Estimation of Land Surface Temperature and Urban Heat Island effect for Australian urban centres

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Contents

Figures

Tables

Acknowledgments

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Amati, M. Boruff, B. Caccetta, P. Devereux, D. Kaspar, J. Phelan K. and Saunders, A. (2017) *Where should all the trees go? Investigating the impact of tree canopy cover on socio-economic status and wellbeing in LGA's prepared for Horticulture,* Innovation Australia Limited by the Centre for Urban Research, RMIT University.

Executive summary

This report describes the generation of land surface temperature (LST) and urban heat island (UHI) estimates for major Australian urban centres.

Landsat 8 thermal infrared imagery was obtained for each urban centre for as many overpasses as possible during the summer of 2015/16. Each image was processed to LST using the *single channel method* (Jiménez-Muñoz & Sobrino, 2003, Jiménez-Muñoz et al, 2009). The required atmospheric parameters were obtained from publicly available observations by the Australian Government Bureau of Meteorology (BOM). The required land surface emissivity (LSE) values were estimated using the *NDVI approach* (Sobrino & Raissouni 2000). Images were then averaged to obtain an estimate of typical summer LST.

The UHI is a measure of the deviation of urban temperatures relative to a non-urban baseline. Native vegetated sites were used to establish the baseline. This was achieved by estimating a first-order fit to the temperature of native vegetation within and around each urban centre. This fit captures any broad-scale temperature trend that is likely independent of urbanisation, such as cooling with increased latitude or proximity to the coast. After subtracting this fit, the residuals may be interpreted as showing finer scale deviations from this trend, including deviations attributable to urbanisation of the landscape.

The quality of results vary with the availability of cloud- and haze-free data. Due to the limited number of satellite overpasses for each region for the time-period considered, cloud- and haze-free data is not guaranteed for each region, in which case the best available data was used. In locations where cloud-affected imagery was used, artefacts in the results may remain due to limitations in the accuracy of the cloud masks. UHI estimates for the cities including Sydney, Perth, Melbourne and Adelaide were relatively free of cloud induced artefacts, whereas Brisbane, Hobart and Cairns contain some artefacts which limit their utility.

Where adequate cloud-free data was available, the results may be safely interpreted as showing significant temperature increases across all urban areas, with the largest increases occurring in areas with extensive concrete, such as airports and industrial areas. Although the data is too coarse to allow examination of fine scale features such as individual houses and roads, there is some evidence of temperature increases along major roads and above some large industrial or commercial buildings such as shopping centres and distribution warehouses.

1 Introduction

This task report describes work undertaken to investigate the urban heat island (UHI) impact of major urban areas in Australia. The UHI is a measure of temperature increase that is attributable to urbanisation; it is thus the difference between the actual temperature at an urban location and what the temperature would have been if the location had not been urbanised.

The task thus breaks down into two parts:

- Estimating the land surface temperature (LST) at urban locations
- Forming an estimate of how much of the LST is attributable to urbanisation

Estimates of land surface temperature can be computed from remotely sensed thermal infrared imagery. Landsat 8 carries thermal infrared sensors (TIRS), and high-quality preprocessed data is readily available. The first part of the task, then, is to process Landsat 8 TIRS data to LST.

2 Method

Landsat 8 has two thermal infrared sensors (TIRS) that collect measurements at different target wavelengths, storing the data as Band 10 (TIRS-1) and Band 11 (TIRS-2). By intent, these two sensors make it possible to calculate LST using the *Split Window method* — a method that is both simpler and more accurate than alternatives, and so best practice. Unfortunately, both sensors are subject to calibration issues caused by stray light entering the sensors from outside the intended field of view. The impact on Band 10 is small, and calibration adjustments have largely accounted for it. Band 11, on the other hand, is more severely affected. To date, USGS recommend

"Due to the larger calibration uncertainty associated with TIRS band 11, it is recommended that users refrain from relying on band 11 data in quantitative analysis of the TIRS data, such as the use of split window techniques for atmospheric correction and retrieval of surface temperature values." (USGS, 2014)

We therefore use the *Single Channel method,* using Band 10 data only. A generalised single channel method is due to Jiménez-Muñoz & Sobrino (2003) and has been widely adopted. Minor revisions were published in Jiménez-Muñoz *et al* (2009). In 2014, implementation and validation details specific to Landsat 8 were published independently in Jiménez-Muñoz *et al* (2014) and Yu *et al* (2014). These papers differ only in minor points, the most significant being the polynomial coefficients used to estimate certain atmospheric values. Here we have followed Yu *et al* (2014).

In addition to Landsat 8 Band 10 data and metadata, the method requires an atmospheric parameterisation and measures of land surface emissivity.

2.1 Scene selection and pre-processing

For each city, the urban extents were calculated as the extents covering all urban local government areas (LGAs), with a buffer of 10 kilometres.

The extents having been determined, thermal imagery was selected for processing if:

- The collection date fell within the temporal window of October 2015 to April 2016.
- The image overlapped the study area; note that much of each scene image is null because Landsat 8 paths do not run north-south; thus a scene image overlapping the study area did not guarantee that it would contain data in the study area.
- The cloud percentage in the scene metadata indicated that the scene would likely contribute usable data. The threshold varied with the overall quality of images available: there is no need to process an image that is 50% cloud if there are a large number of cloud-free images available; but the image would be processed if it was the best available. To formalise this, images were sorted into descending order of cloud percentage, and processed until the aggregate cloud percentage exceeded 100.

Band 10 TIRS data for the chosen scenes was obtained from USGS. The native resolution of the sensor is 100m but USGS resamples to 30m. The datum and projection are WGS84 and NUTM respectively.

Reflectance data (Landsat 8 bands 4 and 5) was also needed for estimation of land surface emissivity (LSE). For this, Australian Reflectance Grid 25 (ARG25) (Geoscience Australia, 2015) data was used. This is 25m data in GDA94 / MGA.

For consistency, the Band 10 TIRS data was reprojected to the ARG25 grid. As part of this step, the extents were set to the extents of the study area, so that all further processing occurred only on those parts of the scene that overlap the study area.

Figure 1 Contribution to Sydney study extents of Landsat 8 image for path 89, row 83, date 29 December 2017, shown in truecolor (Band 3 in red, 2 in green, 1 in blue)

shows an example of a scene partially overlapping the Sydney study extents.

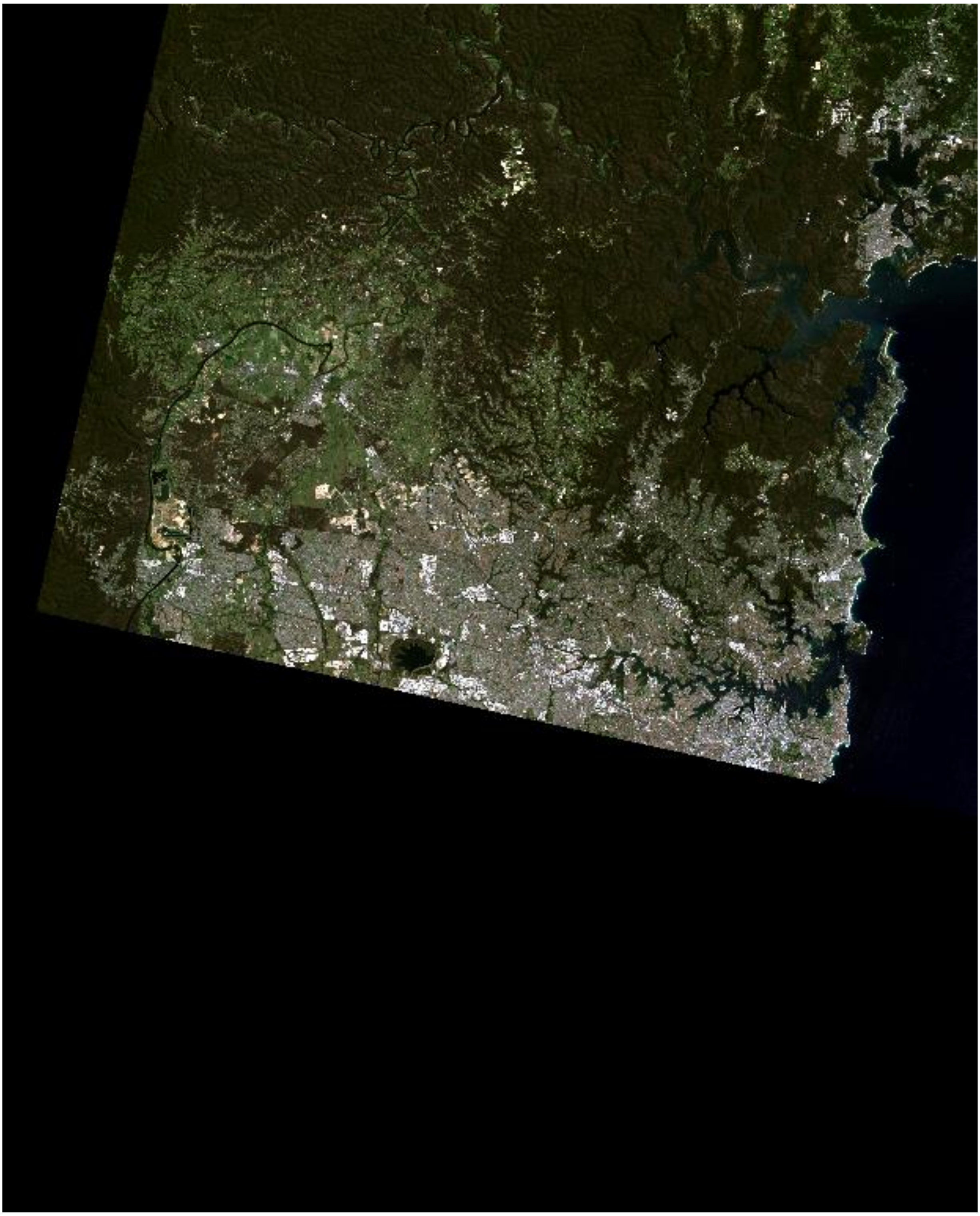

Figure 1 Contribution to Sydney study extents of Landsat 8 image for path 89, row 83, date 29 December 2017, shown in truecolor (Band 3 in red, 2 in green, 1 in blue)

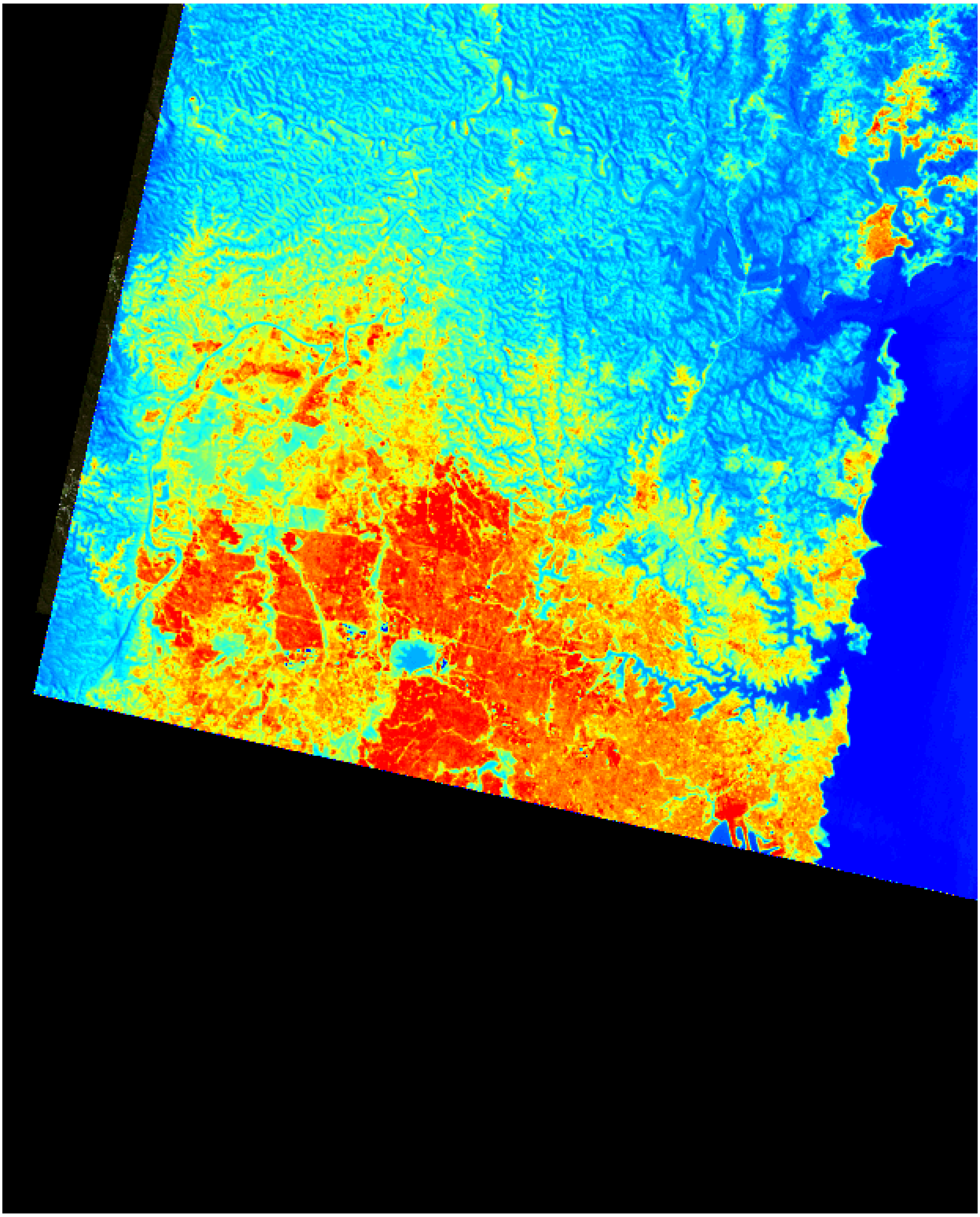

Figure 2 Landsat 8 TIRS digital numbers for path 89, row 83, date 29 December 2017.

2.2 Atmosphere

The general LST equation requires three atmospheric parameters ψ_1, ψ_2 and ψ_3. These may be computed from estimates of atmospheric transference, upwelling and downwelling, if known. Because of the difficulty of accurately establishing these values, the SC approach recommends estimating the atmospheric parameters as a polynomial equation over the total atmospheric water vapour. The polynomial coefficients are related to the band wavelength and must be estimated by simulation. Coefficients are provided by Yu *et al* (2014). Thus only the total atmospheric water vapour content is required.

The total atmospheric water vapour content can be calculated from temperature and relative humidity. The steps are:

- Calculate the saturation pressure from the temperature. We follow Yu *et al* (2014) in using the formula given by Buck (1981).
- The relative humidity then gives the ratio of vapour pressure to saturation pressure.
- A conversion factor of 0.098 allows for conversion from hP to g/cm^2.

Daily observations of temperature and relative humidity were obtained from the Bureau of Meteorology. Since Landsat 8 always overpasses Australia during mid-morning, we used the 9am observations.

2.3 Land surface emissivity

Land surface emissivity (LSE) varies with the material and cover of the land surface, such as its vegetation, surface moisture and roughness. Following Yu *et al* (2014), the *NDVI-based approach* (Sobrino & Raissouni 2000) was used to estimate LSE.

The NDVI-based approach was developed as a simple method for estimating LSE in natural areas. Vegetation and non-vegetation are each assigned a nominal emissivity value. NDVI is then calculated for each pixel, and two NDVI thresholds are set, such that

- A pixel with an NDVI above the upper threshold is treated as pure vegetation, and assigned the vegetation emissivity value.
- For a pixel with an NDVI between the two thresholds, a fractional vegetation value is calculated, and that fraction determines an emissivity intermediate between the vegetation and non-vegetation emissivity values.
- A pixel with an NDVI below the lower threshold is treated as containing no vegetation, and assigned the non-vegetation emissivity value.

With respect to the last of these cases, the method as published treats the non-vegetation case as “soil” and allows for a further calculation step based on a known linear relationship between emissivity and brightness of soil in the red band. This approach is not taken here, because “non-vegetation” need not imply “soil” in urban areas. It is more likely to be asphalt, brick, concrete, etc.

Based on the values in

Table 1, we set the emissivity of non-vegetation as 0.93. We follow Yu *et al* (2014) in setting the emissivity of vegetation to 0.9863.

Table 1: Emissivity of some common urban materials

Material	Emissivity
Asphalt	0.93
Brick	0.93
Concrete	0.85
Limestone	0.90–0.93
Paint	0.96
Sand	0.76
Soil	0.9–0.95

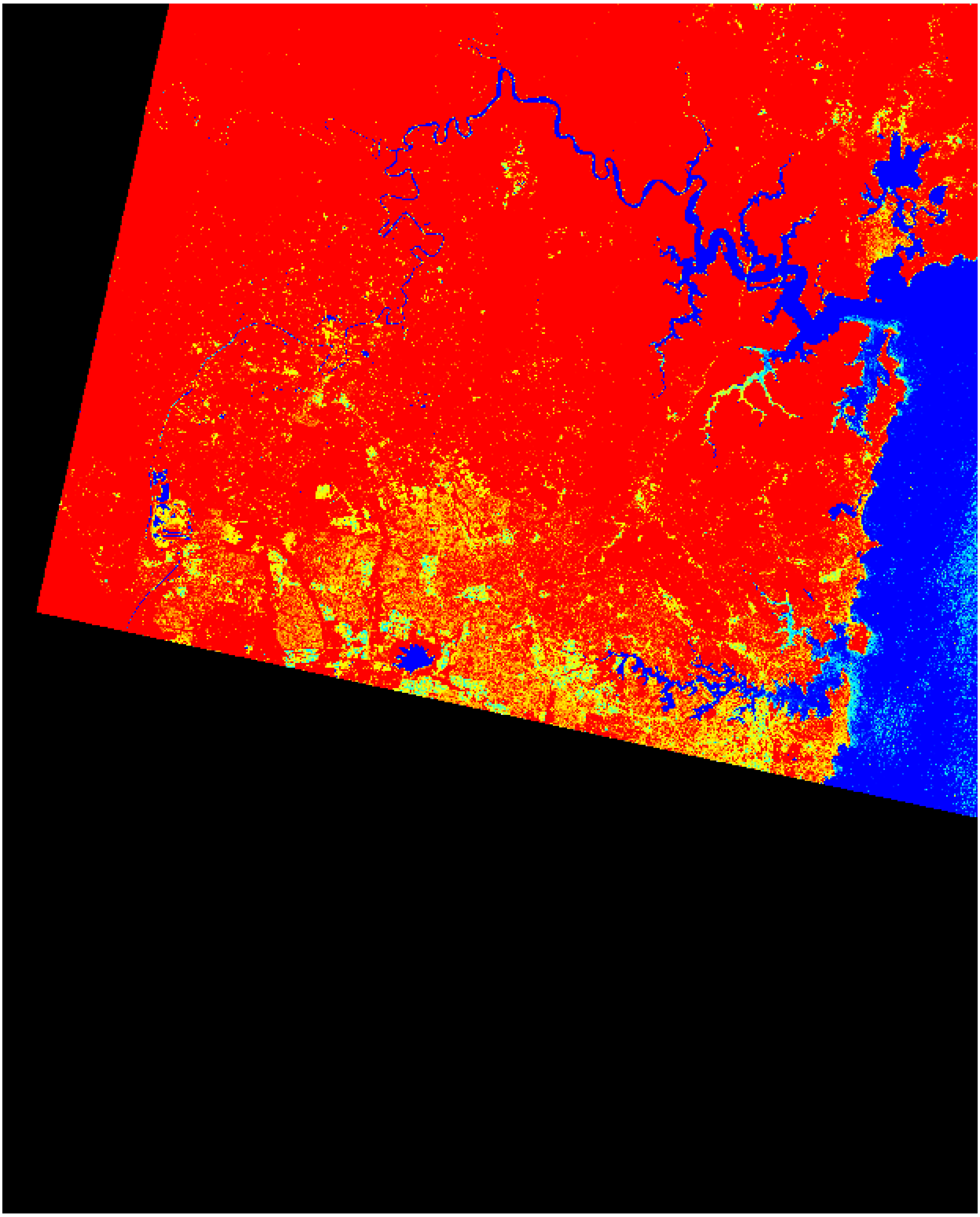

Figure 3 Land surface emissivity estimate for Landsat 8 for path 89, row 83, date 29 December 2017

2.4 Land surface temperature

The steps to calculating land surface temperature are as follows

- Convert Landsat 8 TIRS digital numbers (DN) to at-sensor radiance using linear calibration parameters provided in the metadata
- Convert to brightness temperature using the equations of Planck's law.

- Calculate coefficients for the atmospheric functions; see above
- Estimate LSE; see above
- Final calculation of LST using equations of Jiménez-Muñoz *et al* (2009)

Figure 4 shows the LST image for the Toowoomba area.

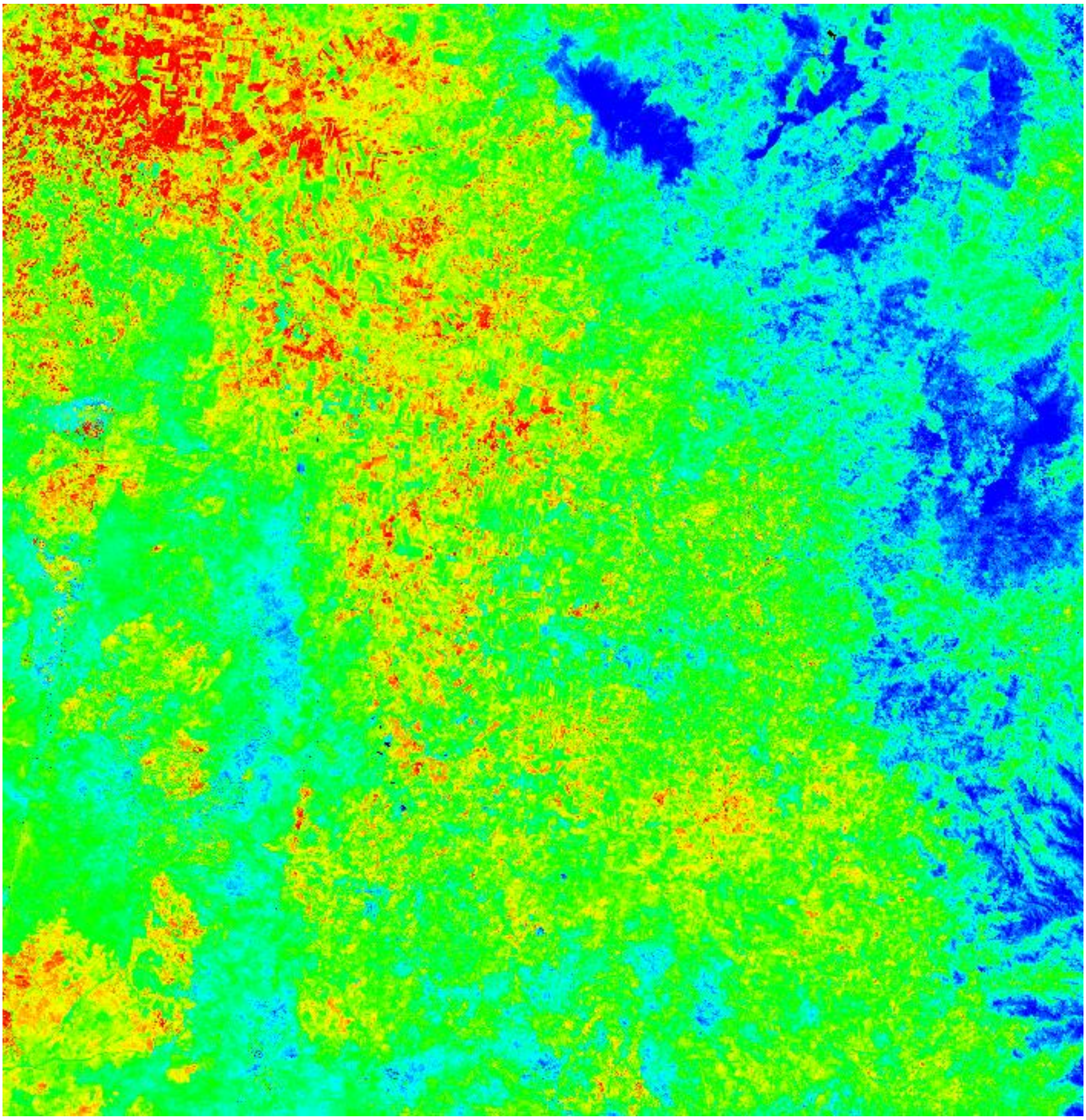

Figure 4 LST image for Toowoomba and surrounds.

2.5 Scene compositing

Once the LST has been calculated for each individual scene, a composite image is formed by calculating for each pixel the mean value of all the calculated LST images that contain data for it. The resulting composite typically covers the entire study area, whereas individual scene LST images generally do not.

We take a mean temperature in order to minimise sampling effects — we do not want an area to appear relatively hot merely because Landsat 8 overpassed it on a hot day. Instead we produce a 'seasonal average' composite. Some sampling effects are nevertheless visible, in particular at path boundaries, on different sides of which the average temperature has been calculated from entirely different sets of dates.

2.6 Urban heat island

Once an LST image has been computed, we apply a first order correction to remove any broad-scale linear temperature trend that appears to be independent of any urbanisation, such as a cooling trend attributable to increased latitude, increased elevation, or proximity to the coast.

Figure 4 shows the LST image for Toowoomba. There is a clear trend, with cooler temperatures occurring in the east, and hotter temperatures in the west. This trend may appear spurious, since the hot areas in the west are agricultural, whereas the cooler areas to the east are native forest (see Figure 5 for a land cover map). However, comparing like for like, we see agricultural areas in the south-east that are much cooler than agricultural areas in the north-west. Similarly, the native forest in the south-west is warmer than the native areas in the east.

This trend is easily explained by altitude. The ridge of the Great Dividing Range runs in a roughly north-south direction through the eastern parts of the image, subsiding into the much lower altitude Darling Downs in the west.

To calculate an estimate of this trend, we first identify candidate points that

1. are well within a substantial block of native forest. This is done by taking forest maps produced as part of the National Carbon Accounting System Land Cover Change Project (NCAS-LCCP), eroding their boundaries by 20 pixels, and accepting any remaining forest pixels. Figure 5 shows the forest map for the area, with forested areas indicated in green. Only areas 20 or more pixels within the boundary of forest areas are included in the pool of

candidates fit points.

