervious
- Acquire night-time airborne thermal data at the same resolution over the same area to calculate the residual surface temperature and compare with the day-time dataset for identification of the thermal-holding capacity of different materials within the region.
- Use the acquired data and findings from this report to assist urban design throughout the Resilient South region and increase the resilience of those who live within the region.
- Following all of the above-mentioned analysis, develop KPI’s for vegetation cover and surface heat for zones managed within the region, and in subsequent years acquire data for the measurement of progress against KPI’s.
- Use the developed KPI’s within management plans for the different land-use zones and sites within the Resilient South region.
- Further explore additional opportunities for analysis of the acquired datasets for land management outside and within the urban areas.

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Abbreviations

Ap	Band specific additive rescaling factor
BoM	Bureau of Meteorology
°C	Degrees Celsius
Fig.	Figure
≥	Equal or Greater than
HA	hectares
Km	Kilometre
KPI	Key Performance Indicator
m	metre
Mp	Band specific multiplicative rescaling factor
NDVI	Normalised Difference Vegetation Index
NNW	North North West
%	percentage
Qcal	Quantized and calibrated standard product pixel values
TIR	Thermal Infra-Red
TOA	Top of Atmosphere Planetary Reflectance
WNW	West North West

1.0 INTRODUCTION

ArborCarbon was engaged by Resilient South (*the client*) to acquire high-resolution airborne thermal infrared imagery in 2016 for the purpose of providing a baseline measure of land-surface temperature across the region. This acquisition was successfully completed on 22 February 2016. Subsequently ArborCarbon has been engaged to analyse this data and identify cool and heat islands throughout the region, their respective temperatures, and likely causes.

The Southern Region of Adelaide is aligned with the boundaries of the Council areas of Holdfast Bay, Marion, Mitcham and Onkaparinga. It covers 650km^2 (Fig. 1) and is home to over 340,000 people, or about 21% of South Australia's population. These four Councils have partnered together on the Resilient South program to make their communities more resilient to climate change.

The goal of Resilient South is a Region that is resilient to natural hazards associated with climate change, is focused on preparedness and crisis avoidance and has captured opportunities in innovation in adapting to Climate Change.

Figure 1. The Resilient South Region of South Australia

The Resilient South Regional Climate Change Adaptation plan[1] describes the projected climate change impacts for 2070 including warming temperatures, more frequent and intense heatwaves, reduced annual rainfall but increased rainfall intensity, rising sea levels, and a longer bushfire season. Adaptation actions for 10 key decision areas across the environment and natural resources, economy and infrastructure and social and community domains are described for the consideration of all stakeholders in the southern Adelaide region.

In response to the Regional Adaptation Plan, the Southern Region Local Government Implementation Plan (2015 to 2019) (the Regional Implementation Plan) takes those actions most relevant for the four partner Councils and prioritises their implementation by adopting four foundation projects[2].

One of the foundation projects is Cool Places. Cool Places will focus on projects in our open space and public realm where Councils have most influence including our parks, streetscapes, natural landscapes and sporting hubs. The project has a number of regional and local actions including to understand the urban heat island effect on our local communities.

In 2015, the state government partnered with Resilient South and provided the Cool Places project with a $25,000 grant to obtain evidence of the impacts of urban heat and the value of green infrastructure[3] in mitigating these impacts. The first step was to work with Flinders University of South Australia to look at existing data and satellite imagery to broadly explore heat in the Resilient South region. The subsequent report identified some areas that appear to be more sensitive to heat and the potential causes, and compared night-time and day-time hotspots[4].

Following the Flinders University report Resilient South and the state government decided to obtain high-resolution airborne thermal imagery that could tell the story of heat at a local scale. The purpose of this mapping would be to identify and prioritise open space and public realm areas most vulnerable to urban heat impacts that could benefit from green infrastructure.

This report discusses the findings from heat mapping undertaken by ArborCarbon during the summer of 2015-16.

[1] www.resilientsouth.com
[2] The Regional Implementation Plan has been endorsed by the Cities of Holdfast Bay, Marion, Mitcham and Onkaparinga. It is available at www.resilientsouth.com
[3] "Green Infrastructure describes the network of green spaces and water systems that deliver multiple environmental, economic and social values and benefits."
[4] "Mapping Summer Temperatures in the Resilient South Region" Huade Guan School of the Environment Flinders University of South Australia.

Future changes to southern Adelaide temperatures

NASA scientists have recorded a long-term warming trend in global temperatures and report that in 2015 temperatures were the warmest, and in Australia the 5th warmest, since record keeping began in 1880[5].

Looking forward to the year 2070 the southern Adelaide region can expect warming temperatures, and more frequent and intense heatwaves[6].

In South Australia, annual average maximum temperature (recorded at Adelaide Airport[7]) has increased by 0.22°C per decade since records began in 1956. Annual temperature is projected to continue to increase by nearly 3°C by 2070 compared to the period 1980-1999. Average temperatures in winter and summer are projected to increase by 1.7°C and average temperatures in spring are projected to increase by 2.2°C by 2070.

By 2070, maximum temperatures during January and February are projected to exceed 45°C, up from 43°C in 1980-1999 and 44°C in 2000-2012.

The duration, frequency and intensity of heatwaves have been increasing across Australia and are projected to continue to increase in coming decades. The number of days where the maximum temperatures exceeds 40°C is projected to increase from periods of up to three consecutive days in 1980-1999 to periods of up to five consecutive days by 2070. It is projected that the frequency of two consecutive days where maximum temperatures exceed ≥40°C will increase from once every 10 years to once every 1-2 years.

The impact of heat on vulnerable people

Heatwaves have serious health and wellbeing implications for the elderly and young, culturally and linguistically diverse communities, people from a low socio-economic background and those needing assistance with everyday activities[8].

Heatwaves are known to cause greater morbidity and mortality than other climate extremes. Access to heat refuges or cooler places is an essential part of people's adaptive capacity under such circumstances. Yet many elderly people and those reliant on assistance for core activities in particular may not have access to cool places or the ability to finance an air-conditioner. They may live in non-climate sensitive housing or may not be mobile enough to access heat refuges or other support services when needed.

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[5] http://www.nasa.gov/press-release/nasa-noaa-analyses-reveal-record-shattering-global-warm-temperatures-in-2015

[6] Resilient South (2014) *Climate Change Scenarios Report – Resilient South* available at www.resilientsouth.com

[7] Adelaide Airport data was used on the basis that it is the closest meteorological station with quality long term records, and is also representative of the climate zone that includes the Southern region.

[8] Increased temperatures and heatwaves do impact on our coasts, natural landscapes, sea surface temperatures, and the demand for our emergency services. For adaptation actions related to these areas please refer to the Regional Adaptation Plan at www.resilientsouth.com

The Resilient South Regional Climate Change Adaptation Plan identified a number of adaptation actions to increase the resilience of vulnerable people to a hotter future[9]. One of these actions is to increase and improve the green spaces in our urban areas to mitigate heat.

Land Surface Temperature and Air Temperature

High-resolution thermal infra-red remote sensing technologies, such as that used in this current project, have the capacity to monitor the surface Urban Heat Island (UHI) through measurement of surface temperatures. Although different to the urban canopy layer UHI, the surface UHI is a primary driver of canopy layer climate as surface temperature has a large influence on the adjoining air temperature and lower layer of the urban atmosphere (Weng, 2009; Harris and Coutts 2011). Most studies of the UHI effect refer to air temperature. It is important to understand that many factors can impact the readings obtained from airborne surface measurements, including but not limited to emissivity, shadows, moisture, wind, building geometry, cloud cover, sun-angle and anthropogenic effects. In order to accurately measure surface temperatures, data must be corrected for effects from the atmosphere, reflectance and emissivity.

2.0 SCOPE OF REQUIREMENTS

This project has been divided into three parts:

1. Acquire and process the airborne high-resolution thermal infrared (TIR) imagery
2. Generate georeferenced radiometric and surface temperature datasets
3. Analyse all datasets for heat and cool islands and present statistics and a report detailing the findings

[9] www.resilientsouth.com

3.0 METHODS

3.1 Acquisition and processing of airborne thermal infrared imagery

ArborCarbon and Spatial Scientific were engaged to acquire high-resolution TIR imagery at a spatial resolution of 2.0m on 22 February 2016 in a north-south flight pattern between the hours of 11:25 and 15:30. Data was acquired from a light aircraft using a FLIR A615 thermal imaging camera. Weather conditions for acquisition included a clear atmosphere without interference from cloud, cloud shadow or haze. The maximum temperature recorded in Adelaide (BoM station ID station 023090) for that day was 39.5 degrees Celsius.

3.2 Generation of georeferenced radiometric and surface temperature datasets

Data was acquired over a period of several hours (between 11:25 and 15:30) on one day rather than across several days to avoid any radiometric errors that may arise due to changing weather conditions. Data was mosaiced by aligning individual images to the base data set. Base data (high resolution aerial photography) was supplied by the Department of Environment, Water and Natural Resources, South Australia. The data was resampled and supplied at a spatial resolution of 1.0m.

The mosaiced data was supplied in radiometric format and also converted to surface temperature data for analysis.

3.3 Analysis of airborne datasets and presentation of statistics

A total of 285 square kilometres of imagery was analysed and the statistics derived for individual areas within the extent based upon the boundaries supplied by the client. A total of twelve distinct zones were defined and we have labeled as follows: Holdfast Bay, Mitcham, Marion, Onkaparinga, Maslin Beach, McLaren Flat, McLaren Vale, Port Willunga, Aldinga Beach, Willunga, Aldinga Beach Esplanade and Sellicks Beach (Fig. 2). These distinct zones will be referred to throughout the remainder of this report. Statistics derived from the dataset are based upon the analysis of the surface temperature data. It is important to note that a standard emissivity value has been applied to the dataset to derive surface temperature and due to the variation in emissivity between surface materials like water, rooftops and vegetation, it is likely that individual materials such as rooftops may be inaccurate by several degrees. The values provided are therefore an estimate and are not conclusive.

3.4 Processing and Analysis of Satellite thermal infrared imagery

We processed and analysed satellite thermal data from the Landsat 8 sensor over the project area on the hottest day of 2015 within the orbit cycle (22 December 2015). The data is 100m pixel resolution and resampled to 30m. Further detail about the methods used to convert the raw data into surface temperature data is provided in Appendix 37. Polygons were provided by the clients of the council areas and suburbs within. These were used to extract surface temperature data and calculate the mean temperatures and ranges in temperature

3.5 Processing and Analysis of Satellite NDVI

We processed and analysed NDVI data from the Landsat 8 sensor over the project area on the hottest day of 2015 within the orbit cycle (22 December 2015). NDVI is a algorithm using the visible (VIS) and near infrared (NIR) bands of the electromagnetic spectrum and provide an indication of the presence or absence of vegetation. Values vary from -1 to +1. NDVI of Australian native vegetation ranges from 0.1 up to 0.7 with the higher values indicating a greater density and greenness of canopy. The data from Band 5 (near infrared) and Band 4 (red) of Landsat8 is 30m pixel resolution. Spectral radiance data was converted to Top of Atmosphere planetary reflectance using supplied reflectance coefficients and the following equation:

TOA = Mp Qcal + Ap

Where:

- Mp = Band specific multiplicative rescaling factor
- Ap = Band specific additive rescaling factor
- Qcal = Quantized and calibrated standard product pixel values (DN).

A further correction for sun angle was applied using the following equations:

TOA = TOA'/cos

OSZ = TOA'/sin OSE

Where: TOA = Top of atmosphere planetary reflectance.

OSE = Local sun elevation angle

OSZ = Local solar zenith angle

NDVI was then calculated on Band 5 (Red) and Band 4 (NIR) using the equation:

NDVI = (NIR – Red) / (NIR + Red)

Where: NDVI = (Band 5 corrected – Band 4 corrected)/(Band 5 corrected + Band 4 corrected)

Mean and range in NDVI values were extracted from the council region and suburbs within using the supplied vector files.

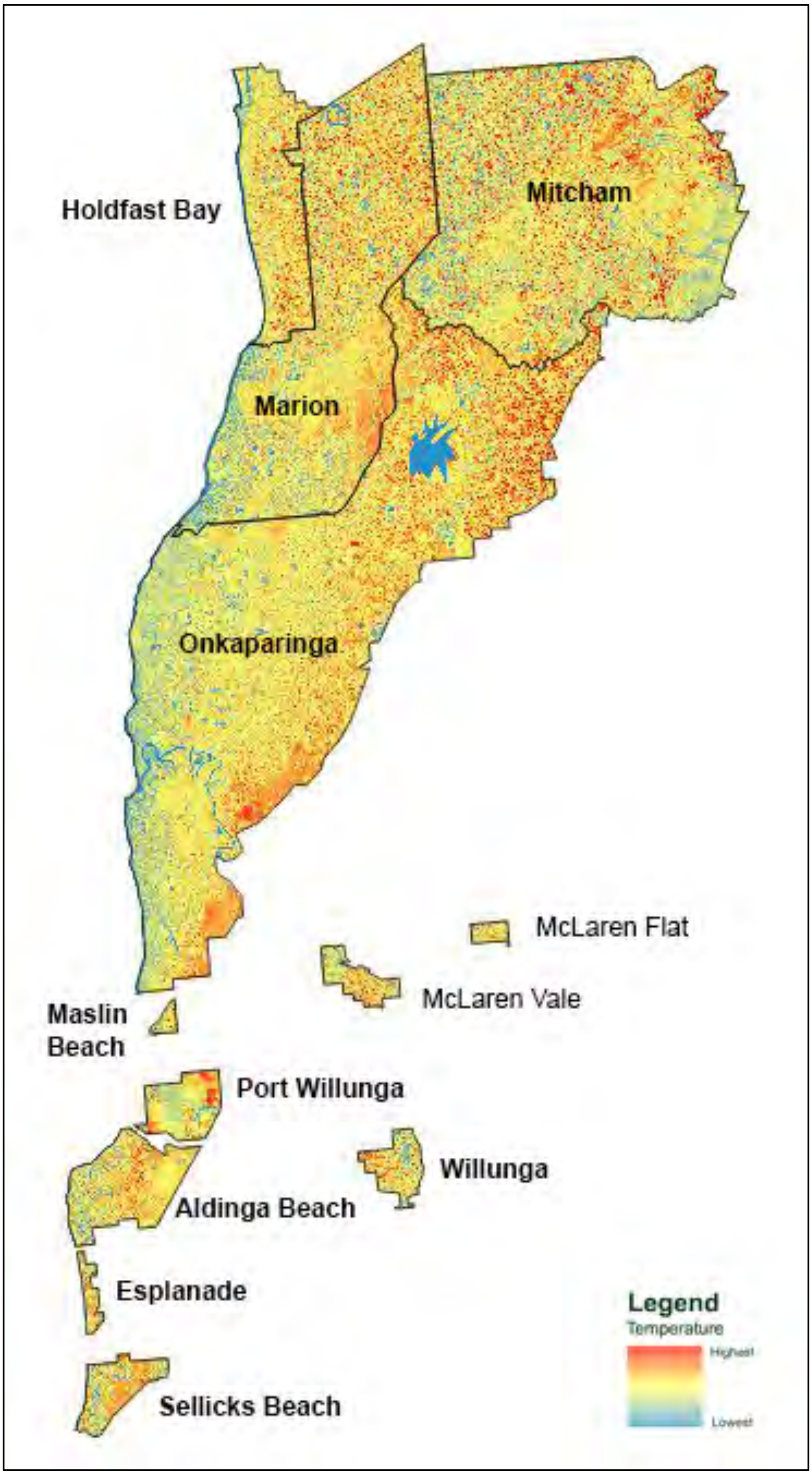


Figure 2. Twelve distinct zones within the Resilient South region with boundaries overlaid onto the high-resolution airborne thermal dataset. Temperatures are scaled from lowest (blue) to highest (red).

4.0 RESULTS

4.1 Baseline surface temperature imagery

Geospatial datasets have been provided to the client including the georeferenced radiometric and surface temperature data in single band grayscale, and surface temperature data for each of the 12 separate zones with colour scale. These colour-scaled images have been provided in high-resolution in tiff format and also in lower resolution on map templates (Appendices 1-12).

It is apparent when observing the datasets that a gradient from cooler surface temperatures through to hotter surface temperatures occurs with distance from the coast-line (Fig. 2). This gradient can be seen in more detail in the Aldinga Beach and Onkaparinga images (Appendices 4 and 9). There are several possible reasons for the presence of this gradient, including an increase in temperatures with distance from the ocean (coastline) and therefore a reduction in the effect of the westerly sea-breeze that was present on that day, and differences in the proportion of materials that vary in their surface temperature. For example, a higher density of housing development and less vegetation would give the overall appearance of warmer surface temperatures. When viewing the higher resolution airborne imagery it appears that there in some cases there is a distinct difference in the density of housing where noticeable differences in temperature occur, for example, on either side of Rowley Rd in Aldinga Beach.

It is evident when viewing the surface temperature maps that the hottest temperatures are mostly the building roofs and areas of dead grass, whilst the coolest areas are living vegetation and water. The bitumen and pavement/concrete fall somewhere in between. It is also interesting to note that image acquisition occurred by flying in lines of a north-south direction, beginning in the west and finishing in the east. We could therefore expect to see an increase in surface temperatures from west to east as air temperature increased and duration of surface exposure to UV increased. Adelaide Airport weather data indicated an increase in air temperature from 25.5°C at 9am to 34.6°C at 3pm. An increase in surface temperature from a west to east direction is somewhat apparent in the imagery shown, with cooler surface temperatures generally occurring with proximity to the coast-line (Fig. 2). It is quite possible, and likely, that the cooler temperatures closer to the coast-line are partly due to the presence of a sea-breeze and also lower density residential development. This is covered in more detail below.

The wind direction and speed recorded at Adelaide Airport (BOM station Id 023034) on 22 February 2016 at 9am was WNW at 2km/hr and at 3pm was NNW at 13 km/hr. Image acquisition was completed by 3:30pm and therefore we can suggest that the wind direction during the time of acquisition was likely between WNW and NNW and of velocity ranging between 2km/hr and approximately 13km/hr. This data suggests that a light sea-breeze existed on that day and this is supported by the observations of Dr Paul Barber who was concurrently acquiring terrestrial thermal surface temperature data in the City of Onkaparinga during that time.

4.2 Analysis

4.2.1 Resilient South Region

The total area (HA) was calculated for each of the different regions, along with the minimum, maximum and mean surface temperatures (Appendix 23). Aldinga Beach recorded the lowest minimum temperature (7.18°C) whilst Maslin Beach recorded the highest minimum temperature (17.86°C), slightly higher than Port Willunga (17.45°C). Onkaparinga recorded the highest maximum temperature (86.76°C) whilst Maslin Beach recorded the lowest maximum temperature (41.47°C). These results suggest Maslin Beach had the smallest range in temperatures of all regions. Aldinga Beach Esplanade had the lowest mean surface temperature (29.73°C) and McLaren Flat had the highest mean surface temperature (36.67°C), almost 7°C warmer than Aldinga Beach Esplanade (Fig. 3).

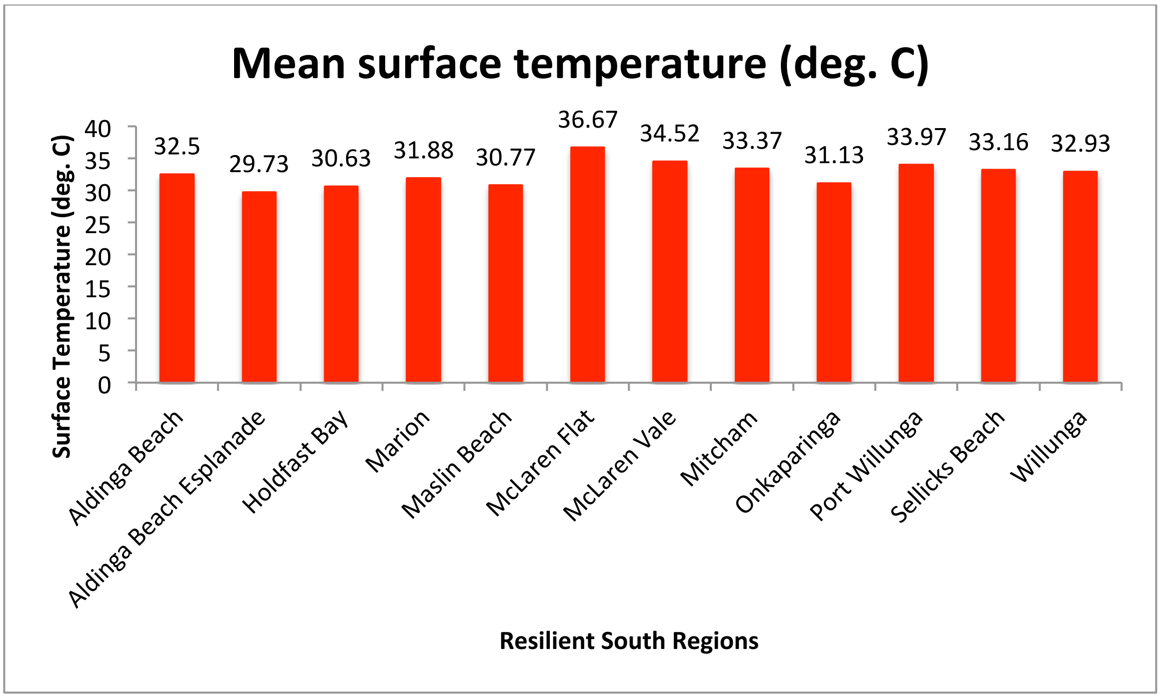


Figure 3. Mean surface temperature of selected Resilient South Regions showing Aldinga Beach Esplanade as the coolest and McLaren Flat as the hottest.

4.2.1.1 Anomalies

Random noise typically occurs as individual pixels with digital numbers that are much higher or lower than the surrounding pixels. It was noted that some datasets had a noticeably higher or lower range in surface temperature values than others. For example, in the Onkaparinga dataset the majority of surface temperature values range from 12.5°C upwards, however, there are 7 pixels in the dataset with a 0 value and the range increases to 86°C. Analysis of the dataset shows that most values cluster between 17°C and 43°C, with only seven pixels with a 0°C value, and only 47 pixels ranging from 50.7-86.8°C. Closer analysis showed that these values were all found on the same object (Fig. 4). It is important to note that these anomalies are confined to a very small number of pixels, and therefore, is likely to have a very small effect on the mean values presented in this report.

Figure 4. Pixels located (highlighted red) in the Onkaparinga region with a surface temperature ranging between 50.7°C and 86.8°C.

