TOWARDS LIVEABLE CITIES: EXTREME HEAT DISTRIBUTION IN SOUTH AFRICAN CITIES

Timothy Chambers

University of Cape Town

This study was funded by the American Red Cross and the Global Disaster Preparedness Center (GDPC) with technical support from GDPC, the Red Cross Red Crescent Climate Center and the Global Heat Health Information Network (GHHIN)

American Red Cross

PrepareCenter.org
Prepare. Innovate. Learn. Together.

Global Disaster Preparedness Center

Climate Centre

GLOBAL HEAT HEALTH INFORMATION NETWORK

Table of Contents

Executive Summary 2

Study Flowchart 2

Purpose....3

Study areas 4

Part 1

1.1 Methods.... 5

1.1.1 Landsat 8 Thermal imagery.... 5

1.2 Results and Discussion 12

1.2.1 Landcover contrasts.... 12

1.2.2 Reversed urban heat island....12

1.2.3 Thermal inequality and apartheid legacy....13

1.2.4 Limitations....13

Part 2

2.1. Methods....14

2.1.1 WRF model....14

2.1.1.1 Landcover datase.... 16

2.1.1.2 WRF-Coupled Urban Canopy Model (UCM)....16

2.1.1.3 Experimental design....16

2.2 Results and discussion....18

2.2.1. Landcover dataset....18

2.2.2. Land Surface Temperature validation....22

2.2.3 Air Temperature validation....23

2.2.4 WRF air temperature distribution....24

2.2.5 Model skill and limitations....25

2.3 Heat adaptation scenarios....26

2.3.1 LST's....26

2.3.2 Air Temperatures....29

2.3.3 Albedo vs Trees....29

2.3.4 Limitations....29

3 Conclusionss....30

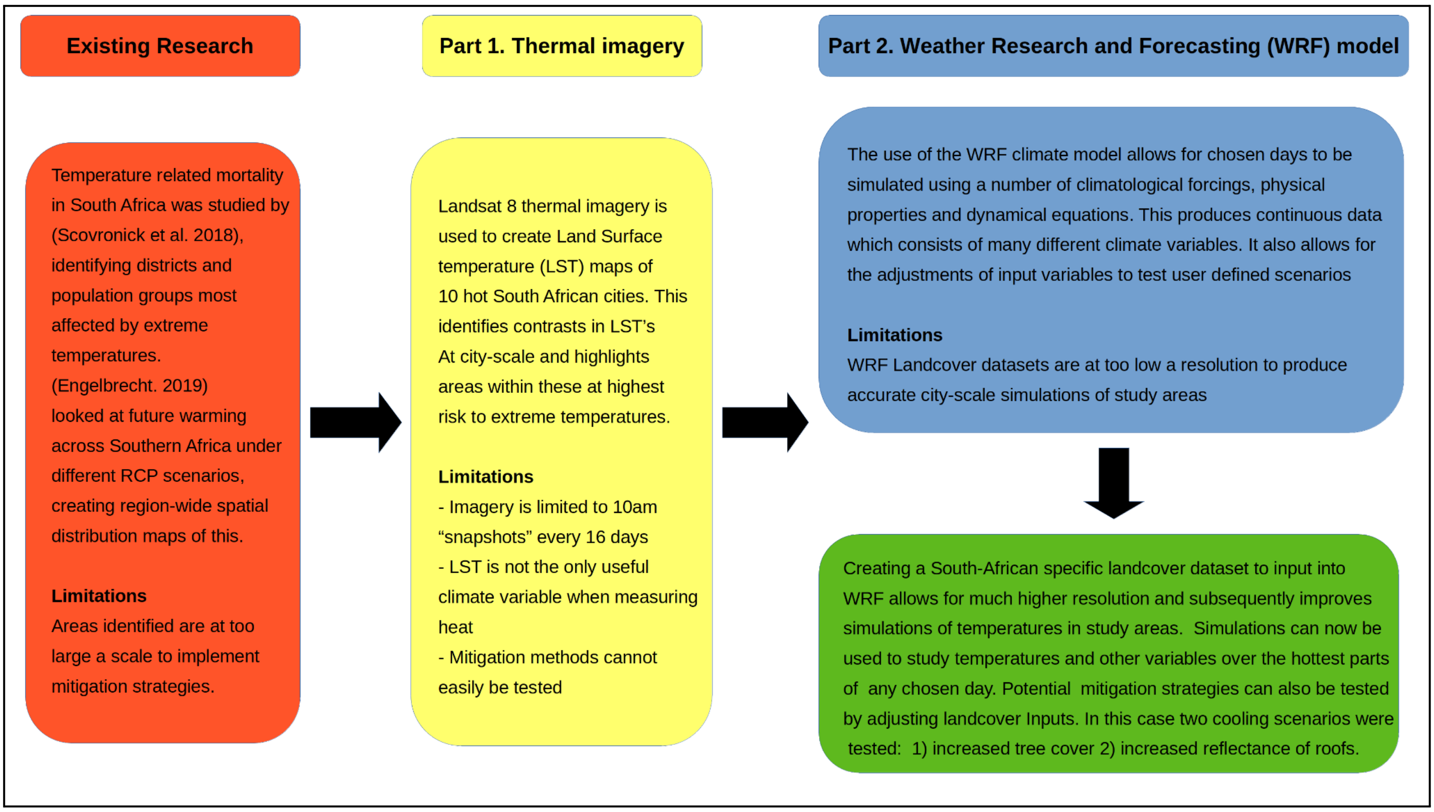
4. References.... 31

5. Appendix.... 33

Executive summary

Extreme heat has severe impacts on human health (Ebi et al., 2021), and in a climate that is projected to significantly warm in the near future, this is an issue that we will need to adapt to. Southern Africa in particular is a hotspot for future warming (Engelbrecht 2019) and combined with large populations of vulnerable people- it is at great risk from these heat events. There are however ways of reducing exposure and adapting to or mitigating its effects, but these require significant resources. To allocate the limited resources effectively, it is necessary to identify those at the highest risk This study aims to map and model the heat distributions in 10 South African cities at a city-level scale in order to identify these vulnerable populations and what makes them so . To do this, we start by taking Landsat thermal imagery and producing thermal maps across the cities, identifying strong contrasts in Land Surface Temperatures (LST's) between different areas, LST's close association with Land cover type as well as trends of both thermal inequality and an inverse urban heat island effect . This imagery is however limited in its temporal coverage and its measure of only LST. By using the Weather Research and forecasting model, combining it with an Urban Canopy model and converting and creating a new high resolution South African landcover dataset , it is possible to address this. The simulations produced with the updated landcover show good skill in reproducing observed spatial patterns and values in both surface and air temperatures. The model can therefore be used to adjust Land cover input variables and test the effectiveness of a) increasing tree coverage and b) increasing the albedo of roofs. Results show reductions in LST's of around 2-3℃) and minor reductions in air temperatures as well.

Keywords: Heat distribution, Thermal maps, WRF model, Landcover change, Adaptation scenarios



Flowchart of study report.

Purpose

The on-going effects of climate change have been projected to increase the frequency and duration of extreme heat events and intensities, particularly in Sub-Saharan Africa (IPCC2021). This is expected to aggravate the negative impacts heat has on thermal comfort and increase the related mortality as well as increase stress on already fragile energy supplies and health systems. (D'Amato et al., 2013) and (Chand and Murthy, 2008) found that extreme air temperatures place humans at higher risk of asthma and heart attacks. (Johnson et al., 2005, Stafoggia et al., 2006) show how the exposure to extreme heat increases morbidity and mortality due to the body's inability to thermoregulate. This is most apparent in the very young, very old and the sickly. (Zhang et al., 2016) found that heat waves caused up to 25% increases in non-accidental deaths in Jinan, China. This mortality is often skewed along socio-economic lines, with poorer populations having far greater exposure to extreme temperature. (Scovronick et al. 2018; Jagarnath et al., 2020). In less developed countries the proportion of the population exposed is far greater and is subsequently more likely to be ill affected. In order to reduce health impacts and mortality, climate change adaptation and heat resilience strategies have been suggested. Planting trees and increasing man-made surfaces albedo's have both been tested as potential strategies to do this. Trees can reduce temperatures through their shade and evapotranspirative cooling while increasing reflectivity of surfaces can reduce the amount of heat absorbed. (Chen et al., 2014; Santamouris and Fiorito, 2021). In a country like South Africa however, there are limited resources to effectively implement these strategies. This makes it essential to identify areas and people most vulnerable to extreme heat, as well as to identify solutions which are both effective and implementable

Research by (Scovronick et al. 2018) contributed to this by conducting an epidemiology study of the temperature-mortality association in South Africa over the period 1997-2013. From this they identified districts *(appendix Fig. A1)* and groups most at risk, finding that Bojanala district in the North-West was the most severely affected, with over 3% of total deaths being attributed to extreme hot temperatures. Children (0-4 years) and elderly (65 years+) were the most at risk groups. (Engelbrecht. 2019) looked at future warming, producing a report that provides detailed projections of future climate change over South Africa. This strongly identified that the interior of the country is likely to experience the largest increases in temperatures and heat waves. *(appendix Fig. A2)*

Both these studies provide very useful information for identifying vulnerable people and areas, but at too large of a scale for adaptation strategies to be implemented at. To address this, this study aims to use the available research and downscale it to the city level, choosing areas which have significant populations and which also fall within these vulnerable regions. By studying these locations it is hoped that useful information is produced about the distribution of heat within cities, what influences it, and what methods could subsequently be used to reduce heat and it's impacts on the health of the population.