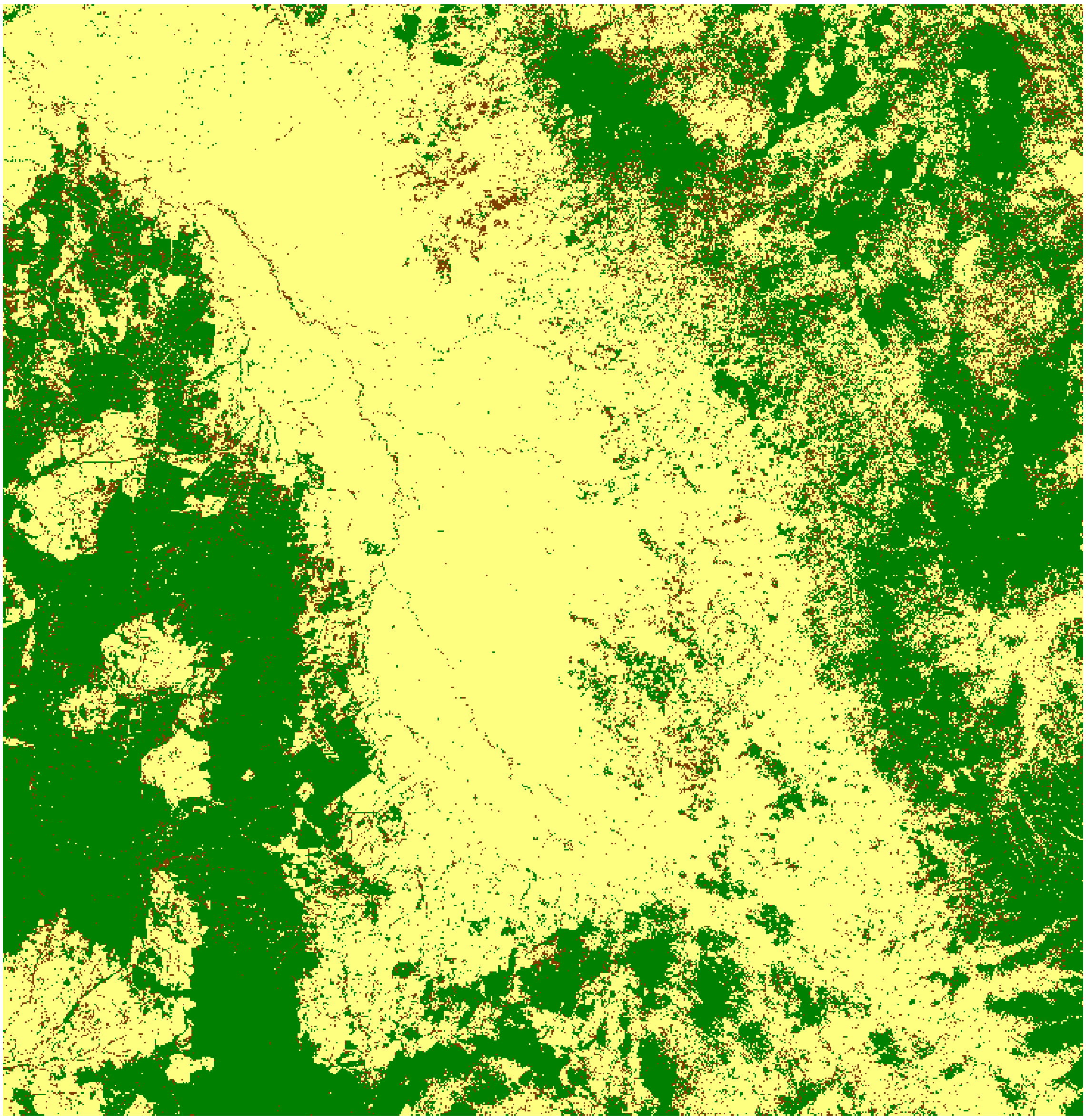

Figure 5 NCAS-LCCP forest map, with forest in green, cleared land in yellow, a small amount of sparse vegetation cover in brown.

2. have an elevation similar to that of the urban area. This restriction is due to Martin-Vide *et al* (2015) which recommends avoiding comparisons of temperatures from disparate elevations. Figure 6 shows the elevation of the Toowoomba area. The red and yellow line marks the ridge of the Great Dividing Range, with areas in green being highlands of the range. Roughly speaking, only areas in shades of blue are similar enough in elevation to

that of Toowoomba to warrant inclusion in the pool of candidate points.

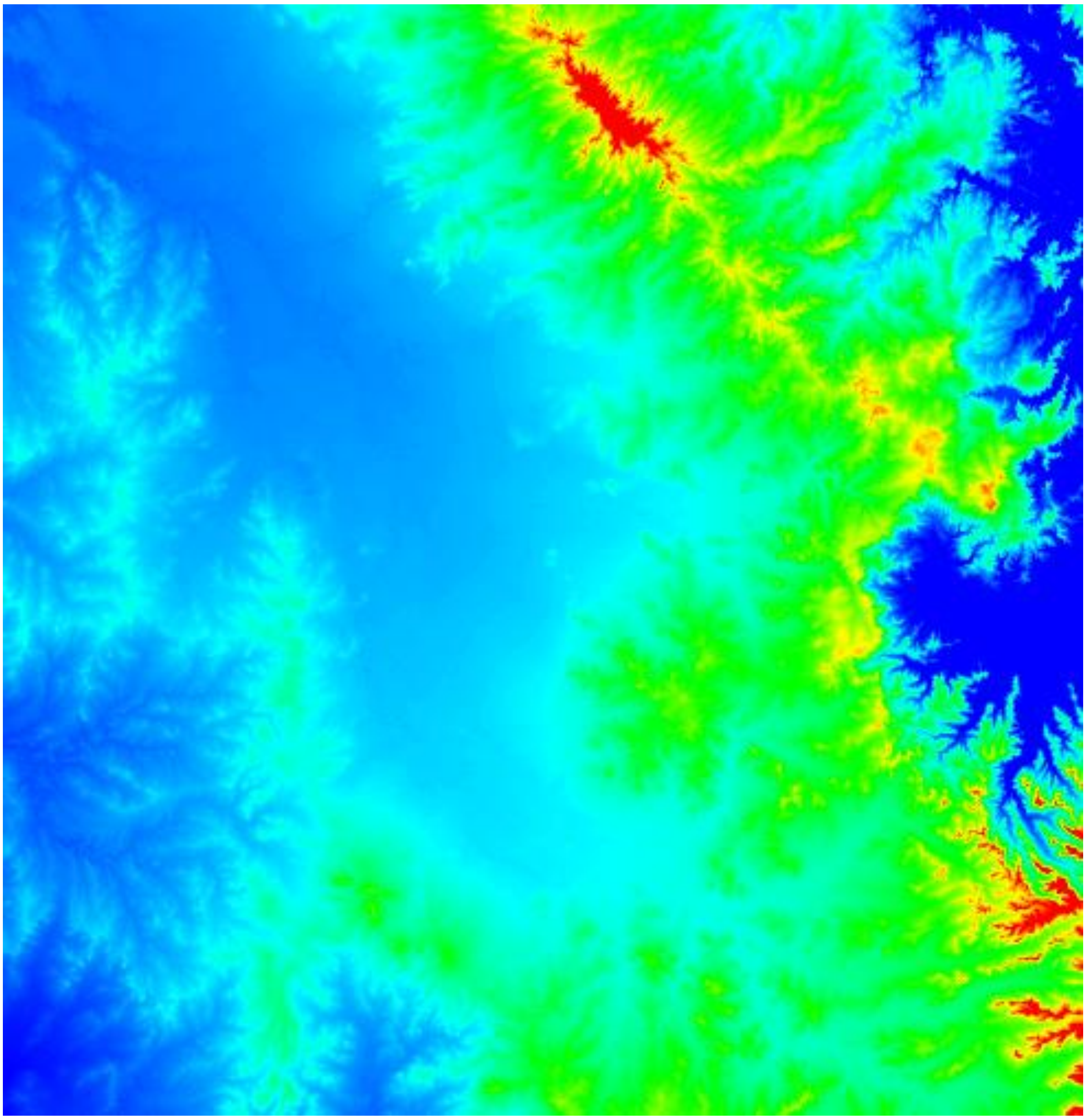

Figure 6 Elevation, Toowoomba and surrounds. The red and yellow line marks the ridge of the Great Dividing Range.

3. are on fairly level and flat ground, so as not to be unduly affected by sun angle or shade (Landsat 8 collects over Australia in the morning, when eastern slopes are warmed by the sun, and western slopes will be cooler and may be in shade.) This is done by calculating the sliding-window local variance of a DEM over the area. The DEM used is the Geoscience Australia's "SRTM-derived 1 Second Digital Elevation Models Version 1.0" product, which is a smoothed DEM derived from NASA's Shuttle Radar Topography Mission (SRTM) DEM (Gallant *et al* 2010). Areas with large slope will have high local variance, as will areas of rough terrain. Figure 7 shows a visual representation of this variance, with high variance in red and low variance in blue. Both the ridge of the Great Dividing Range and the steep downslope to the east of it show as high variance. Some other local features have relatively

high variance, but much of the western half of the image has acceptably low variance.

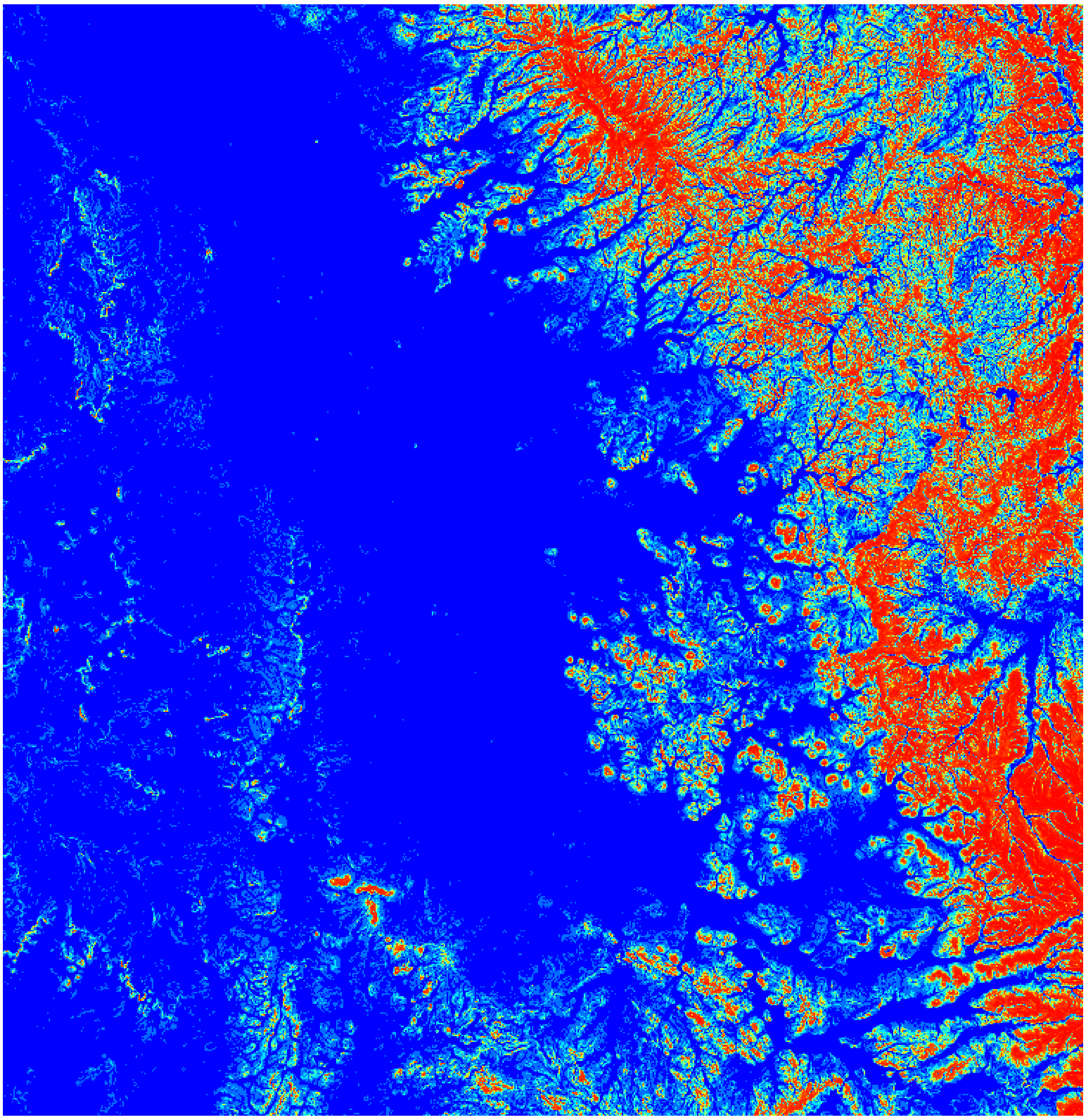

Figure 7 DEM variance. High variance in red, low variance in blue.

The candidate points are those which meet all three conditions. Figure 8 shows the set of such points for Toowoomba. These points were then inspected to ensure there is a sufficiently broad spatial distribution to allow an accurate fit. In the case of Toowoomba, a relatively small number of candidates along the eastern edge provide sufficient spatial balance to the preponderance of points in the west, and we can be confident of a stable linear fit.

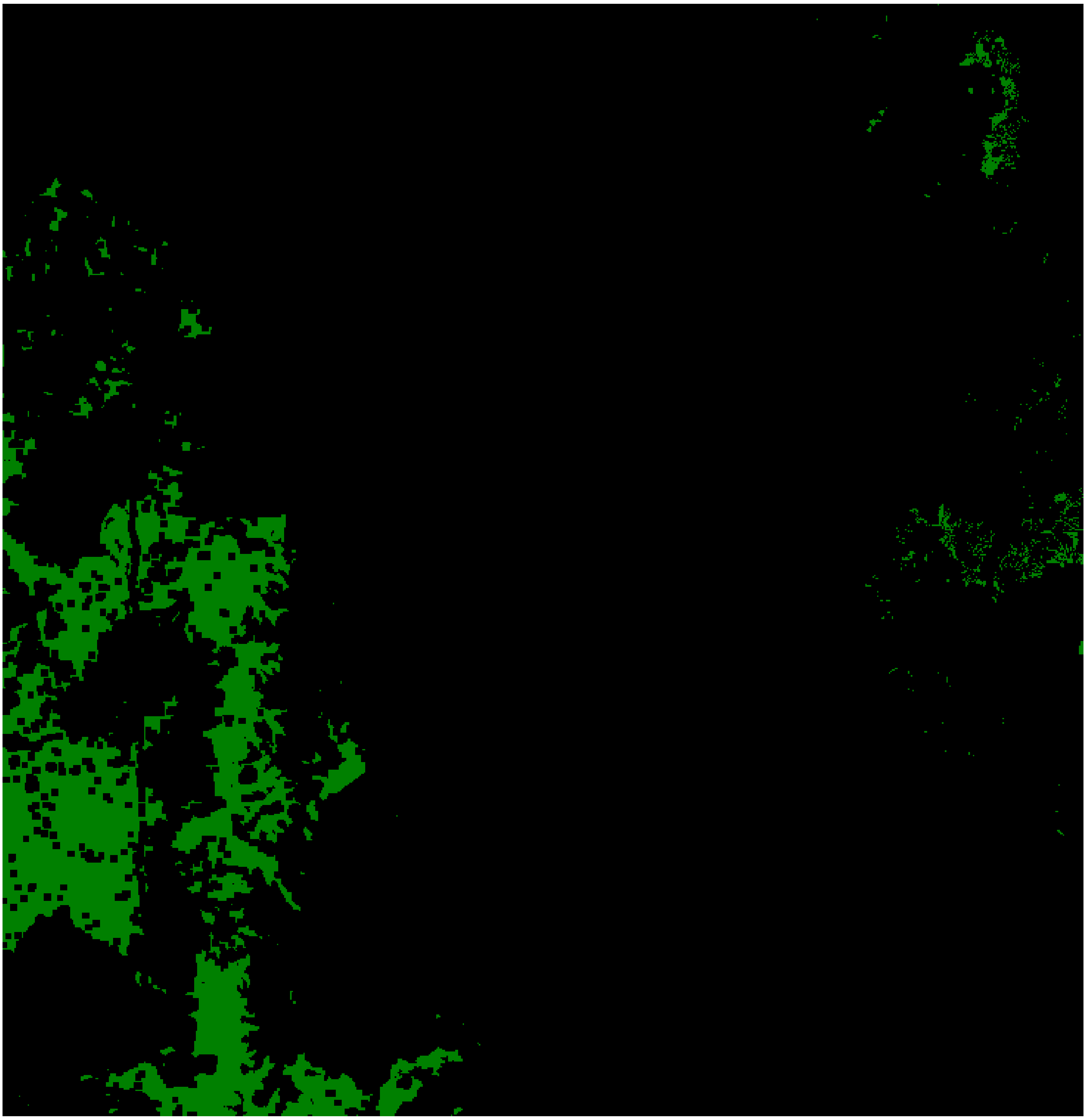

Figure 8 Candidate UHI fit points

An affine fit is then calculated as the least square solution to the equation $A\mathbf{x}=b$, where A is constructed from the (x,y) location of the candidate points, and b is constructed from their values. The least squares solution to x gives us the parameters of any broad-scale linear trend in the candidate points across the image.

Figure 9 visualizes the temperature trend across the candidate points for Toowoomba. As expected, the variation is oriented in an east-west direction. Note that the colour stretch is not the same as that of the LST image; the temperature difference between the hotter areas in the west marked red, and the cooler areas to the east marked blue, is about 9°C.

Figure 9: Linear trend in temperature across candidate points

This trend is then subtracted from the LST image, resulting in the UHI image. Figure 10 shows the UHI image for Toowoomba. Note that there is far more like-for-like consistency across the image: large blocks of native forest have values close to zero, as we would expect for UHI, since the purpose is to calculate temperature increase attributable to urbanisation. Agricultural areas also have similar temperature increases across the image. Thus we have corrected for the broad scale temperature trend, which in this case appears to be attributable to change in elevation across the image.

Since we have fit only to points with a similar elevation to that of Toowoomba, the resultant correction cannot be considered valid for locations at a very different elevation, such as the crest of the Great Dividing Range. To the extent that the temperature trend identified is attributable to an elevation gradient, that gradient is the slope of the Darling Downs towards the foothills of the Great Dividing Range, not the steeper slopes of the Range itself.

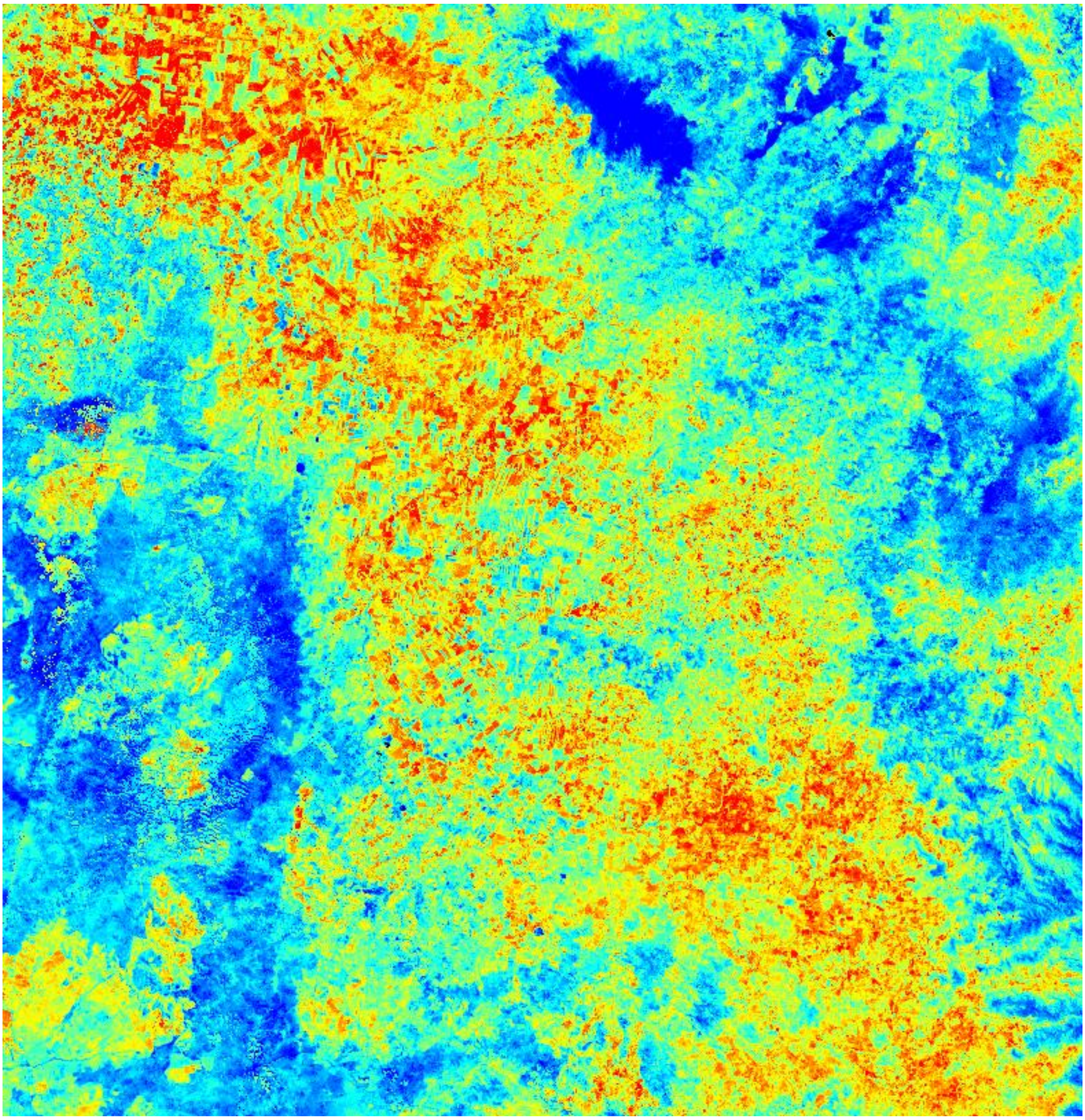

Figure 10 UHI image, Toowoomba and surrounds

Note that this first order correction does not remove the finer scale, localised trends. It is expected that some of these more localised trends are attributable to urbanisation, but there will also be local trends attributable to local changes in elevation, or the local presence of water such as lakes and rivers.

3 Results

Processing details and results for each city may be found in Appendix A . In summary:

- For cities where an adequate amount of cloud-free data was available, the results appear visually to be clear of artefacts and amenable to further visual interpretation. These include Sydney, Melbourne, Canberra, Adelaide, and Perth.
- In cloud-prone locations such as Brisbane, Cairns and Launceston, it was necessary to process imagery with extensive cloud. Due to the inadequacy of available cloud masks, the LST and UHI image contain visible artefacts. The averaging of individual scenes to form a seasonal average image tended to compound these artefacts rather than reduce them.
- No results were available for Darwin within the summer temporal window, but a cloud-free image from April 2016 was processed.
- No results were obtained for Hobart or Warnambool. In the case of Hobart, all images were too heavily cloud-affected to enable meaningful processing. In the case of Warnambool, there were two suitable images, but imagery was not available from Geoscience Australia for either of them.

Where adequate cloud-free data was available, the results may be safely interpreted as showing significant temperature increases across all urban areas, relative to a native vegetation baseline, with the largest increases occurring in areas with extensive concrete, such as airports and industrial areas.

One limitation of the data is its spatial coarseness. Landsat 8 TIRS produces image pixels at 100m diameter. In this work, the images were resampled to 25m for consistency with the other bands. The result is a thermal image with relatively smooth variations even in the presence of very sharp thermal changes on the ground. For example, when validating some pixels that were apparently extremely hot, the location was found to be an ironworks with some large exhaust fans. If those fans were venting very high-temperature exhaust fumes, then this would appear in the thermal image not as a single very hot point but as a unusually hot 100m pixel prior to resampling, and thus an unusually hot 4x4 block of 25m pixels after resampling.

The spatial coarseness of the results renders it infeasible to attribute thermal temperatures to fine scale features such as individual houses. However, there are evident temperature increases attributable to larger scale features such as along major roads and above some large industrial or commercial buildings such as shopping centres and distribution warehouses.

Appendix A Results by city

A.1 Adelaide

Adelaide was processed in MGA zone 54.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 138.355297°E / 259800E
- East: 139.117753°E / 327250E
- South: 35.407754°S / 6080075N
- North: 34.514373°S / 6177700N

Table 2 lists the Landsat 8 images that were tentatively detected as intersecting the extents above, and included in processing.