4.2.2 City of Holdfast Bay

The City of Holdfast Bay covers a total area of approximately 1449 HA with the entire western boundary bordered by the large waterbody St Vincent Gulf and Patawalonga River residing in the north (Appendix 1). The surface temperature ranged from 7.18°C to 47.9°C, with a mean of 32.50°C (Appendix 23). The lowest temperatures are confined to the waterbodies. The density of development appears to be quite uniform across the city, and besides this, there appears to be a band of cooler temperatures moving from a north-westerly direction (Fig. 5). This is likely to be the effect of the sea-breeze on the temperature data. House roofs have an apparent higher surface temperature than the bitumen roads and the vegetation appears cooler than both these surfaces. The roofs of Sacred Heart College are most noticeable as hot surfaces, and this is possibly due to their temperature but also the large surface area. In contrast, the irrigated turf within the college has a much cooler surface temperature.

Two distinct zones were chosen for comparison of mean surface temperatures within Holdfast Bay. These were south of Jetty Road along the coast as a cool-island and further south and inland as the heat island (Appendix 14). The mean surface temperature of the cool island was 30.1°C and the heat island was 32.5°C (Appendix 24).

Analysis of satellite-derived (Landsat) surface temperature and Normalised Difference Vegetation Index (NDVI) was previously carried out by ArborCarbon. This data showed the suburb with the hottest mean surface temperature was Glenelg East, extending furthest inland, and the coolest suburbs (Glenelg, Glenelg South and Kingston Park) were found closest to the coast (Appendix 27, 28). Mean satellite-derived NDVI values of Glenelg and Glenelg South were amongst the lowest of all suburbs, with Glenelg East amongst the highest (Appendices 25, 26).

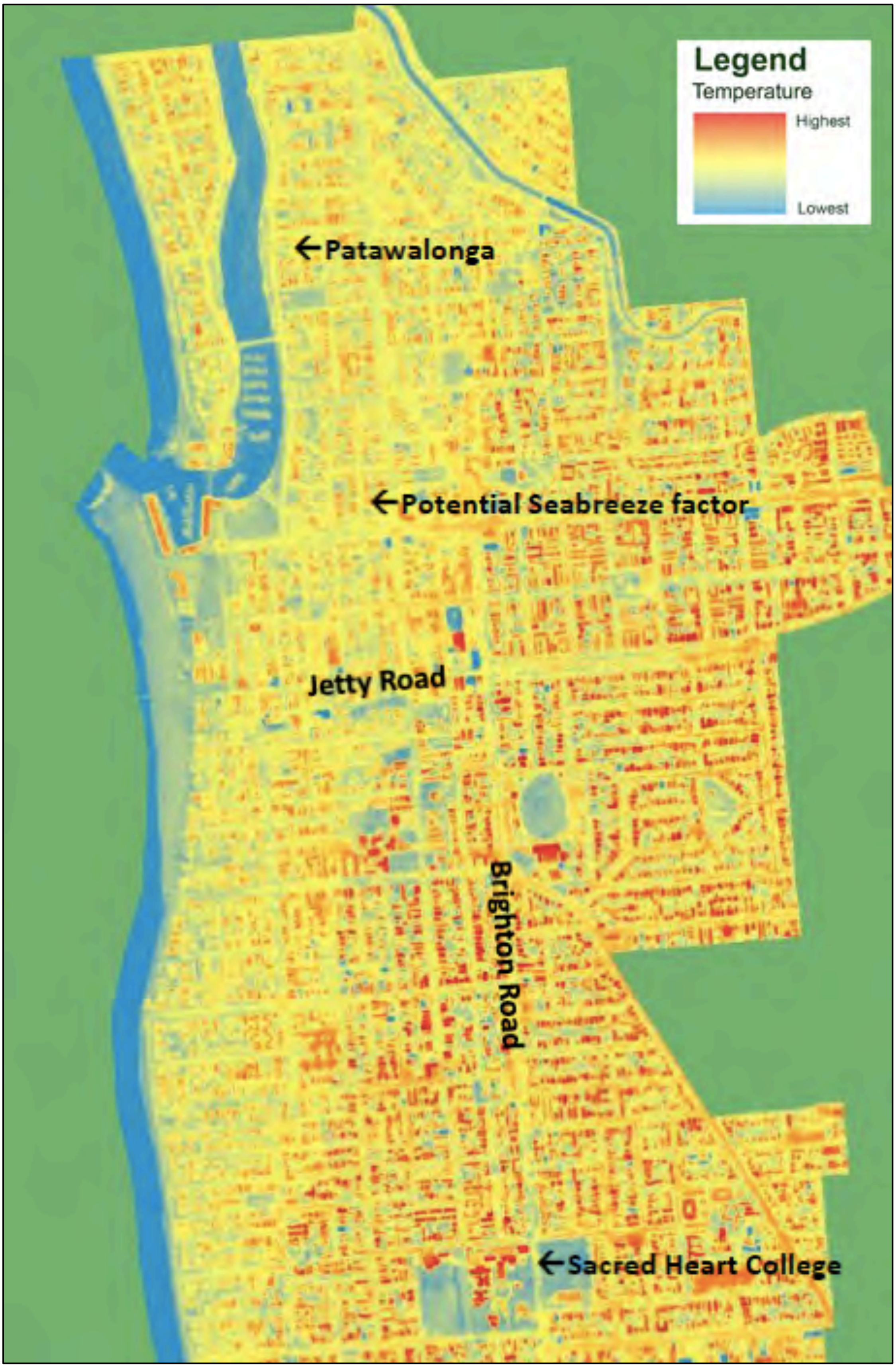


Figure 5. Selected heat and cool islands throughout the City of Holdfast Bay and what appears to be a noticeable impact of seabreeze on surface temperature data

4.2.3 City of Marion

The City of Marion covers a total area of approximately 5620 HA and unlike Holdfast Bay, only the south-western boundary is bordered by the large waterbody of St Vincent Gulf (Appendix 2). The surface temperature ranged from 15.37°C to 57.35°C, with a mean of 31.88°C (Appendix 23). The lowest temperatures are confined to the waterbodies. The density of development appears vary widely across the City, with higher density housing through to large areas of rural land. A possible effect of the sea-breeze on the temperature data may also be apparent in the City of Marion, with the south-west suburbs closest to the coast with a noticeably cooler surface temperature than the northern and north and eastern suburbs further inland. Like the City of Holdfast Bay, house roofs have an apparent higher surface temperature than the bitumen roads and the vegetation appears cooler than both these surfaces. In contrast to Sacred Heart College, the roofs of Westminster School vary from apparently cool through to hot surfaces (Fig 6). This large difference may be due to the actual temperatures, but may also be due to differences in emissivity of materials, with some roofs possibly metal and others tile. In contrast, the irrigated turf within Morphetville Racecourse has a markedly cool surface temperature.

Two distinct zones were chosen for comparison of mean surface temperatures within the City of Marion. These were in the south-west section near the coast-line in the suburb of Hallett Cove as a cool-island and in the north-east around Ascot Park as a heat island (Appendix 15). The mean surface temperature of the cool island was 30.1°C and the heat island was 33.1°C (Appendix 24).

Analysis of satellite-derived (Landsat) surface temperature and Normalised Difference Vegetation Index (NDVI) was previously carried out by ArborCarbon. This data showed the suburbs with the hottest mean surface temperatures were the inland suburbs of Ascot Park, Clovelly Park, Mitchell Park and O'Halloran Hill, and the coolest suburb, Marino, was found closest to the coast in the south-west (Appendices 31, 32). Mean satellite-derived NDVI values of Morphettville, Marion and Bedford Park were amongst the highest of all suburbs, with Ascot Park, Edwardstown, Clovelly Park, and interestingly, Marino amongst the highest (Appendix 29, 30).

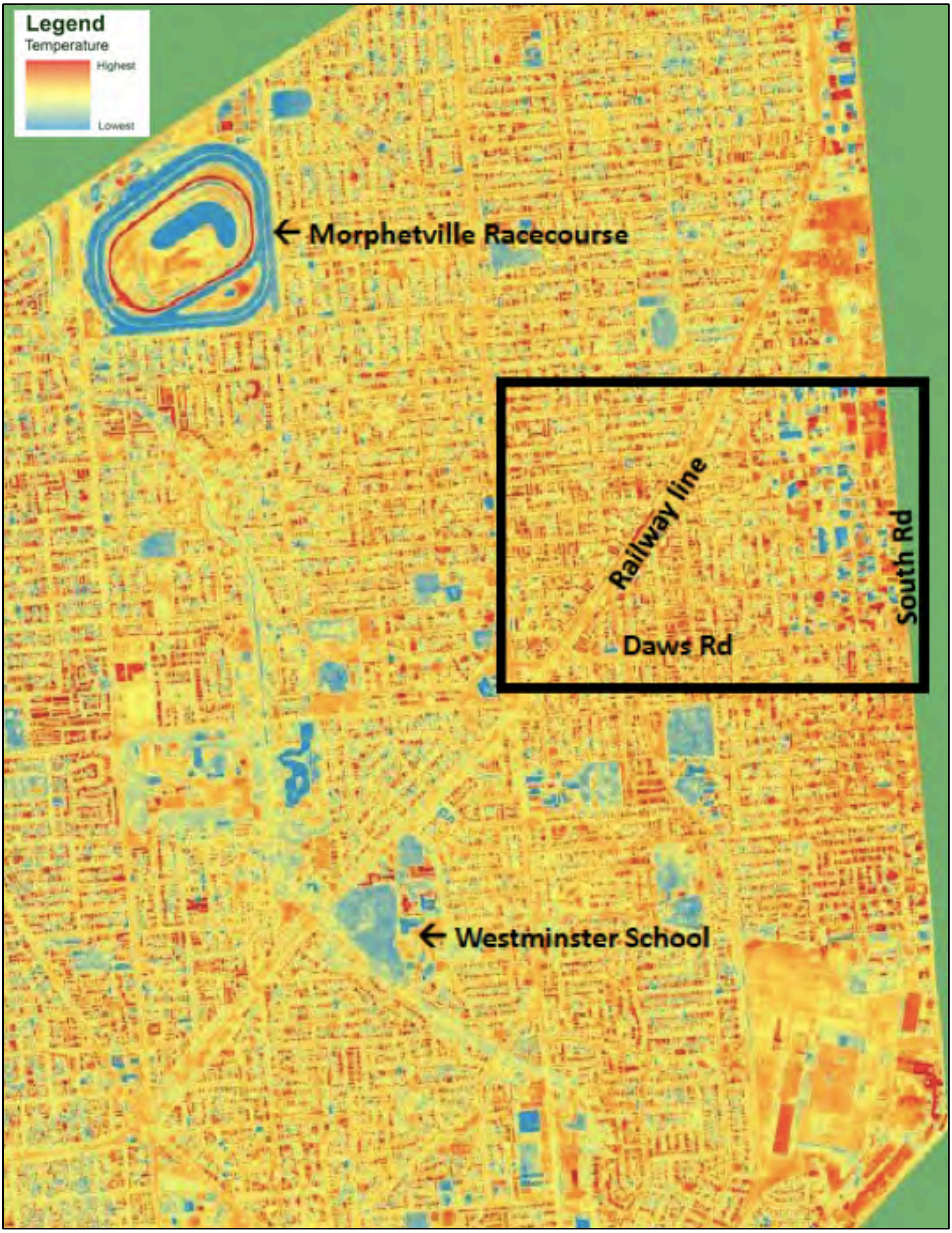


Figure 6. Selected heat and cool islands throughout the City of Marion.

4.2.4 City of Mitcham

The City of Mitcham covers a total area of approximately 7569 HA and unlike Holdfast Bay and Marion, has located inland and therefore has no boundary on St Vincent Gulf (Appendix 3). The surface temperature ranged from 12.93°C to 69.78°C, with a mean of 33.37°C (Appendix 23). The lowest temperatures are confined to the waterbodies. The density of development appears vary widely across the City, with higher density housing through to large areas of rural land. There is no apparent effect of a sea-breeze on the surface temperature data. Like the City of Holdfast Bay, house roofs have an apparent higher surface temperature than the bitumen roads and the vegetation appears cooler than both these surfaces, with exception of large areas inland, which may in fact be vegetation. Differences in surface temperature are clearly evident between irrigated turf surfaces such as Scotch College and Mitcham Reserve, which are both noticeably cooler than Mitcham cemetery with unirrigated grasses (Fig. 7). This large difference may be due to the actual temperatures, but may also be due to differences in emissivity of materials, with dead or dying vegetation having a different emissivity to lush, living vegetation.

Four distinct zones were chosen for comparison of mean surface temperatures within the City of Mitcham. Two smaller areas were selected to compare lower density housing development (Mitcham cool 1) with higher density housing development (Mitcham hot 1) (Appendix 18), and two larger areas were chosen further inland to compare an apparent cool island (Mitcham cool 2) with a heat island (Mitcham hot 2). It is not known what differed about the composition of these two locations. The mean surface temperature of Cool island 1 was 32.4°C and Cool Island 2 was 31.8°C , whilst Heat Island was 34.2°C and Heat Island 2 was 35.4°C (Appendix 24).

Analysis of satellite-derived (Landsat) surface temperature and Normalised Difference Vegetation Index (NDVI) showed the suburbs with the hottest mean surface temperatures were the northern and western most suburbs of Netherby, Lower Mitcham, Westbourne Park, Clarence Gardens, Cumberland Park, Melrose Park, Daw Park, St Marys and Pasadena, almost totally covered by residential and industrial zones, and the coolest suburbs were Crafers West and Upper Sturt (Appendices 35, 36). Mean satellite-derived NDVI values of Clarence Gardens, Cumberland Park, Melrose Park, Daw Park, and St Marys, were lowest and almost totally covered by residential and industrial zones, and the suburbs highest in NDVI were Belair, Hawthorndene and Crafers West (Appendices 33, 34).

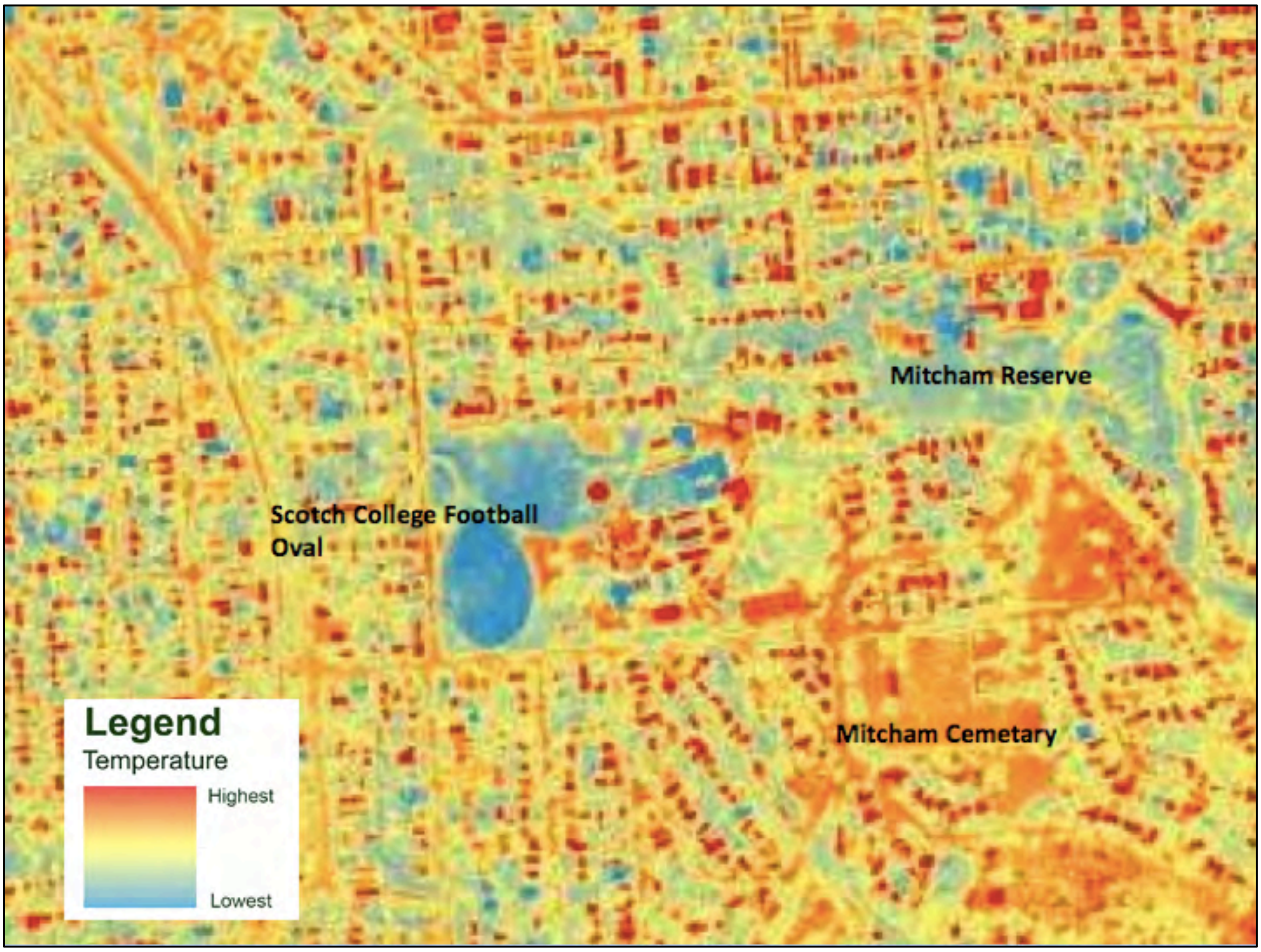


Figure 7. Selected heat and cool islands throughout the City of Mitcham

4.2.5 City of Onkaparinga

The City of Onkaparinga covers a much larger area than the area acquired during this study, which totalled approximately 11,479 HA and covers a wide range of land-use categories bordered by the St Vincent Gulf in the west to McLaren Vale in the east. The urban regions within the City of Onkaparinga have been acquired and divided into different regions for analysis in the present study as follows: Aldinga Beach, Aldinga Beach Esplanade, Maslin Beach, McLaren Flat, McLaren Vale, Onkaparinga, Port Willunga, Sellicks Beach and Willunga (Appendices 4 to 12). The surface temperature ranged from 7.18°C (Aldinga Beach) to 86.76°C (Onkaparinga) (Appendix 23). Aldinga Beach, a small coastal suburb, had the coolest mean surface temperature (29.73°C), whilst McLaren Flat, a small inland suburb, had the highest mean surface temperature (36.67°C).

The lowest temperatures were generally confined to the waterbodies on the coast and inland. The density of development appears vary widely across the City, with higher density housing through to large areas of rural land. There is an apparent effect of a sea-breeze on the surface temperature data along the coast (e.g. Appendix 4). Like other areas within the Resilient South Region, house roofs have an apparent higher surface temperature than the bitumen roads and the vegetation appears cooler than both these surfaces, with exception of large areas inland, which may in fact be vegetation. There are apparent differences in surface temperature between higher density and lower density residential areas and this is apparent in the western and eastern parts of McLaren Vale (Appendix 6). This is also very apparent on either side of Rowley Road in Aldinga Beach, with lower density residential zone to the west noticeably cooler than the higher density residential zone to the east (Fig. 8). Aldinga Shopping Centre is a noticeable heat island also in this suburb (Fig. 8), with irrigated reserves like Symonds Reserve standing out as reasonably large cool islands.

A selection of cool and heat islands were chosen throughout the selected urban regions within the City of Onkaparinga (Appendices 16, 17, 20-22). Notable differences in temperature were observed between golf courses and residential areas, with the golf course 4.1°C cooler in Onkaparinga 1 and 3.8°C in Willunga (Appendix 24). The major difference in temperature in McLaren Flat was between a wetland/water-body (32.5°C) and residential (37.6°C), whilst in Port Willunga and Sellicks Beach the coolest areas were due to the presence of woody vegetation in a residential area forming canopy as compared to a agricultural field that we suspected had been recently harvested with dry stubble or exposed soil. Differences of up to 5.6°C were measured between these zones.

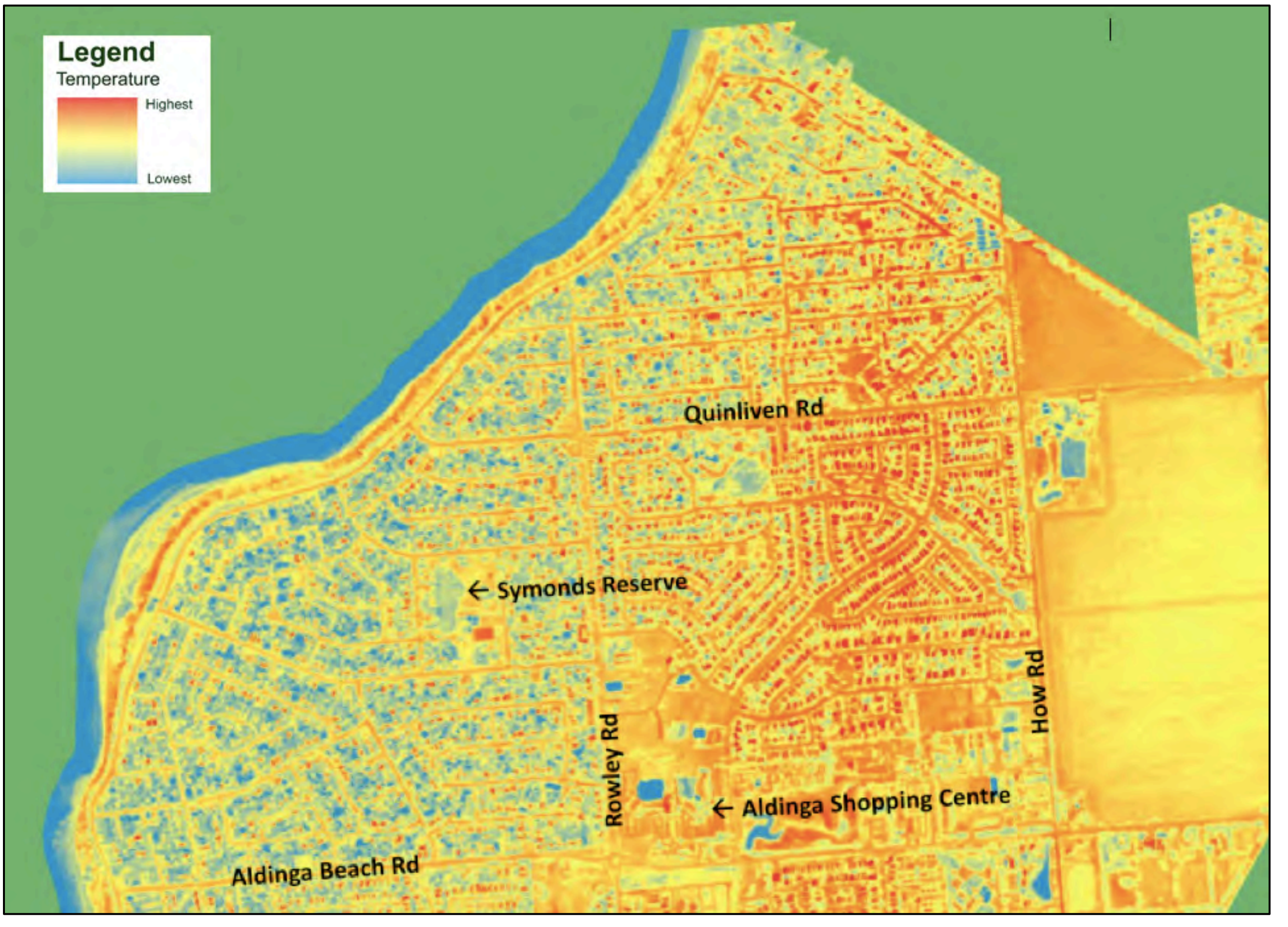


Figure 8. Selected heat and cool islands throughout the City of Onkaparinga

4.2.6 Terrestrial Thermal

A selection of sites representative of the cool and heat island examples listed in the previous section were visited and terrestrial thermal images of the surface temperature collected concurrently with the acquisition of airborne thermal data. At one site a newly developed two storey blocks of units with low to no canopy cover revealed high surface temperatures on the drive way and building where no shade existed (Fig. 9A), compared with an older, established house with a high density of canopy cover where almost the entire house frontage and house was shaded by trees (Fig. 9B). The higher temperature scale observed in Fig. 9B is due to the presence of a hotter spot on the footpath than in Fig. 9A. It should be noted that a greater proportion of the image in 9A is hotter in surface temperature than in Fig. 9B.