Study areas

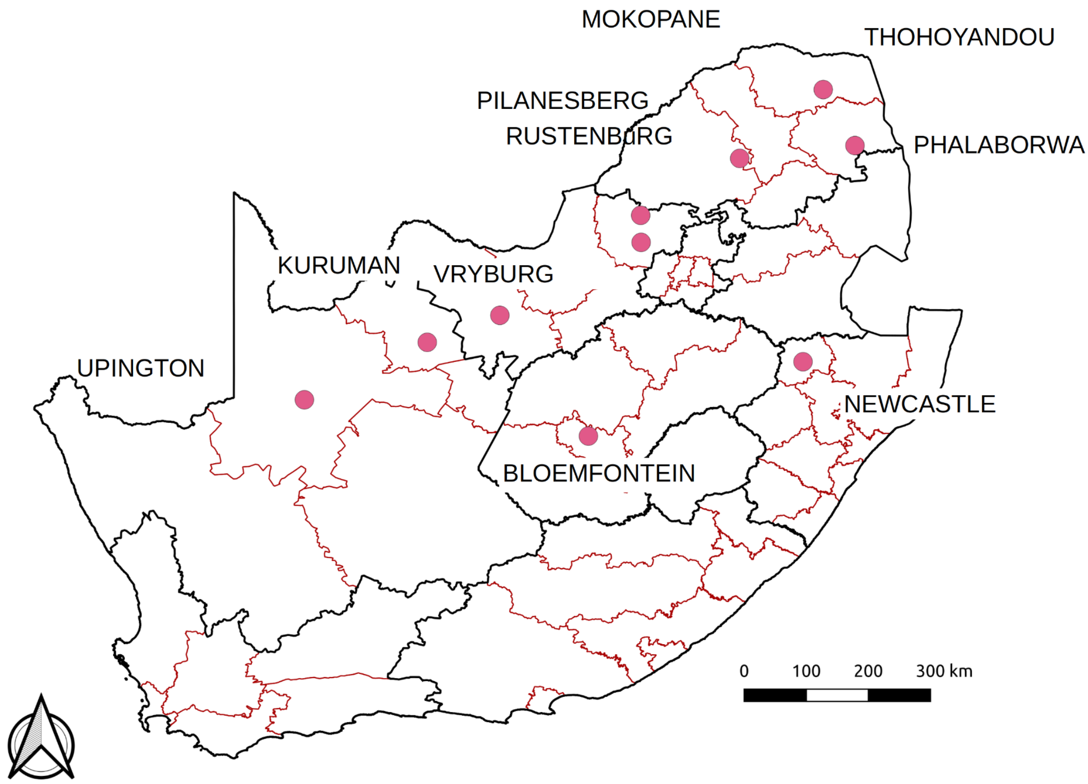


Figure 1. Locations of study areas across South Africa

10 locations across South Africa were chosen for this study. These were chosen considering the following factors: 1) Districts with high heat-related deaths according (Scovronick et al. 2018), 2) Vulnerability to future warming (Engelbrecht. 2019) 3) currently experience extreme temperatures, 4) having significant population numbers

Table 1 Locations and their relevant heat information extracted from the CSAG Climate Information Platform

Study Area	December average max (℃)	Hot days (number of days)			Number of heat related deaths in district (1997-2013)	Heat related deaths in district (% of total deaths)
		≥ 32℃	≥ 36℃	≥ 95%		
#1 Bloemfontein	30	40	5	18	1404	0.8
#2 Kuruman	33	75	15	19	565	1.5
#3 Mokopane*	28	17	1	19	530	0.7
#4 Newcastle	29	30	13	18	1448	1.5
#5 Phalaborwa	32	82	18	14	2000	1.3
#6 Pilanesberg**	32	98	24		7522	3.5
#7 Rustenburg	31	52	5	17	7522	3.5
#8 Thohoyandou	29	38	5	17	1849	1.4
#9 Upington	36	130	55	17	509	1.1
#10 Vryburg**	36	123	36		2086	2.5

** information is only available for Polokwane ~50km away **Hot day information from SAWS observations 2014-2018*

PART 1

1.1 Methods

1.1.1 Landsat 8 Thermal imagery

Satellite thermal imagery has provided a fantastic tool for studying the spatial variability of Land surface temperature (LST). Compared to traditional station measurements, it has vastly greater spatial coverage and is not dependent on a country's meteorological observation network, meaning information is not skewed towards more developed countries with denser networks and can be used anywhere in the world. A number of studies have made use of it to observe LST distribution in cities, and in particular the urban heat island phenomenon (Rinner & Hussain, 2011), . Landsat 8 imagery gives very high (for a satellite sensor) 30m resolution information that can be used to identify microscale changes in LST. In order to use this information properly, the LST's first need to be calculated from the digital numbers which are collected by the satellite sensors. For this study the RS&GIS plugin (Barane and Dwarakish 2017) for QGIS was used. Following the calculations in the Landsat 8 users Handbook (Vaughn Ihlen, 2019) the images were first atmospherically corrected to account for the sun elevation and angle - turning the thermal band 10 digital numbers into Top of Atmosphere Radiance (TOA), Reflection (TOR) and then Brightness temperature (BT). From here, the land surface emissivity (e) was calculated using an NDVI image based method from (Sobrino et al. 2004), making use of bands 4 and 5 to calculate NDVI and proportion vegetation (pv). The final LST calculation was based on an equation from Artis and Carnahan (1982) and Weng et al. (2004):

$$LST = \frac{T_\lambda}{1 + \left(\frac{\lambda * T_\lambda}{\rho}\right) lne} \qquad \text{(Eq 1)}$$

Here LST is Land Surface Temperature in °C), T is at satellite brightness temperature (°C), λ is the wavelength of radiation emitted (11.5 μm), p is 1.438x 10^-2 mK and e is land surface emissivity

Table 2 Landsat 8 thermal images used in each location

City	Number of images used	Time of day for imagery (UTC+2)
Bloemfontein	18	10:09
Kuruman	15	10:21
Mokopane	10	10:01
Newcastle	9	09:56
Phalaborwa	9	09:55
Pilanesberg	9	10:08
Rustenburg	13	10:08
Thohoyandou	11	09:55
Upington	11	10:28
Vryburg	9	10:15

Images for each of the cities were collected from Landsat 8 TIR (Collection 2 level 1 product) from the period January 2014 to December 2018 through the USGS EarthExplorer portal. These were manually filtered to choose images which had no clouds or shadow over the study areas and were days which reached maximum temperatures of at least 30°C (checked using observational data from *weather underground* and South African Weather Service station data). The selected days were then processed to extract LST according to the method above. The imagery for each location is taken at roughly the same time (within 1-2 minutes) across all years, and all locations imagery is taken between 09:55 and 10:28am.