Table 2 Landsat 8 Images processed for Adelaide, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
96	85	20151215	27.6	32
96	85	20160116	19.0	42
96	85	20160320	16.4	55
96	85	20151231	32.5	12
96	85	20160304	22.9	50
97	84	20160107	21.4	55
97	84	20160311	23.9	76
97	84	20151222	22.1	37
97	84	20160208	20.4	61
97	85	20160107	21.4	55
97	85	20151222	22.1	37
98	84	20151229	25.7	33
98	84	20160302	24.9	36

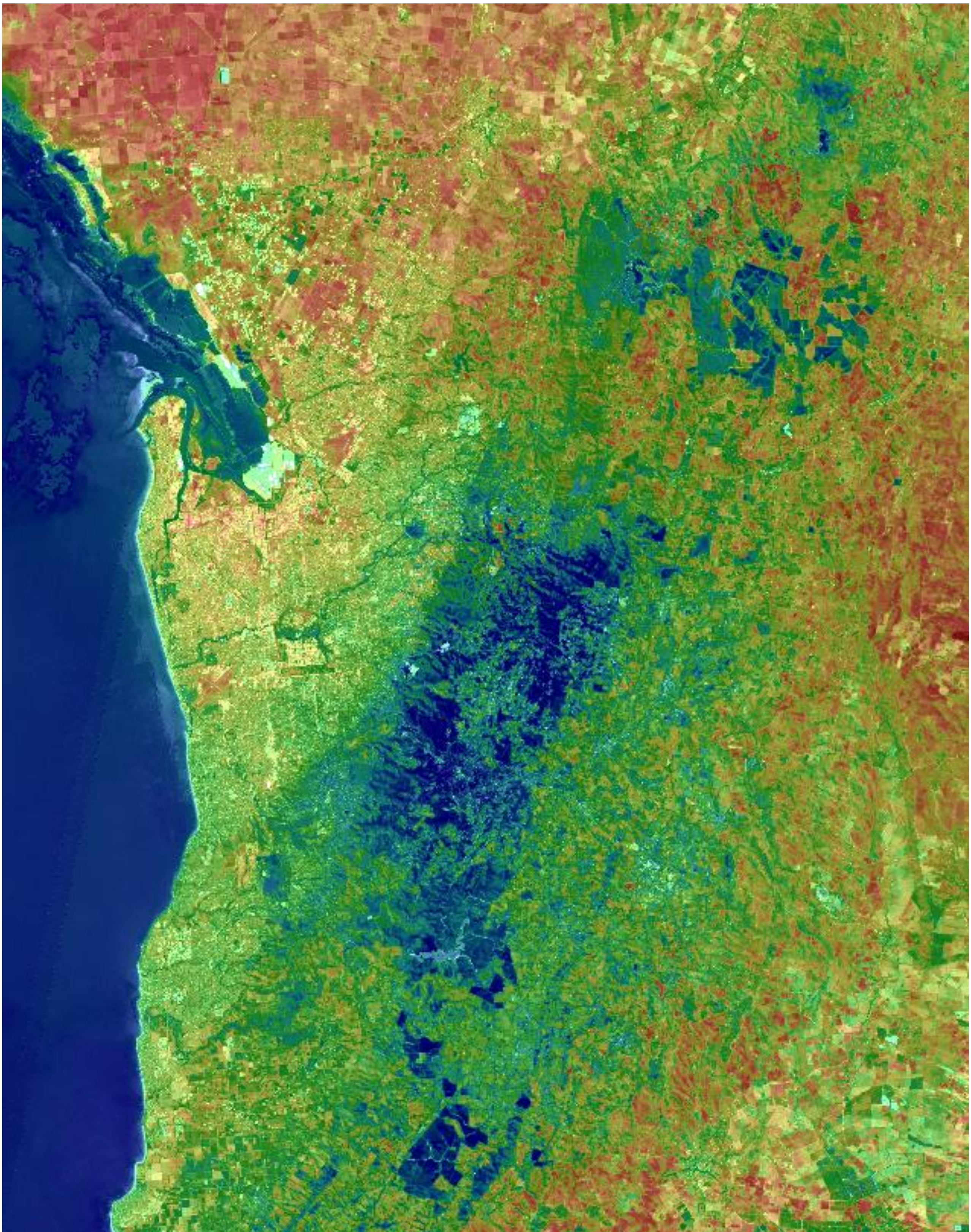

Figure 11: Averaged LST map for Adelaide and surrounds, in pseudocolor (red=hotter, blue=colder), partially transparent and overlaying greyscale Landsat 8 visible imagery from 22 December 2015

The averaged land surface temperature varies from about 306°K (33°C) to 322°K (49°C).

Due to there being almost no large blocks of native vegetation in the low-lying vicinity of Adelaide, the UHI correction was calculated from data that included native vegetation on the Mount Lofty Ranges up to an elevation of 400m.

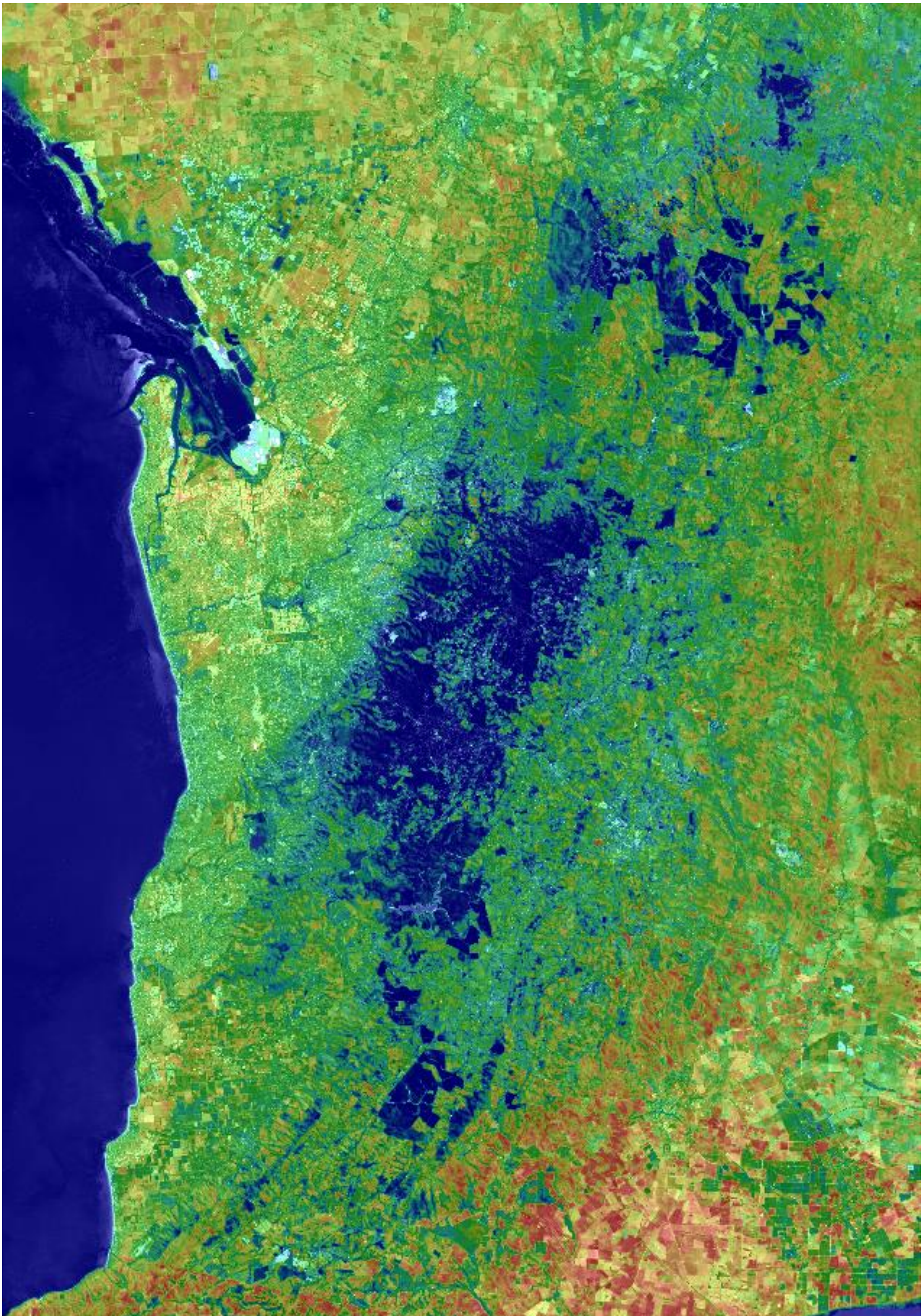

Figure 12: UHI, Adelaide and surrounds

The Mount Lofty Ranges show a cooling effect, but this should be treated as an artefact of the first-order correction. Lower-lying vegetation on the foothills of the Ranges show little to no change, as expected. Urban and suburban Adelaide shows warming in the range of 3–13°C. Land cleared for agriculture in the north-west and south shows the greatest temperature rise.

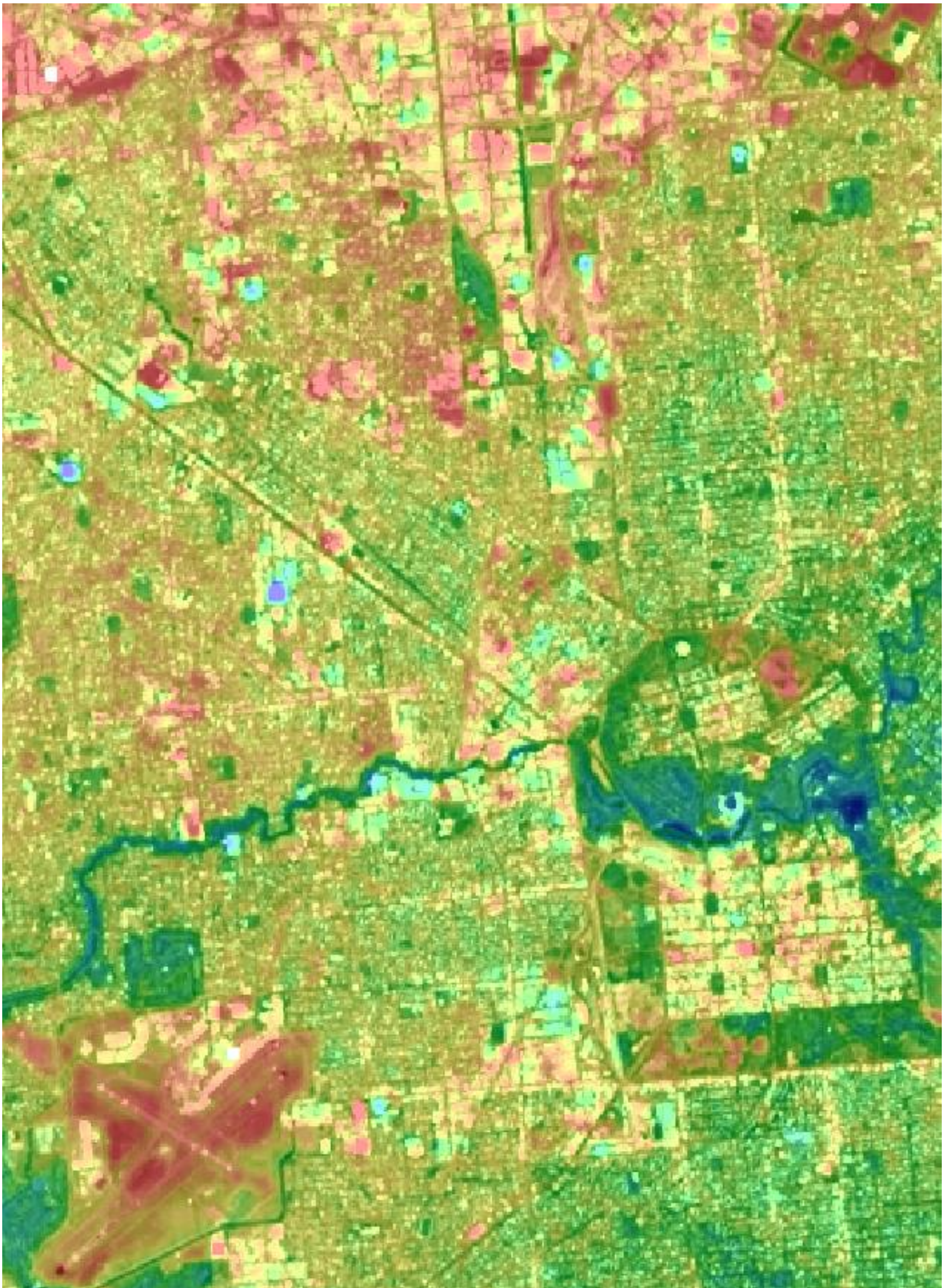

Figure 13: UHI, detail around city centre

A.2 Bendigo

Bendigo was processed in MGA zone 55.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 143.941778°E / 228225E
- East: 144.929092°E / 314150E
- South: 37.124436°S / 5889275N
- North: 36.321153°S / 5976175N

The following Landsat 8 images were tentatively detected as intersecting the extents above, and included in processing:

Table 3 Landsat 8 Images processed for Brisbane, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
92	86	20151203	18	46
92	86	20151219	35	18
92	86	20160205	19.8	62
92	86	20160221	17.1	56
92	86	20160308	26.5	44
93	85	20151210	—	—
93	85	20160111	31	20
93	85	20160212	19.7	60
93	85	20160228	17.0	65
93	85	20160315	17.8	67
93	86	20151210	—	—
93	86	20160228	17.0	65
93	86	20160315	17.8	67
94	85	20151201	18	45
94	85	20151217	27	37
94	85	20160102	23	45
94	85	20160118	26	26
94	85	20160219	18.5	67
94	85	20160306	24.3	51
94	85	20160322	14.2	65
94	86	20151217	27	37
94	86	20160118	26	26
94	86	20160322	14.2	65

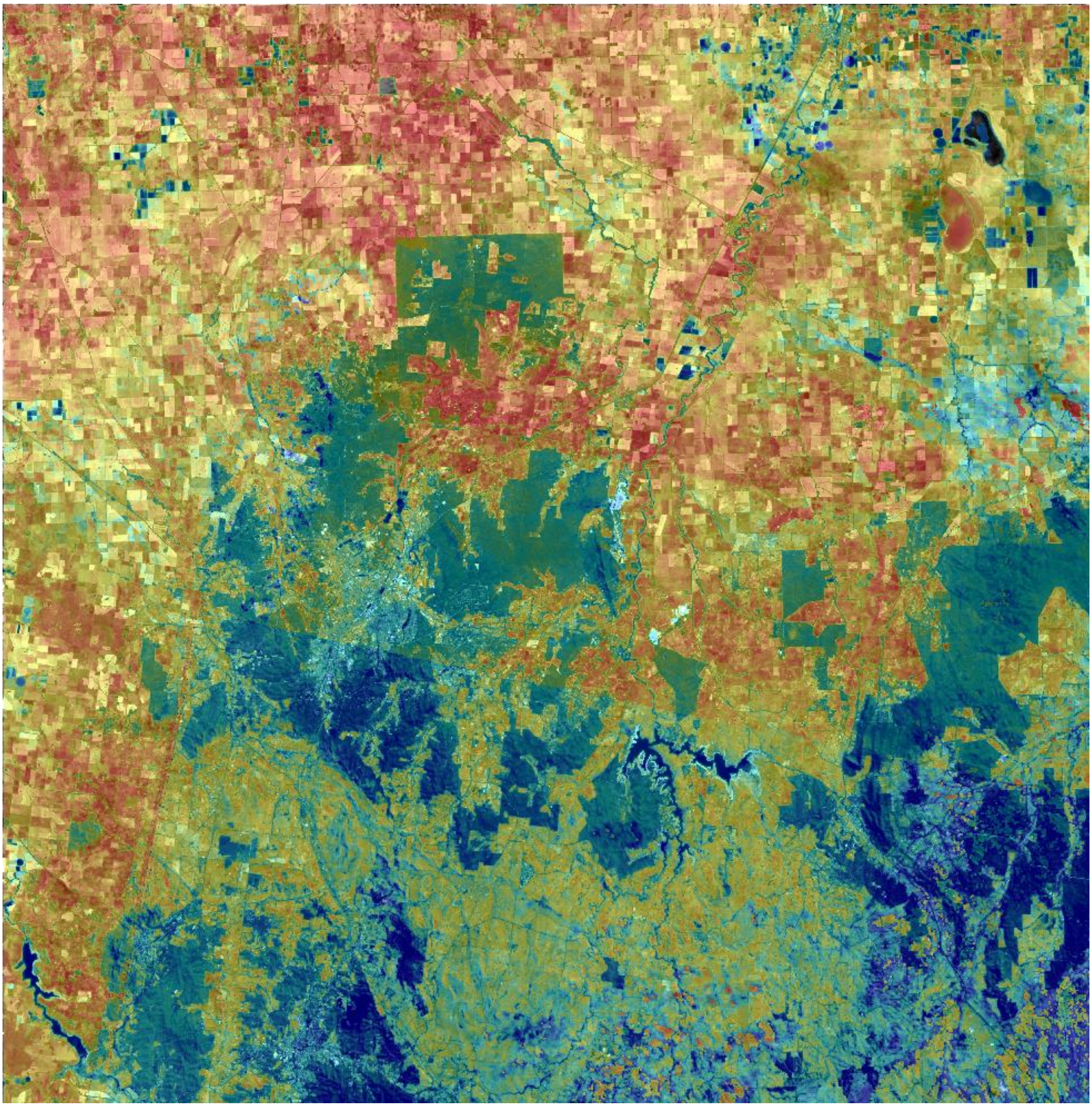

Figure 14 Averaged LST map of Bendigo and surrounds, in pseudocolor (red=hotter, blue=colder), partially transparent and overlaying greyscale Landsat 8 imagery from 10 December 2015

The land surface temperature varies from about 300°K (27°C) to 324°K (53°C), with the hottest temperatures appearing north of Bendigo on cleared agricultural land and intensive livestock production farm e.g. piggery with abattoir. Urban Bendigo itself is relatively cool.

Unfortunately, the overlap of scene rows 85 and 86 occurs right through Bendigo, and the overlap of scene paths 93 and 94 occurs only a little west of Bendigo. As such, each scene used covered no more than half the study extents, and there is a good deal of inconsistency across the area due to different images having been used. Averaging of images is intended to minimise any impact, but cannot remove it entirely. The LST image in Figure 14 shows some of the effect — areas to the south appear significantly cooler than areas to the north, but this is associated with scene boundaries and does not reflect a true trend. This effect dominates the first order correction used to estimate UHI — the UHI ramp seeks to correct the inconsistencies between scenes rather than any true trend. As such it arguably overcompensates, leaving northern agricultural areas appearing cooler than those in the south. Figure 15 illustrates this effect.

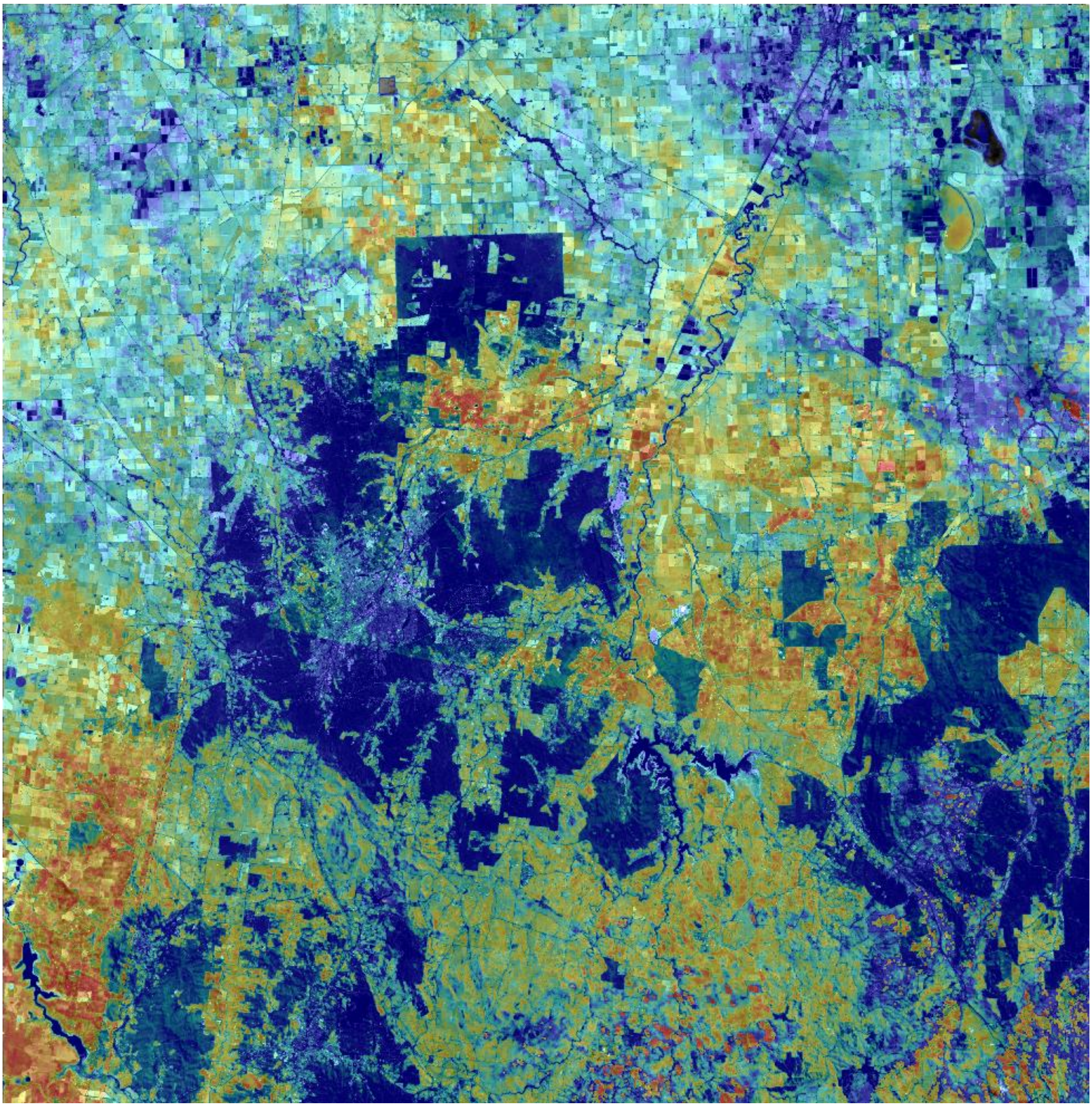

Figure 15 UHI, Bendigo and surrounds

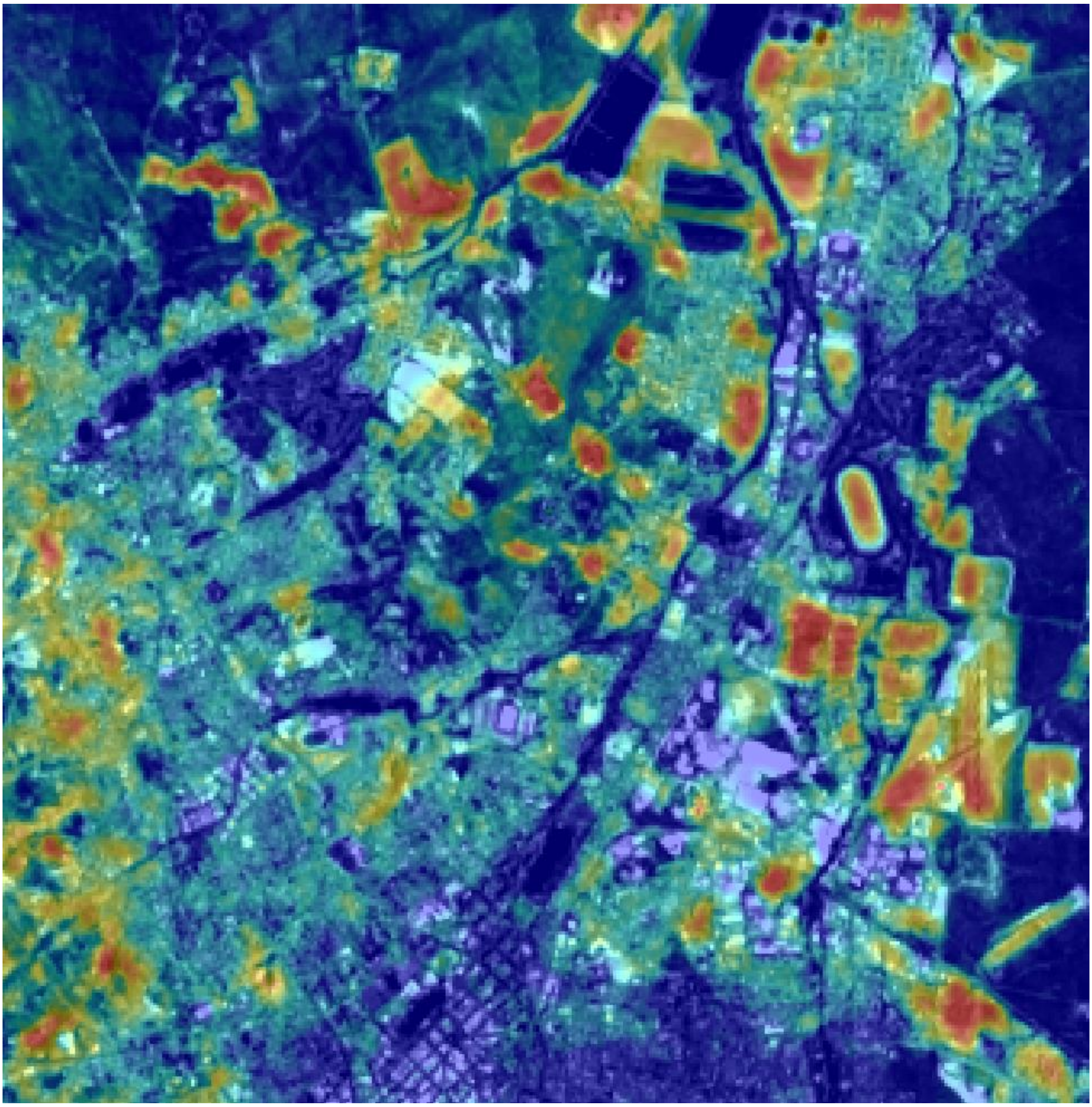

Figure 16 UHI, detail from urban Bendigo

A.3 Brisbane

Brisbane was processed in MGA zone 56.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 152.319671°E / 433300E
- East: 153.613778°E / 560175E
- South: 28.310485°S / 6868250N
- North: 26.091611°S / 7114000N

The following Landsat 8 images were tentatively detected as intersecting the extents above, and included in processing:

Table 4 Landsat 8 Images processed for Brisbane, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
89	79	20151229	23.4	51
89	79	20160215	27.6	60
89	79	20160318	26.5	68
89	80	20151213	20.7	91
89	80	20151229	23.4	51
89	80	20160130	29.0	70
89	80	20160215	27.6	60
89	80	20160318	26.5	68
90	78	20151204	23.8	52
90	78	20160121	27.6	50
90	78	20160325	25.5	62
90	79	20151204	23.8	52
90	79	20151220	28.0	43
90	79	20160105	20.9	95
90	79	20160121	27.6	50
90	79	20160222	27.1	56
90	79	20160309	25.1	84
90	79	20160325	25.5	62
90	80	20151204	23.8	52
90	80	20151220	28.0	43
90	80	20160206	25.9	72
90	80	20160222	27.1	56
90	80	20160309	25.1	84
90	80	20160325	25.5	62

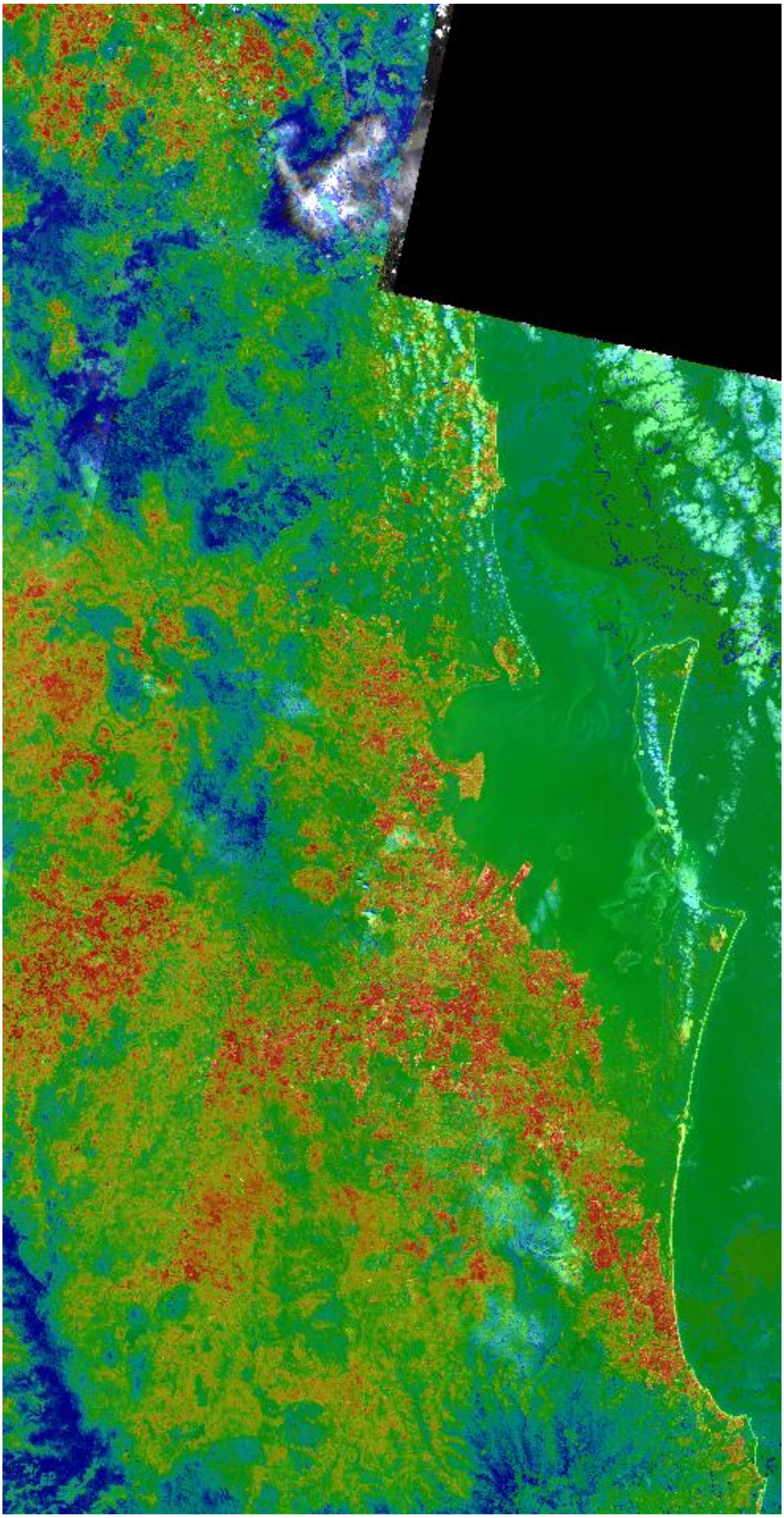

Figure 17 Averaged LST map of Brisbane and surrounds, in pseudocolor (red=hotter, blue=colder), partially transparent and overlaying greyscale Landsat 8 imagery mostly from 15 February 2016

The land surface temperature varies from about 300°K (27°C) to 315°K (42°C).