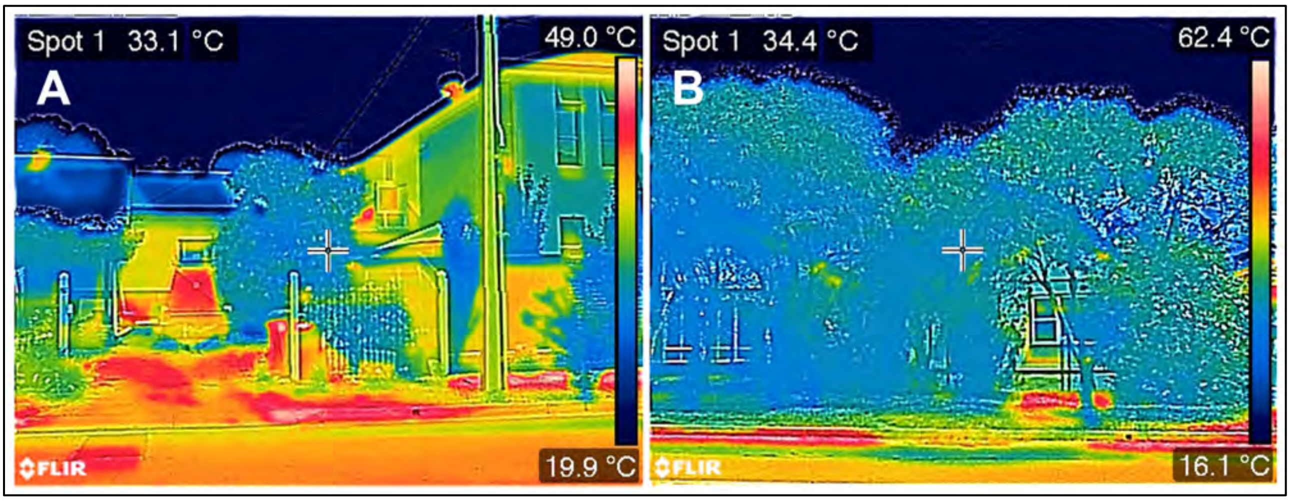


Figure 9. Differences in surface temperatures between houses with little to no canopy cover (A) and high to almost total canopy cover (B).

Large differences in surface temperatures were also apparent along walking trails and parks where paths/trails were covered by canopy and not covered by canopy (Fig. 10). These differences reached up to 30°C along the path comprised of the same material.

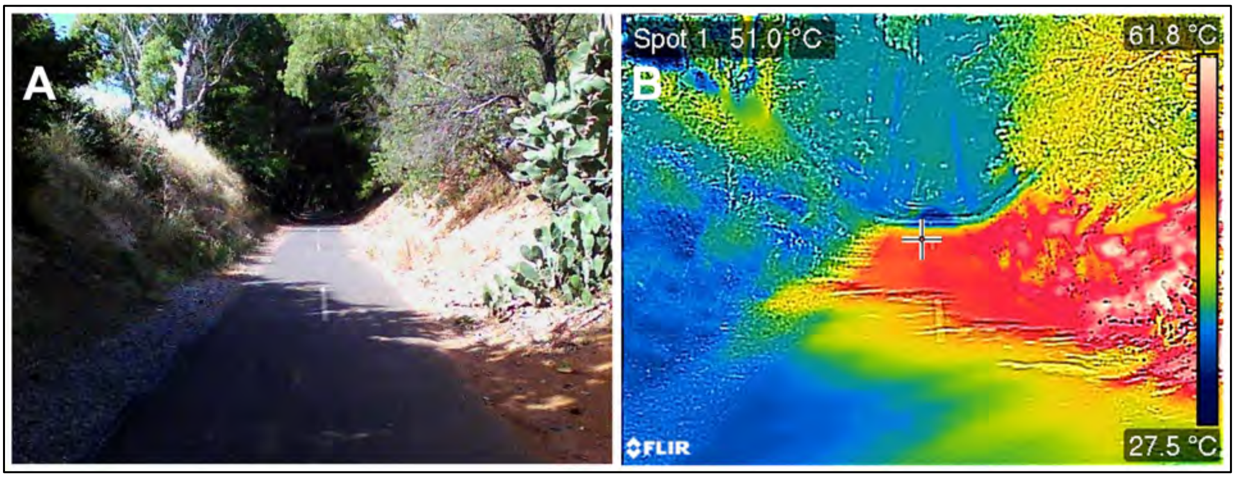


Figure 10. Walking trail (A) showing the difference in surface temperatures along this trail with high and no canopy cover.

Large differences were observed in surface temperatures between unirrigated and dead turf and irrigated, living turf (Fig. 11). High surface temperatures were measured at Waverley Way Reserve on the stone path leading to the shelter, with dead patches of grass a similar surface temperature to the stone path (Fig 11A). In comparison, the irrigated, lush turf at the Eternal Flame site was approximately 30° cooler and a similar temperature to the trees (Fig. 11B).

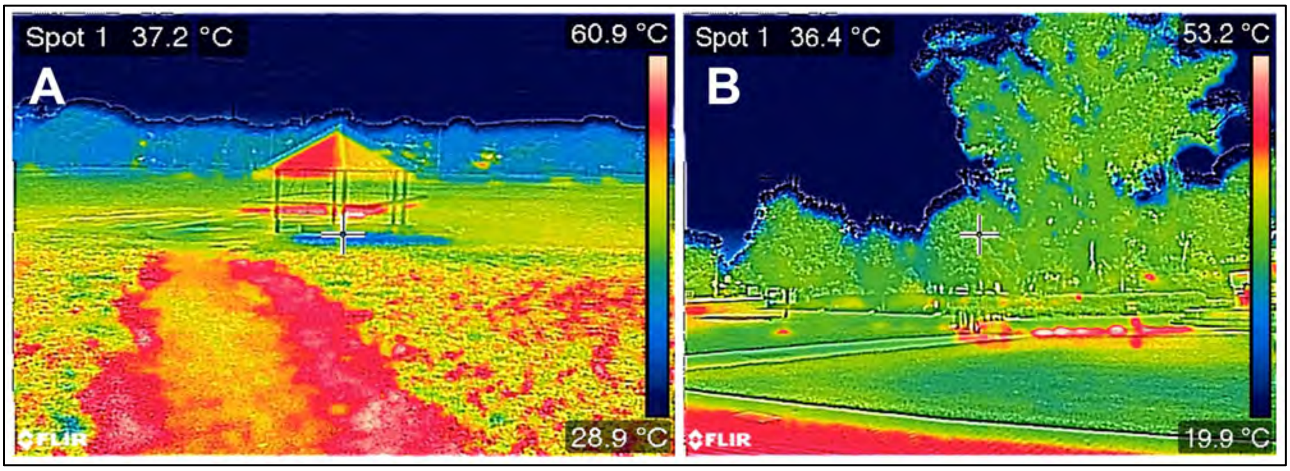


Figure 11. High surface temperatures recorded at Waverley Way Reserve on the metal roof, stone path and dead patches of grass (A), compared with the much cooler surface measured on a lush, irrigated turf site (B).

5.0 DISCUSSION

The main objectives of this project were to acquire high-resolution airborne thermal imagery to provide a baseline measure of land-surface temperature across the region, generate radiometric and surface temperature datasets, and to analyse all datasets to identify heat and cool islands, statistics and a report. All of these objectives have been successfully achieved and more. One of the regional and local actions of the Cool Places foundation project is to understand the urban heat island effect on the community. High-resolution airborne thermal imagery is required to identify and prioritise open space and public realm areas most vulnerable to urban heat impacts that could benefit from green infrastructure projects. These green infrastructure projects have the potential to greatly increase and improve the green spaces and mitigate heat.

In this study we have acquired high-resolution airborne thermal data across a 285 square kilometre region and have provided surface temperature data at a resolution of 2.0m pixels. This has enabled the clear differentiation between hotter surfaces such as roofs, dry vegetation and bitumen, from cooler surfaces such as water-bodies, trees and irrigated turf. We have previously discussed the fact that airborne thermal data is measuring the surface UHI rather than the canopy layer UHI effect, although the surface temperatures are known to have a large influence on adjoining air temperatures. The factors affecting air temperature are complex in urban systems and have been covered in detail in numerous scientific studies. These factors include but are not limited to emissivity, shadows, moisture, wind, building geometry, cloud cover, sun-angle and anthropogenic effects. An example of the likely impact of different emissivities on surface temperature was observed in the Westminster School site in the City of Marion. Within this school large differences in surface temperature were observed between different roofs of buildings. Although these differences in actual temperature may have in fact been large, we are unable to determine whether these differences are accurate as they are likely to be of different material (i.e. metal and tile) and therefore will have noticeably different emissivities.

It is important to note that although the approach used in this project does not allow us to accurately measure surface temperatures of all pixels throughout the region, it does enable us to differentiate between hot and cool surfaces throughout the region, and identify those sites that are likely to benefit from the introduction of greening initiatives that will shade these surfaces and have the resultant positive effect of cooling the air-temperature.

For example, the Aldinga Shopping Centre was identified as a noticeable heat island in the suburb of Aldinga Beach, whilst the irrigated grass of Symonds Reserve was a cool island. The shopping centre can be targeted as a site that will greatly benefit from a greening project to cool the surface of the car-park and other hard-scapes, providing cooling benefits to the occupants and also increasing the longevity of the asphalt due to protection from harmful UV rays. In contrast, irrigated turfed sites are a cool island and can provide clear benefits to the community. Distinct differences in surface temperature were also observed between the west side and east side of

Rowley Rd, with the western region noticeably cooler than the east side. Analysis of the data suggests this is related to the density of the residential development, with the west side containing larger blocks and smaller houses, and therefore greater space for vegetation.

Noticeable differences were not only observed between different densities of housing. This study has shown that the coolest sites were also comprised of golf courses, water-bodies, dense woody vegetation and irrigated turf, whilst the hottest areas were generally comprised of buildings, dry agricultural fields, dry/dead grass and vegetation, exposed soil and unshaded hard surfaces. These findings from the airborne thermal data were also supported by the terrestrial data collected concurrently, with apparent differences in surface temperature of up to 30°C observed.

Prior to this project some satellite-derived surface temperature and NDVI data was acquired and analysed over the Cities of Holdfast Bay, Marion and Mitcham. This was a secondary focus of this study and was not carried out for the City of Onkaparinga. These datasets have been included in this report for comparison. There were apparent relationships between NDVI and the surface temperatures throughout all regions, and the mean NDVI and mean surface temperature classes of some suburbs. For example, in the City of Mitcham many of the suburbs mostly comprised of residential land-use and relatively low NDVI values were the suburbs with the highest mean surface temperatures, whereas those suburbs with the highest NDVI further inland, lacking residential development, had the coolest mean surface temperatures. There were certainly exceptions to this with some suburbs in the City of Holdfast Bay showing the opposite relationship. We have been careful not to draw conclusions on the relationship between the satellite and airborne-derived surface temperature datasets, due to their differences in spatial resolution, date of acquisition, and differences in the sensors and impacts from atmosphere. We must also be cautious when interpreting NDVI, as this is simply a measure of greenness using medium-resolution (25m pixels), and therefore will in many cases even within a single pixel have a mixture of many different surfaces. NDVI also does not differentiate between canopy and grass, and therefore does not take into account the positive benefits that canopy and shade can have on surface and air temperatures. These datasets have been provided in a georeferenced format to allow further analysis to be undertaken by Resilient South councils using the Resilient South Maps tool.

A great deal more analysis can be undertaken on the available datasets to achieve some of the important adaption actions required to increase the resilience of vulnerable people to a hotter future, such as increasing and improving the green spaces in urban areas to mitigate heat. For example, we recently acquired and analysed high-resolution (0.4m pixel) height-stratified vegetation cover across the City of Onkaparinga urban area (Fig. 12). This has enabled us to very accurately differentiate between vegetation forming canopy, identify the location of trees providing the greatest amount of shade, and precisely calculate the percentage cover and hectares of cover of vegetation and canopy throughout the City and all suburbs and managements within. We have not acquired such data for the Cities of Holdfast Bay, Mitcham or Marion. Now that we have the georectified high-resolution airborne thermal dataset for the City of

Onkaparinga, we could use both to determine the correlations between these different types of vegetation and surface heat, and more importantly, identify heat and cool islands, precisely determine their attributes, benchmark them against each other, and set KPI's for measuring future actions. This would be a logical step in adapting to climate change and improving the resilience of communities in the City of Onkaparinga. We recommend that such analysis be undertaken for the City of Onkaparinga, and that height-stratified canopy cover data be acquired over the Cities of Holdfast Bay, Mitcham and Marion to enable detailed analysis to be undertaken for the entire Resilient South region. This would also assist with determining the causes for the unexpected relationships between surface heat and NDVI observed, such as Glenelg East.

The amount of heat that remains within an urban area (residual heat) is also a very important factor when considering the health of the communities who live within. It is well known that increased human stress occurs if people are unable to sleep well or rest at night due to high-residual urban temperatures. The acquisition of night-time thermal within the Resilient South region would enable analysis of surface temperature of materials and identify those materials and sites within the region that remain warmer at night-time, and thereby identifying their thermal-holding capacity.

This project has largely focused on the urban areas within the Resilient South region. There is a great deal more analysis that can be undertaken on the rural areas, woodlands and forests that can improve efficiencies of land management. For example, the NDVI and surface temperature datasets can be analysed to identify areas of vegetation under water stress, and can assist with improving irrigation efficiency and fire risk mapping. Analysis could also be undertaken to compare the surface temperature of different impervious materials in the urban area (i.e. roofs of different colour) to assist with future urban design. We encourage Resilient South and the councils within to explore these opportunities and maximize the use of the valuable datasets that have been acquired.

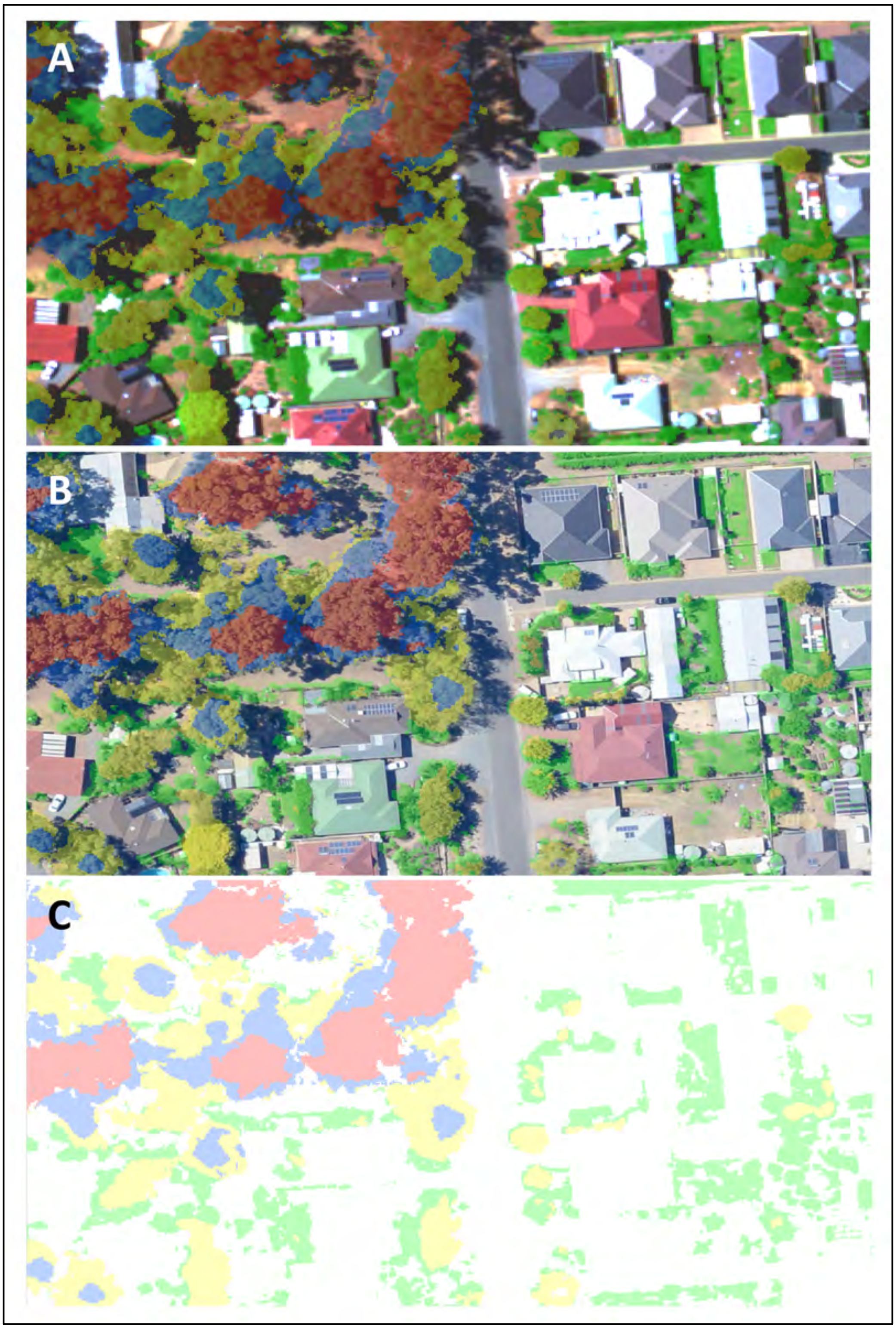


Figure 12. Height-stratified vegetation cover dataset derived from high-resolution multispectral imagery over the City of Onkaparinga in 2016 A) Height-stratified vegetation cover overlaid onto 0.4m true colour composite base layer, B) Height-stratified vegetation cover overlaid onto 0.15m true colour composite base layer, C) Height-stratified vegetation cover. Note height classes of the vegetation cover represented as follows: green (0-3m), yellow (3-10m), blue (10-15m), red (>15m).

6.0 CONCLUSIONS AND RECOMMENDATIONS

The main findings of this study are as follows:

- A total of 285 square kilometres was analysed for surface temperature based upon high-resolution (2.0m pixels) thermal infra-red imagery acquired on 22 February 2016 where air temperatures exceeded 38°C in Adelaide
- A total of twelve distinct regions were analysed in this study
- In general surface temperatures based upon the analysis of this dataset increase with distance from the coast-line
- Aldinga Beach recorded the lowest minimum temperature (7.18°C) whilst Maslin Beach recorded the highest minimum temperature (17.86°C), slightly higher than Port Willunga (17.45°C).
- Onkaparinga recorded the highest maximum temperature (86.76°C) whilst Maslin Beach recorded the lowest maximum temperature (41.47°C).
- Maslin Beach had the smallest range in temperatures of all regions
- Aldinga Beach Esplanade had the lowest mean surface temperature (29.73°C) and McLaren Flat had the highest mean surface temperature (36.67°C), almost 7°C warmer than Aldinga Beach Esplanade.
- The surface temperature of the City of Holdfast Bay ranged from 7.18°C to 47.9°C, with a mean of 32.50°C
- Satellite-derived surface temperature showed Glenelg East to be the hottest suburb within the City of Holdfast Bay, Glenelg, Glenelg South and Kingston Park were the coolest suburbs.
- Mean satellite-derived NDVI values of Glenelg and Glenelg South were amongst the lowest of all suburbs, with Glenelg East amongst the highest in the City of Holdfast Bay
- In the City of Marion the surface temperature ranged from 15.37°C to 57.35°C, with a mean of 31.88°C
- Satellite-derived surface temperature showed the suburbs with the hottest mean surface temperatures were the inland suburbs of Ascot Park, Clovelly Park, Mitchell Park and O'Halloran Hill, and the coolest suburb, Marino, was found closest to the coast in the south-west.
- Mean satellite-derived NDVI values of Morphettville, Marion and Bedford Park were amongst the highest of all suburbs, with Ascot Park, Edwardstown, Clovelly Park, and interestingly, Marino amongst the highest.
- In the City of Mitcham the surface temperature ranged from 12.93°C to 69.78°C, with a mean of 33.37°C.
- Mean satellite-derived surface temperature showed the suburbs in the City of Mitcham with the hottest mean surface temperatures were the northern and western most suburbs of Netherby, Lower Mitcham, Westbourne Park, Clarence Gardens, Cumberland Park,

Melrose Park, Daw Park, St Marys and Pasadena, and the coolest suburbs were Crafers West and Upper Sturt
- Mean satellite-derived NDVI values of Clarence Gardens, Cumberland Park, Melrose Park, Daw Park, and St Marys, were lowest and the suburbs highest in NDVI were Belair, Hawthorndene and Crafers West.
- In the City of Onkaparinga the airborne-derived surface temperature ranged from 7.18°C (Aldinga Beach) to 86.76°C (Onkaparinga).
- Aldinga Beach had the coolest mean surface temperature (29.73°C), whilst McLaren Flat had the highest mean surface temperature (36.67°C).
- The coolest sites across the study were comprised of golf courses, water-bodies, dense woody vegetation and irrigated turf, whilst the hottest areas were generally comprised of buildings, dry agricultural fields, dry/dead grass and vegetation, exposed soil and unshaded hard surfaces.
- The findings from the airborne thermal data were also supported by the terrestrial data collected concurrently, with apparent differences in surface temperature of up to 30°C observed.