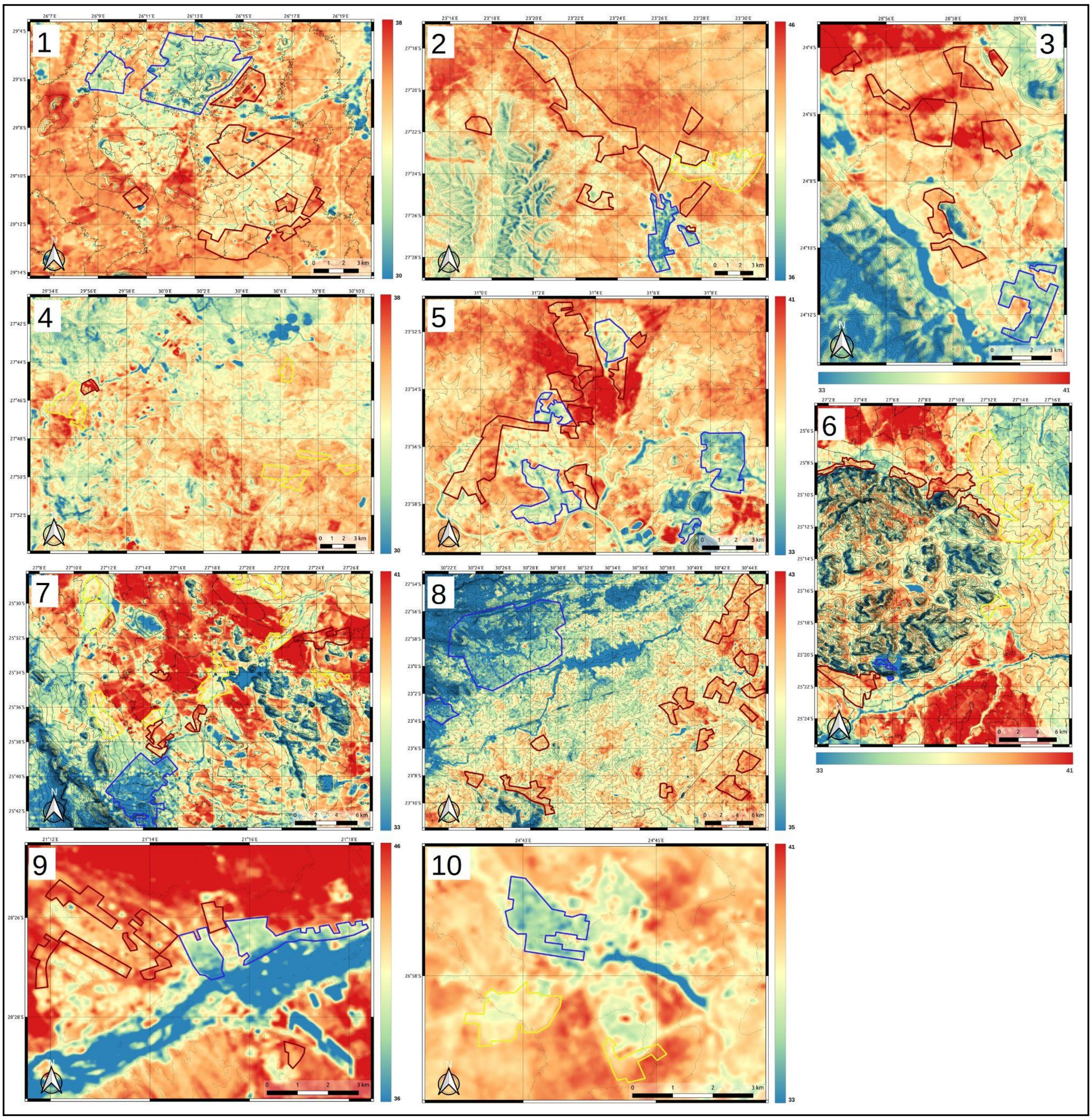


Figure 2 Land Surface Temperature (LST) maps of the 10 study locations with urban temperature anomalies outlined. Blue showing significantly cooler than average, red significantly hotter than average and yellow slightly warmer than average.

After inspecting all converted images using the QGIS interface, each area's collection (9-18 images) was combined into 1 image using the QGIS raster calculator. This gave the final representative image for each location *(Fig 2)*. The image was then overlaid with contour data from SRTM 30m digital elevation models (USGS), SANLC2020 Landcover from Department of Forestry, Fisheries and the Environment (DFFE), 2019 population density data from Africa data hub And satellite imagery from Google earth. These layers were then used to visually and numerically analyse the distribution of the landsat LST's and identify urban areas noticeably hotter (red) or colder (blue) as shown in Fig 3 (Bloemfontein) below. The images for the other 9 locations are on pages 2-4 of the appendix.

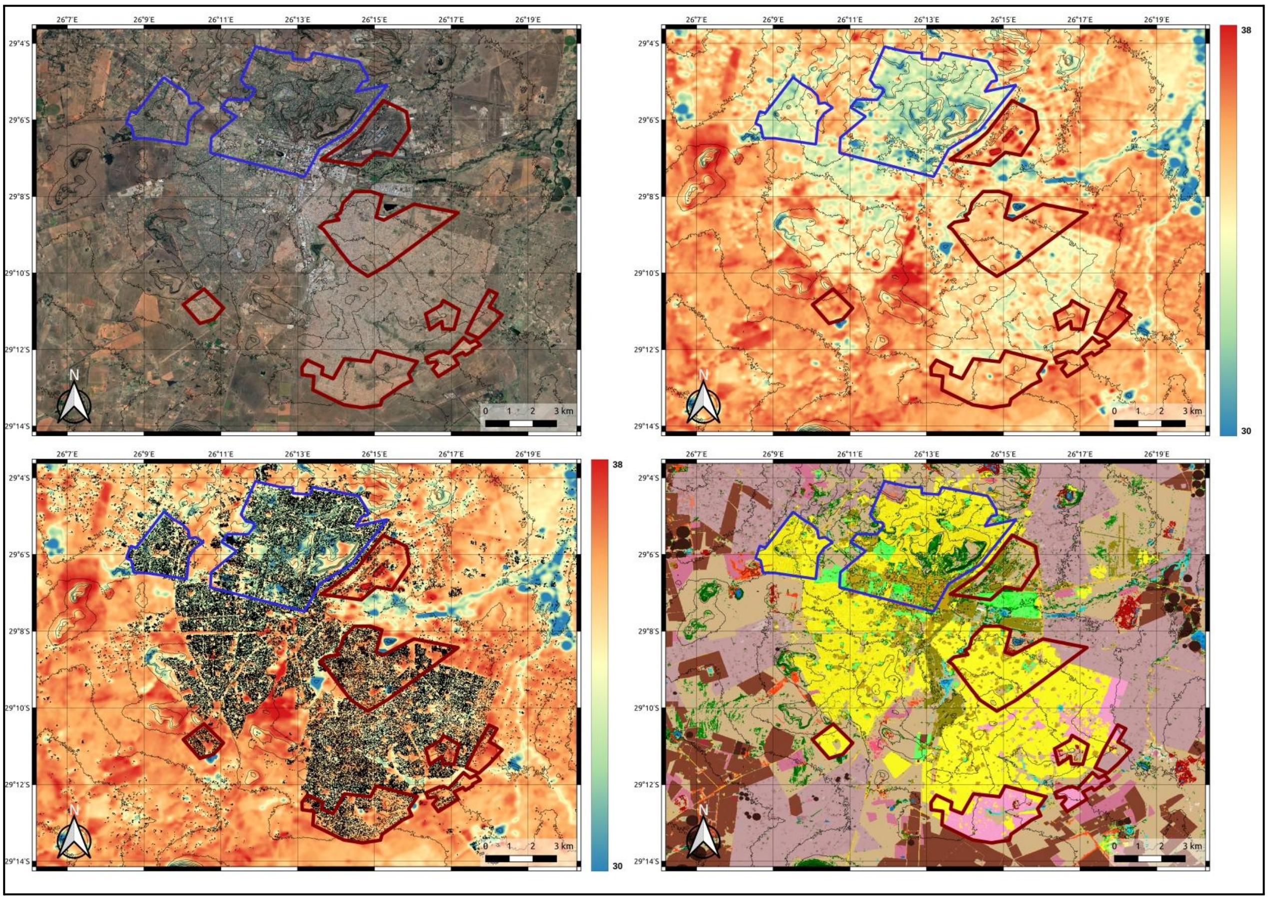


Figure 3. Maps of the Bloemfontein study area used to analyse LST differences, their drivers and their spatial relationship with the population a) google earth satellite image, b) Landsat LST image, c) Landsat LST image with population density overlaid, d) SANLC2020 landcover dataset