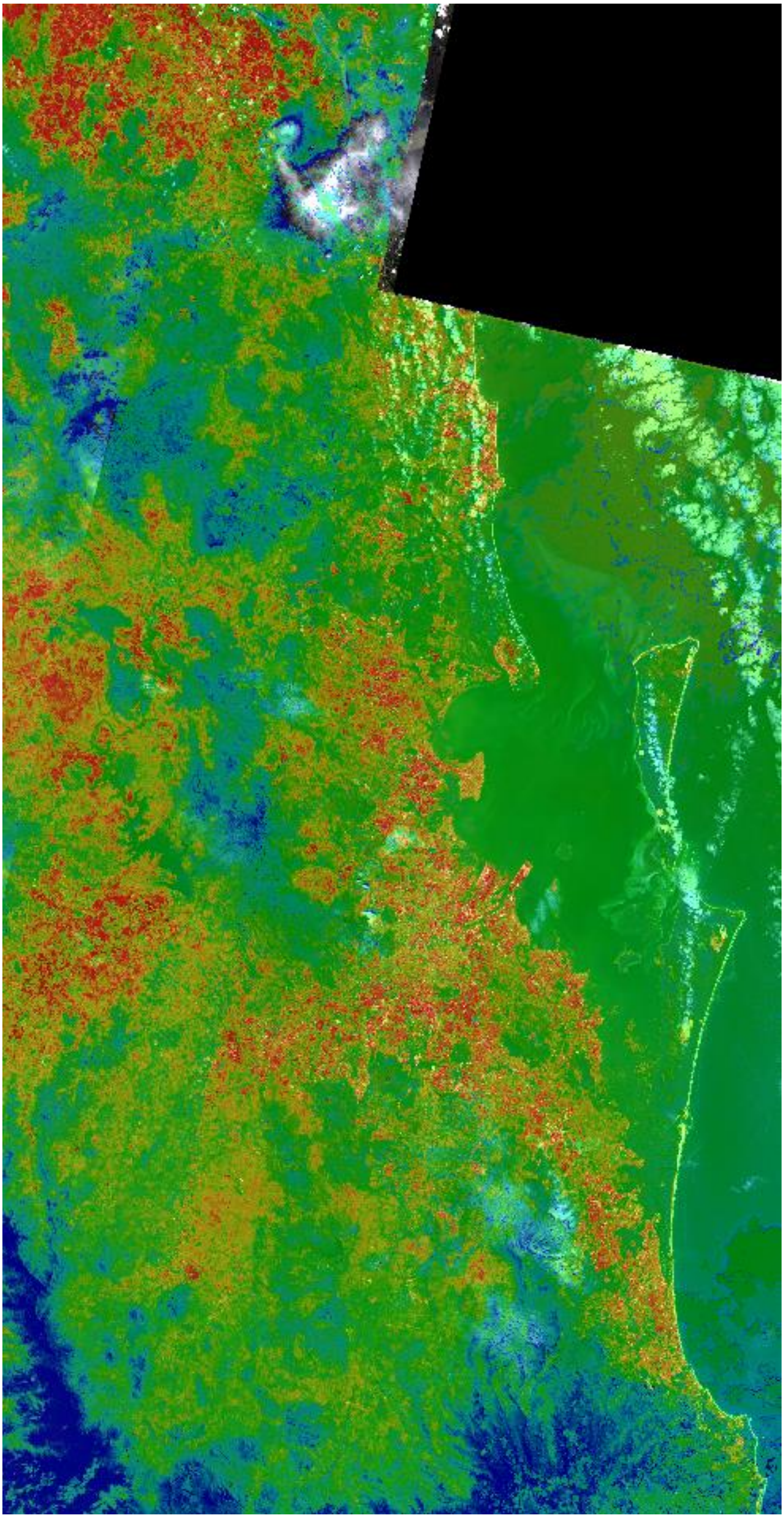

Figure 18 UHI, Brisbane and surrounds

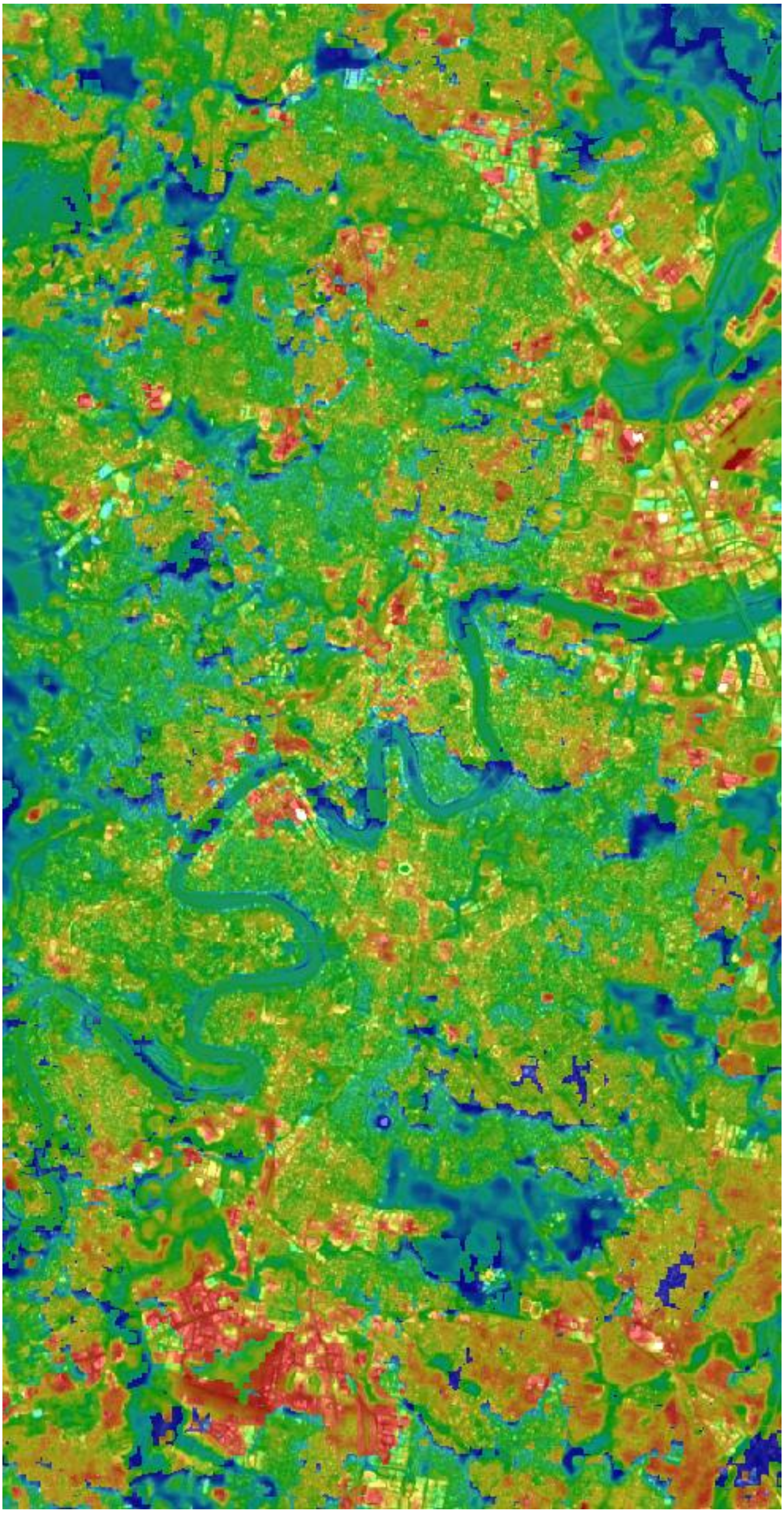

Figure 19 UHI, detail from urban Brisbane. There are many artefacts caused by the extensive cloud-cover in the input images

The D'Aguilar Range shows a cooling effect, but this should be treated as an artefact of the first-order correction. Other vegetated areas show little to no change, as expected. Urban and suburban Brisbane shows warming in the range of 4–10°C.

The greatest temperature rises, of up to 17°C, are seen in agricultural land around Gympie north of Brisbane; however this area belongs to a different Landsat 8 path/row so temperatures were calculated from a different set of images, and the large rises indicated may therefore be spurious.

A.4 Cairns

Cairns was processed in MGA zone 55.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 144.919625°E / 279175E
- East: 146.150558°E / 409050E
- South: 17.559666°S / 8058325N
- North: 15.849738°S / 8246600N

The following Landsat 8 images were tentatively detected as intersecting the extents above, and included in processing:

Table 5 Landsat 8 Images processed for Cairns, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
95	72	20160329	28.3	66
96	71	20160217	31.5	57
96	71	20160320	27.9	76
96	72	20151215	29.2	64
96	72	20160116	28.9	69
96	72	20160217	31.5	57
96	72	20160320	27.9	76

Only a very small number of images were available. Many images were excluded from analysis due to being almost entirely cloud. The seven included images were themselves cloud-affected in various degrees, resulting to a poor quality and incomplete LST image.

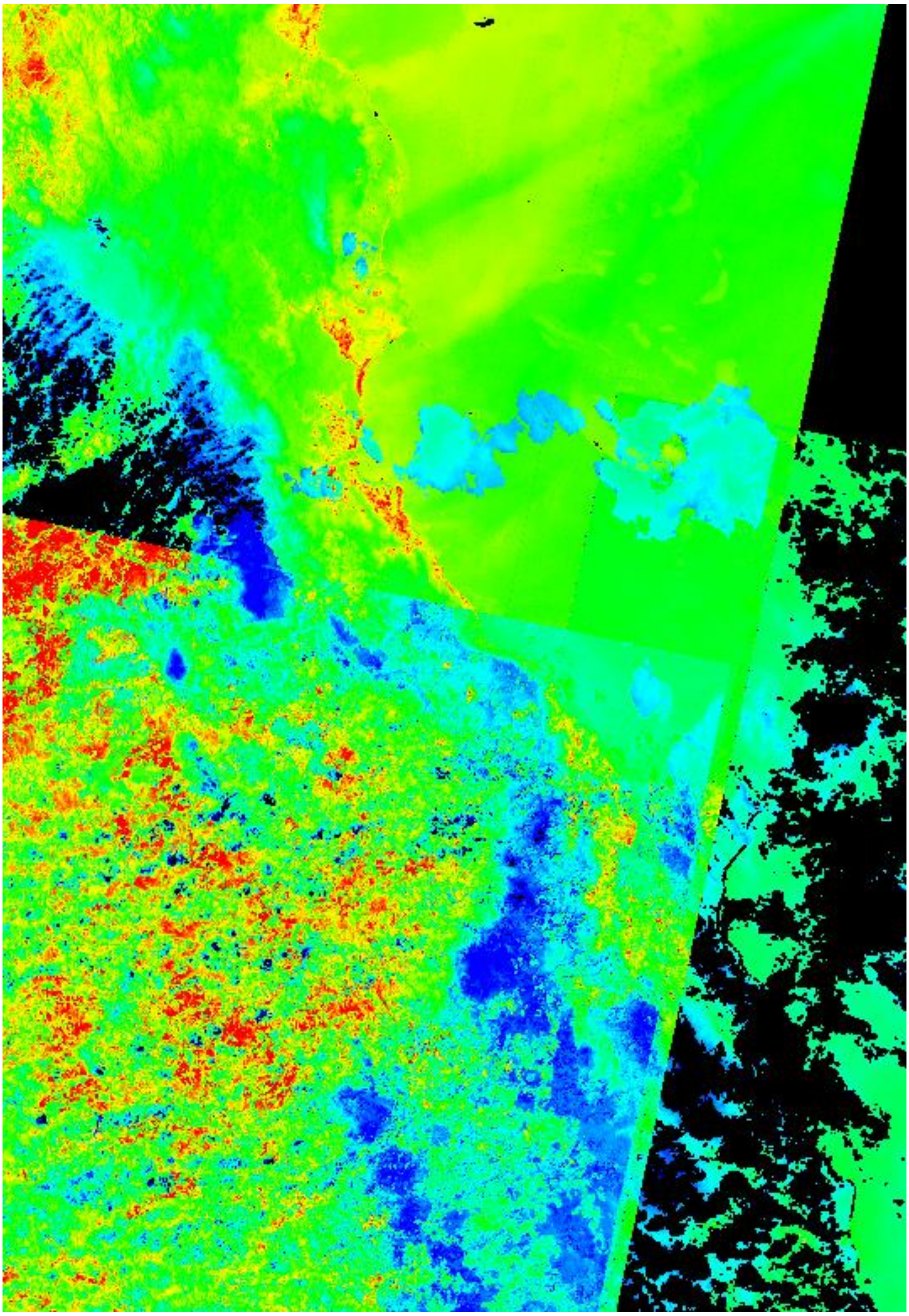

Figure 20 Averaged LST map of Cairns and surrounds, in pseudocolor. No greyscale imagery is displayed beneath, as the images are all too cloud-affected

The land surface temperature varies from about 300°K (27°C) to 322°K (49°C). Areas marked as relatively hot include urbanised and agricultural areas around Cairns and Mareeba, as expected, but also extensive areas along the Mitchell River that appear to be open woodland used only for cattle grazing. It is not known whether these are genuinely hot due to the relatively low vegetation cover, or an artefact of cloud. Care should be taken in interpreting this data.

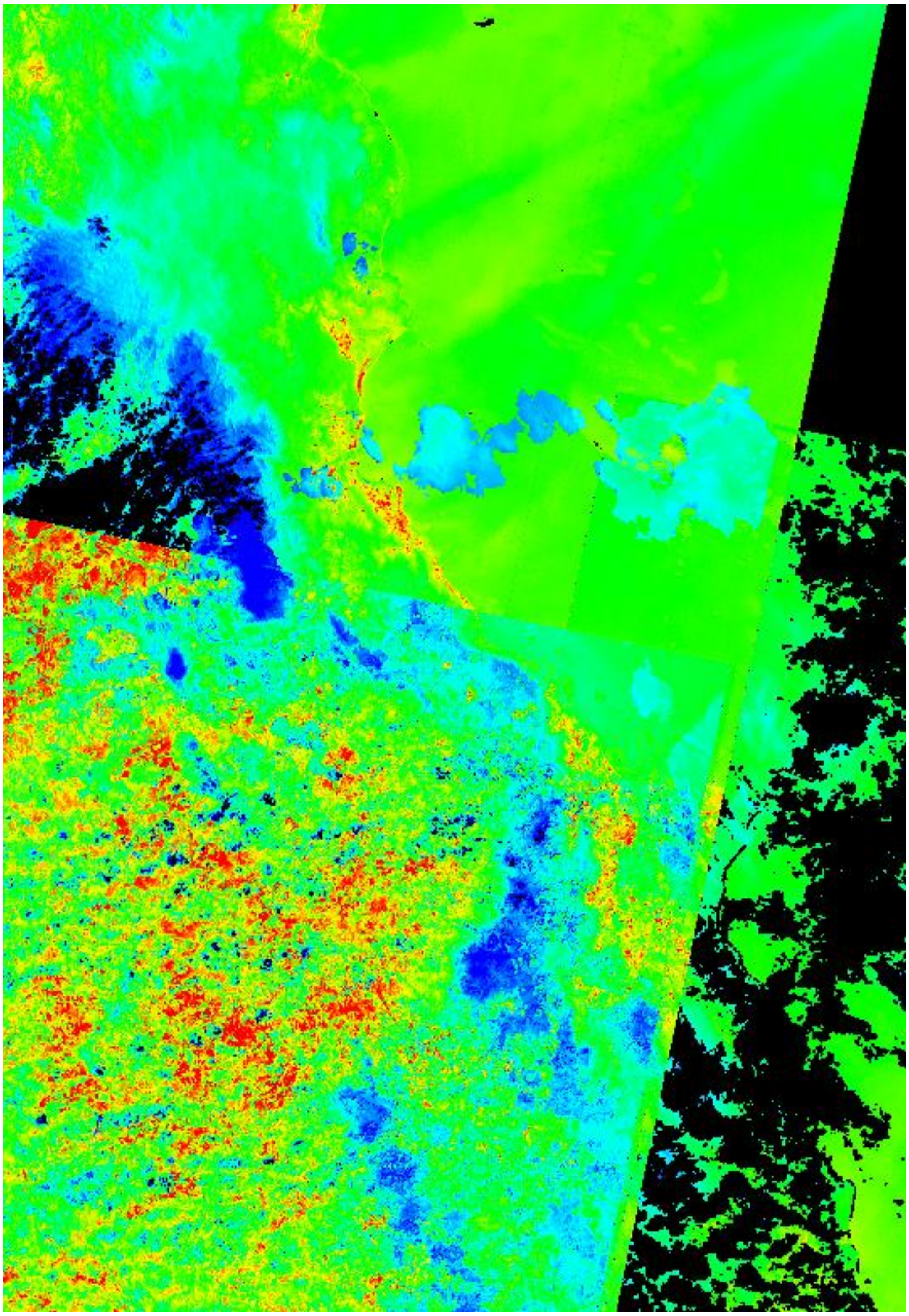

Figure 21 UHI, Cairns and surrounds

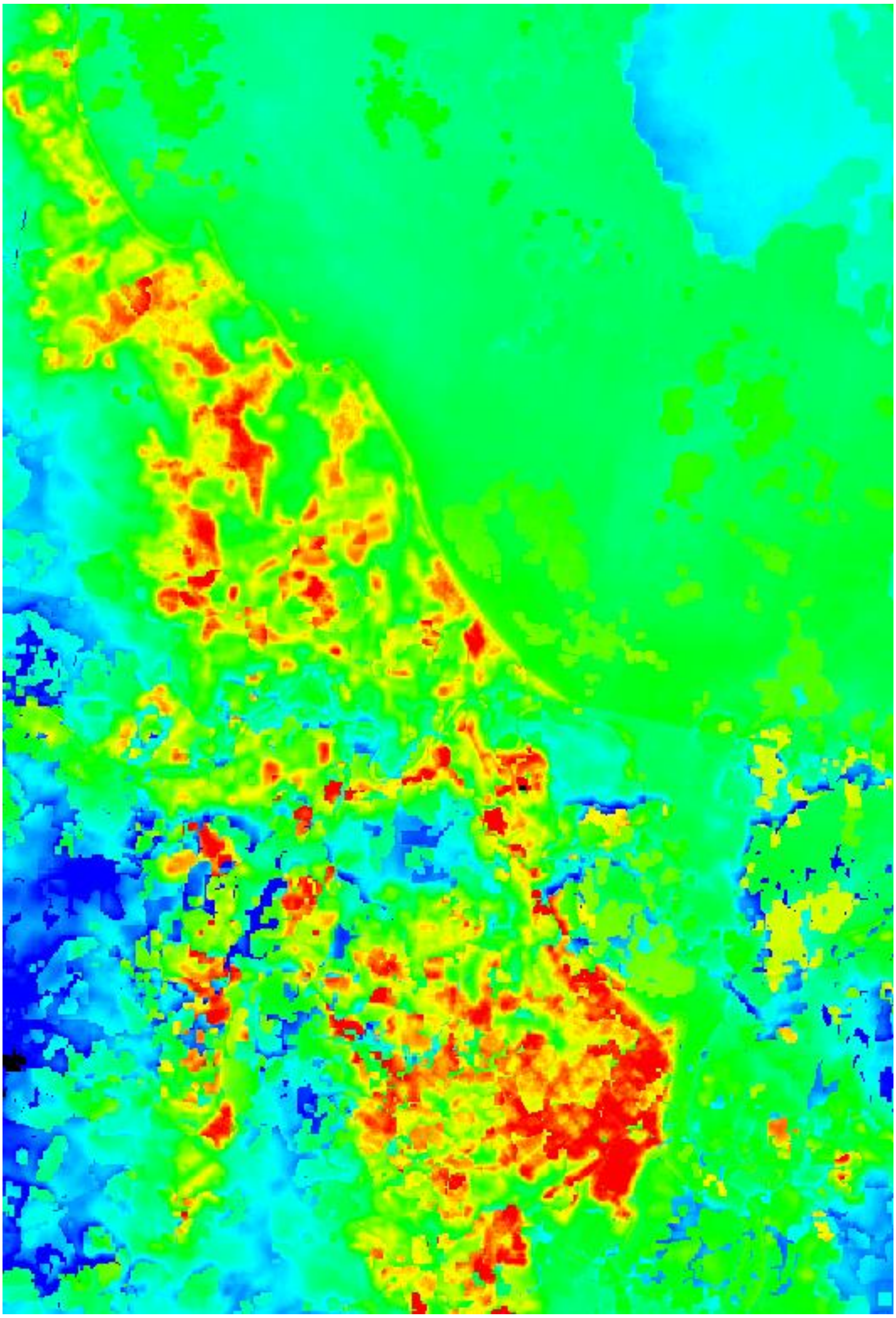

Figure 22 UHI, detail showing urban Cairns

A.5 Canberra

Canberra was processed in MGA zone 55.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 148.689487E / 654025E
- East: 149,479842°E / 723625E

- South: 35.977706°S / 6017175N
- North: 35.067462°S / 6116725N

The following Landsat 8 images were tentatively detected as intersecting the extents above, and included in processing:

Table 6 Landsat 8 Images processed for Canberra, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
90	84	20151204	17.1	52
90	84	20160206	17.8	63
90	84	20160222	20.2	72
90	84	20160309	18.7	79
90	84	20160325	16.2	80
90	85	20151204	17.1	52
90	85	20160206	17.8	63
90	85	20160222	20.2	72
90	85	20160325	16.2	80
91	84	20151227	15.0	47
91	84	20160112	27.1	37
91	84	20160213	20.4	79
91	84	20160229	18.9	72
91	84	20160316	17.4	65
91	85	20151227	15.0	47
91	85	20160112	27.1	37
91	85	20160213	20.4	79
91	85	20160229	18.9	72
91	85	20160316	17.4	65

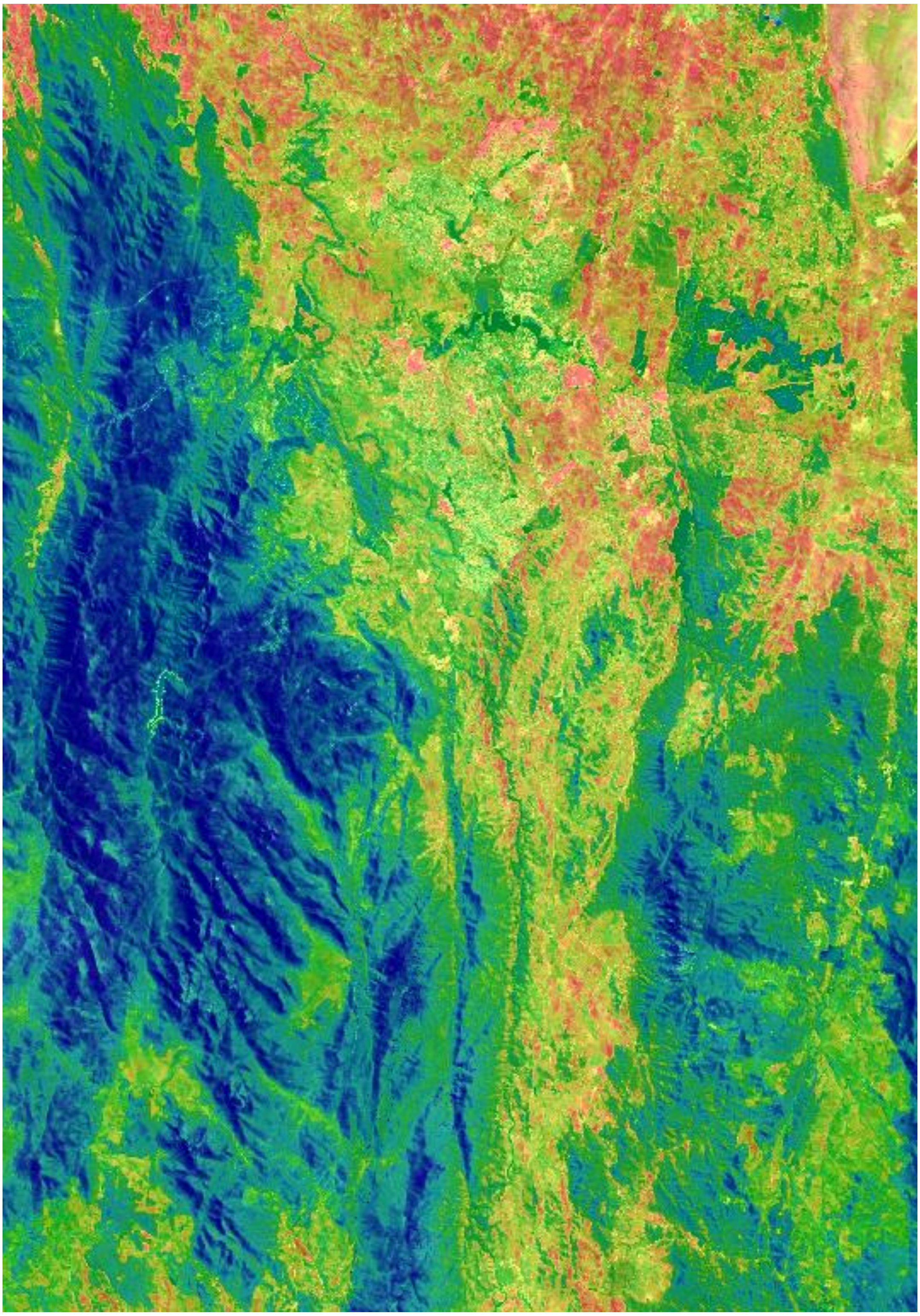

Figure 23 Averaged LST map of Canberra and surrounds, in pseudocolor red=hotter, blue=colder) , partially transparent and overlaying greyscale Landsat 8 imagery from 22 February 2016.