This study has very clearly identified the heat and cool islands throughout the Resilient South Region based upon airborne-derived surface temperature data. We provide the following recommendations based upon the findings of this study:

- Acquire high-resolution multispectral height-stratified vegetation cover data for the Cities of Holdfast Bay, Mitcham and Marion as previously acquired for the City of Onkaparinga
- Following acquisition of the high-resolution multispectral height-stratified vegetation cover for the Cities of Holdfast Bay, Mitcham and Marion, undertaken further analysis to determine the precise relationships between vegetation cover types (i.e. canopy versus non-canopy) and surface temperature
- Undertake analysis of the high-resolution multispectral height-stratified vegetation cover data for the City of Onkaparinga to determine the relationship between canopy cover of specific areas (i.e. Suburbs, parks, residential, commercial, roads) and surface temperatures
- Undertake analysis of the high-resolution airborne surface temperature data to determine the relationship between different residential development zones (i.e. R-codes) and surface temperature
- Undertake analysis of the high-resolution airborne surface temperature data to determine the relationship between different impervious layers and their surface temperature
- Analyse the high-resolution multispectral height-stratified vegetation cover data to classify individual materials (i.e. vegetation, impervious
- Acquire night-time airborne thermal data at the same resolution over the same area to calculate the residual surface temperature and compare with the day-time dataset for identification of the thermal-holding capacity of different materials within the region.

- Use the acquired data and findings from this report to assist urban design throughout the Resilient South region and increase the resilience of those who live within the region.
- Following all of the above-mentioned analysis, develop KPI's for vegetation cover and surface heat for zones managed within the region, and in subsequent years acquire data for the measurement of progress against KPI's.
- Use the developed KPI's within management plans for the different land-use zones and sites within the Resilient South region.
- Further explore additional opportunities for analysis of the acquired datasets for land management outside and within the urban areas.

7.0 REFERENCES

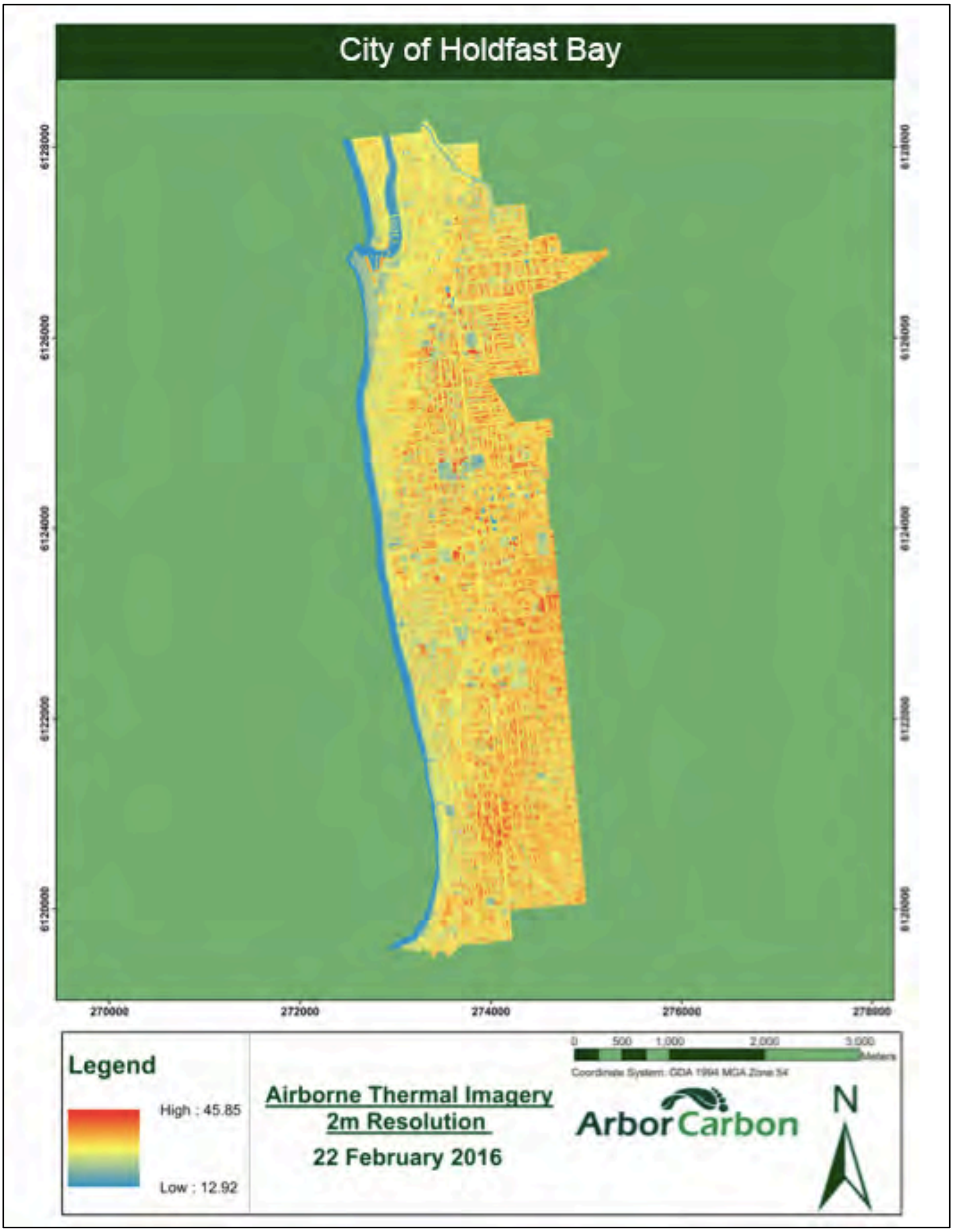
Weng, Q. (2009) Thermal infrared remote sensing for urban climate and environmental studies: Methods, applications, and trends. *Journal of Photogrammetry and Remote Sensing* **64**, 335-344.

Harris, R. and Coutts, A. (2011). Airborne thermal remote sensing for analysis of the Urban Heat Island. Technical Report. Published by Victorian Centre for Climate Change Adaptation Research. 34 pp.

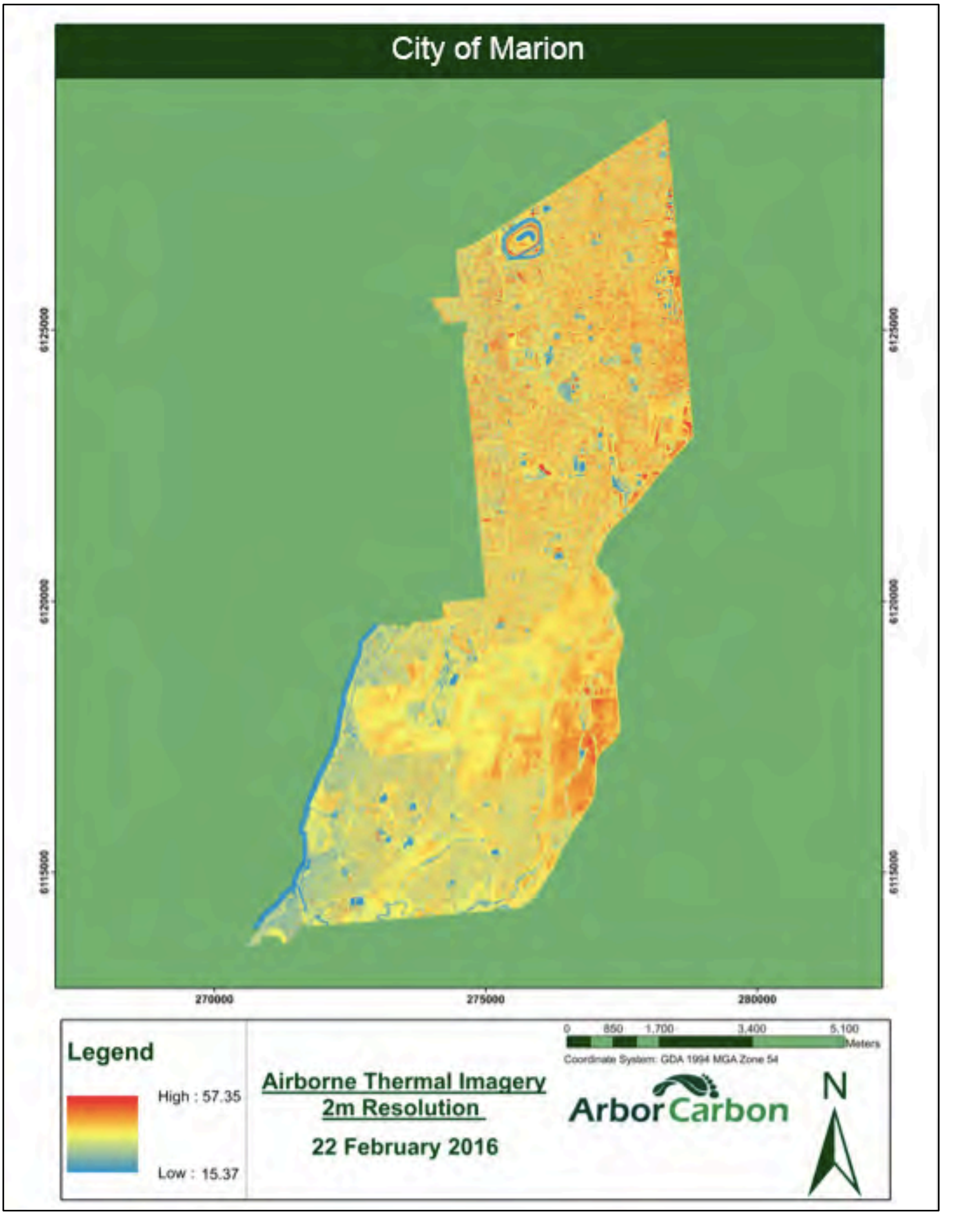
Guan, H. (2012) “Mapping Summer Temperatures in the Resilient South Region” Huade Guan School of the Environment Flinders University of South Australia.

Resilient South (2014) *Climate Change Scenarios Report – Resilient South* available at www.resilientsouth.com

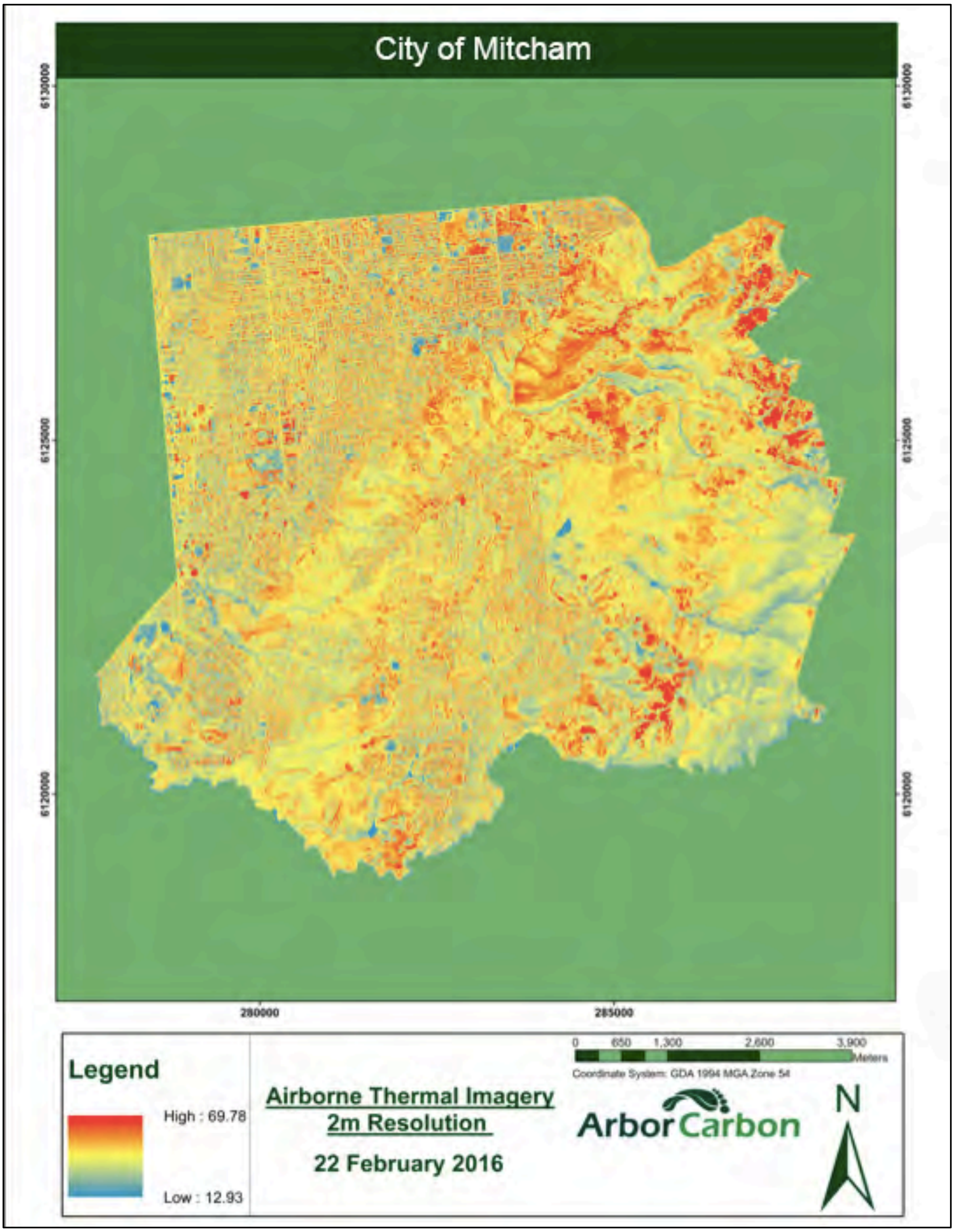
APPENDIX 1. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – CITY OF HOLDFAST BAY



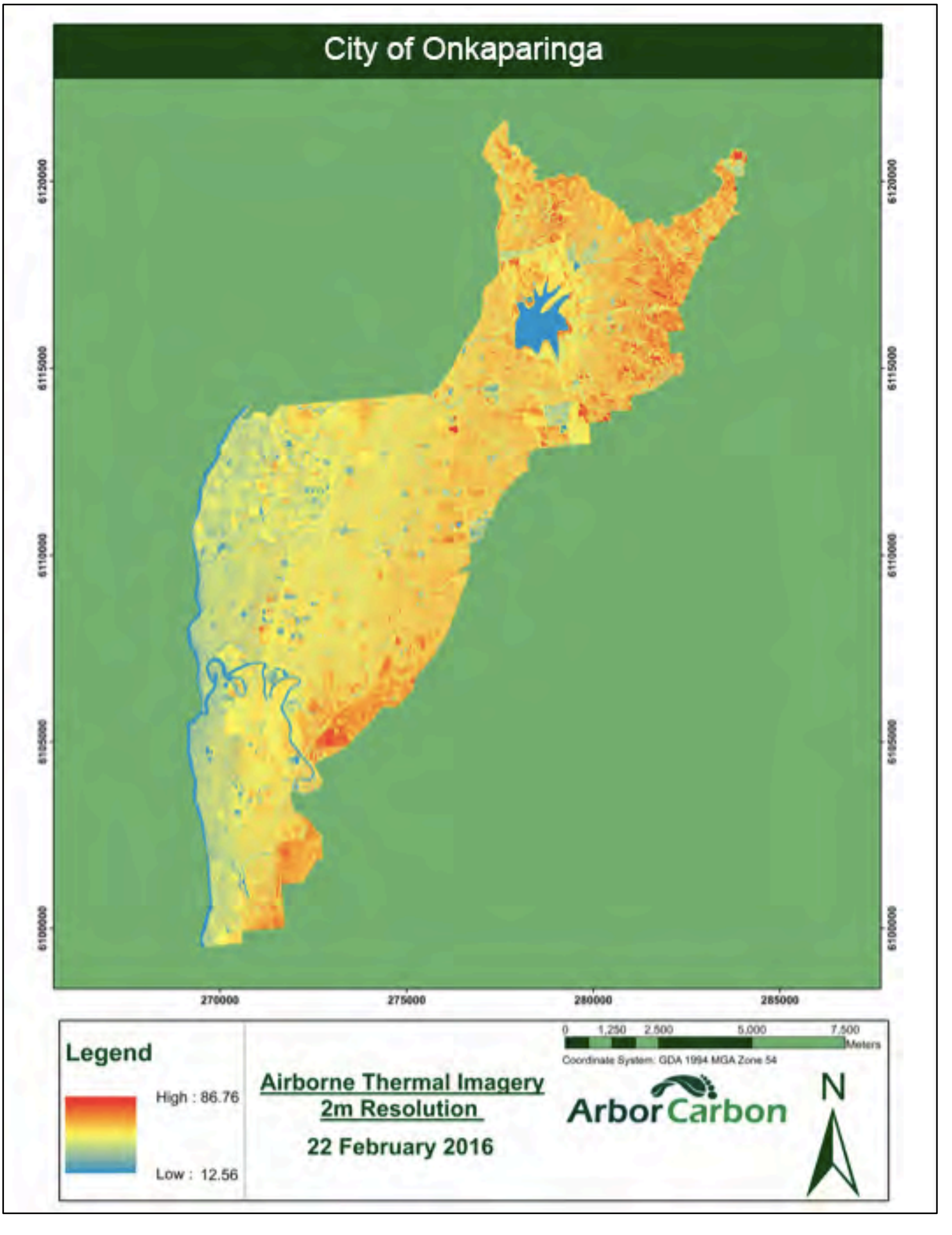
APPENDIX 2. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – CITY OF MARION



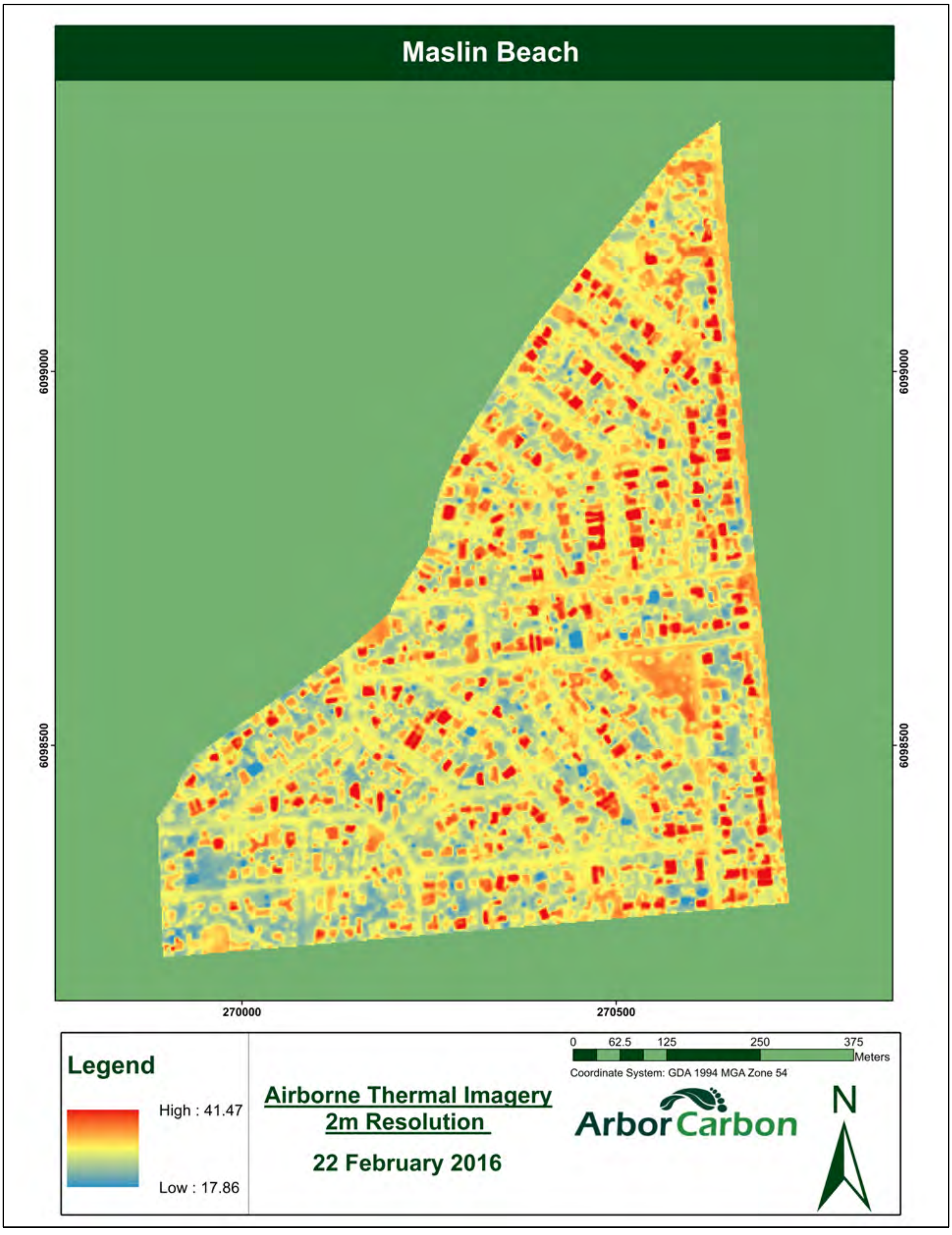
APPENDIX 3. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – CITY OF MITCHAM