Table 3. Characteristics and LST's of each study location

City and Figure	Description	Temperature
Bloemfontein *Fig 3.* *Population 600'000* *(-29.11, 26.22)* *1400masl*	A large star-shaped city with a significant commercial and light industrial center, interspersed with recreational grounds.	Predominantly cooler temperatures, mostly ranging from 30 to 34°C depending on roof reflectivity. Transnet train yard (East) and its large dark rooves show much higher temperatures (36-40°C)
	Higher-income, mostly well forested residential and recreational areas to the North, NW and SW of the center (large houses, medium to high density).	Temperatures of between 31°C and 33°C for the most part, with the grassed recreational grounds warmer at 34-37°C
	South-East of the center is an expansive area of mostly lower to middle income residential housing with sections of open land scattered between (medium houses, high density). Tree cover is low across the area - Houses on the settlement edges become smaller, less formal, more scattered and with more bare ground between them	Temperatures sitting around 35°C across most parts, with the small valleys and more densely built up areas slightly cooler (32-34°C) - The barer settlement edges are slightly warmer, reaching over 36°C (5°C warmer than the vegetated Northern sectors)
	Non-built-up areas are dominated by grassland and crops (irrigated and rain fed). Grassland and rainfed crops are warm (36-37°C) while irrigated cropland (center pivots especially) show much cooler temperatures (28-30°C).	
Kuruman Appendix *Fig A3 #1* *Population 80'000* *(-27.36, 23.39)* *1350masl*	Kuruman town to the South. Small commercial sector in the middle, higher-income, well- forested and relatively dense residential areas immediately to the East and North.	Kuruman Town (including the commercial center) shows relatively cool temperatures- between 35 and 38°C.
	Moving northwards are the settlements of Bankhara (NW), Maruping (North and far NW) and Mothibistad (NE). These are far more spread out, have lots of bare ground and low vegetation between houses, and generally have sparse tree cover. The roads in these areas are also predominantly sand, with only the town centers being tarred.	Bankhara warms to between 39 and 41°C. Mothibistad 40-42°C, but with small denser and more vegetated sections of it being a bit cooler (38-39°C.), Maruping has fewer cooler spots and the range increases slightly (41-43°C) with small sections reaching up to 44 °C (9°C warmer than more forested parts of Kuruman)
	Non-built-up areas are mostly grassland and savanna. These range from 42-45 °C (depending on reflectivity) with the more vegetated savanna and more reflective grassland often slightly cooler (42-43°C)	
Mokopane Appendix *Fig A3, #2* *(Population 200'000)* *(-29.11, 26.22)*	The older, well established commercial/industrial center is in the South, with a higher income and well forested residential area South-adjacent to this.	The forested residential areas have temperatures between 33 and 35°C, with the adjacent non-vegetated commercial/industrial area far warmer (38-39°C).
	Moving NW, there are large, sparsely forested, middle-lower income residential areas, with a general trend of decreasing density and formality of housing as one moves further North-West. This also correlates to an increase in bare ground between housing.	The denser, more formal built-up areas sit around 36-37°C while the more spread out areas are generally warmer (37-40°C). In the far North these even rise up to 42°C (9°C difference from the South) with the slightly darker vegetation and soil and increased bare ground seemingly the main contributors to this.

1400masl	The non-built-up valley areas consist of mostly rainfed crop/grazing land and savanna with sections of denser and cooler woodland (35°C). The soil and vegetation colour significantly impact the temperatures of with some areas of darker vegetation reaching up to 42°C while lighter vegetation/soils sit at 38°C	
Newcastle Appendix *Fig A3, #3* *(Population 300'000)* *(-27.75, 30.09)* *1200masl*	The main commercial center sits to the West of the study area, with a number of moderately forested, higher income residential areas surrounding it and large industrial areas around 3 kilometers to the East and 10km to the North-East.	Temperatures across the residential areas vary little, with almost all of the areas sitting around 33-34°C with some small more forested areas to the North of the center being closer to 32°C and some small areas of more open and less-established housing, as well as darker roofed houses, rising up to 35°C (a 3°C difference to forested sections). What does however show a considerable difference is the commercial center which rises up to 39°C, likely due to its darker roofs, exposed tarred areas and minimal tree cover. The industrial areas also show some slightly warmer temperatures in sections (35-37°C), but also have sections of more reflective roof cover where temperatures drop down to 32-33°C.
	A couple of kilometers further East starts an expansive, mostly middle-lower income residential area made up of several settlements varying in density and level of establishment. Again there is a general trend of decreasing density as one moves towards the outskirts of these settlements. Tree cover across these Eastern settlements is generally very sparse, but the vegetation and open spaces (mostly grass) between buildings is very green in comparison with other study areas	
	Non-built-up areas are mostly grassland and crops (irrigated and rainfed). The natural grassland and rainfed crops are generally warmer than the residential areas (35-36°C), while the irrigated crops are considerably lower (down to below 30°C in the case of many center pivots).	
Phalaborwa Appendix *Fig A4, #1* *(Population 100'000)* *(-23.92, 31.08)* *400masl*	To the East is the more established town of Phalaborwa with a commercial sector in the SW and the remainder predominantly higher-income and well forested residential areas.	Phalaborwa's forested residential areas have temperatures around 33-34°C. The small commercial center generally sits around 36°C, with darker surfaced areas reaching up to 38°C.
	Lulekani settlement to the far North is predominantly medium-density residential with small pockets of recreational and commercial. It has a reasonably well forested and established central area between two small rivers with a general trend of more scattered trees, more open land and less established areas as one moves outwards.	The temperatures in Lulekani mostly follow its layout, with the more forested central section generally having lower temperatures (35-36°C) while the less vegetated outskirts and Western parts increase to around 38-39°C and even up to 41°C in the case of Southern sections. The warmer Western parts are most likely due to their East facing aspect and more direct sun.
	Just South of this, Ben shows a similar trend, with the majority of the area being quite well forested, but with the Eastern outskirts becoming far more open and less established.	In Ben, the forested South-West sector also has far cooler temperatures, around 34-35°C, with the temperatures increasing gradually as one moves North and East (up to 40-41°C on the outskirts, 8 degrees warmer than forested sections in Phalaborwa).
	Namakgale to the far South varies across it, but generally has fewer trees than the other areas, particularly along the less dense Northern, Eastern and Southern boundaries. It also has large areas of open land (natural grass and cropland) between residential areas	Namakgale temperatures vary quite significantly with denser areas nearer to the rivers/streams being slightly more forested and having lower temperatures (35-36°C). Areas more on the ouLSTirts, and further away from the rivers and streams are generally more dispersed, have less vegetation and are warmer-increasing up to 40°C, particularly the more open sections.

	Outside of the mining area , non-built-up land is dominated by savanna (around 38°C) , with significant areas of non-irrigated cropland and grassland around the edges of the settlements (over 40°C and reaching up to 42°C).	
Pilanesberg Appendix *Fig A4 #2* *Population 100'000)* *(-25.29, 27.20)* *1050-1150masl*	Study area is very spread out, consisting of a number of isolated settlements along the borders of the national park. These are predominantly lower-middle income residential areas with low to medium density of houses interspersed with grassland and some trees. Soils and vegetation vary slightly across the area.	Temperatures are similar across most Eastern settlements (36-38°C.), but a number of areas further North (Saulspoort) as well as Kagiso to the South have warmer temperatures (39-41°C), likely as a result of less reflective vegetation/soils and more bare ground.
	The Sun city resort (tucked into the Southern section of the mountains) and the residential area just South of it are the major exception to this, being heavily forested and well irrigated	Built up areas in the resort show temperatures of 31-33°C vs and the residential area just South around 34°C
	Non-built-up land is mostly grassland and savanna (predominantly 36-37°C), far cooler (4-5°C) than in the adjacent Rustenburg. Some darker more degraded grass and cropland rise to 40°C and more vegetated savanna/woodland are cooler at around 34°C	
Rustenburg *Appendix* *Fig A4, #3* *(Population 550'000)* *(-25.65, 27.25)* *1050-1300masl*	Commercial center in the South of the area. This is surrounded by well-forested, higher income residential areas and irrigated recreational grounds	Commercial and industrial areas (30-37°C) vary significantly depending on roof reflectivity. Residential areas are around 32°C with more forested down to 30°C and less up to 34°C
	To the NE and NW are industrial and lower to middle income residential areas. First of high building density and becoming more spread out as one moves away - More spread out areas are interspersed with cropland, grass, light savanna and mining activity	Denser areas are slightly cooler (35-36°C) with most of the sparse areas rising up to 38°C. Some informal settlements (built on previously mined, darker bare ground) get even hotter, going up to 38-40°C
	The non-built-up grassland, savanna, rainfed cropland and bare ground show very warm temperatures (generally around 40-42°C) while irrigated cropland drops down to below 30°C. Small areas of indigenous forests are between 27 and 32°C (depending on thickness and aspect). Land to the West of the mountains is less degraded and is far cooler (30-34°C).	
Thohoyandou *Appendix* *Figure A5 #1* *(Population 250'000)* *(-23.06, 30.59)* *500-800masl*	Small commercial centert the NW with a number of medium density residential suburbs spread out around it. Hillier, denser and more vegetated suburbs in the northern parts of the area	Lower temperatures averaging about 35-36°C in the Northern suburbs, with more heavily vegetated areas down to 33°C and less vegetated up to 37°C
	More spread out, slightly flatter, less dense and less vegetated suburbs as one moves to the South and East (Xigalo, Malamulele, Jimmy jones, Phapazela, Ramukhuba)	Moving to the South and East, temperatures start rising, with most areas around 38-40°C and a number reaching up to 42°C
	Non-built-up land is predominantly wooded savanna (35-37°C), with large areas of more open savanna (37-39°C), croplands/savanna mosaic (38-42°C) and plantation and indigenous forest in the hillier North and West (27-28°C).	