The land surface temperature varies from about 295°K (22°C) to 317°K (44°C). The hottest areas are agricultural areas around Canberra. Canberra itself is relatively cool.

The correction of UHI is slightly problematic in the Canberra region because urban areas are nearly all located at relatively low elevations, whereas nearly all significant blocks of vegetation are at relatively high elevation. A first-order correction was made based on the lowest elevation vegetation available.

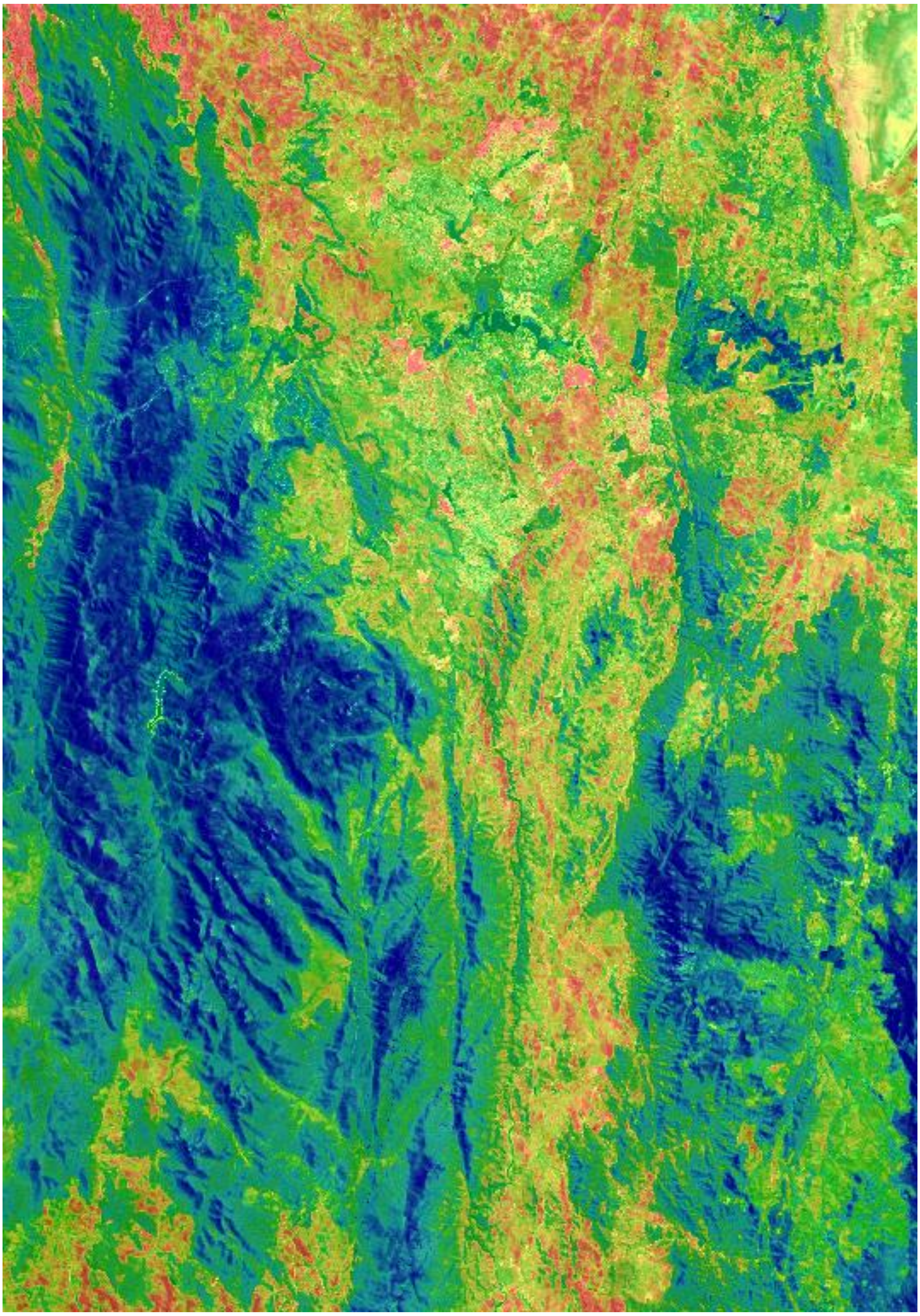

Figure 24 UHI, Canberra and surrounds

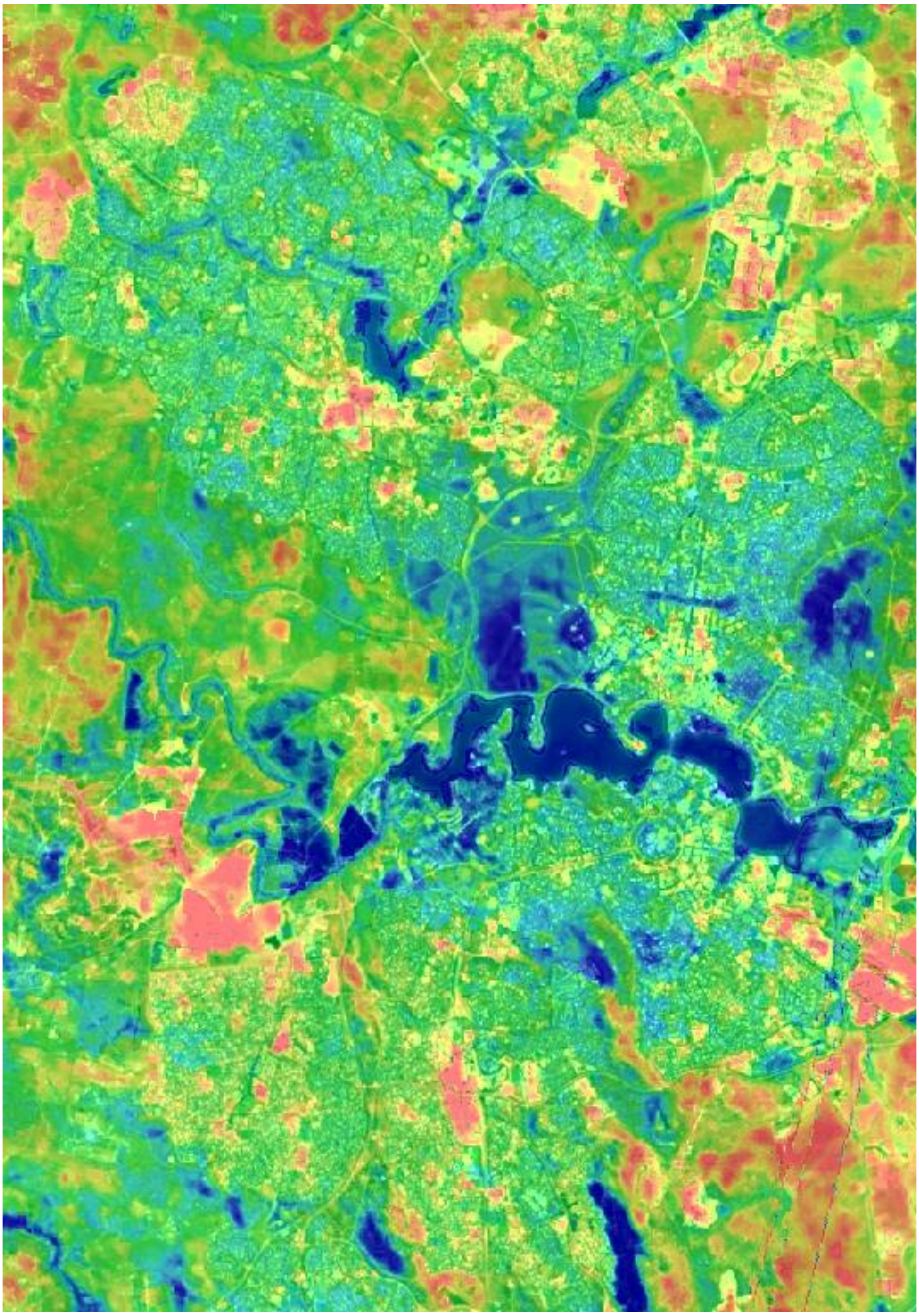

Figure 25 UHI, detail showing urban Canberra

A.6 Darwin

Darwin was processed in MGA zone 52.

When examining Darwin, it was found that the urban extents greatly exceeded the extents of the vectors provided, which covered only the LGAs of Darwin and Palmerston. It was therefore decided to manually increase the extents to cover the majority of urban, suburban and peri-urban Darwin. The extents selected were:

- West: 130.767209°E / 692200E
- East: 131.398190°E / 760200E
- South: 12.939402°S / 8568900N
- North: 12.283186°S / 8641275N

There were no Landsat 8 images at all within the given window, but the Landsat 8 images for path/row 106/69 dated 11 April 2016 was cloud-free over the extents and only just outside the temporal window. This single image was processed.

Table 7 Landsat 8 Images processed for Darwin, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
106	69	20160411	29.3	70

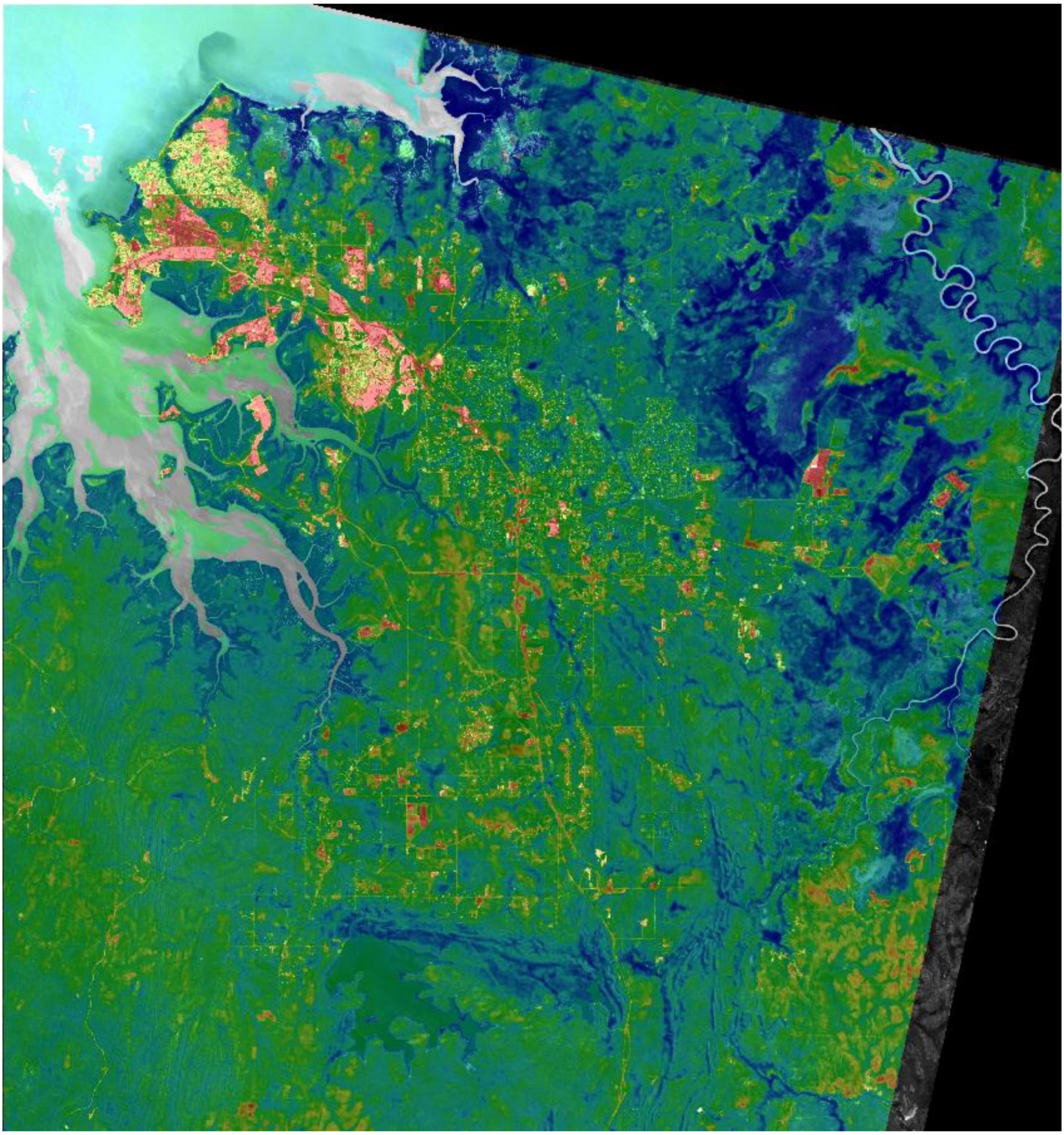

Figure 26 LST map of the Darwin extents for the single image of 11 April 2016. Temperature is in pseudocolor (red=hotter, blue=colder), partially transparent, overlaying a greyscale image of the visible image

The land surface temperature varies from about 312°K (39°C) to 325°K (52°C). It appears to be very strongly correlated with vegetation cover — areas with little vegetation are marked as very hot regardless of the land use.

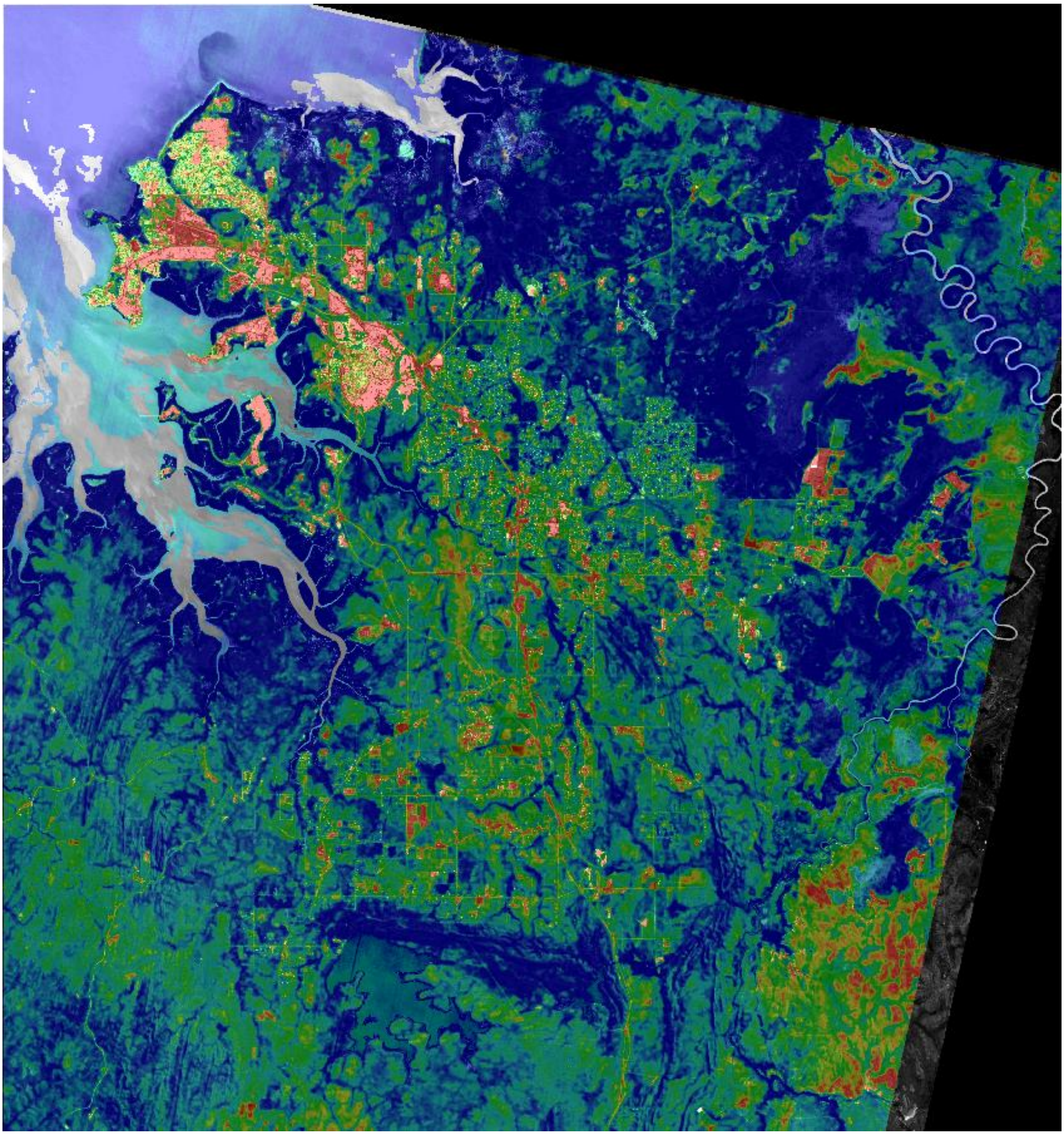

Figure 27 UHI, Darwin and surrounds

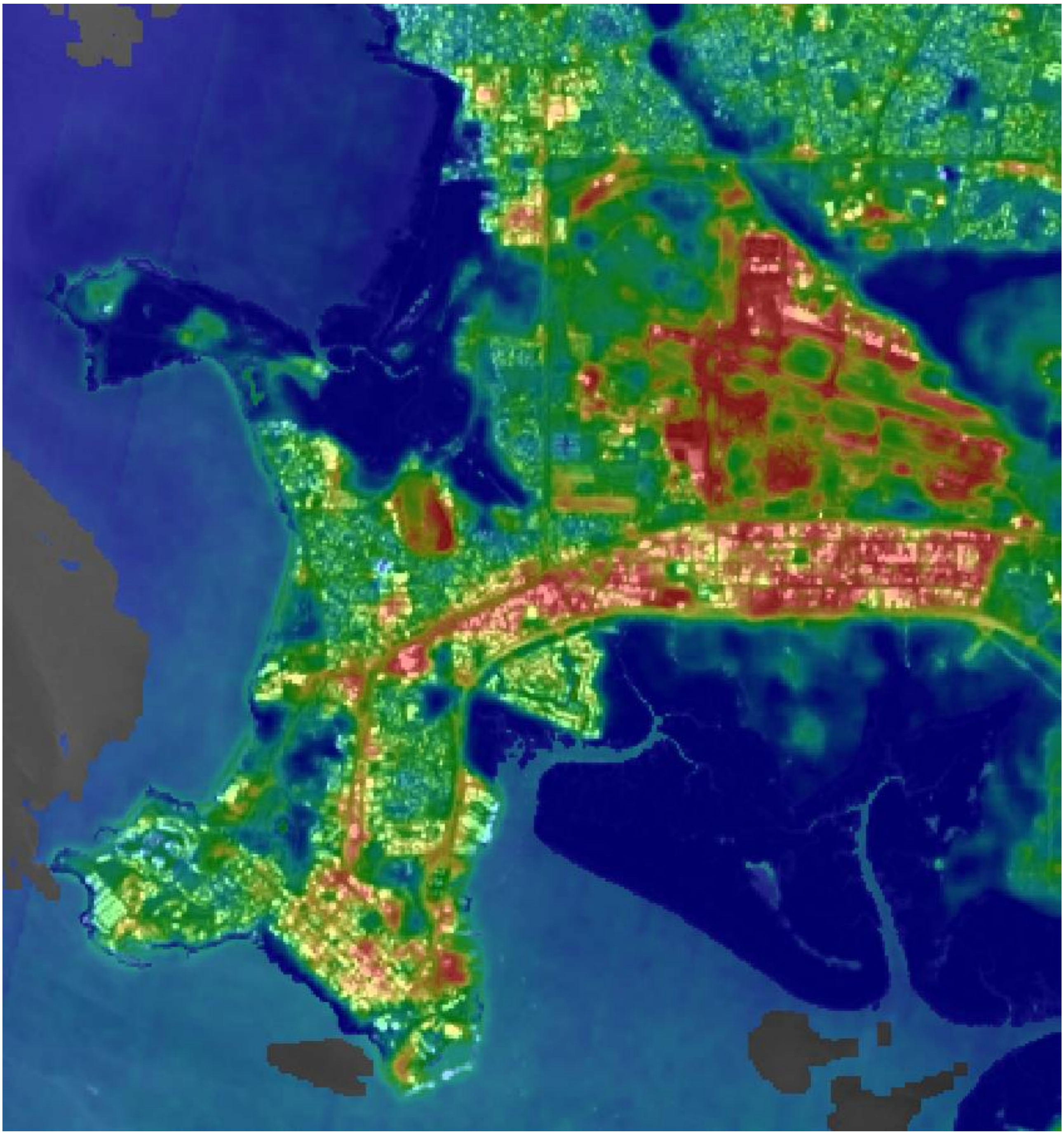

Figure 28 UHI, detail showing Darwin city centre and airport

A.7 Hobart

Due to cloud cover across the entire summer temporal window, no data was available for Hobart.

A.8 Launceston

Launceston was processed in MGA zone 55.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 146.916297°E / 493025E
- East: 147.713101°E / 559425E
- South: 41.603201°S / 5394275N
- North: 41.038755°S / 5456700N

The following Landsat 8 images were tentatively detected as intersecting the extents above, and included in processing:

Table 8 Landsat 8 Images processed for Launceston, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
90	88	20151204	16.3	63
90	88	20151220	27.8	46
90	88	20160105	17.9	56
90	88	20160222	17.7	83
90	88	20160325	10.8	93
90	89	20151220	27.8	46
90	89	20160325	10.8	93
91	88	20151227	14.6	43
91	88	20160112	19.2	63
91	89	20151227	14.6	43
91	89	20160112	19.2	63

Every available image was significantly affected by cloud, resulting in a poor quality and incomplete land surface temperature image.

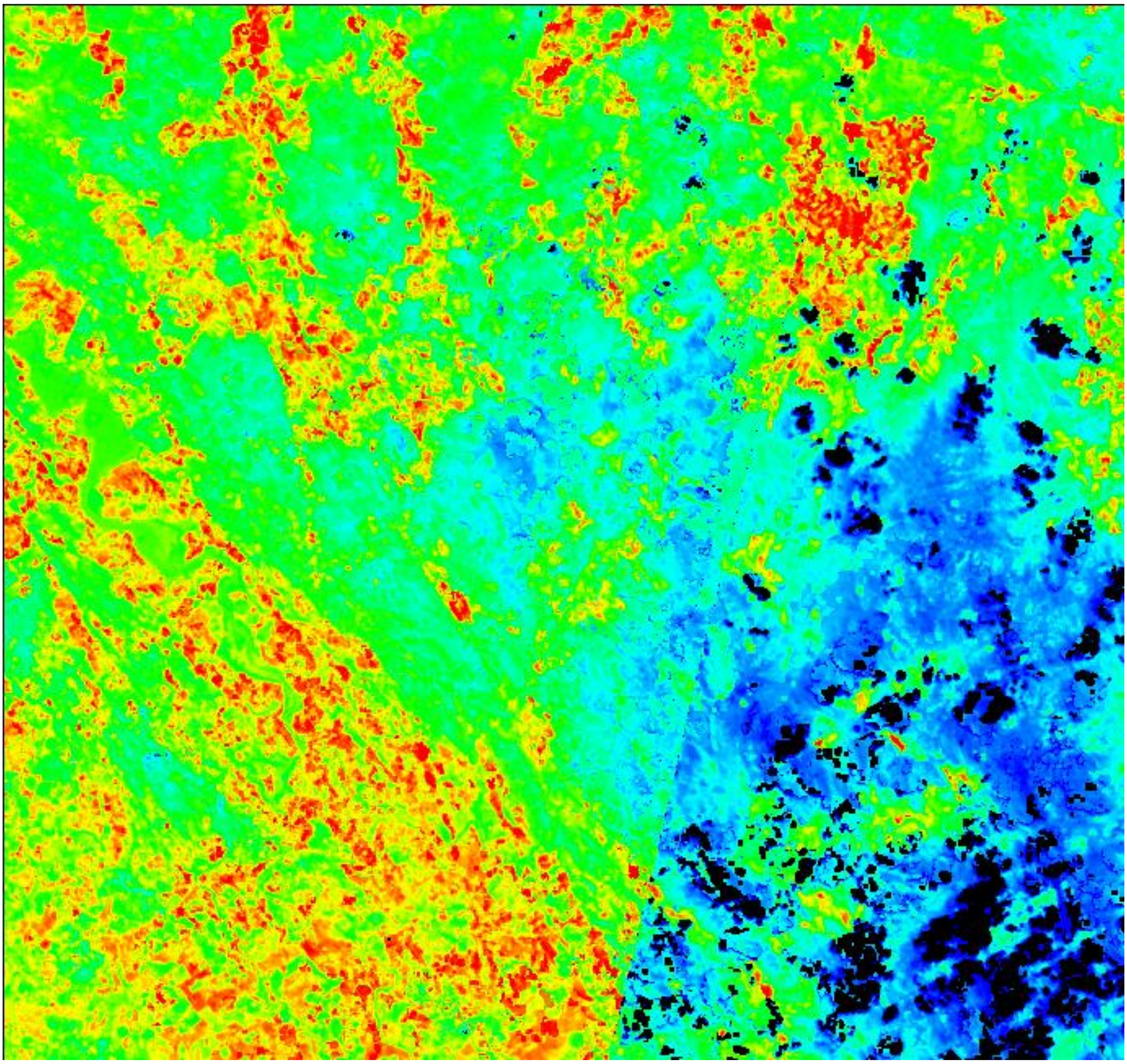

Figure 29 Averaged LST map of Launceston and surrounds, in pseudocolor (red=hotter, blue=colder). No truecolor imagery is displayed beneath, as all images are too cloud-affected

The land surface temperature varies from about 285°K (12°C) to 313°K (40°C).