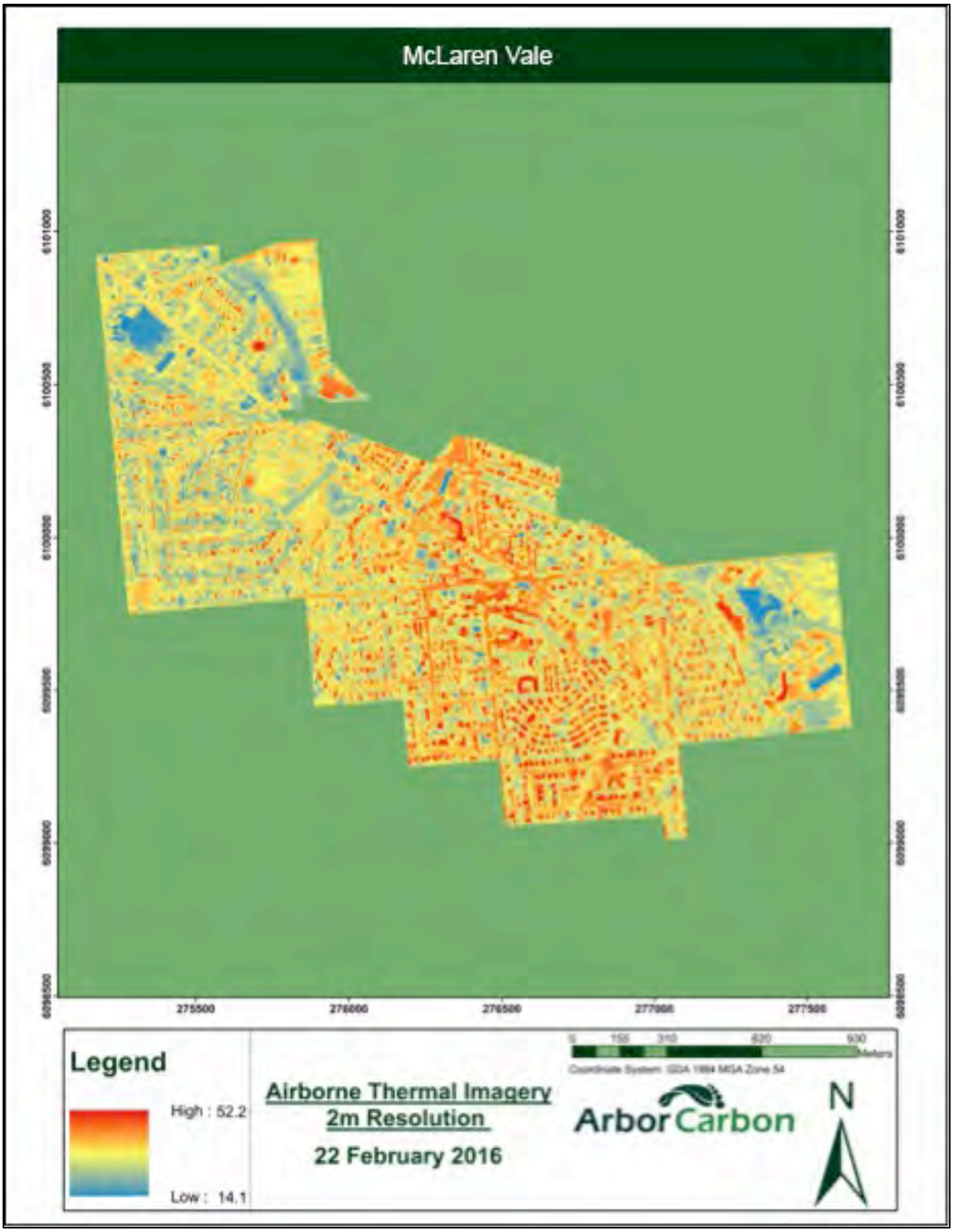
APPENDIX 4. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – CITY OF ONKAPARINGA



APPENDIX 5. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – MASLIN BEACH



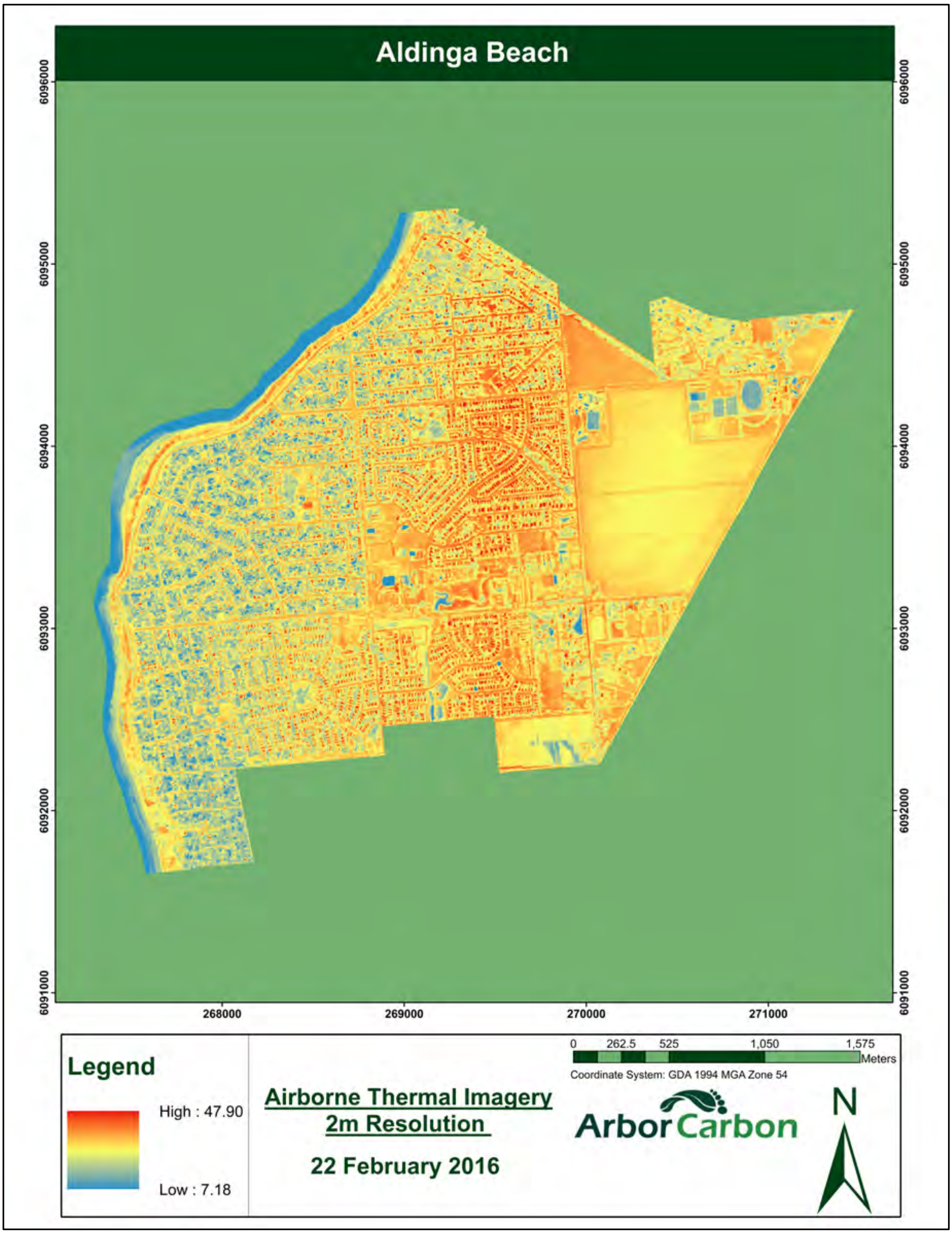
APPENDIX 6. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – McLAREN VALE



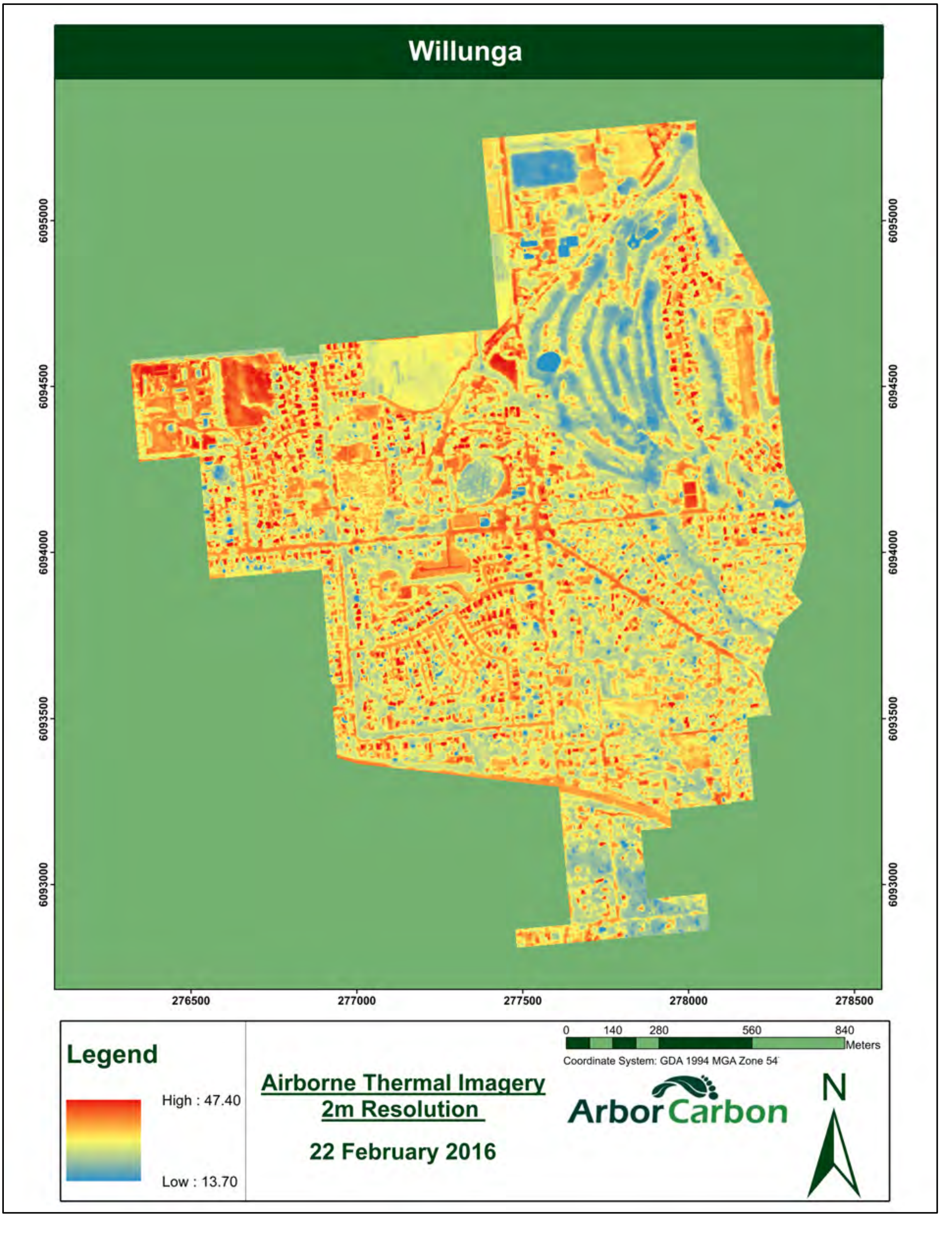
APPENDIX 7. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – McLAREN FLAT

APPENDIX 8. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – PORT WILLUNGA

APPENDIX 9. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – ALDINGA BEACH

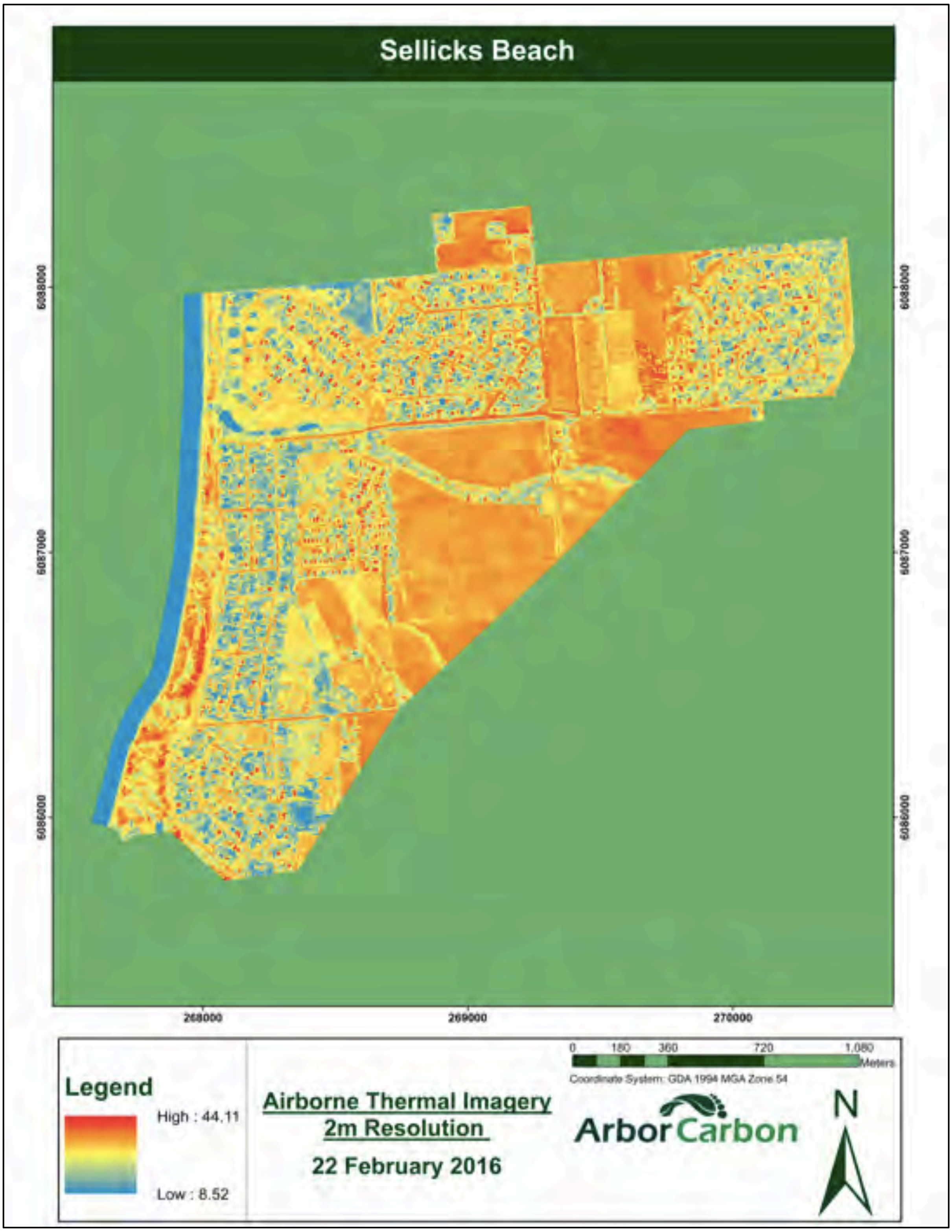


APPENDIX 10. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – WILLUNGA

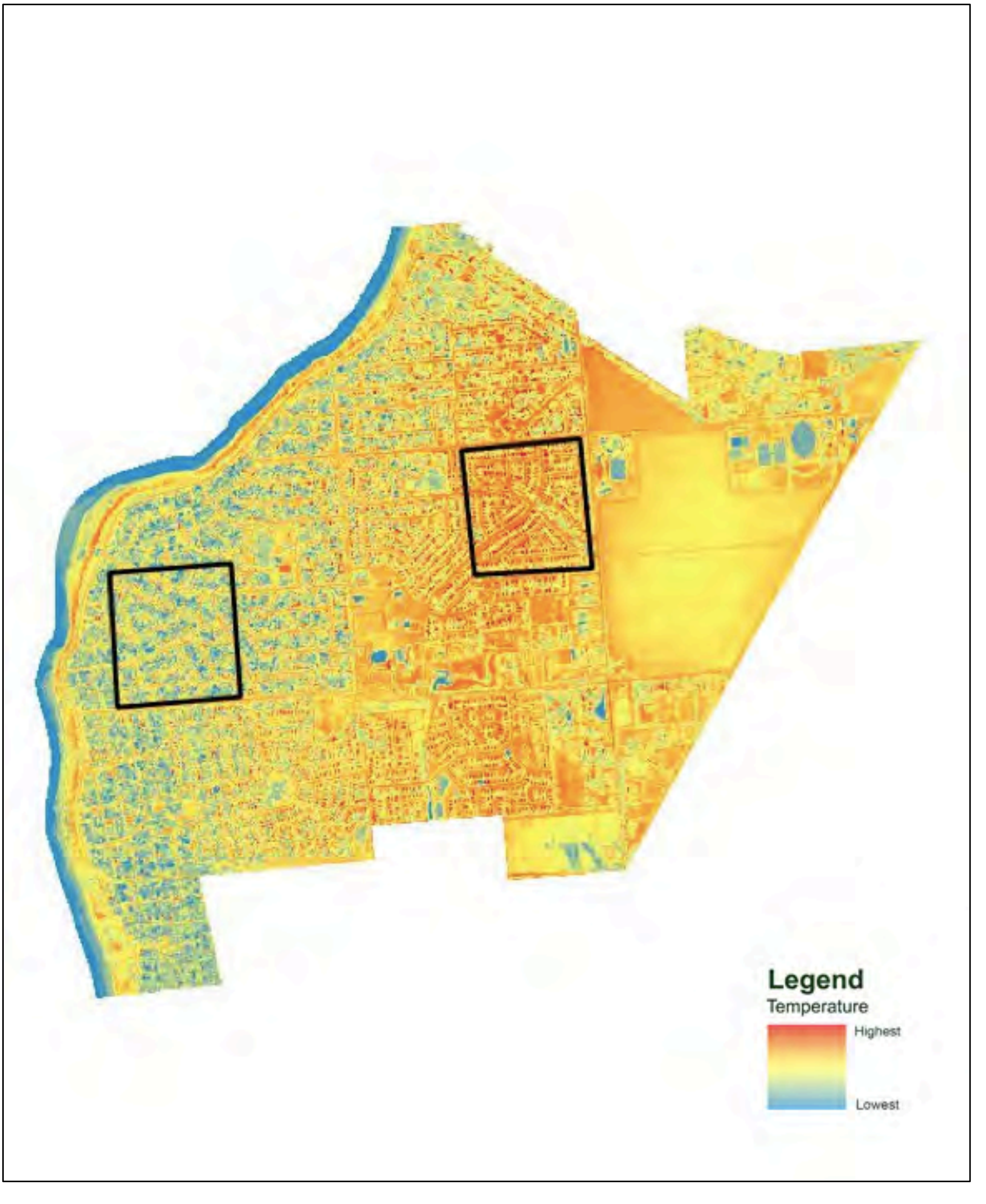


APPENDIX 11. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – ALDINGA BEACH ESPLANADE