Upington *Appendix* *Fig A5 #2* *(Population 70'000)* *(-28.45, 21.24)* *800masl*	The main commercial center is situated right against the banks of the river with 2 main industrial areas to the North and North-West. A couple of higher-income, medium density and more forested residential areas lie to the North-East of the center, also hugging the banks of the river or the adjacent irrigated farmland.	The more vegetated North East sectors have relatively lower (but still hot) temperatures of around 36-39°C, with a general trend of closer to the river = more forested, cooler temperatures and further away warmer and less forested. The commercial center shows similar ranges to the SE and SW sectors. Generally around 41°C with slightly cooler over reflective white roofs and slightly more over darker surfaces. The roof reflectivity also plays a large role in the two industrial areas, but with slightly warmer temperatures on average (around 43°C)
	To the South-west and South East (across the river) lies slightly small, less forested middle-income housing a little bit away from the banks of the river.	The South-West and South East settlements (closest to the rivers) generally lie between 40°C and 42°C, again very dependent on tree density. This temperature range is very similar for the more established settlements a bit further away from the river as well. The less established areas on the settlement edges however, show significantly warmer temperatures due to increased bare land and less tree cover, sitting around 44-45°C and even going up to 46°C in parts.
	Moving further away from the river (NW) we get a few more lower-middle income residential areas (medium density), also sparsely vegetated, but with most houses having at least a tree or two outside of them. On the outskirts of many of these settlements, are lower income, smaller and less established housing with very little vegetation and a lot of bare ground around them.	
	Non-built up land is predominantly open shrubland, with mostly low grass/bare ground interspersed with infrequent small bushes. This vegetation shows very hot temperatures, generally around 44°C in the few km's nearer to the orange river and around 47°C further away. Adjacent to the orange river (normally around 1 km each side), there are well irrigated croplands where temperatures range between 32 and 38°C depending on types and size of crops and irrigation.	
Vryburg Appendix *Fig A5, #3* *(Population 50'000)* *(-26.96, 24.73)* *1200masl*	Star shaped settlement with a commercial center; a more established, higher income residential and forested North West sector	The more forested NW sector shows significantly cooler temperatures (33-35°C),
	a North-Eastern sector with a mix of smaller and larger residential houses and scattered trees	The NE and SE areas both vary a bit depending on the density of housing and open spaces, but are generally around 36-37°C
	South-Western Huhudi Township with a mix of smaller, lower income and larger middle income housing and few trees and a Sotuh-Eastern more recently constructed lower-middle income residential area with few trees and bare ground around houses.	South West settlement is a bit warmer at 37-38°C. The commercial and industrial sectors are very dependent on the reflectivity of the roof's with lighter colours as low as 33-34°C and darker 37°C
	The vegetation is predominantly grassland with sections of cropland, open shrubland and savanna between. This results in warm temperatures outside the built up land, mostly sitting between 37 and 40°C, varying with levels of degradation and reflectivity of the vegetation/ground. Small areas of river valleys (33-35°C) and center pivot fields (30-31°C) show far cooler temperatures	

1.2 Results and discussion

1.2.1 Landcover contrasts

Built up land and non built up land. In almost all cases, the LSTs of the built up areas are significantly cooler than the surrounding natural vegetation,croplands and recreational land. This difference is most apparent in the drier, more barren and more degraded areas, with fallow and non irrigated croplands and mining areas often sitting at least 4-5°C higher than the nearby built up land. The Rustenburg and Pilanesberg areas are a good example of the degraded land heat, with its darker colour and lack of vegetation showing temperatures of around 42°C while the built up areas generally range from 33-37°C. Upington is another example of these extreme differences, with its natural sparse shrubland reaching in excess of 47°C while most of the urban areas sit around 40°C.

*Vegetation characteristics within settlement*s. Almost every study area (bar Newcastle) shows very different vegetation patterns from one part to the next. This predominantly follows a form of socio-economic line where more established higher income areas have large numbers and coverage of trees and as one moves towards lower income areas, the trees get fewer and there is more barren land and low vegetation. The temperatures follow this trend very closely, with the most forested parts often being 5+°C cooler than the least forested. Pilanseberg and Rustenburg again show the largest differences here, with the higher income well forested sections being as low as 30°C while informal settlements constructed on barren, degraded land with little to no vegetation rise up to over 40°C. Kuruman, Thohoyandou and Upington also show large differences (all around 9°C) between the coolest and warmest residential areas. In Upington's case, this is closely tied into the closeness to the orange river, with wealthier, forested parts (down to 36°C) built very close to its banks and having amble water to irrigate and support tree growth, while housing areas further away from the river (up to 45°C) are far less vegetated, suggesting less access to irrigation.

Sparse vs densely built up areas. There is a large difference in the temperatures of the built up areas in relation to density. Denser housing areas often show temperatures that are 3°C or more cooler than dispersed areas with large spots of open or bare land between. This is also most apparent where the natural vegetation is more barren or less vegetated. Rustenburg shows this very well, with denser and not well forested areas being as low as 34°C, while their sparser counterparts sit above 37°C and even reach up to 40°C in parts. Upington (40°C vs 45°C), Vryburg (35°C vs 39°C), Mokopane (36°C vs 39°C) and Phalaborwa (36°C vs 40°C) also all illustrate this well.

Reflectivity of roofs. This is particularly apparent in the larger industrial and commercial areas and in residential areas with dense housing. Buildings or areas with very reflective roofs can be as much as 10°C cooler than those with darker, absorbent roofs. In Bloemfontein for example, the very reflective white roofs are as low as 30°C, with darker clay coloured roofs a little higher at 33-34°C and the large, dark metallic roofs of the transnet industrial area up to 40°C.

1.2.2 Reversed urban heat island

The Urban Heat Island (UHI) is a phenomenon seen where built-up areas experience warmer temperatures than their rural counterparts through changes in the energy and water balance. Though this is more related to air temperature and is most apparent at night, it is still very interesting to see how far reversed the situation is in the LST's of all the study areas. Non-built up areas are in most cases warmer than the settlements, with a trend that the denser the settlement, the cooler the temperatures. This is generally due to a) settlements often having more tree cover than naturally occurs in these areas (i.e planted and irrigated), so denser settlements equals more trees (with their cooling properties), more water and cooler temperatures. b) urban surfaces take longer to warm up, so denser equals higher heat capacity and lower temperatures earlier on in the day. c) the reflectivity of the settlements being greater than that of the non-built up land, so denser equals more reflective. All of these show that in warmer South African climates where the natural vegetation is low/minimal there is great potential to create urban landscapes that are thermally more liveable than their rural counterparts.

1.2.3 Thermal inequality and apartheid legacy.

The layout of the study areas and their above mentioned characteristics are themselves dependent on socio-economic and historical factors. Higher income, larger house areas are in most cases far more forested than their lower income counterparts and are subsequently found to be significantly cooler. This is most apparent in study areas where the climate doesn't naturally support extensive tree cover, but where trees and water are available at a cost (i.e Upington and Kuruman). Another factor in this vegetation contrast can be put down to the legacies left behind by South Africa's apartheid policies. The forced removal and relocation of people of colour to townships and homelands meant that the wealthier white population had their pick of the best places to live while others were forced into areas that weren't necessarily suitable or ideal for settlements. In many of the study areas, this separation is very apparent. In Upington the more vegetated, wealthier areas are situated right along the cooler river banks with greater access to its water, while the poorer less vegetated townships are further out and fully exposed to the very harsh temperatures where tree growth is difficult. Rustenburg has a similar geographical separation, with wealthier suburbs situated on the cooler hillside more hospitable for vegetation growth while poorer townships are located in the hotter, more degraded flats and mining areas. These show that while apartheid policies are no longer in place, their impacts on current settlement characteristic are still very much observed. This contributes to the situation where people who are most exposed to extreme temperatures are also those who are the least equipped to deal with them. The people living in these hotter areas have limited access to air conditioning and fans, live in housing which isn't effective in reducing heat, have limited access to healthcare and are also forced to lead more physical lives to access resources and move around.

1.2.4 Limitations

The use of landsat thermal imagery to identify surface temperature distributions has been shown to be very effective, picking up significant differences between settlements and helping to identify areas most susceptible to extreme heat. The imagery itself is however limited in its usefulness. The images used (and all available daytime South African Landsat imagery of the areas) are taken between 9:54am and 10:28am depending on location. The hottest surface temperatures are experienced between 12pm and 1pm, so this means that the landsat temperatures are not necessarily a true reflection of LST distribution or values during the time we are most interested in. Images are also only taken every 16 days and their accuracy is sensitive to cloud cover. This often means that specific heat events are very difficult to study and one is limited to the available clear weather days. Its final limitation when it comes to understanding heat distribution is the fact that surface temperature is just that- surface temperature. What we as humans normally think of as temperature is air temperature or near surface temperature and this is often the more important variable when it comes to impact on human health (Ho et al., 2016). To address these limitations, the addition of a model based study was introduced- the Weather Research and Forecasting (WRF) model.