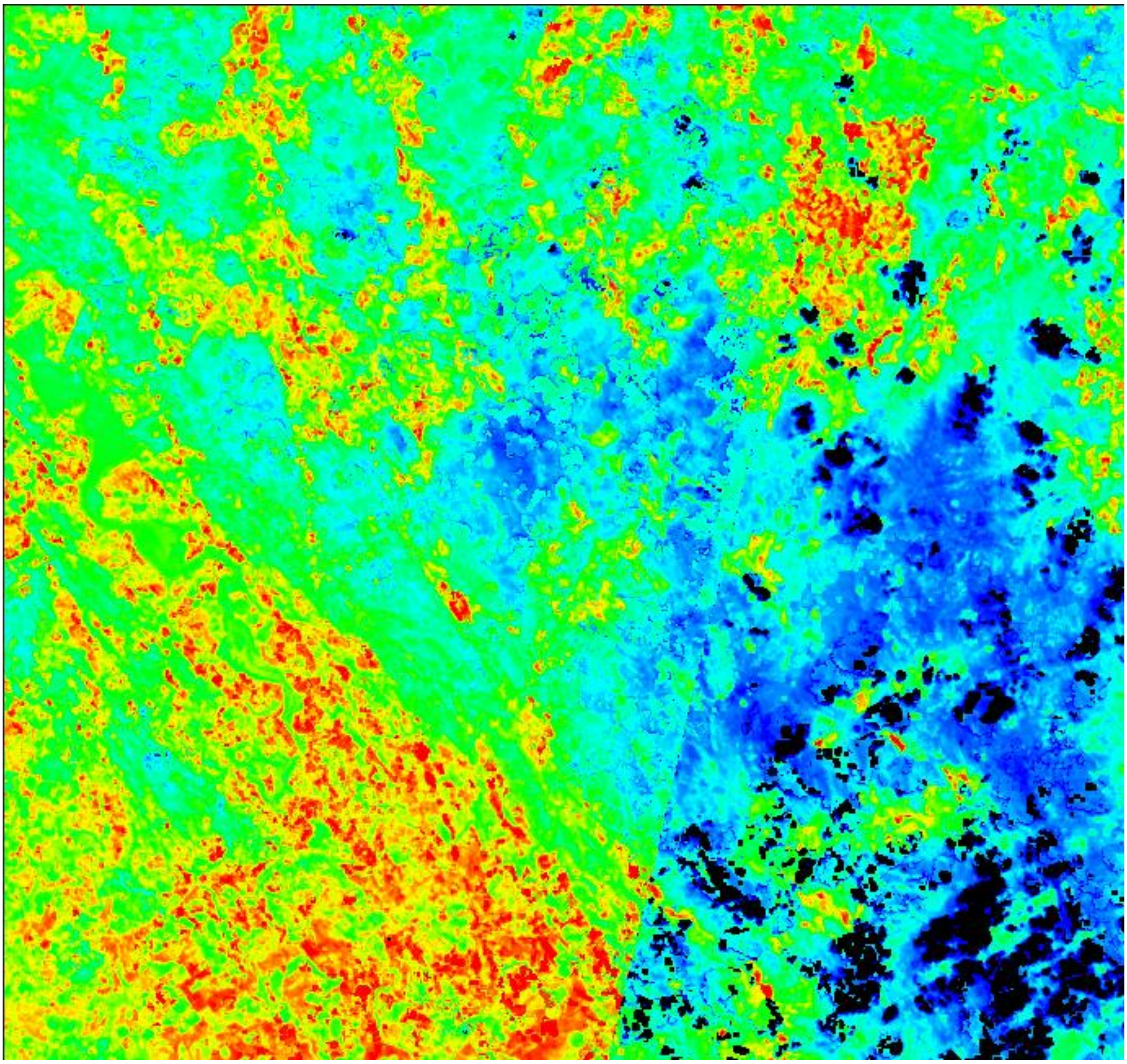

Figure 30 UHI, Launceston and surrounds

A.9 Melbourne

Melbourne was processed in MGA zone 55.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 142.665789°E / 124075E
- East: 146.265956°E / 434925E
- South: 38.975490°S / 5685675N
- North: 37.203657°S / 5874125N

The following Landsat 8 images were tentatively detected as intersecting the extents above, and included in processing:

Table 9 Landsat 8 Images processed for Melbourne, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
91	86	20151227	13.7	63
91	86	20160112	19.6	70
91	86	20160229	18.0	70
91	86	20160316	16.7	81
91	87	20151227	13.7	63
91	87	20160112	19.6	70
91	87	20160316	16.7	81
92	85	20151203	14.1	59
92	85	20151219	33.8	18
92	85	20160205	18.0	73
92	85	20160221	15.3	71
92	85	20160308	21.4	80
92	86	20151203	14.1	59
92	86	20151219	33.8	18
92	86	20160205	18.0	73
92	86	20160221	15.3	71
92	86	20160308	21.4	80
92	87	20151219	33.8	18
93	85	20151210	15.6	69
93	85	20160111	29.9	22
93	85	20160212	17.7	73
93	85	20160228	17.6	58
93	85	20160315	17.0	75
93	86	20151210	15.6	69
93	86	20160212	17.7	73
93	86	20160228	17.6	58
93	87	20151210	15.6	69
94	85	20151201	15.9	52
94	85	20151217	26.1	33
94	85	20160102	17.2	70
94	85	20160118	27.9	19
94	85	20160219	17.5	72

94	85	20160306	18.3	83
94	85	20160322	13.5	87
94	86	20151217	26.1	33
94	86	20160118	27.9	19
94	86	20160322	13.5	87
95	85	20151208	23.9	61
95	85	20151224	25.6	40
95	85	20160109	16.8	75
95	85	20160125	17.2	76
95	85	20160210	18.4	72
95	85	20160313	17.7	94

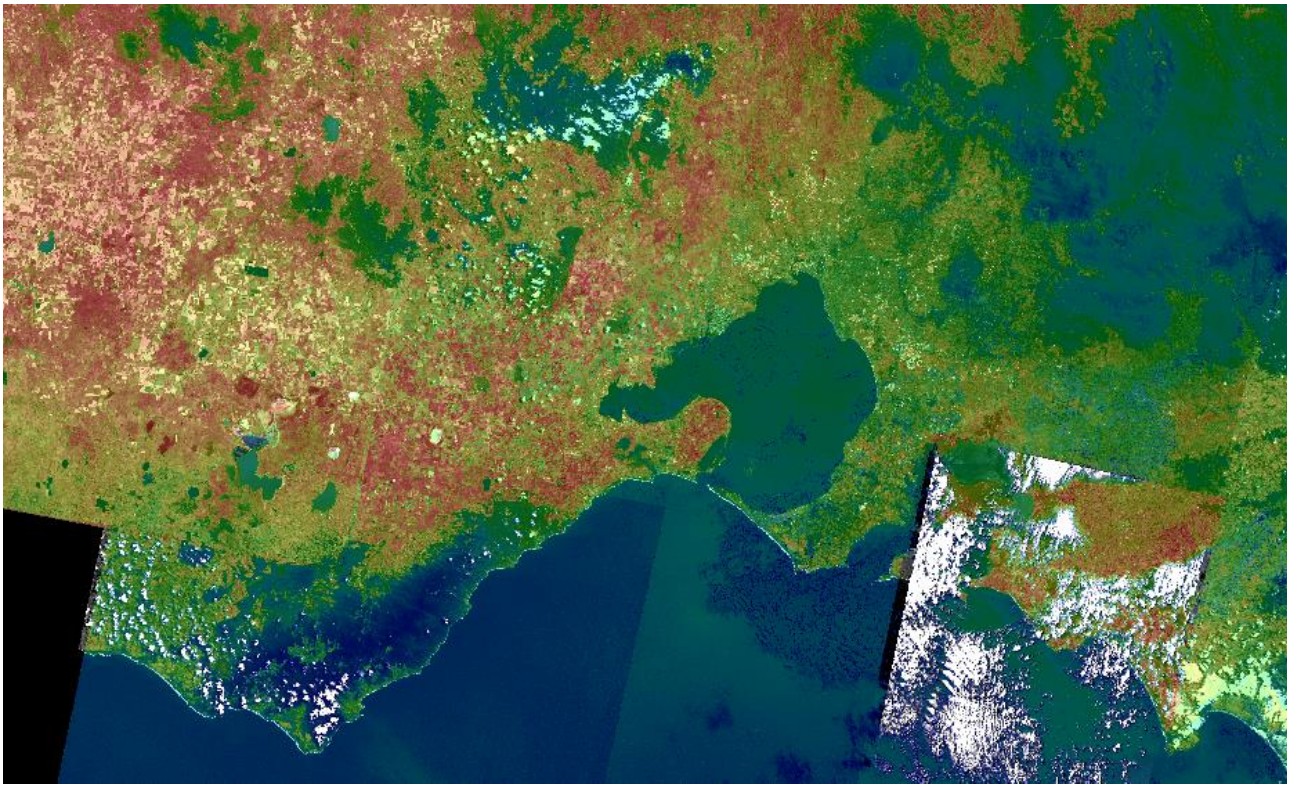

Figure 31 Averaged LST map of Melbourne and surrounds, in pseudocolor (red=hotter, blue=colder), partially transparent and overlaying greyscale Landsat 8 imagery from a range of dates

The land surface temperature varies from about 293°K (20°C) to 320°K (47°C).

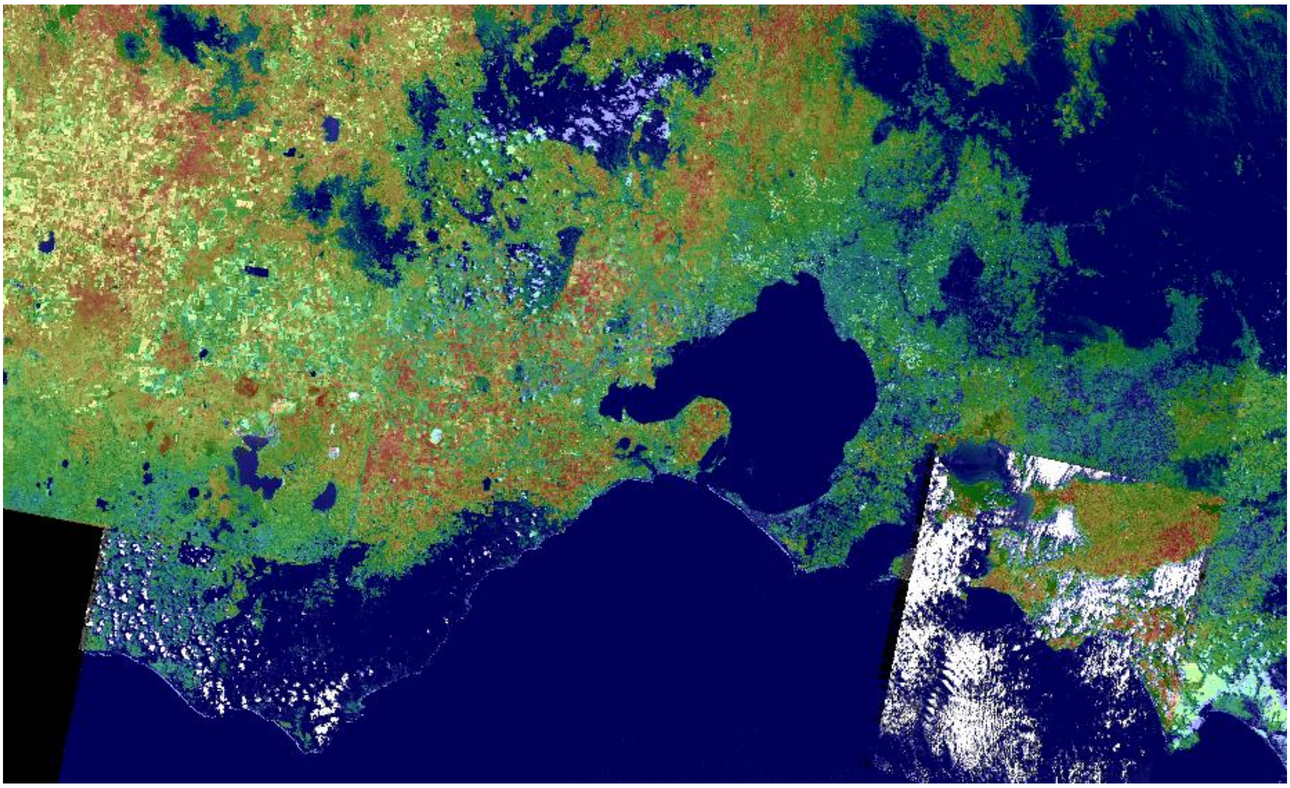

Figure 32 UHI, Melbourne and surrounds

Urban and suburban Melbourne shows warming of up to 11°C.

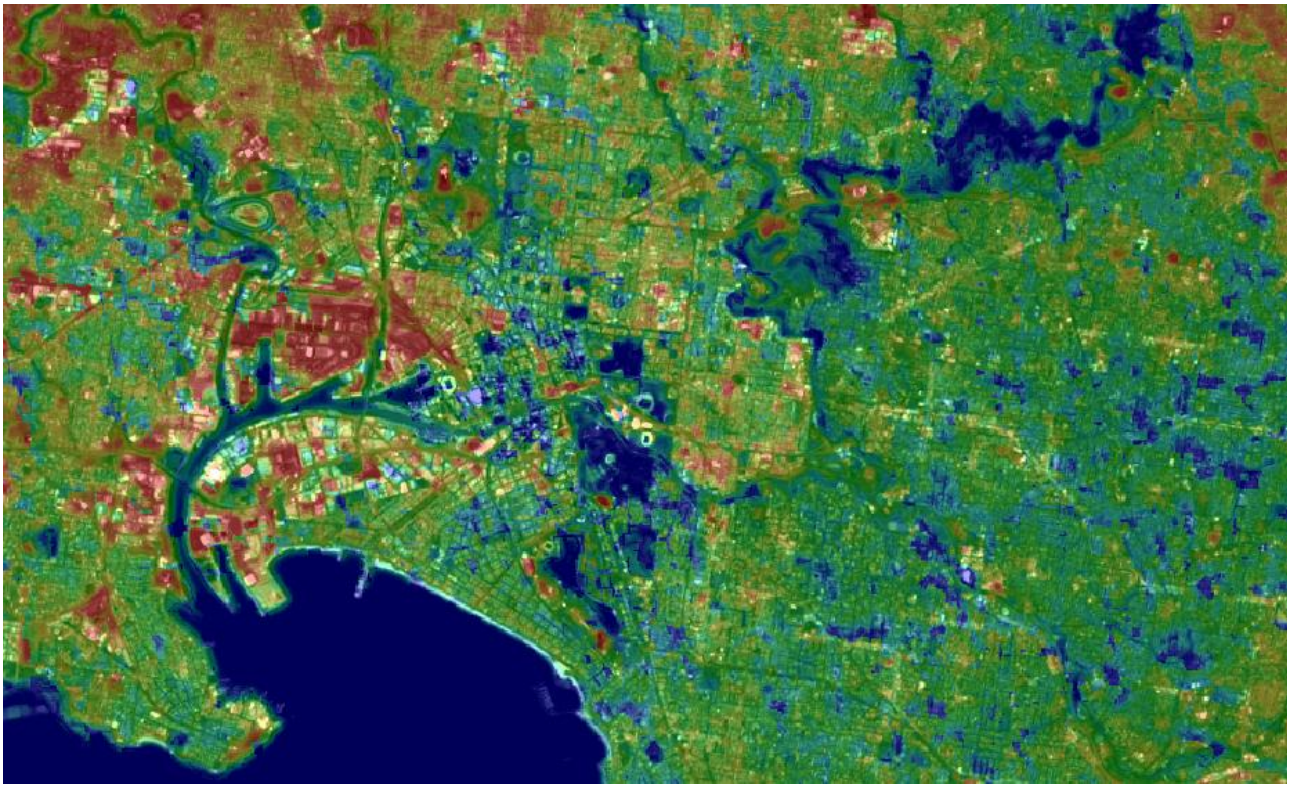

Figure 33 UHI, detail from urban Melbourne

A.10 Newcastle

Newcastle was processed in MGA zone 56.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 151.533113°E / 362975E
- East: 152.262550°E / 430750E
- South: 33.013927°S / 6346925N
- North: 32.527989°S / 6400100N

The following Landsat 8 images were tentatively detected as intersecting the extents above, and included in processing:

Table 10 Landsat 8 Images processed for Newcastle, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
89	82	20151213	19.9	77
89	82	20151229	20.6	56
89	82	20160130	24.1	88
89	82	20160215	24.8	81
89	82	20160302	23.4	75
89	82	20160318	21.4	86
89	83	20151213	19.9	77
89	83	20151229	20.6	56
89	83	20160130	24.1	88
89	83	20160215	24.8	81
89	83	20160302	23.4	75
89	83	20160318	21.4	86
90	82	20151204	20.1	61
90	82	20151220	22.9	71
90	82	20160206	20.5	85
90	82	20160222	24.6	79
90	82	20160309	22.4	89
90	82	20160325	20.5	73

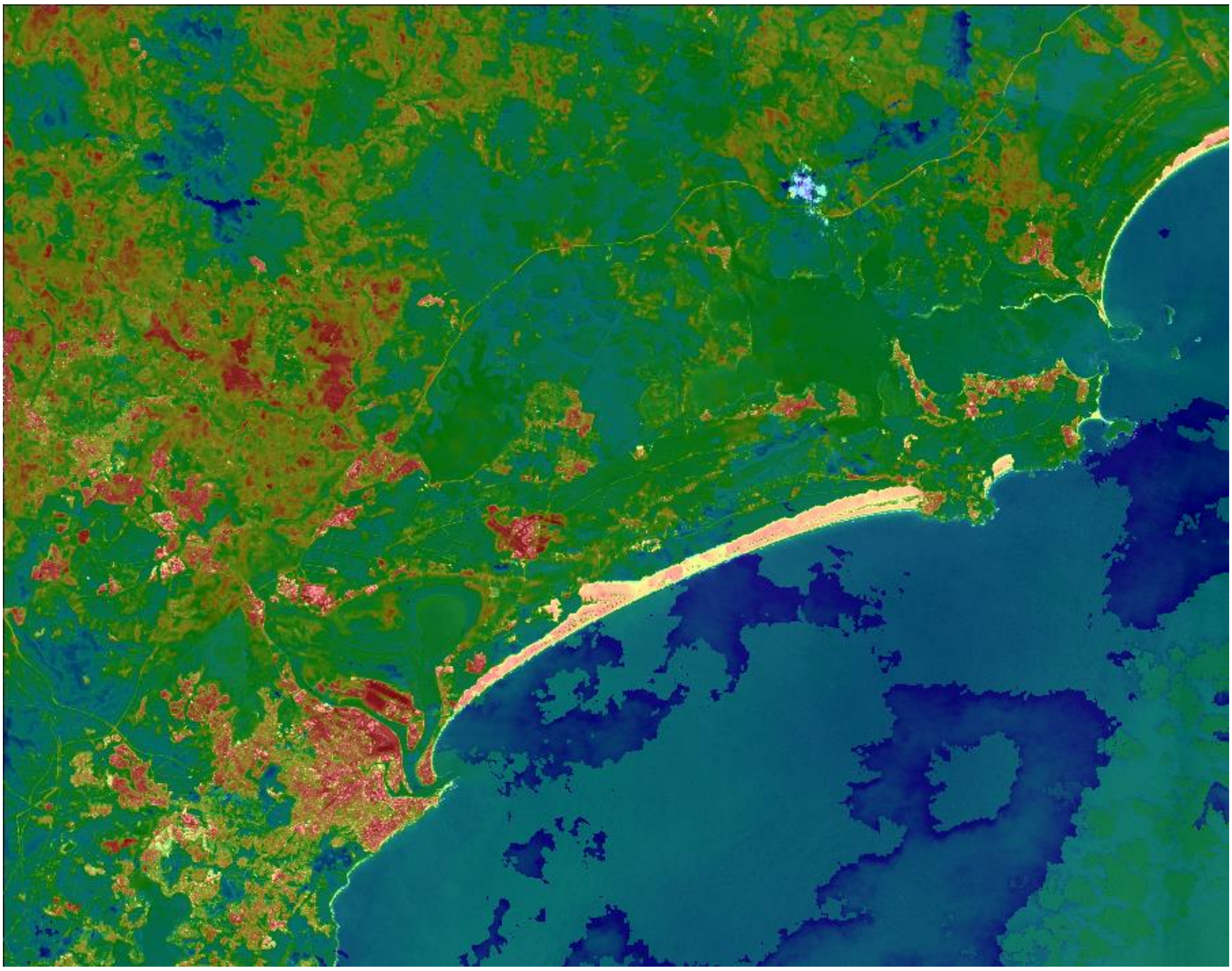

Figure 34 Averaged LST map of Newcastle and surrounds, in pseudocolor (red=hotter, blue=colder), partially transparent and overlaying greyscale Landsat 8 imagery from 30 January 2016

The land surface temperature varies from about 300°K (27°C) to 315°K (42°C).

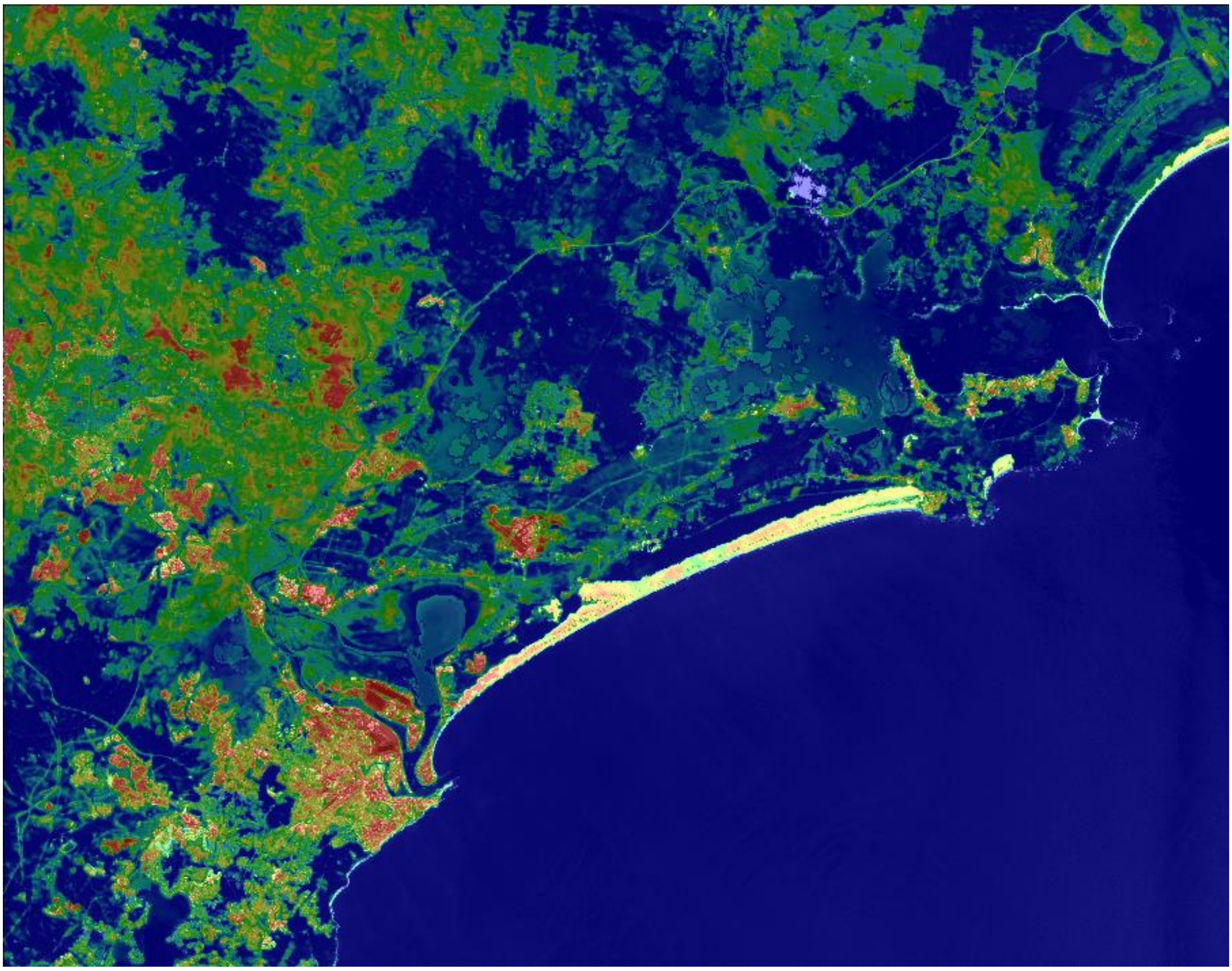

Figure 35 UHI, Newcastle and surrounds

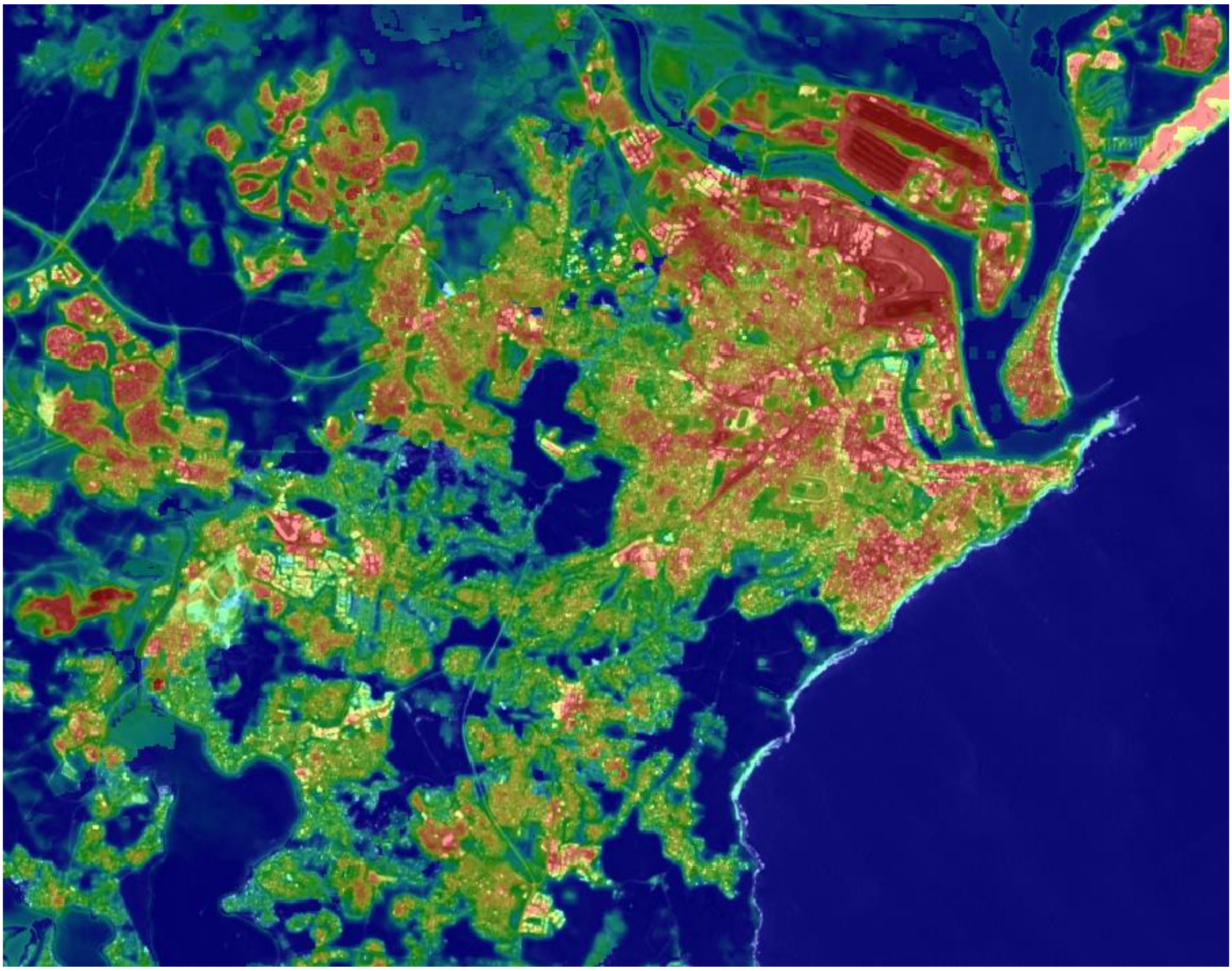

Figure 36 UHI, detail from urban Newcastle

Urban and suburban Newcastle shows warming of up to 11°C, with greatest rises occurring at the port.