APPENDIX 12. AIRBORNE TIR-DERIVED SURFACE TEMPERATURE 22 FEBRUARY 2016 – SELLICKS BEACH

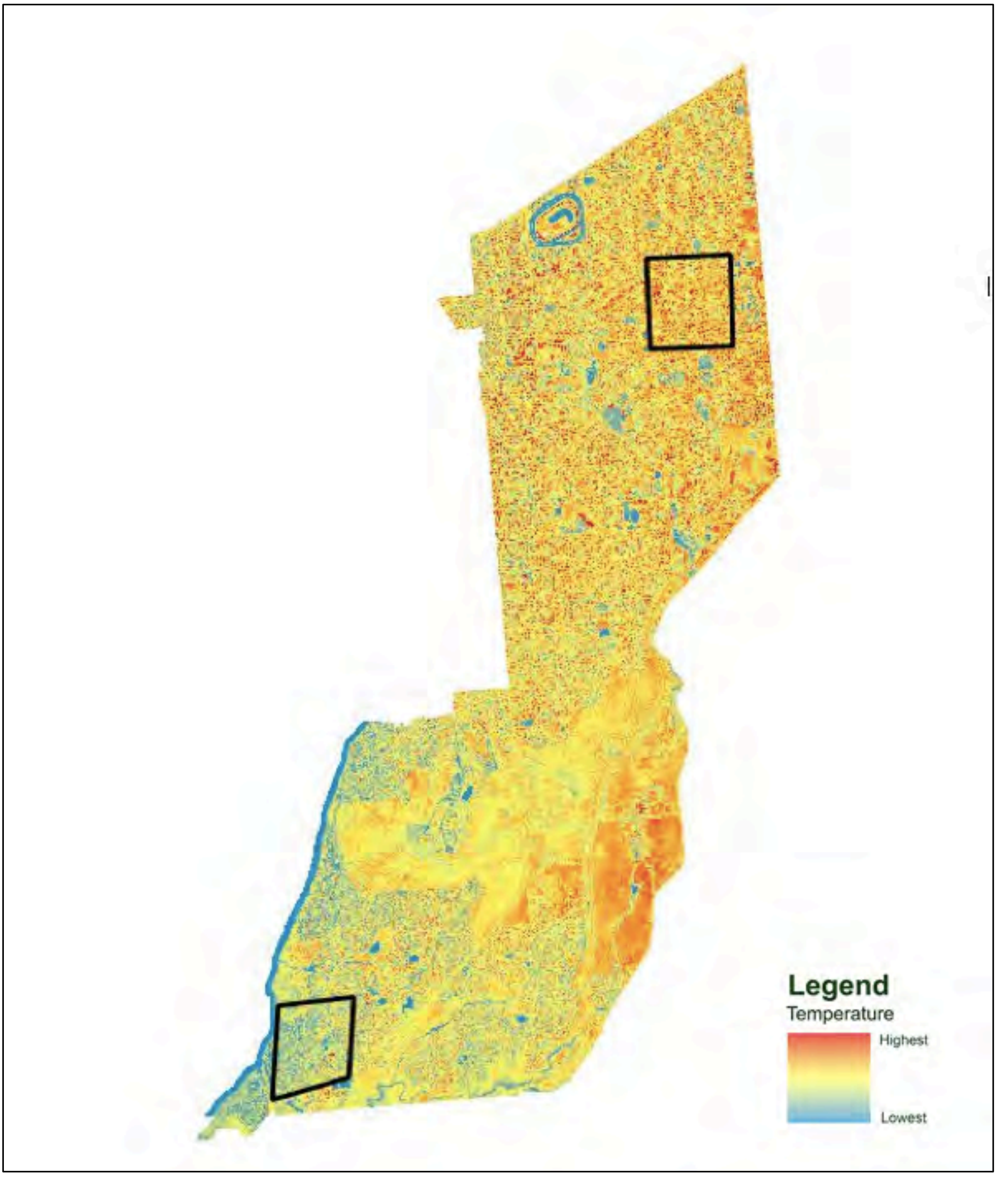


APPENDIX 13. COOL AND HOT SPOT LOCATIONS SELECTED WITHIN ALDINGA BEACH



APPENDIX 14. COOL AND HOT SPOT LOCATIONS SELECTED WITHIN CITY OF HOLDFAST BAY

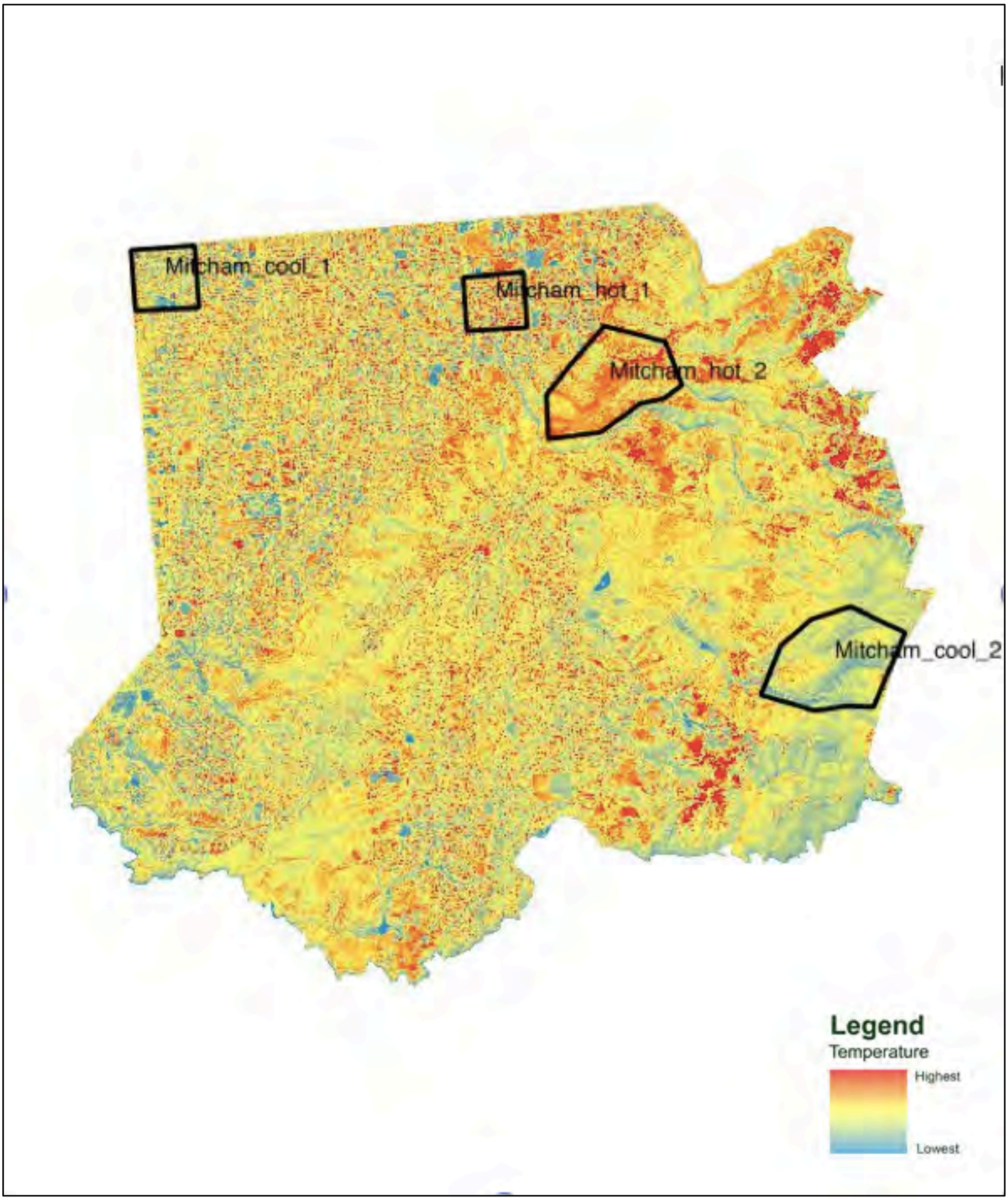
APPENDIX 15. COOL AND HOT SPOT LOCATIONS SELECTED WITHIN CITY OF MARION



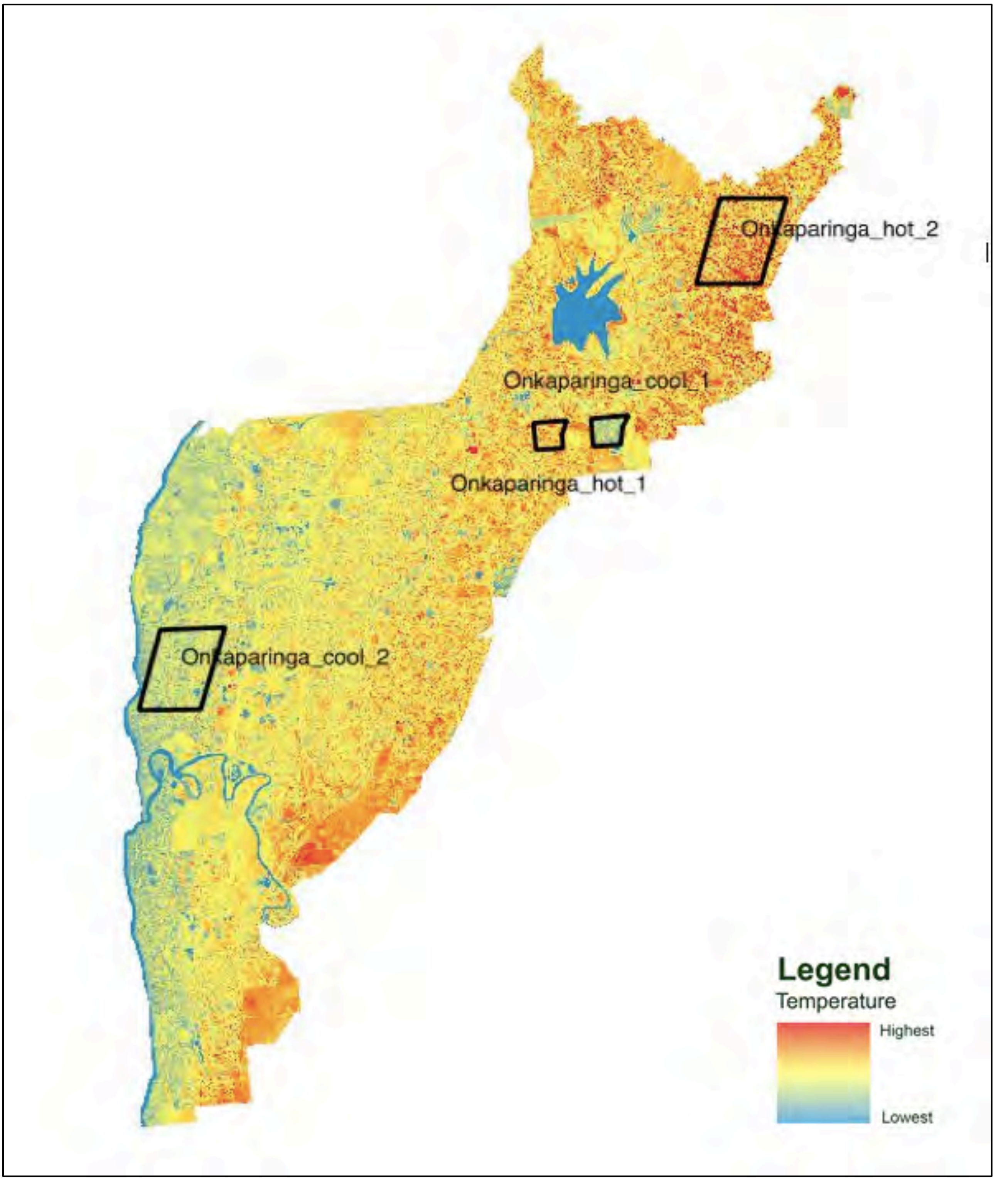
APPENDIX 16. COOL AND HOT SPOT LOCATIONS SELECTED WITHIN McLAREN FLAT

APPENDIX 17. COOL AND HOT SPOT LOCATIONS SELECTED WITHIN McLAREN VALE

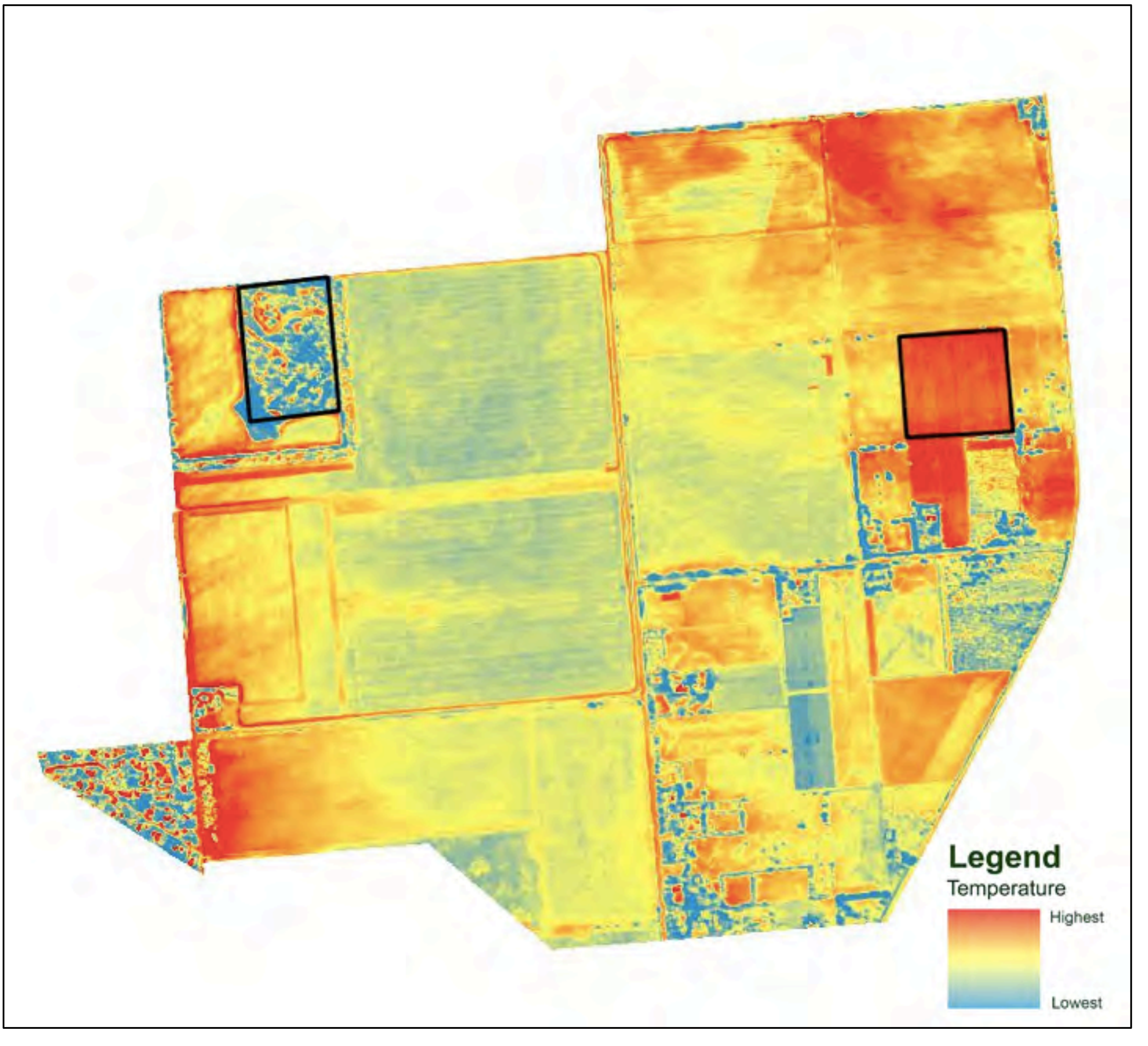
APPENDIX 18. COOL AND HOT SPOT LOCATIONS SELECTED WITHIN CITY OF MITCHAM



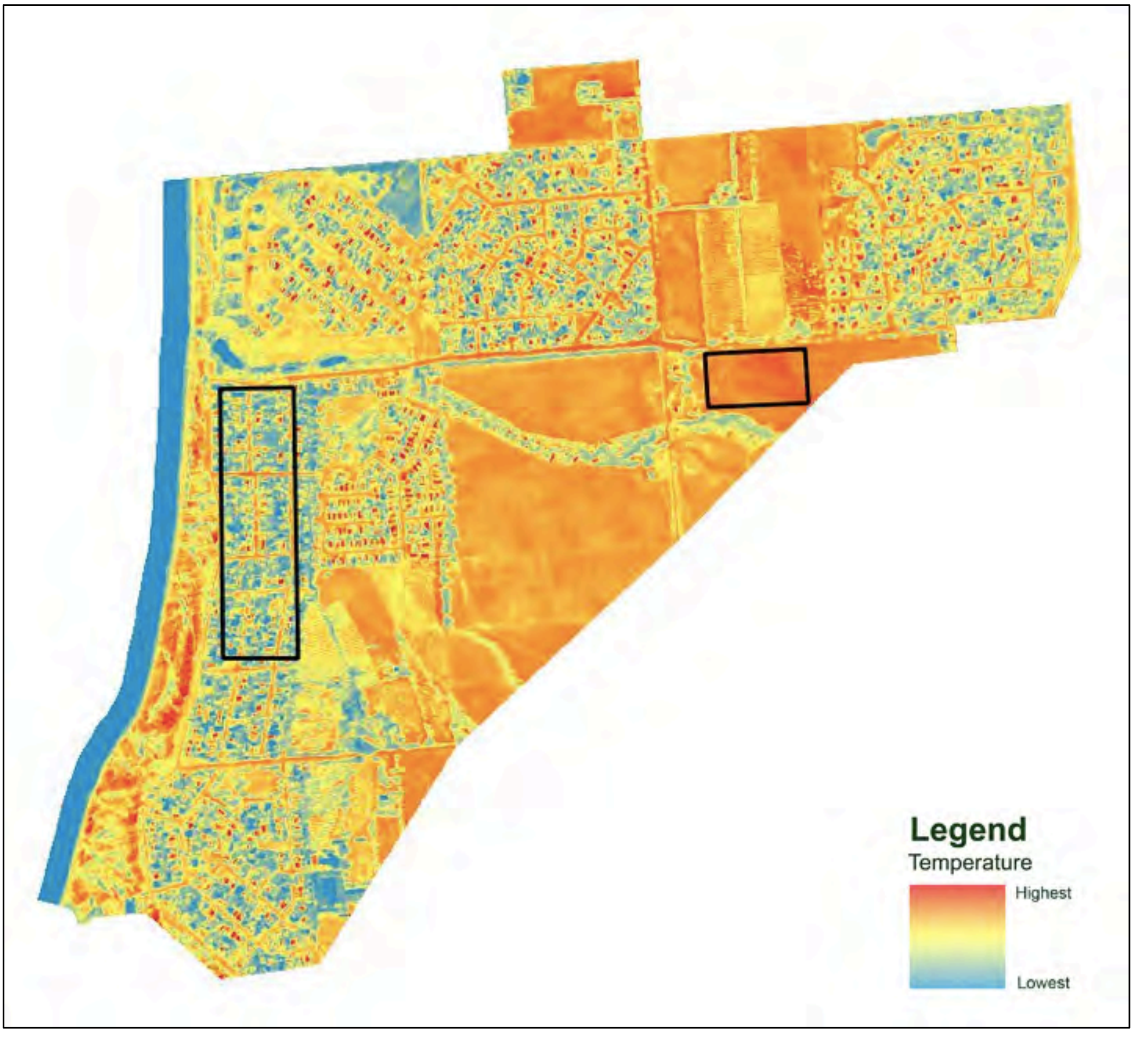
APPENDIX 19. COOL AND HOT SPOT LOCATIONS SELECTED WITHIN ONKAPARINGA



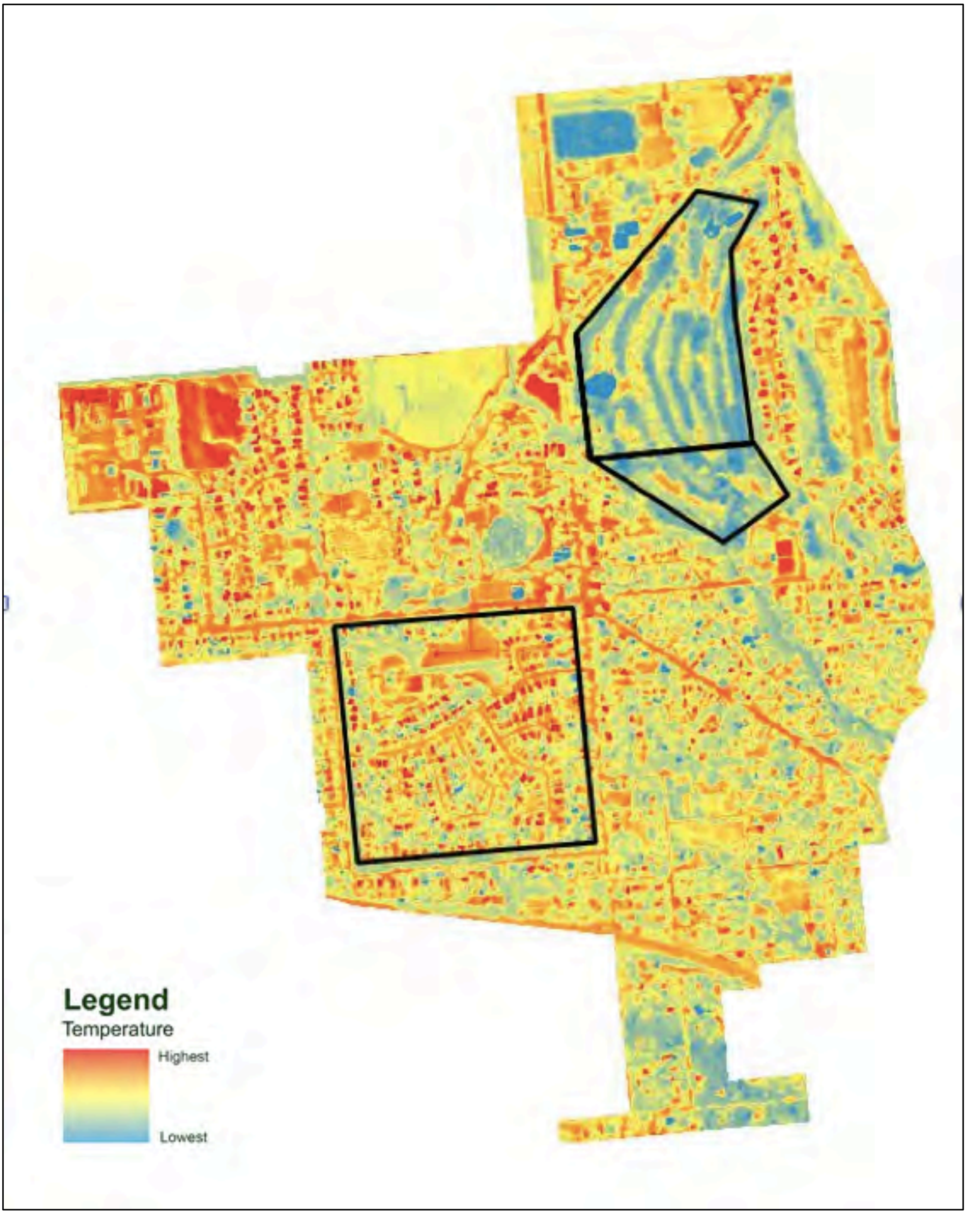
APPENDIX 20. COOL AND HOT SPOT LOCATIONS SELECTED WITHIN PORT WILLUNGA



APPENDIX 21. COOL AND HOT SPOT LOCATIONS SELECTED WITHIN SELLICKS BEACH



APPENDIX 22. COOL AND HOT SPOT LOCATIONS SELECTED WITHIN WILLUNGA



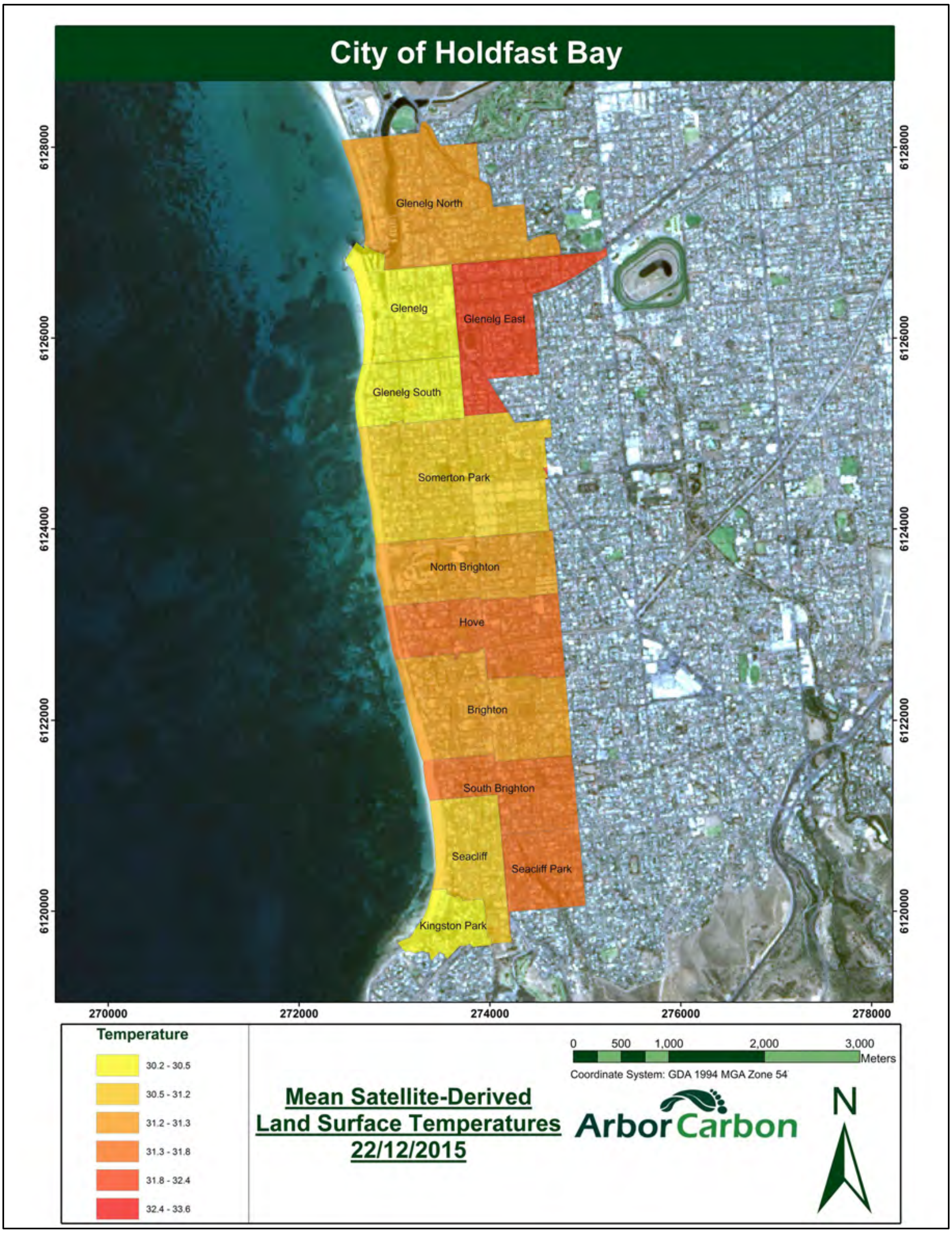
APPENDIX 23. Area, minimum, maximum and mean surface temperature of the twelve regions, based on high-resolution TIR imagery