Part 2

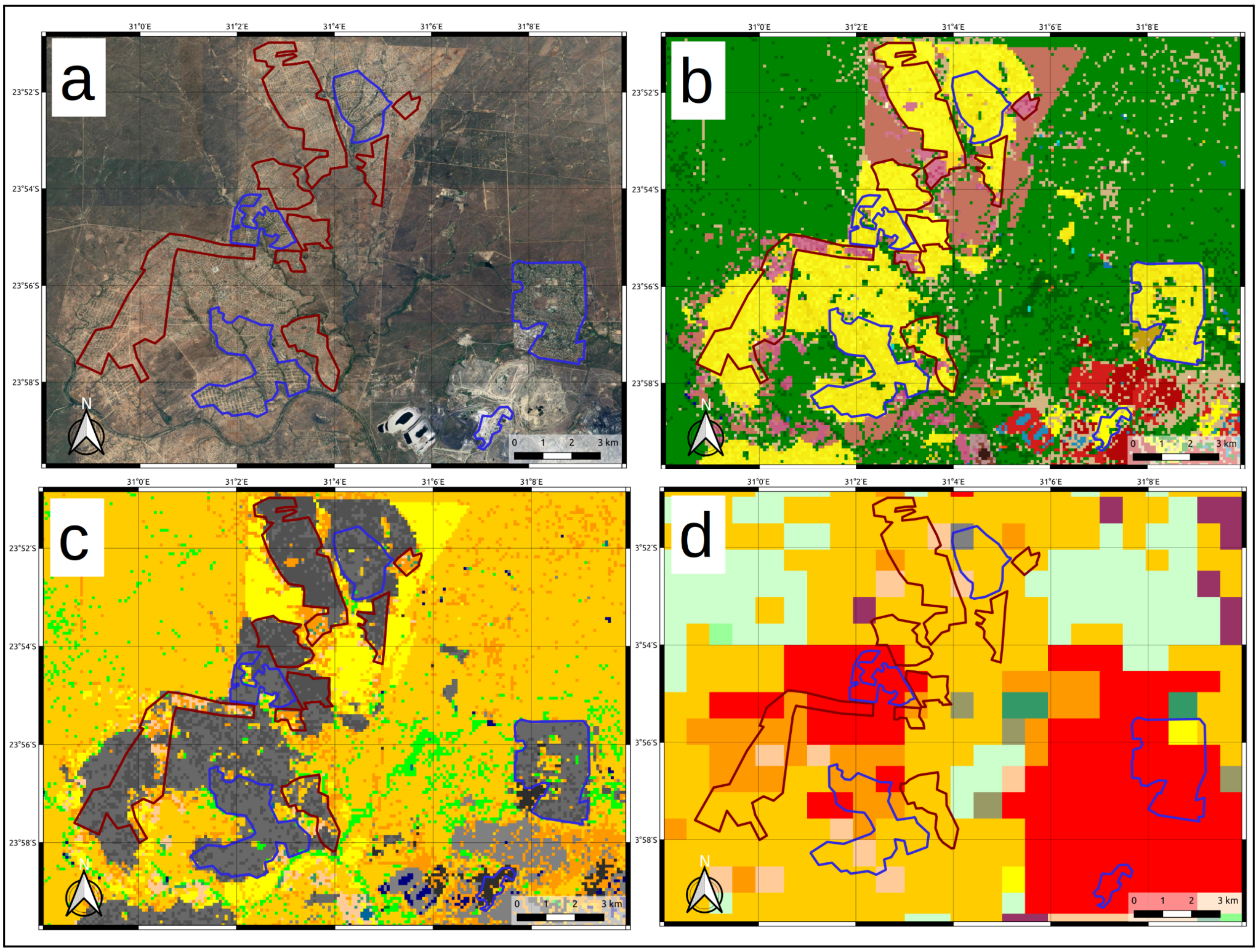


Figure 4 Images of the Phalaborwa study area. a) google satellite. b) SANLC2020 landcover c) SANLC landcover converted to modis classes d) Modis 20class Landcover available in WRF

2.1 Methods

2.1.1 Wrf model

The NCAR Weather Research and Forecasting Model (WRFV4.2.1) (Skamarock et al., 2008) is a non-hydrostatic, fully compressible, and terrain-following (sigma) coordinate model (Skamarock and Klemp, 2008; Skamarock et al., 2008). It is designed for both meteorological research and numerical weather predictions from the microscale to the regional and even global scales (Soltanzadeh et al., 2016). It’s ability to simulate weather at the city level while still taking into account larger atmospheric systems makes it a very good tool for the research conducted in this study..

Table 4. Landcover classes for MODIS, SANLC2020 and the converted SANLC

MODIS category	**SANLC categories converted to MODIS**
Evergreen Needleleaf Forest (1)	5
Evergreen Broadleaf Forest (2)	1, 2, 3
Mixed Forest (5)	42, 57, 61
Closed Shrubland (6)	9
Open Shrubland (7)	8, 10, 11, 43, 46, 58, 62
Savannas (9)	4, 6
Grasslands (10)	7, 12, 13, 59, 63
Permanent Wetlands (11)	22, 23, 24, 33, 34, 38, 39, 73
Croplands (12)	32, 35, 36, 37, 40, 41
Barren or sparsely vegetated (16)	25, 26, 27, 28, 29, 30, 31, 45, 55, 60, 64, 69, 70, 71, 72
Water (17)	14, 15, 16, 17, 18, 19, 20, 21
Low density residential (31)	47, 48, 51, 52, 53, 56
High density residential (32)	49, 50, 53, 54
High intensity industrial (33)	65, 66, 67, 68

SANLC 2020 categories	
1.	Contiguous (indigenous) Forest
2.	Contiguous Low Forest & Thicket
3.	Dense Forest & Woodland (35 - 75% cc)
4.	Open Woodland (10 - 35% cc)
5.	Contiguous & Dense Planted Forest
6.	Open & Sparse Planted Forest
7.	Temporary Unplanted Forest
8.	Low Shrubland (other regions)
9.	Low Shrubland (Fynbos)
10.	Low Shrubland (Succulent Karoo)
11.	Low Shrubland (Nama Karoo)
12.	Sparsely Wooded Grassland (5 - 10% cc)
13.	Natural Grassland
14.	Natural Rivers
15.	Natural Estuaries & Lagoons
16.	Natural Ocean, Coastal
17.	Natural Lakes
18.	Natural Pans (flooded @ obsv time)
19.	Artificial Dams (incl. canals)
20.	Artificial Sewage Ponds
21.	Artificial Flooded Mine Pits
22.	Herbaceous Wetlands (currently mapped)
23.	Herbaceous Wetlands (previous mapped extent)
24.	Mangrove Wetlands
25.	Natural Rock Surfaces
26.	Dry Pans
27.	Eroded Lands
28.	Sand Dunes (terrestrial)
29.	Coastal Sand Dunes & Beach Sand
30.	Bare Riverbed Material
31.	Other Bare
32.	Cultivated Commercial Permanent Orchards
33.	Cultivated Commercial Permanent Vines
34.	Cultivated Commercial Sugarcane Pivot Irrigated
35.	Commercial Permanent Pineapples
36.	Cultivated Commercial Sugarcane Non-Pivot
37.	Cultivated Emerging Farmer Sugarcane Non-Pivot
38.	Commercial Annuals Pivot Irrigated
39.	Commercial Annuals Non-Pivot Irrigated
40.	Commercial Annuals Crops Rain-Fed / Dryland
41.	Subsistence / Small-Scale Annual Crops
42.	Fallow Land & Old Fields (Trees)
43.	Fallow Land & Old Fields (Bush)
44.	Fallow Land & Old Fields (Grass)
45.	Fallow Land & Old Fields (Bare)
46.	Fallow Land & Old Fields (Low Shrub)
47.	Residential Formal (Tree)
48.	Residential Formal (Bush)
49.	Residential Formal (low veg / grass)
50.	Residential Formal (Bare)
51.	Residential Informal (Tree)
52.	Residential Informal (Bush)
53.	Residential Informal (low veg / grass)
54.	Residential Informal (Bare)
55.	Village Scattered (bare only)
56.	Village Dense (bare only)
57.	Smallholdings (Tree)
58.	Smallholdings (Bush)
59.	Smallholdings (low veg / grass)
60.	Smallholdings (Bare)
61.	Urban Recreational Fields (Tree)
62.	Urban Recreational Fields (Bush)
63.	Urban Recreational Fields (Grass)
64.	Urban Recreational Fields (Bare)
65.	Commercial
66.	Industrial
67.	Roads & Rail (Major Linear)
68.	Mines: Surface Infrastructure
69.	Mines: Extraction Sites: Open Cast & Quarries
70.	Mines: Extraction Sites: Salt Mines
71.	Mines: Waste (Tailings) & Resource Dumps
72.	Land-fills
73.	Fallow Land & Old Fields (wetlands)

2.1.1.1 Landcover dataset

The WRF landcover datasets available over South Africa are very limited in their resolution and spatial accuracy, which at a country-wide or regional level is not an issue, but down at a city scale, this becomes a major limitation. A higher resolution and more accurate landcover dataset therefore becomes very important to show local contrasts. The South African National Landcover Dataset is a GIS based landcover map produced for the Department of Forestry, Fisheries and the environment that aims to "inform a wide variety of activities ranging from environmental planning and protection, economic development, compliance monitoring, enforcement, and strategic decision making." (ref). While it is not made with climate modeling in mind, its separation of landcover types at a resolution of 30m and into an extensive 73class dataset, means that it has the potential to convert into a very useful input for climate models. The creation of the dataset has also now been moved to an automated CALC system which means that it will be updated far more timeously (biennially) than most other landcover datasets, removing errors that could occur with quick changing classes.