A.11 Perth

Perth was processed in MGA zone 50.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 115.378518°E / 347675E
- East: 116.474254°E / 450025E
- South: 32.511873°S / 6402700N
- North: 31.401414°S / 6524800N

The following Landsat 8 images were tentatively detected as intersecting the extents above, and included in processing:

Table 11 Landsat 8 Images processed for Perth, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
112	82	20151215	24.0	50
112	82	20151231	23.0	48
112	82	20160116	32.4	27
112	82	20160201	18.1	49
112	82	20160217	31.4	22
112	82	20160304	19.9	65
112	82	20160320	24.4	64
112	83	20151215	24.0	50
112	83	20151231	23.0	48
112	83	20160116	32.4	27
112	83	20160217	31.4	22
112	83	20160304	19.9	65
112	83	20160320	24.4	64
113	82	20151222	31.6	34
113	82	20160107	33.2	28
113	82	20160123	27.8	45
113	82	20160208	33.2	18
113	82	20160311	23.2	55
113	83	20160208	33.2	18

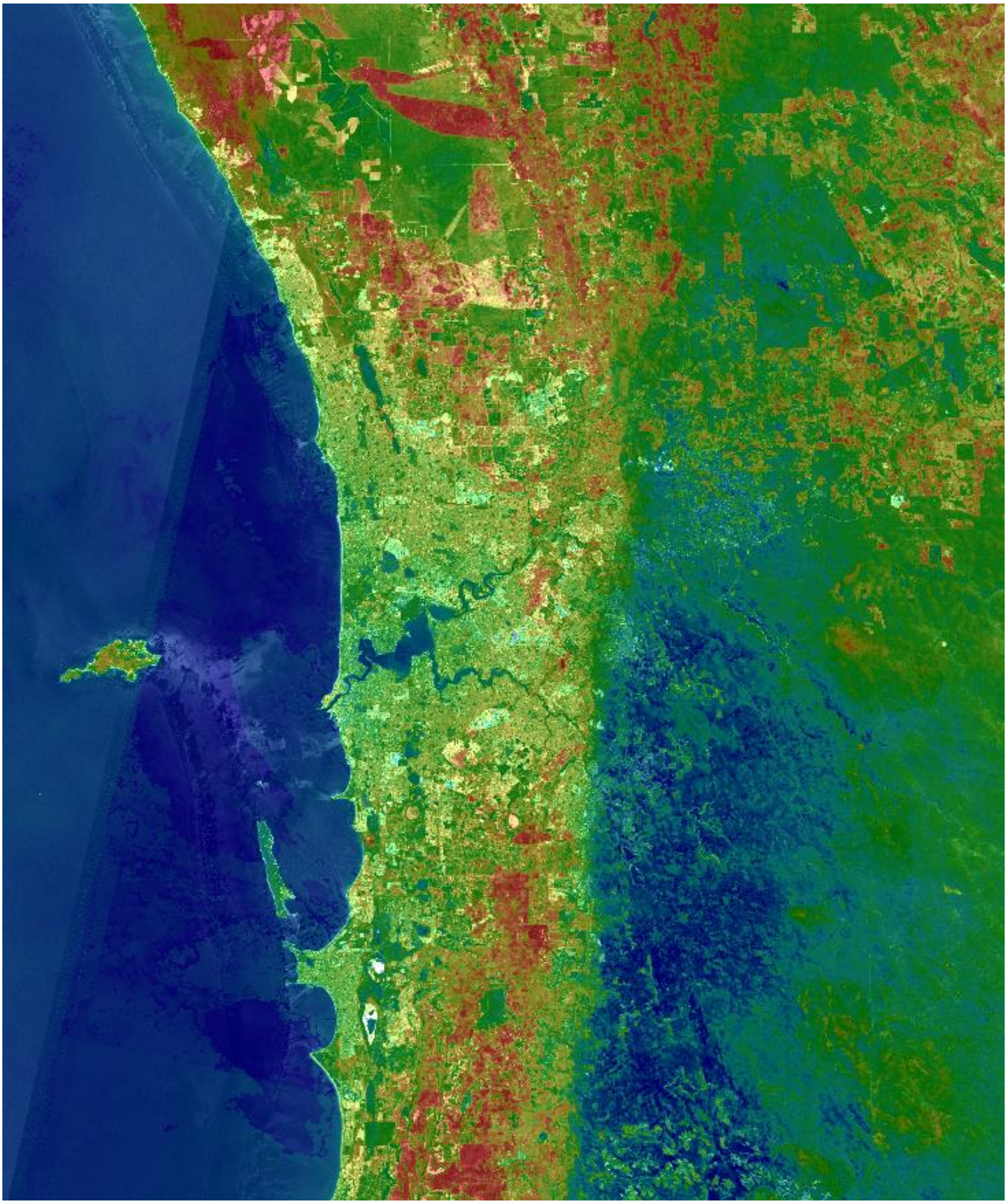

Figure 37 Averaged LST map of Perth and surrounds, in pseudocolor (red=hotter, blue=colder), partially transparent and overlaying greyscale Landsat 8 visible imagery mostly from 15 December 2015

The land surface temperature varies from about 300°K (27°C) to 322°K (49°C).

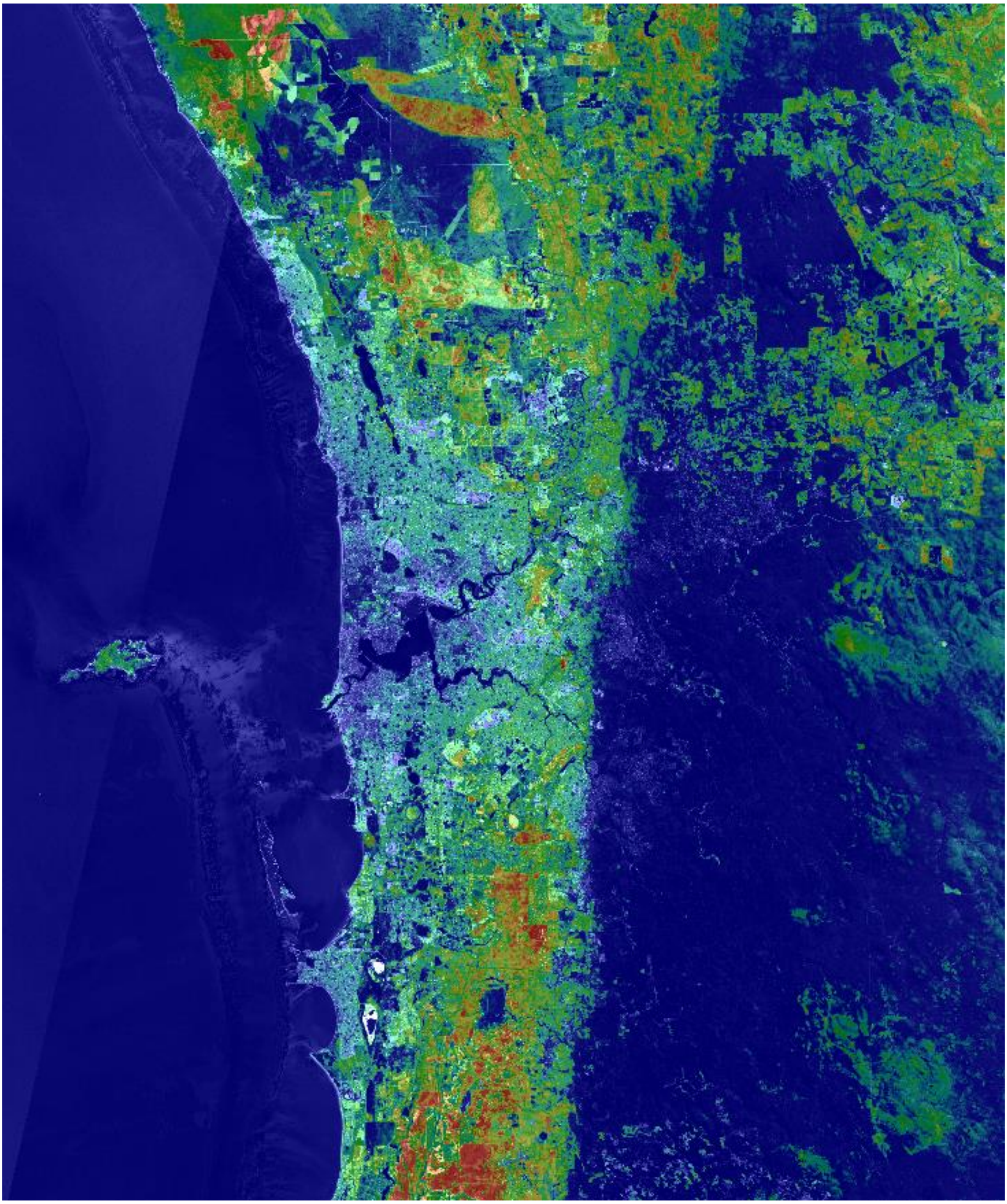

Figure 38 UHI, Perth and surrounds

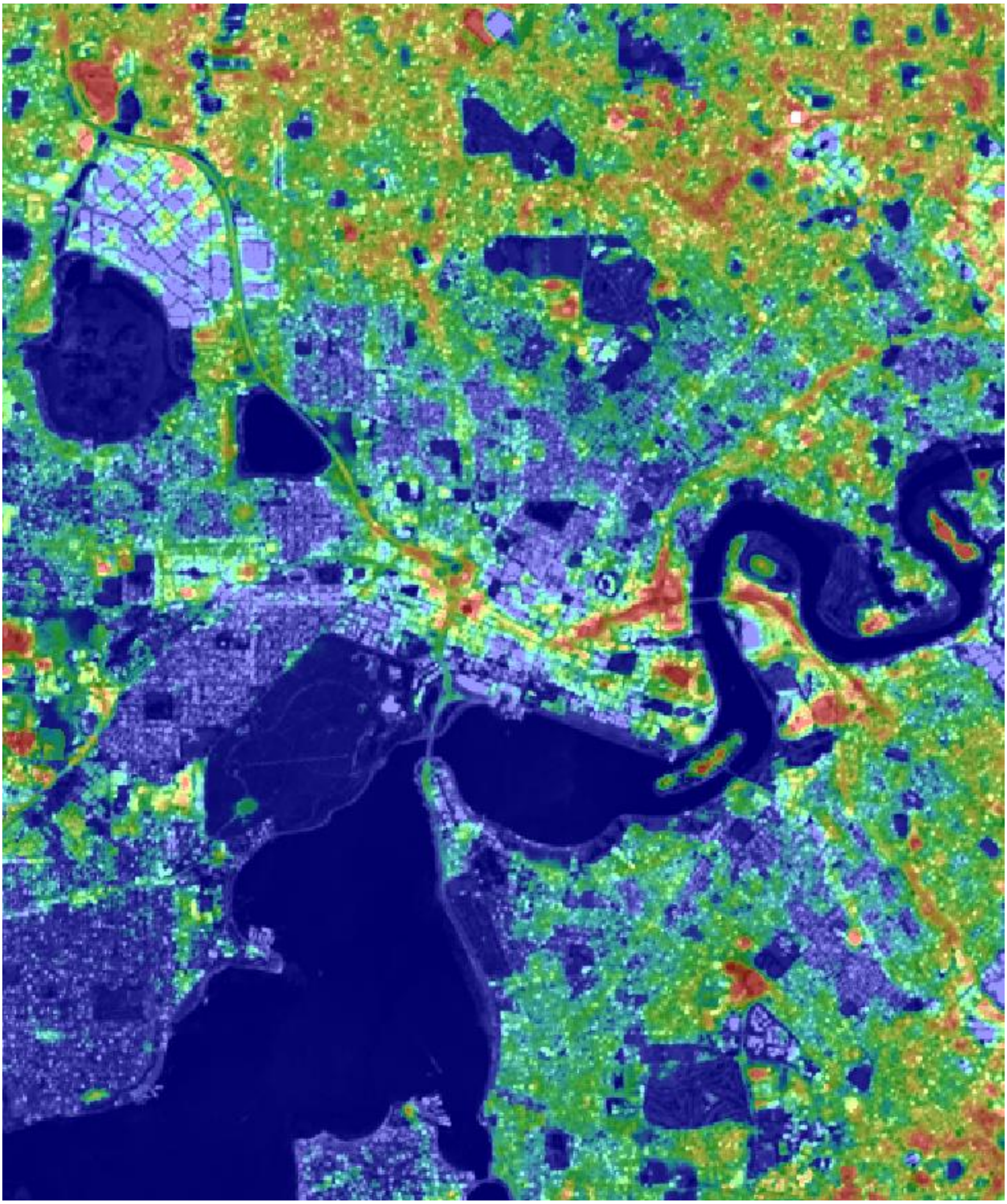

Figure 39 UHI, Perth city centre

The greatest temperature increases are attributed to agricultural areas and fire scars north and south of Perth. Urban and suburban Perth shows warming mostly of up to 5°C, with some construction sites and car parks reaching up to 8°C.

A.12 Sydney

Sydney was processed in MGA zone 56.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 150.509375°E / 270600E
- East: 151.412970°E / 352300E
- South: 34.248063°S / 6209175N
- North: 33.319783°S / 6310550N

The following Landsat 8 images were tentatively detected as intersecting the extents above, and included in processing:

Table 12 Landsat 8 Images processed for Sydney, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
89	83	20151213	21.4	58
89	83	20151229	21.2	51
89	83	20160130	24.4	84
89	83	20160215	24.1	75
89	83	20160302	25.1	59
89	83	20160318	23.4	71
89	84	20151213	21.4	58
89	84	20151229	21.2	51
89	84	20160130	24.4	84
89	84	20160215	24.1	75
89	84	20160302	25.1	59
89	84	20160318	23.4	71
90	83	20151204	20.3	53
90	83	20151220	24.6	61
90	83	20160222	24.3	71
90	83	20160309	24.8	71
90	83	20160325	20.4	78
90	84	20151204	20.3	53
90	84	20160206	22.8	75
90	84	20160222	24.3	71
90	84	20160325	20.4	78

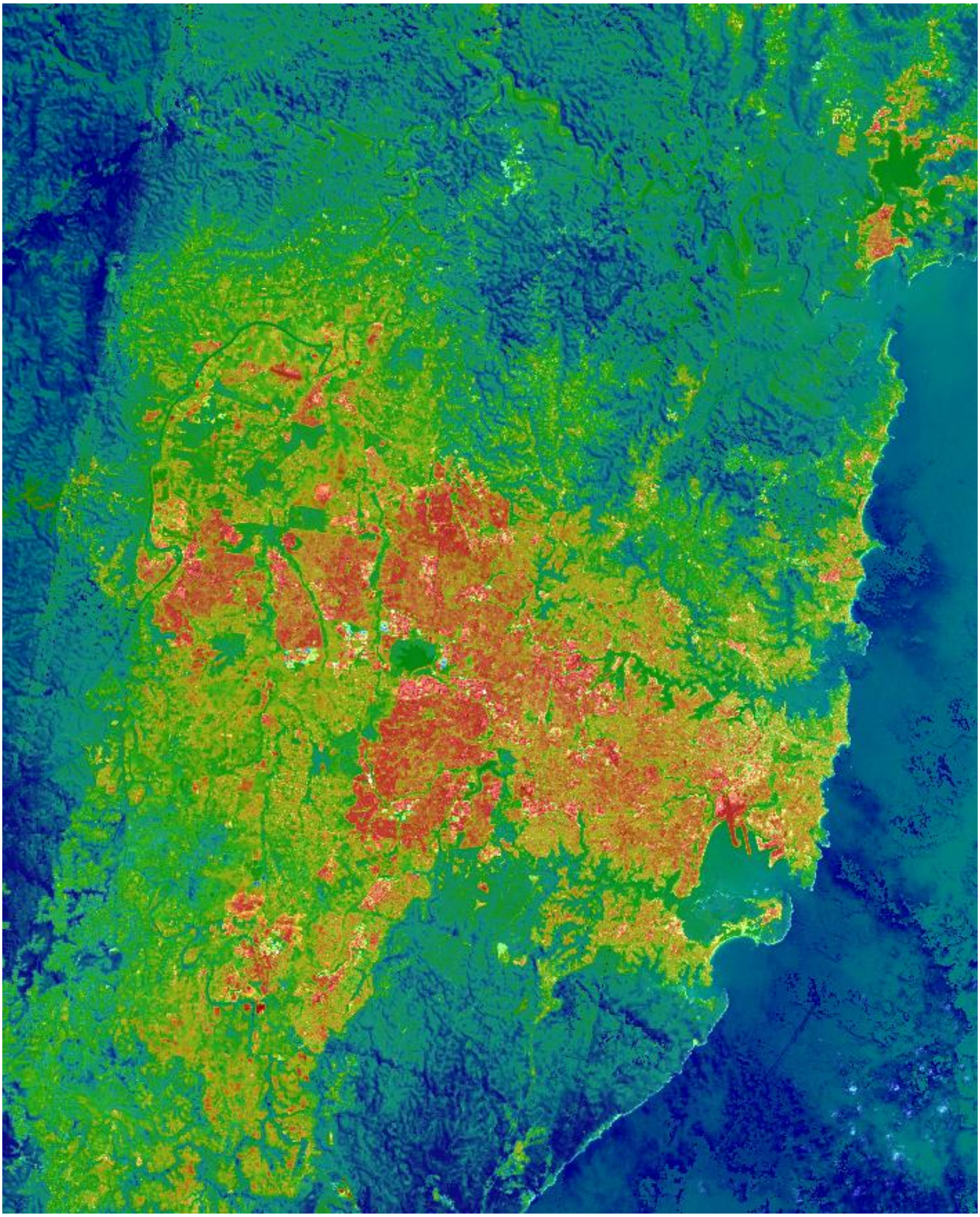

Figure 40 Averaged LST map of Sydney and surrounds, in pseudocolor (red=hotter, blue=colder), partially transparent and overlaying greyscale Landsat 8 imagery from 29 December 2015

The land surface temperature varies from about 297°K (24°C) to 315°K (42°C).

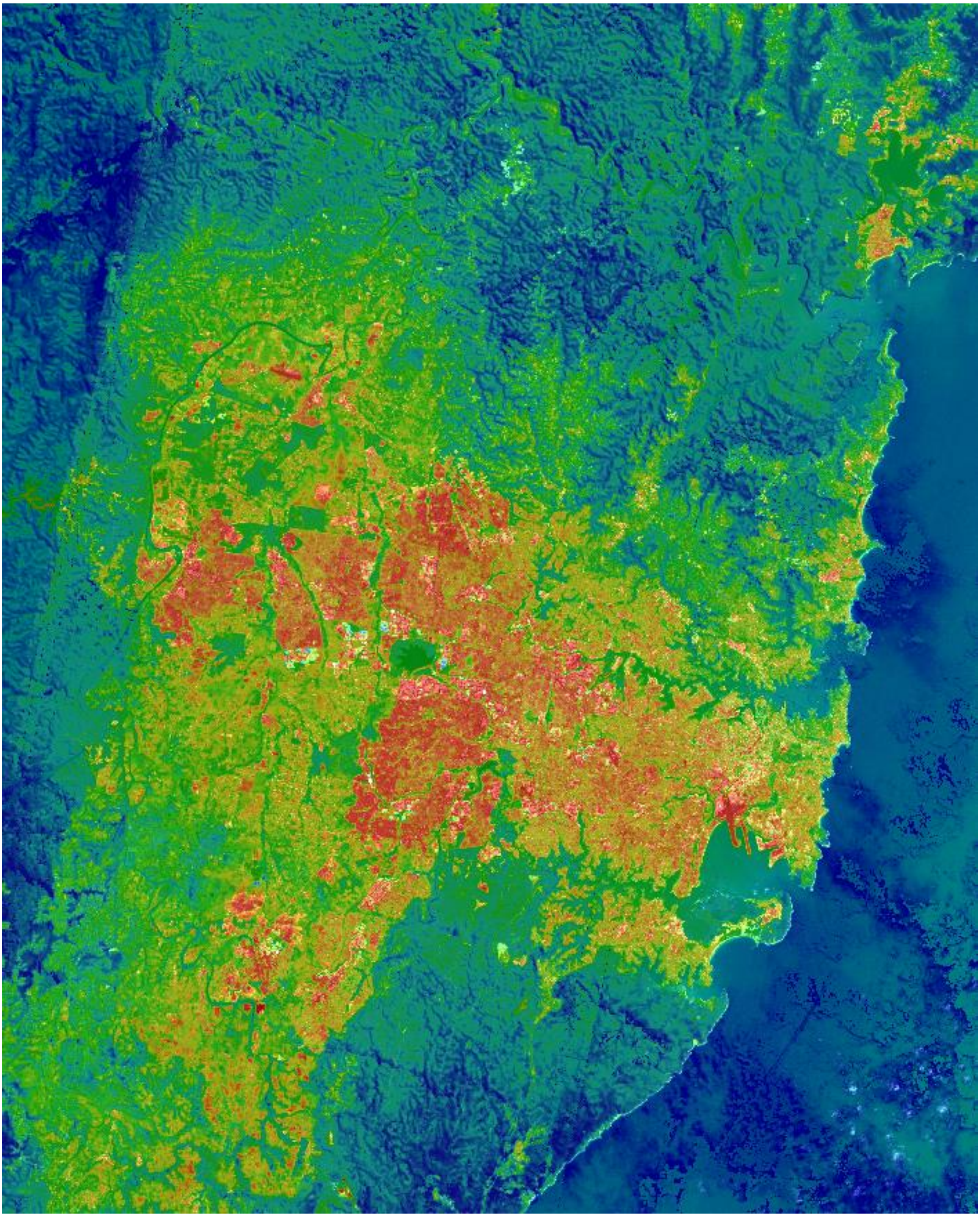

Figure 41 UHI, Sydney and surrounds

Figure 41 shows the UHI image for Sydney and surrounds. Areas of the Blue Mountains west of Sydney show cooling of up to 5°C but this should be discounted due to the high elevation and relief not accounted for in the first-order model of non-urban background temperature. In Sydney proper, the remaining remnants of native vegetation show as zero baseline (no change in temperature) as expected. Urban and suburban Sydney shows warming of up to 12°C.