			Surface Temperature (°C)		
Region	Total Area (m2)	Total Area (HA)	*Minimum*	*Maximum*	*Mean*
Aldinga Beach	8460820.70	846.08	7.18	47.90	32.50
Aldinga Beach Esplanade	1009992.50	101.00	9.70	42.00	29.73
Holdfast Bay	14487905.40	1448.79	12.92	45.85	30.63
Marion	56197370.50	5619.74	15.37	57.35	31.88
Maslin Beach	501436.60	50.14	17.86	41.47	30.77
McLaren Flat	699942.60	69.99	11.63	50.31	36.67
McLaren Vale	2284476.60	228.45	14.07	52.28	34.52
Mitcham	75694541.90	7569.45	12.93	69.78	33.37
Onkaparinga	114782302.80	11478.23	12.56	86.76	31.13
Port Willunga	4123844.40	412.38	17.45	45.93	33.97
Sellicks Beach	3612338.70	361.23	8.52	44.11	33.16
Willunga	2748194.90	274.82	13.70	47.40	32.93

APPENDIX 24. Area and mean surface temperature of the selected hot and cool spots throughout different regions, based on high-resolution TIR imagery

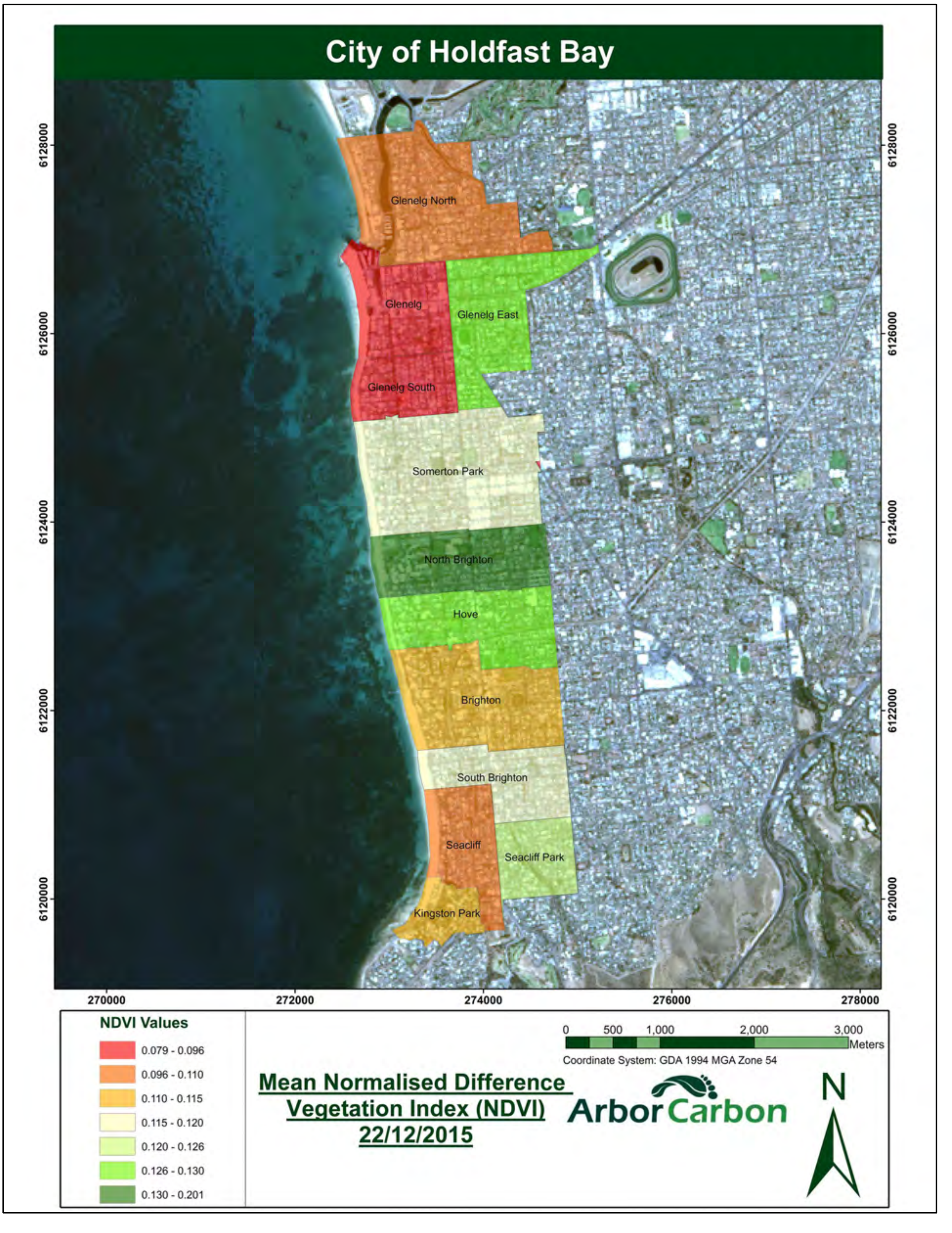
Region	Total Area (m^2)	Total Area (HA)	Mean Surface Temperature (°C)
Aldinga Beach Cool	366851.92	36.69	30.7
Aldinga Beach Hot	336403.87	33.64	35.2
Holdfast Bay Cool	540734.43	54.07	30.1
Holdfast Bay Hot	324908.61	32.49	32.5
Marion Cool	1313240.84	131.32	30.1
Marion Hot	1528183.72	152.82	33.1
McLaren Flat Cool	47505.95	4.75	32.5
McLaren Flat Hot	51027.66	5.10	37.6
McLaren Vale Cool	271369.34	27.14	33.5
McLaren Vale Hot	313708.97	31.37	35.9
Mitcham cool 1	604241.83	60.42	32.4
Mitcham hot 1	508642.56	50.86	34.2
Mitcham cool 2	1558733.79	155.87	31.8
Mitcham hot 2	1456867.36	145.69	35.4
Onkaparinga cool 1	370254.14	37.03	28.8
Onkaparinga hot 1	327795.8	32.78	32.9
Onkaparinga cool 2	2132651.21	213.27	29.4
Onkaparinga hot 2	2342212.6	234.22	33.6
Port Willunga cool	81016.61	8.10	32.3
Port Willunga hot	72276.69	7.23	36.6
Sellicks Beach cool	153519.49	15.35	31.3
Sellicks Beach hot	41491.87	4.15	36.9
Willunga cool	237956.26	23.80	29.9
Willunga hot	306191.16	30.62	33.7

APPENDIX 25. Mean satellite-derived land-surface temperature for City of Holdfast Bay 22 December 2015



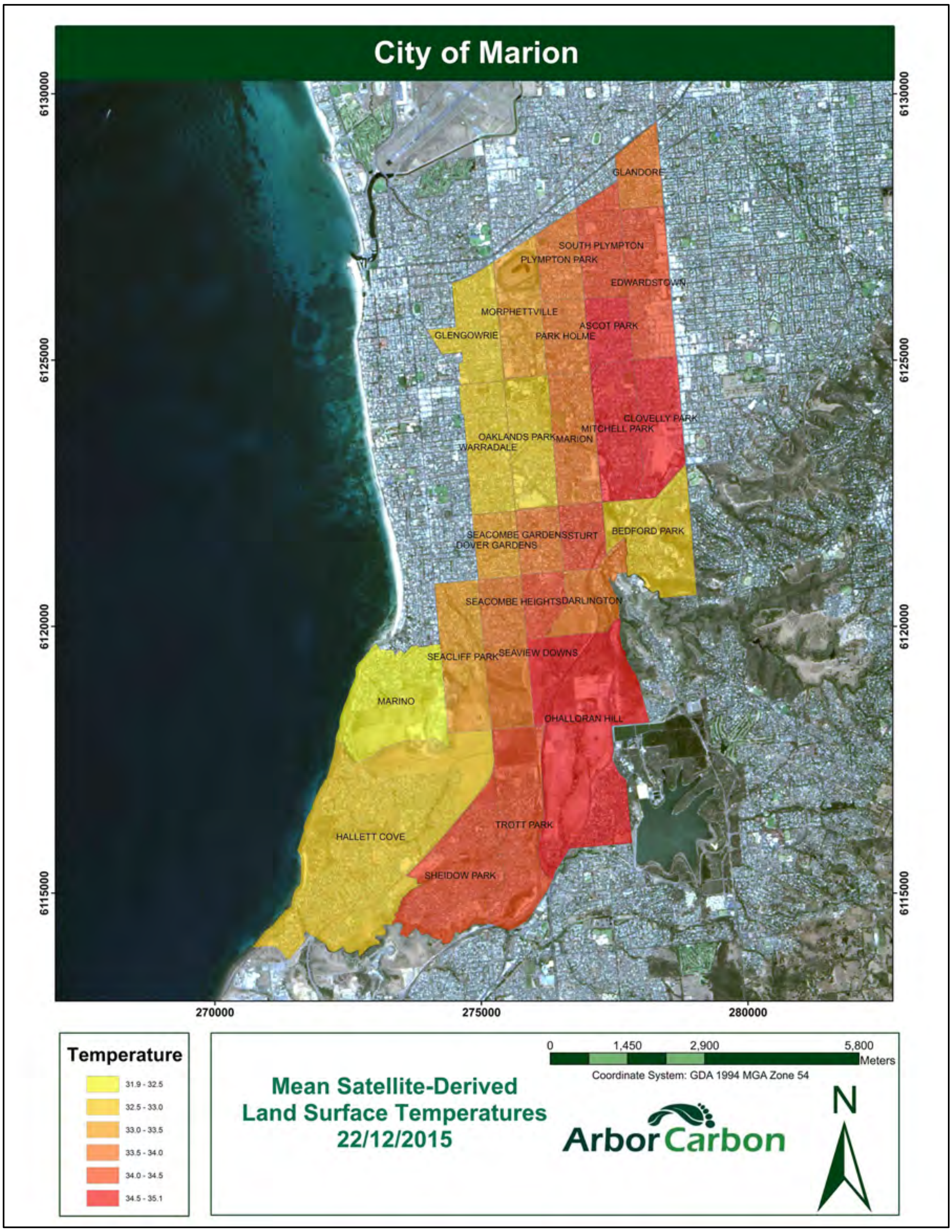
APPENDIX 26. Scaled satellite-derived land-surface temperature for City of Holdfast Bay 22 December 2015

APPENDIX 27. Mean NDVI for City of Holdfast Bay 22 December 2015

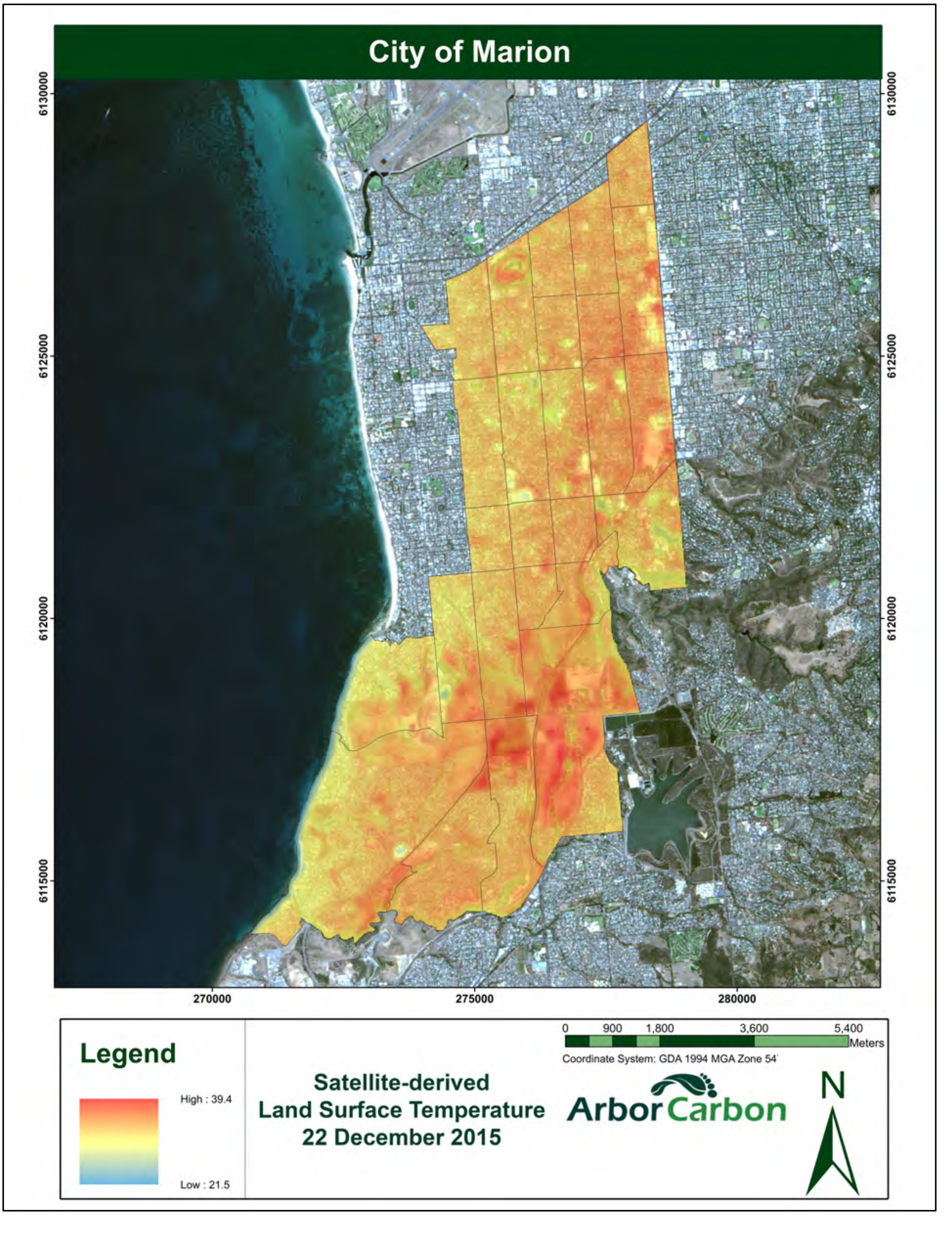


APPENDIX 28. Scaled NDVI for City of Holdfast Bay 22 December 2015

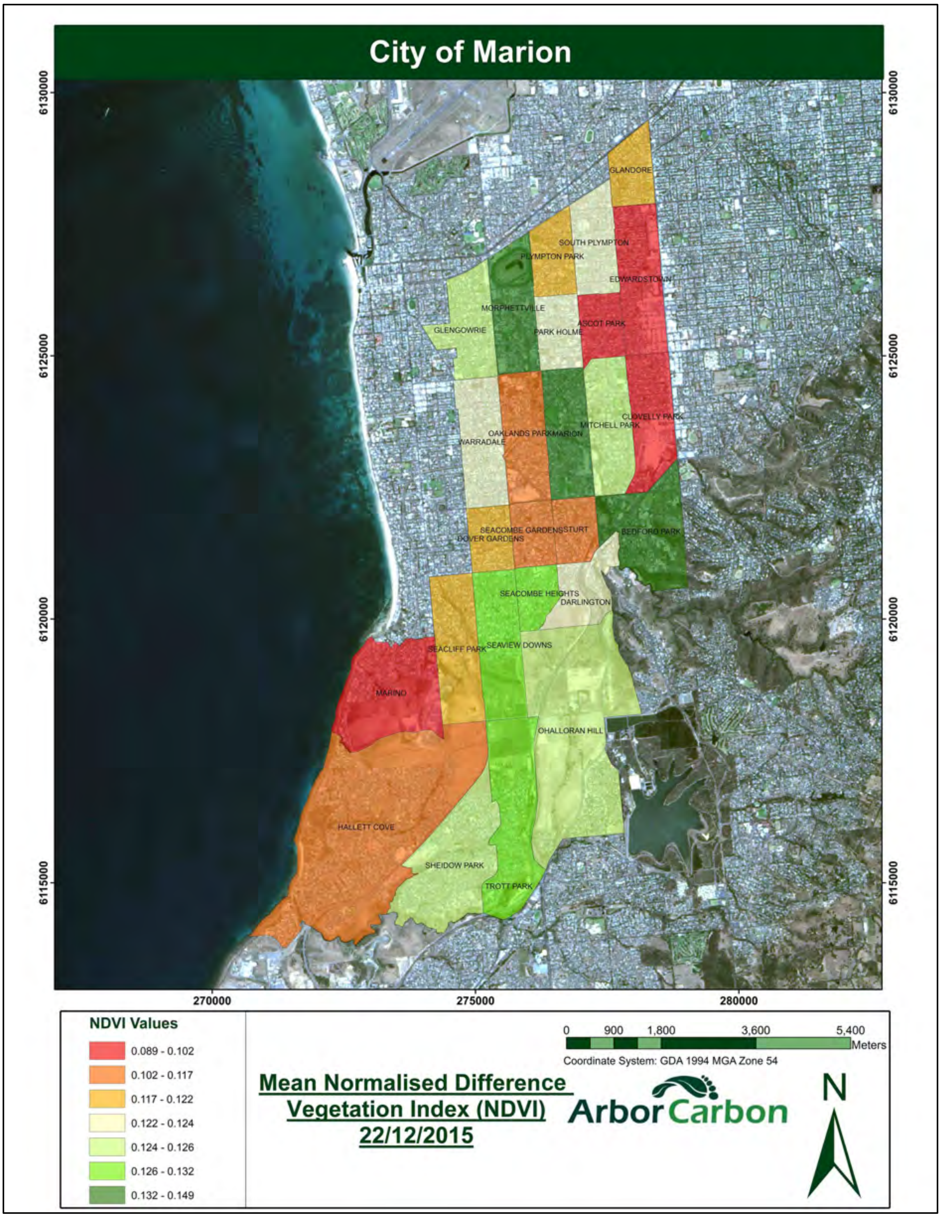
Appendix 29. Mean satellite-derived land-surface temperature for City of Marion 22 December 2015



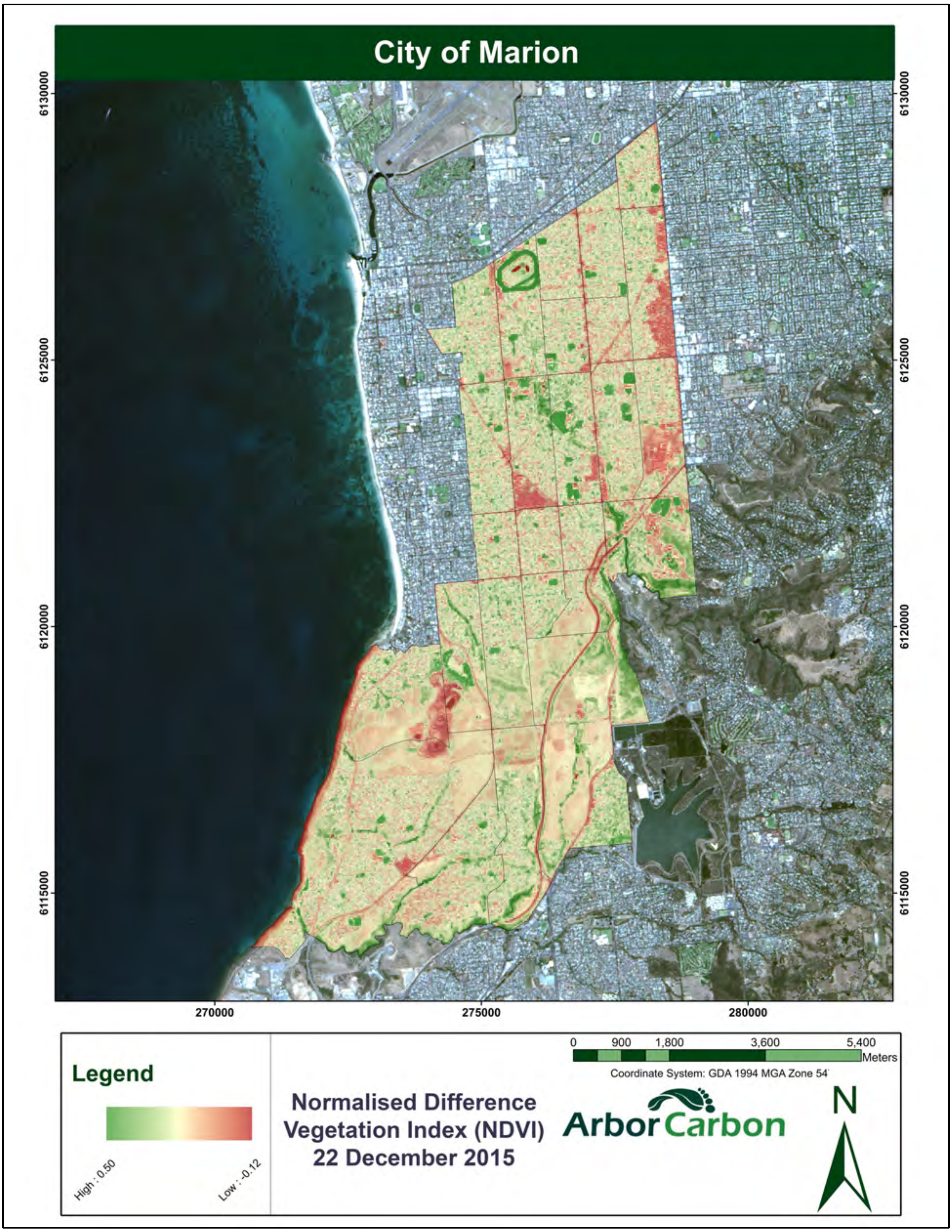
Appendix 30. Scaled satellite-derived land-surface temperature for City of Marion 22 December 2015