To be able to use the dataset in the WRF model, it has to be converted into something the model can read. To do this, the modified IGBP modis noah was chosen as a template to convert the 73class dataset onto, combining classes that would be expected to have similar thermal properties. The method of conversion was based upon the descriptions of each landcover class in the SANLC2020, the observation of different landcovers compared with satellite imagery and the related descriptions of the properties of landcover classes making up the modis dataset. Once it had been decided which modis landcover class each sanlc class would be converted to (Table 4.), a FORTRAN script was created to read in each pixel of the sanlc dataset (Fig 4b) and replace it with the subsequent modis class, producing a final dataset as seen in (Fig 4c)

2.1.1.2 WRF-Coupled Urban Canopy Model (UCM)

The creation of the new sanlc dataset divides urban landcover classes into 3 categories (low density residential, high density residential, and high-intensity industrial) where the original modis dataset had only 1 urban class. This separation of classes means that we can now assign different physical characteristics to the classes to make them more representative of what is on the ground. This is done by coupling the WRF model with a single layer UCM (Kusaka et al, 2001, 2004) and editing the URBPARM table for the specific study/areas needs. In this manner one can adjust variables like building size, road width, urban fraction, roof albedo and a whole host of others.

2.1.1.3 Experimental design

This study requires the model to be run at high resolution in order to pick up city scale changes in variables. To do so while limiting computational power and still picking up larger scale atmospheric forcings, nesting was used. This involved creating a model domain with a parent at 1800m resolution, a daughter domain at 600m and then our final study area domain at 200m resolution (Table 5). Apart from defining the model domains and resolutions, the model has a number of physics schemes which need to be specified according to the scopes of the study. The one used in this research is based on the WRF user guide suggested high resolution setup and is summarised in Table 6.

Table 5. Basic simulation set-up for all 4 simulation scenarios

Length (hours)	Spin-up (hours)	Nests	Initial conditions	Feedback	Time-step (seconds)	Resolution (nest 1, 2, 3)	Number of cells (longitude x latitude
45	21	3	GFS data	One directional	7, 7/3, 7/9	1800m, 600m, 200m	199x199

Table 6.. Physics options used in WRF simulations

Physics Variable	Option used
Microphysics (mp_physics)	Thompson
Longwave radiation (ra_lw_physics)	RRTMG scheme
Shortwave radiation (ra_sw_physics)	RRTMG scheme
Land Surface (sf_surface_physics)	Unified Noah LSM
surface layer (sf_sfclay_physics)	Eta similarity method
Planetary Boundary Layer (bl_pbl_physics)	Mellor Yamada Janjic

To test the influence and usefulness of the newly created sanlc dataset, simulations for each of the locations were run using both the sanlc and the modis landcover datasets (the highest resolution WRF landcover dataset available). The dates of these simulations were chosen from the group of Landsat thermal images that was processed earlier in the study. These were cross-referenced with observational weather data (SAWS and *weather underground)* to choose the hottest day with weak synoptic conditions (winds below 20km/h). (Table 7)
The output variables from simulations were then compared. WRF LST outputs were analysed against the landsat imagery from that day (Fig .5, 6) and WRF Air temperature (T2m) was plotted against observational air temperatures from the South African Weather service (Fig. 7) The station air temperatures for Phalaborwa and Thohoyandou were unfortunately not available on these days, so this was limited to the other 8 locations.

Table 7. Dates used for each locations simulations

City	Simulation date		
Bloemfontein	2015-11-10	Pilanesberg	2015-11-10
Kuruman	2018-11-16	Rustenberg	2015-11-10
Mokopane	2016-01-06	Thohoyandou	2016-10-29
Newcastle	2015-12-30	Upington	2016-12-03
Phalaborwa	2016-10-29	Vryburg	2017-11-06

Once WRF had been validated against the observational data, we were able to manipulate the characteristics of the landcover dataset to represent feasible heat adaptation/mitigation strategies. The review study by (Santamouris and Fiorito, 2021) provided examples of reasonable values of roof albedo, while the tree coverage present in the more vegetated study areas provided a good base to work towards for changing urban fraction. For the two scenarios, the Urban fraction and Roof albedos were adjusted (in separate simulations) to represent a) an increase in tree cover to 60% of the urban area and b) an increase in the albedo of roofs from 0.2 to 0.4. Table 8. Summarises the differences in these, as well as the initial modis and sanlc WRF simulations .
These experiments were then compared with the sanlc “control” simulation to see the impact the changes had on LST and T2m (Fig.9, 10, 11)

Table 8. Differences between the 4 WRF simulation scenarios

WRF Simulations	Landcover resolution and type	Urban Climate Model (UCM)	
		Urban fraction	Roof albedo
MODIS	500m Modis	UCM not used	
SANLC	100m Sanlc converted	0.4, 0.9, 0.9	0.2, 0.2, 0.2
SANLC with 0.4 urban fraction	100m Sanlc converted	0.4, 0.4, 0.4	0.2, 0.2, 0.2
SANLC with 0.4 roof albedo	100m Sanlc converted	0.4, 0.9, 0.9	0.4, 0.4, 0.4

2.2 Results and Discussion

2.2.1 Landcover dataset

The landcover dataset used has a direct influence on the surface temperature and it is therefore very important to understand the differences between the respective modis dataset and the converted sanlc dataset.

Using (Fig. 4d) as an example, one can see how the lower resolution *Modis landcover* doesn't pick up the spatial extent of urban areas very well. It roughly identifies the larger, more established areas, but with little precision, often being skewed a few km away from the actual expanse. It doesn't pick up many of the smaller, newer and less established areas at all. The higher resolution *converted Sanlc dataset* identifies the spatial extent of the populated areas extremely well and also splits the urban areas into three categories (high intensity, low intensity and industrial) versus the Modis 1 category. The sanlc dataset also identifies the majority of water bodies and smaller scale changes in vegetation which the Modis fails to do.