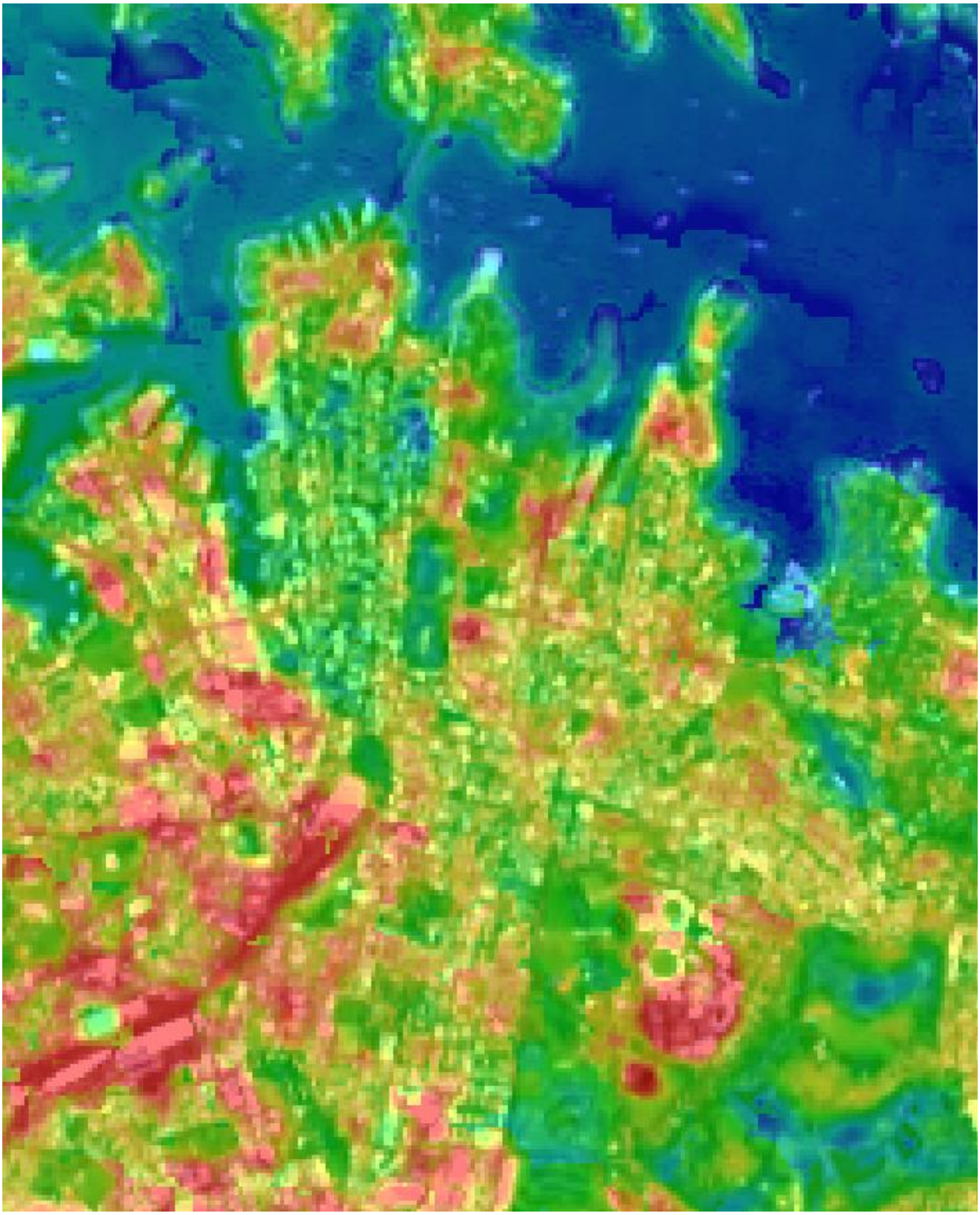

Figure 42 UHI, detail from urban Sydney

A.13 Toowoomba

Toowoomba was processed in MGA zone 56.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 150.620845°E / 266550E
- East: 152.311527°E / 431525E
- South: 28.255018°S / 6874350N
- North: 26.704450°S / 7044150N

Table 13 lists the Landsat 8 images that were tentatively detected as intersecting these extents, and so included in processing:

Table 13 Landsat 8 Images processed for Toowoomba, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
89	79	20151229	19.1	63
89	79	20160215	25.1	41
89	79	20160318	21.9	75
89	80	20151213	20.5	75
89	80	20151229	19.1	63
89	80	20160130	25.1	75
89	80	20160215	25.1	41
89	80	20160318	21.9	75
90	78	20151204	19.0	58
90	78	20160121	23.5	56
90	78	20160325	20.8	73
90	79	20151204	19.0	58
90	79	20151220	20.8	69
90	79	20160105	17.4	99
90	79	20160121	23.5	56
90	79	20160222	21.3	67
90	79	20160309	20.1	98
90	79	20160325	20.8	73
90	80	20151204	19.0	58
90	80	20151220	20.8	69
90	80	20160206	21.3	78
90	80	20160222	21.3	67
90	80	20160309	20.1	98
90	80	20160325	20.8	73
91	78	20160112	24.2	67
91	78	20160213	21.8	61
91	79	20160112	24.2	67
91	79	20160213	21.8	61
91	79	20160229	22.5	66
91	79	20160316	21.4	79
91	80	20151227	21.9	82
91	80	20160112	24.2	67

91	80	20160213	21.8	61
91	80	20160229	22.5	66

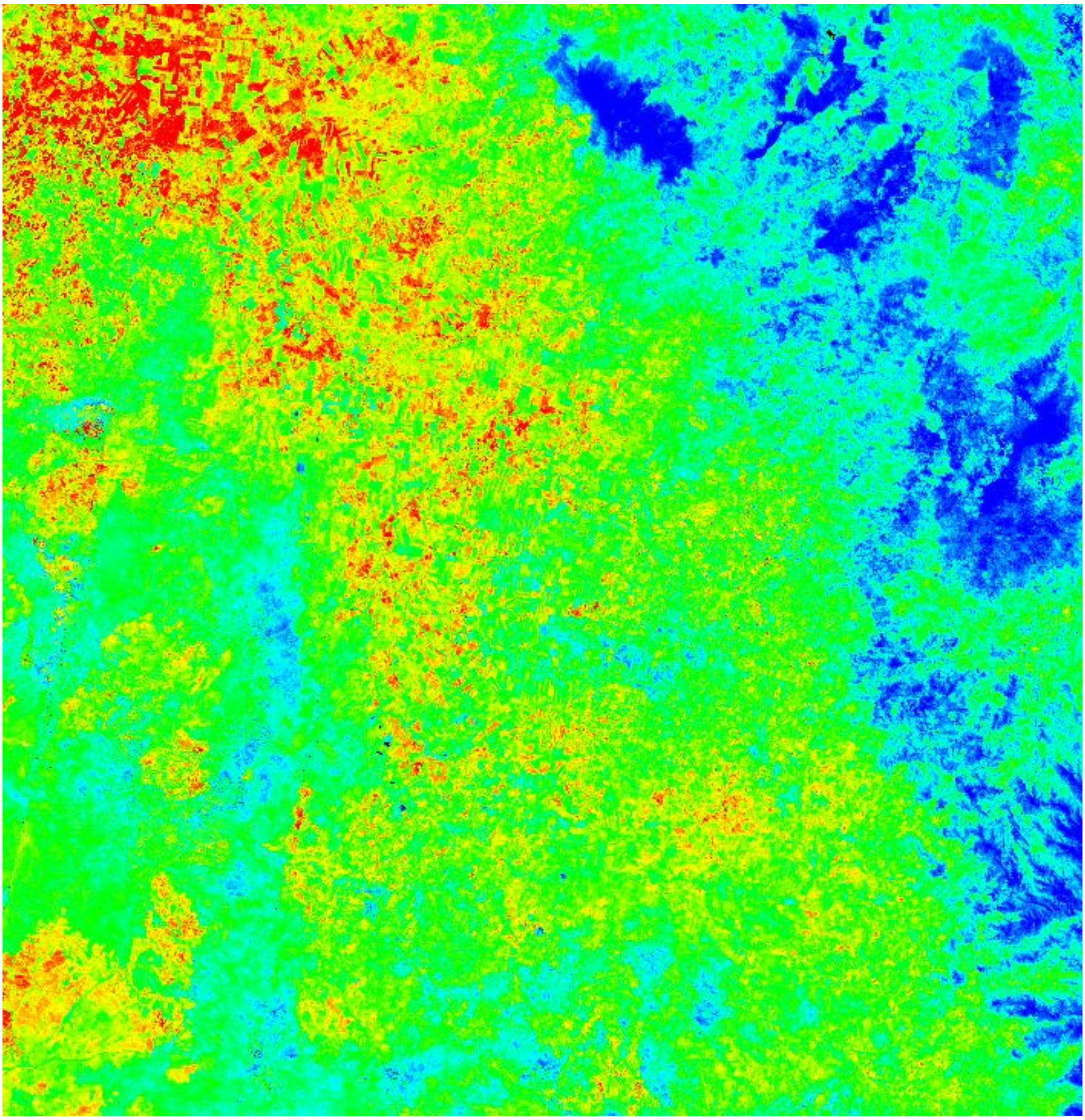

Figure 43 Averaged LST map of Toowoomba and surrounds, in pseudocolor (red=hotter, blue=colder). No truecolor imagery is displayed beneath, as all available such images are significantly cloud-affected

The land surface temperature varies from about 297°K (24°C) to 323°K (50°C).

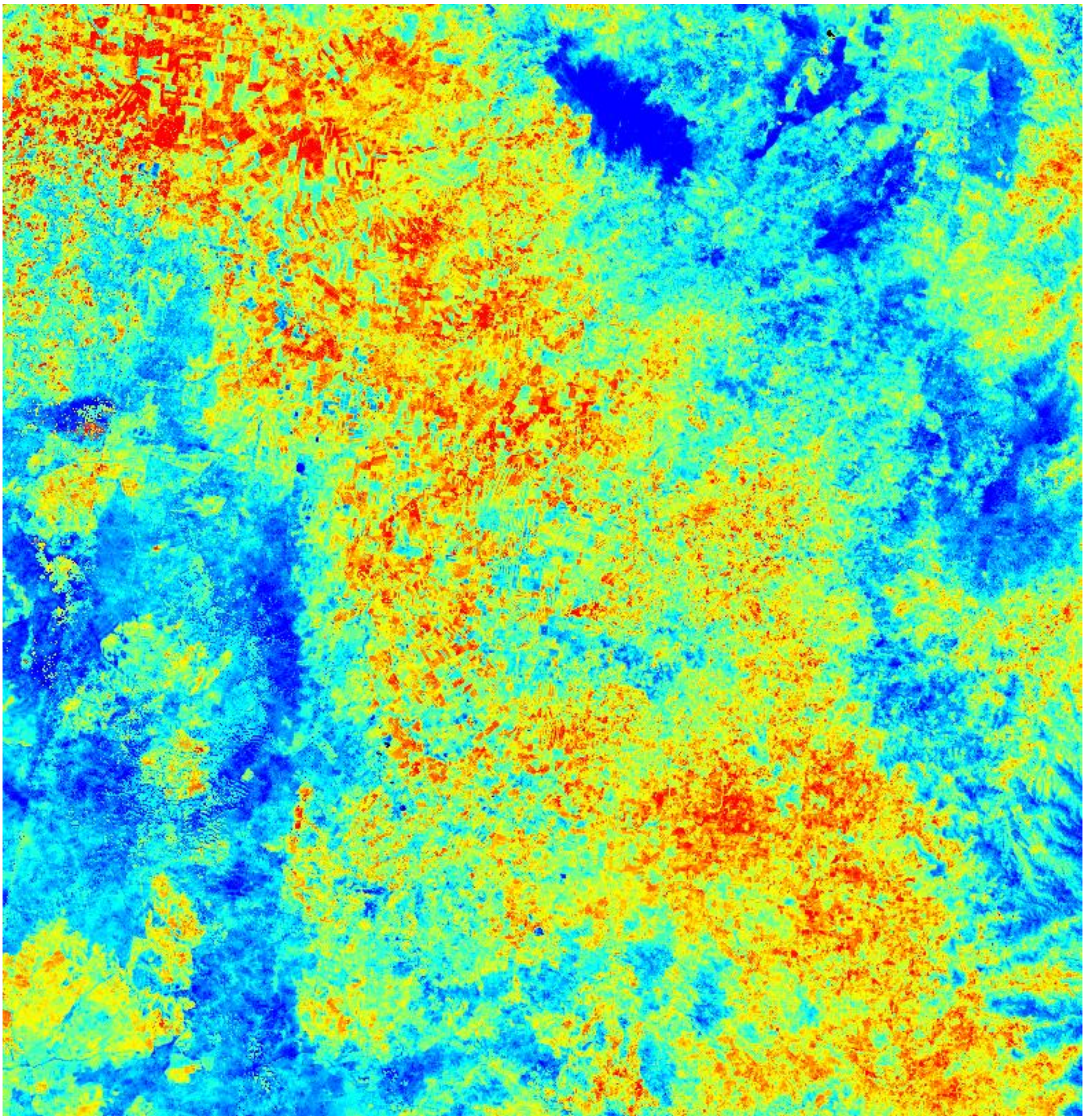

Figure 44 UHI, Toowoomba and surrounds

A.14 Townsville

Townsville was processed in MGA zone 55.

Extents were calculated by taking the extents of the vectors and buffering by 5 kilometres. The extents are:

- West: 146.091868°E / 404900E
- East: 147.168074°E / 517600E
- South: 19.832232°S / 7807075N
- North: 18.871937°S / 7913100N

The following Landsat 8 images were tentatively detected as intersecting the extents above, and included in processing:

Table 14 Landsat 8 Images processed for Townsville, with corresponding weather data

PATH	ROW	DATE (yyyymmdd)	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)
94	74	20151217	28.3	53
94	74	20160219	32.3	65
94	74	20160322	28.3	84
95	73	20151208	29.3	54
95	73	20160109	30.7	66
95	73	20160226	29.7	65
95	73	20160329	28.0	68
95	74	20151208	29.3	54
95	74	20160125	30.1	62
95	74	20160210	29.4	59
95	74	20160226	29.7	65
95	74	20160329	28.0	68

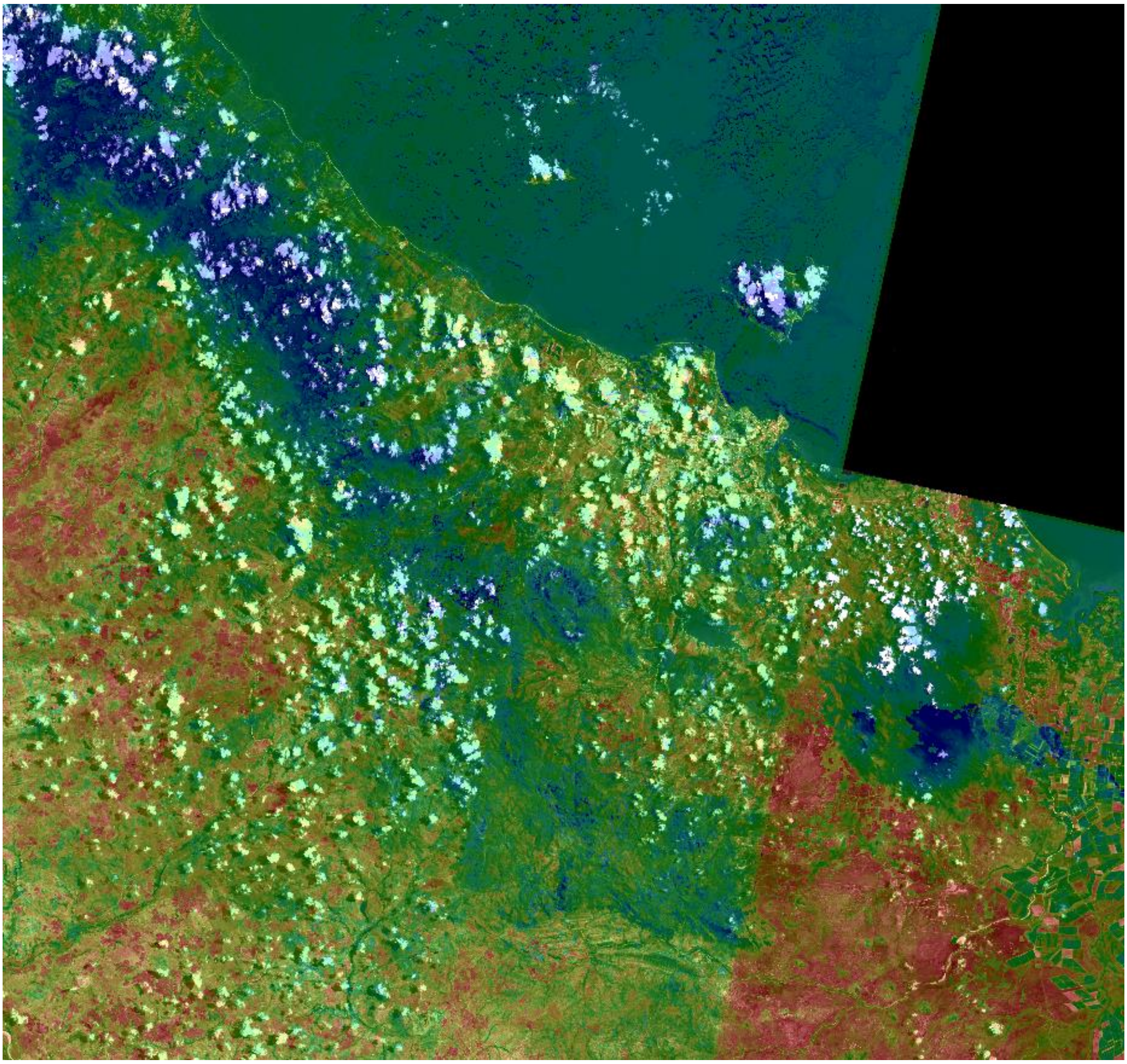

Figure 45 Averaged LST image for Townsville and surrounds, in pseudocolor (red=hotter, blue=colder), partially transparent and overlaying greyscale Landsat 8 imagery from a range of dates.

All input images are quite cloudy, and all have cloud over Townsville city. There is a clear temperature difference between paths 94 and 95, indicating that the dates on which path 94 was overpassed were hotter than the dates on which path 95 were overpassed. Date averaging is intended to account for such artefacts, but when there are few images and all are cloudy, there ends up being little to average.

Land surface temperature readings mostly vary from about 312°K (39°C) to 326°K (53°C), with some cooler values in the ranges.

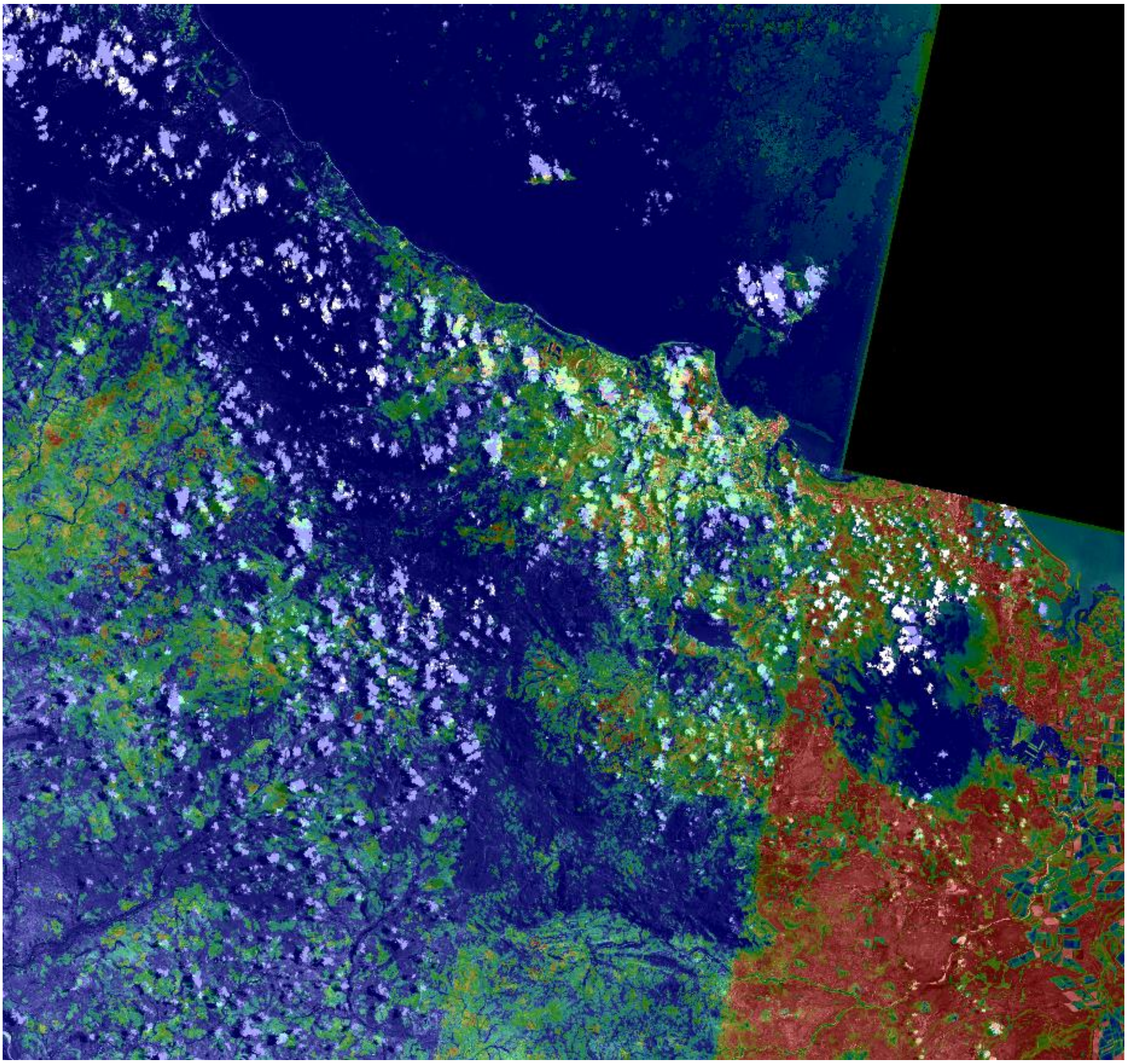

Figure 46 UHI, Townsville and surrounds

Figure 46 shows the UHI map. Townsville city shows temperature increases of up to 10°C.

Unfortunately, local thermal features are almost entirely drowned out by temperature differences between the two paths. Yet despite the path differential and the extensive cloud, the data is not totally without value: Figure 47 shows a heavily cloud-affected UHI image for the city centre, in which one can nevertheless see a clear temperature increase tracking the major transit route along Bowen Road and Charter Towers Road.

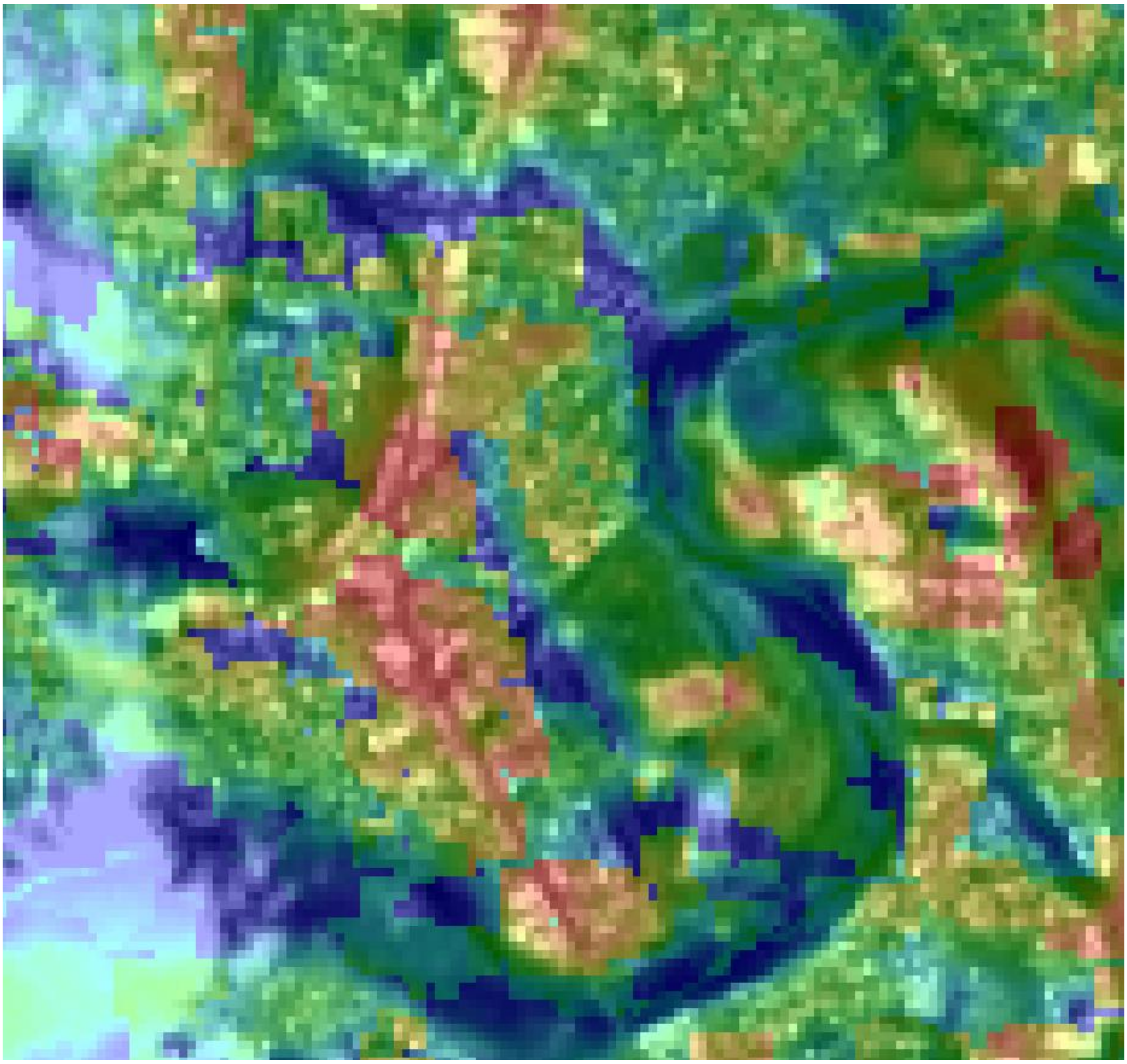

Figure 47 UHI, very fine detail from Townsville city. The data is badly cloud-affected, but some thermal features can be seen

A.15 Warnambool

No data was available for Warnambool.

The area of interest falls almost entirely within Landsat 8 path/row 94/87. There are two suitable scenes for this path/row within the period of interest:

- The image collected 17 December 2015 has extensive cloud but only over the ocean; and
- The image collected on 22 March 2016 is almost cloud-free.

USGS thermal data is available for both, but GA calibrated imagery is available for neither.

There are known problems with Geoscience Australia’s processing stream that make some scenes from some path/rows much more likely than others either to fail to complete processing or to fail post-processing QA checks. Such path/rows include rows at the extreme southern end of a path, and path/rows that are predominantly ocean. Path/row 94/87 meets both conditions.

Shortened forms

DEM — Digital Elevation Model

GA — Geoscience Australia

LSE — Land Surface Emissivity

LST — Land Surface Temperature

NDVI — Normalized Differential Vegetation Index

TIRS — Thermal Infra-Red Sensor

UHI — Urban Heat Island

USGS — United States Geological Survey

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