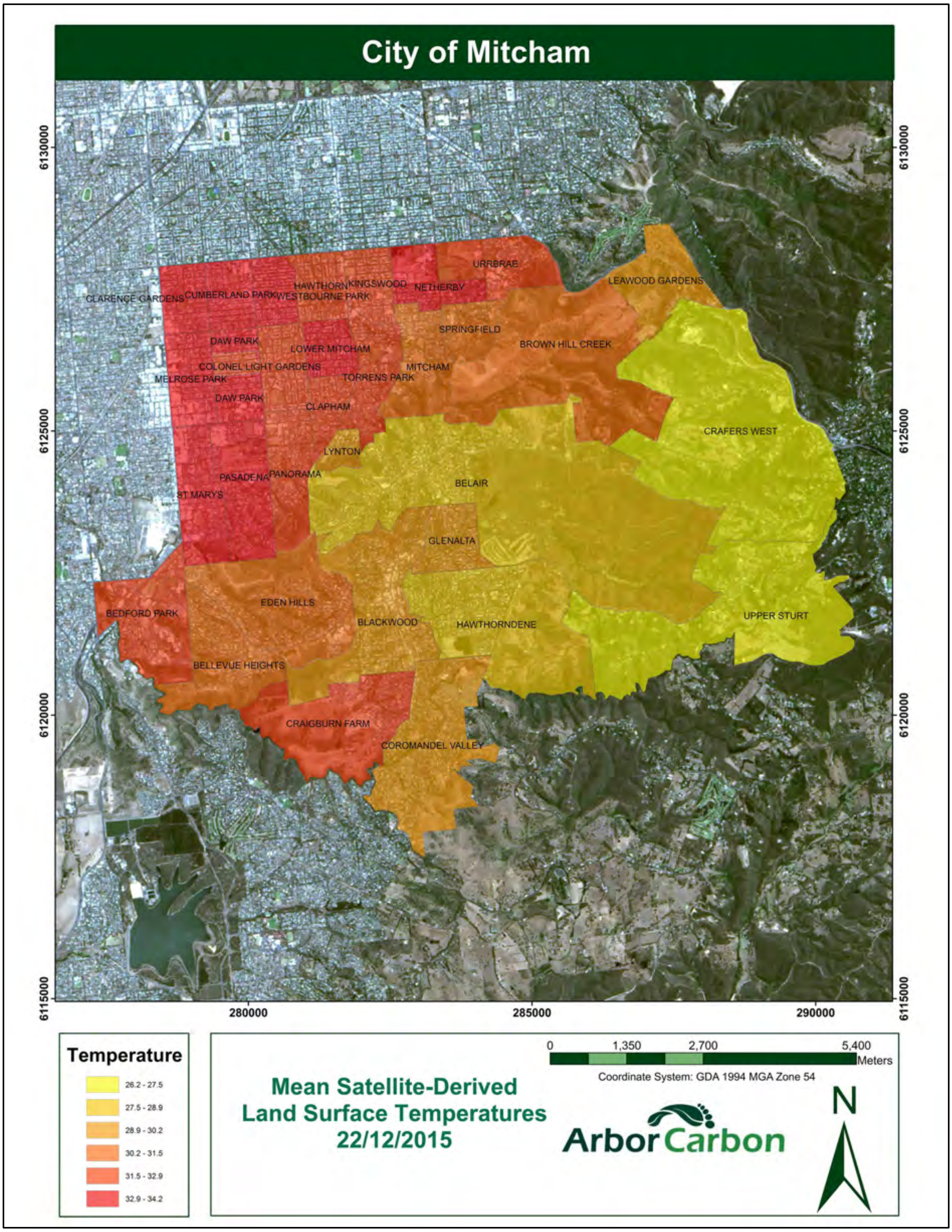
APPENDIX 31. Mean NDVI for City of Marion 22 December 2015



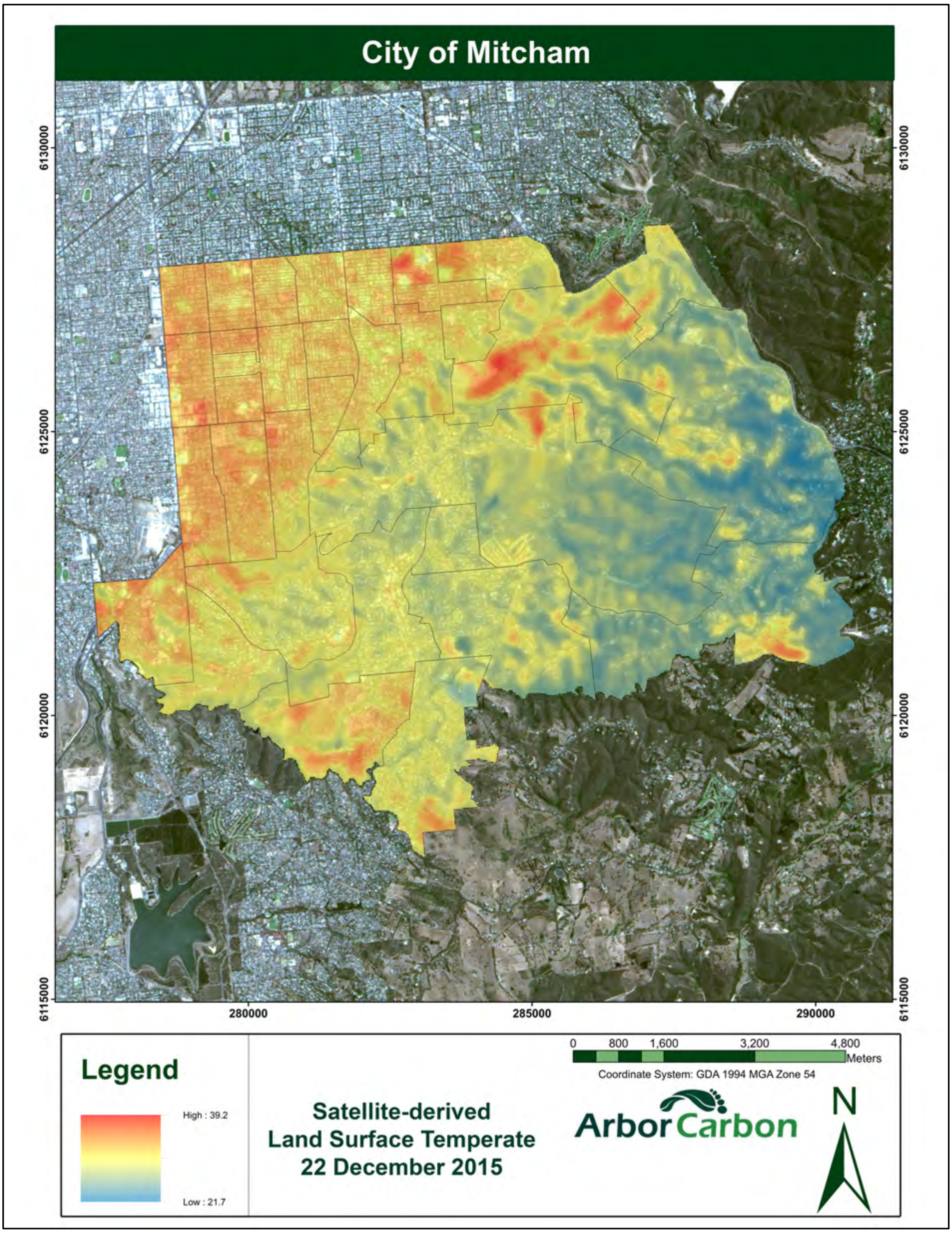
APPENDIX 32. Scaled NDVI for City of Marion 22 December 2015



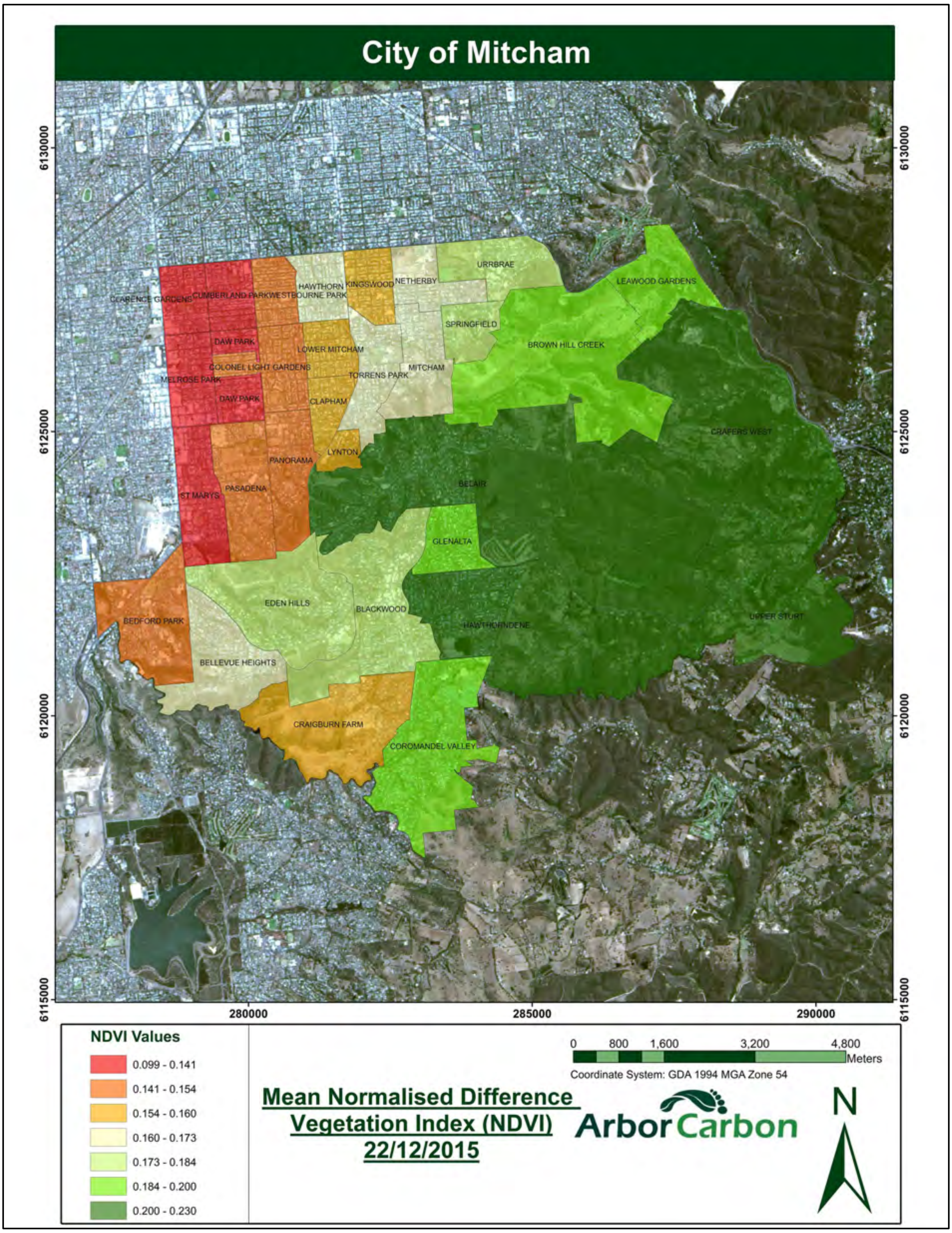
APPENDIX 33. Mean satellite-derived land-surface temperature for City of Mitcham 22 December 2015



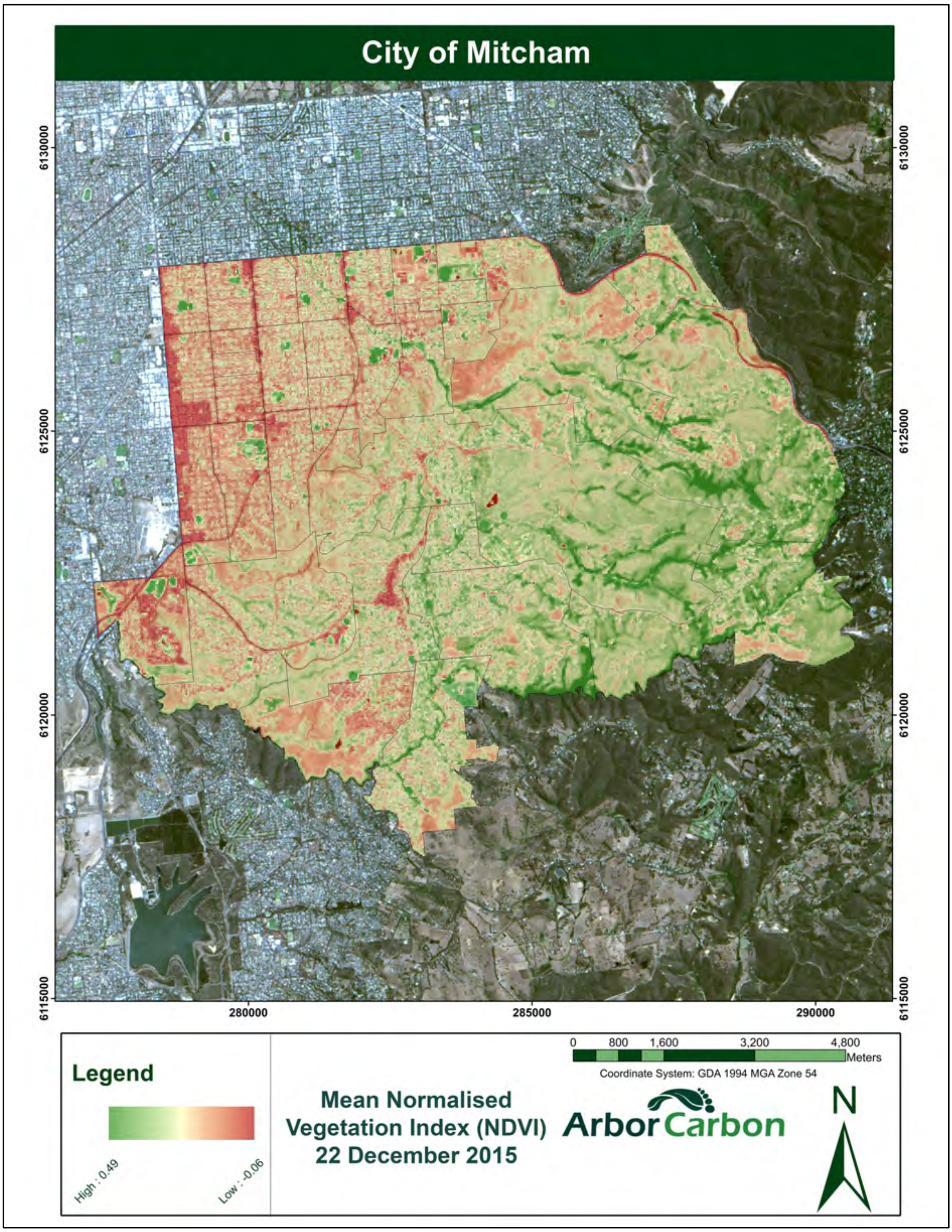
Appendix 34. Scaled satellite-derived land-surface temperature for City of Mitcham 22 December 2015



APPENDIX 35. Mean NDVI for City of Mitcham 22 December 2015



APPENDIX 36. Scaled NDVI for City of Mitcham 22 December 2015



APPENDIX 37. Methods for processing raw satellite thermal infrared data into surface temperature

Radiance is the "flux of energy (primarily irradiant or incident energy) per solid angle leaving a unit surface area in a given direction", "Radiance is what is measured at the sensor and is somewhat dependent on reflectance" (NASA, 2011, p. 47). The Spectral Radiance at the sensor's aperture (L_λ) is measured in [watts/(meter squared * ster * μm)] and for Landsat images it is given by (https://landsat.usgs.gov/Landsat8_Using_Product.php):

$$L_\lambda = M_L * Q_{cal} + A_L$$

where:

- M_L = Band-specific multiplicative rescaling factor from Landsat metadata (RADIANCE_MULT_BAND_x, where x is the band number)
- A_L = Band-specific additive rescaling factor from Landsat metadata (RADIANCE_ADD_BAND_x, where x is the band number)
- Q_{cal} = Quantized and calibrated standard product pixel values (DN)

"For relatively clear Landsat scenes, a reduction in between-scene variability can be achieved through a normalization for solar irradiance by converting spectral radiance, as calculated above, to planetary reflectance or albedo. This combined surface and atmospheric reflectance of the Earth is computed with the following formula" (NASA, 2011, p. 119):

$$\rho_p = (\pi * L_\lambda * d^2)/(ESUN_\lambda * cos\theta_s)$$

where:

- ρ_p = Unitless planetary reflectance, which is "the ratio of reflected versus total power energy" (NASA, 2011, p. 47)
- L_λ = Spectral radiance at the sensor's aperture (at-satellite radiance)
- d = Earth-Sun distance in astronomical units (provided with Landsat 8 metafile, and an excel file is available from http://landsathandbook.gsfc.nasa.gov/excel_docs/d.xls)
- $ESUN_\lambda$ = Mean solar exo-atmospheric irradiances
- θ_s = Solar zenith angle in degrees, which is equal to θ_s = 90° - θ_e where θ_e is the Sun elevation

It is worth pointing out that Landsat 8 images are provided with band-specific rescaling factors that allow for the direct conversion from DN to TOA reflectance. However, the effects of the atmosphere (i.e. a disturbance on the reflectance that varies with the wavelenght) should be considered in order to measure the refletance at the ground. As described by Moran et al. (1992), the land surface reflectance (ρ) is:

$$\rho = [\pi * (L_\lambda - L_p) * d^2]/[T_v * ((ESUN_\lambda * cos\theta_s * T_z) + E_{down})]$$

where:

- L_p is the path radiance
- T_v is the atmospheric transmittance in the viewing direction
- T_z is the atmospheric transmittance in the illumination direction
- E_{down} is the downwelling diffuse irradiance

Therefore, we need several atmospheric measurements in order to calculate rho (physically-based corrections). Alternatively, it is possible to use image-based techniques for the calculation of these parameters, without in-situ measurements during image acquisition.

The Dark Object Subtraction (DOS) is a family of image-based atmospheric corrections. Chavez (1996) explains that "the basic assumption is that within the image some pixels are in complete shadow and their radiances received at the satellite are due to atmospheric scattering (path radiance). This assumption is combined with the fact that very few targets on the Earth's surface are absolute black, so an assumed one-percent minimum reflectance is better than zero percent". It is worth pointing out that the accuracy of image-based techniques is generally lower than physically-based corrections, but they are very useful when no atmospheric measurements are available as they can improve the estimation of land surface reflectance. The path radiance is given by (Sobrino, et al., 2004):

$$L_p = L_{min} - L_{DO1\%}$$

where:

- L_{min} = "radiance that corresponds to a digital count value for which the sum of all the pixels with digital counts lower or equal to this value is equal to the 0.01% of all the pixels from the image considered" (Sobrino, et al., 2004, p. 437), therefore the radiance obtained with that digital count value (DN_{min})
- $L_{DO1\%}$ = radiance of Dark Object, assumed to have a reflectance value of 0.01

Therfore for Landsat images:

$$L_{min} = M_L * DN_{min} + A_L$$

The radiance of Dark Object is given by (Sobrino, et al., 2004):

$$L_{DO1\%} = 0.01 * [(ESUN_\lambda * cos\theta_s * T_z) + E_{down}] * T_v/(\pi * d^2)$$

Therefore the path radiance is:

$L_p = M_L * DN_{min} + A_L -$ v: latest $UN_\lambda * cos\theta_s * T_z) + E_{down}] * T_v/(\pi * d^2)$

There are several DOS techniques (e.g. DOS1, DOS2, DOS3, DOS4), based on different assumption about T_v, T_z, and E_{down}. The simplest technique is the DOS1, where the following assumptions are made (Moran et al., 1992):

- T_v = 1
- T_z = 1
- E_{down} = 0

Therefore the path radiance is:

$$L_p = M_L * DN_{min} + A_L - 0.01 * ESUN_\lambda * cos\theta_s/(\pi * d^2)$$

For Landsat thermal bands, the conversion of DN to At-Satellite Brightness Temperature is given by (from https://landsat.usgs.gov/Landsat8_Using_Product.php):

$$T_B = K_2 / ln[(K_1 / L_\lambda) + 1]$$

where:

- K_1 = Band-specific thermal conversion constant (in watts/meter squared * ster * μm)
- K_2 = Band-specific thermal conversion constant (in kelvin)

and L_λ is the Spectral Radiance at the sensor's aperture, measured in watts/(meter squared * ster * μm); for Landsat images it is given by (from https://landsat.usgs.gov/Landsat8_Using_Product.php)

$$L_\lambda = M_L * Q_{cal} + A_L$$

where:

- M_L = Band-specific multiplicative rescaling factor from Landsat metadata (RADIANCE_MULT_BAND_x, where x is the band number)
- A_L = Band-specific additive rescaling factor from Landsat metadata (RADIANCE_ADD_BAND_x, where x is the band number)
- Q_{cal} = Quantized and calibrated standard product pixel values (DN)

The K_1 and K_2 constant for Landsat sensors are provided in the following table:

Constant	Landsat 4*	Landsat 5*	Landsat 7**
K_1 (watts/meter squared * ster * μm)	671.62	607.76	666.09
K_2 (Kelvin)	1284.30	1260.56	1282.71

* from Chander & Markham (2003)

** from NASA (2011)

For Landsat 8, the K_1 and K_2 values are provided in the image metafile.

References

- Chander, G. & Markham, B. 2003. Revised Landsat-5 TM radiometric calibration procedures and postcalibration dynamic ranges Geoscience and Remote Sensing, IEEE Transactions on, 41, 2674 – 2677
- Chavez, P. S. 1996. Image-Based Atmospheric Corrections – Revisited and Improved Photogrammetric Engineering and Remote Sensing, [Falls Church, Va.] American Society of Photogrammetry, 62, 1025-1036
- Finn, M.P., Reed, M.D, and Yamamoto, K.H. 2012. A Straight Forward Guide for Processing Radiance and Reflectance for EO-1 ALI, Landsat 5 TM, Landsat 7 ETM+, and ASTER. Unpublished Report from USGS/Center of Excellence for Geospatial Information Science, 8 p , http://cegis.usgs.gov/soil_moisture/pdf/A%20Straight%20Forward%20guide%20for%20Processing%20Radiance%20and%20Reflectance_V_24.
- Moran, M.; Jackson, R.; Slater, P. & Teillet, P. 1992. Evaluation of simplified procedures for retrieval of land surface reflectance factors from satellite sensor output Remote Sensing of Environment, 41, 169-184
- NASA (Ed.) 2011. Landsat 7 Science Data Users Handbook Landsat Project Science Office at NASA's Goddard Space Flight Center in Greenbelt, 186 http://landsathandbook.gsfc.nasa.gov/pdfs/Landsat7_Handbook.pdf
- Sobrino, J.; Jiménez-Muñoz, J. C. & Paolini, L. 2004. Land surface temperature retrieval from LANDSAT TM 5 Remote Sensing of Environment, Elsevier, 90, 434-440

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