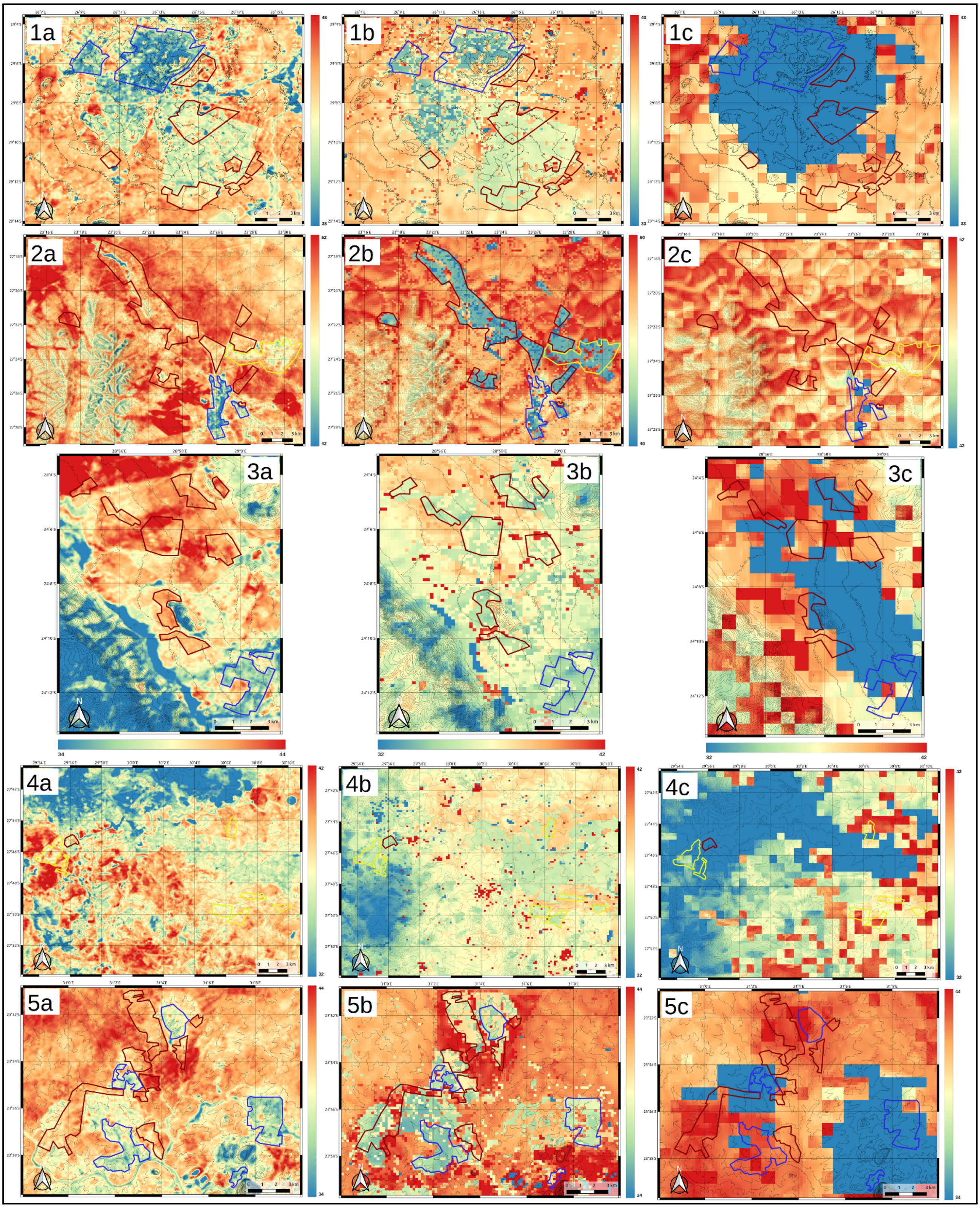


Figure 5. LST at ~10am (UTC+2) for study areas 1-5 with a) Landsat thermal image b) WRF control scenario and c) WRF modis scenario. Note that temperature scales differ between landsat images and wrf images in order to better capture spatial differences

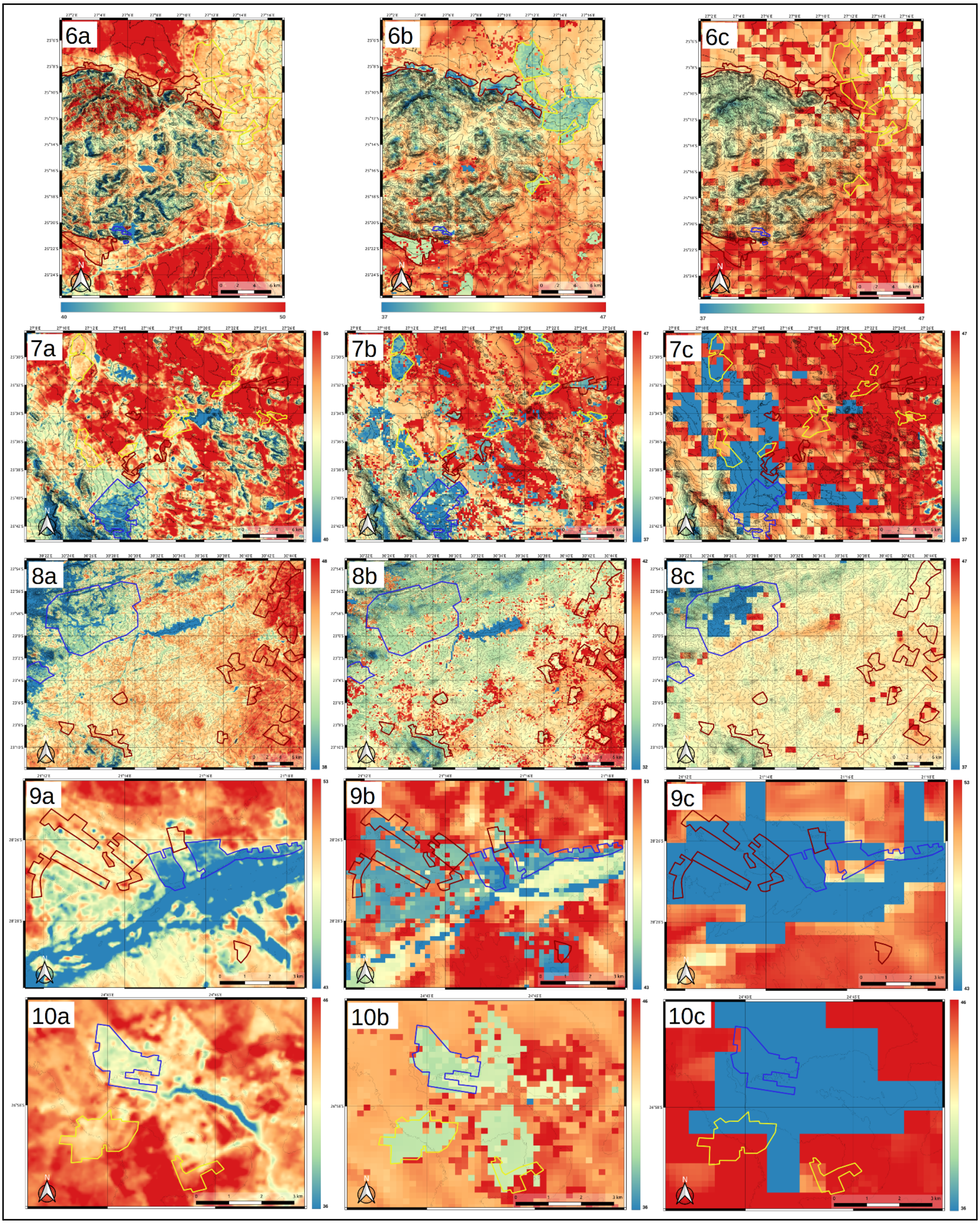


Figure 6. Same as Figure 5.. above, but for study areas 6-10.

Table 9. Summary of LST differences between MODIS and SANLC WRF simulations

City	MODIS	SANLC
Bloemfontein	Most of the urban area identified and shown to be ~15-20℃ cooler than observed with a cooler south vs North. General ~5℃ cool bias across non-built up areas compared to observed	A ~5℃ cool bias across the area when compared to observed. Without this LST's are within 3-5℃ in urban areas and within 3℃ outside. The Cooler North vs South that is observed is well identified identified by the model(3-4℃ difference)
Kuruman	Only 4 small squares are identified as urban with these 10-15℃ cooler than observed. Rest of the areas are identified as natural and are within 4°C of observed.	Significantly underestimates warmer Northern urban area LST's (5-10℃). Identifies the vegetated southern areas well (within 3℃). Shows slight differences in urban LST's ,but not accurately. Outside urban areas are generally well predicted (within 4℃)
Mokopane	Most urban areas are roughly identified, showing 10-15℃ lower LST's than observed with urban areas not identified (i.e natural) being far more similar to observed . Non-built up areas slightly underestimated (3-5℃)	Simulates the cooler Southern section well (within 3°C), but underestimates the less vegetated, warmer urban areas by ~5℃. Picks up the observed differences between cooler and warmer areas with a slightly smaller difference than observed. Non-built up areas slightly underestimated (3-5℃)
Newcastle	Urban expanse roughly identified, but skewed to the N of actual location. and LST's here are 10-15°C lower than observed . Outside of urban areas is a slight cool bias to the West and South (3-5℃) and warm bias to North	Urban areas show very similar LST's to observed (within 3℃). Partly identifies slightly cooler urban areas to the North of center, but not the warmer urban areas to the South. Outside there is a slight cool bias to hilly West and South (3-5℃) and warm bias to North (3-5℃).
Phalaborwa	Extent of the urban area to the East is overestimated and areas to the West very under- represented. ~10℃ underestimation of LST in these urban areas. Outside urban is generally well simulated (within 3℃)	Urban LST's are well represented (within 3℃ of observed for the most part). Differences within urban are picked up, though slightly underestimated and not always spatially accurate. Outside urban is generally good (within 3℃), apart from SE mining area which is strongly overestimated ~10°C
Pilanesberg	No urban areas are identified so urban is treated as natural which shows LST's across all areas very similar to observed (within 3℃) apart from underestimating NW temps (~5℃) and underestimating Sun City (~5℃)	Urban LST's significantly underestimated (5-8℃) apart from cooler Sun city which is similar to observed (within 3℃). Outside of built up area is similar to observed with a slight underestimation trend (3°C rising to over 5℃ in NW)
Rustenburg	Majority of the urban expanse is roughly identified. LST's 10-15℃ cooler than observed here. In general around 2-3℃ underestimation of LST's outside urban area apart from dam/mining areas.	Picks up spatial differences and shows some skill in identifying differences between cooler and warmer urban areas, but underestimates hotter urban areas by 5-10°C. Southern cooler areas are better represented. In general a 3-5°C underestimation of LST's across most areas
Thohoyandou	Only a small area in NW Identified as urban and shows LST's of 10-15℃ lower than observed. Other areas treated as natural show similar values to observed (within 3℃) apart from the NE- being underestimated by ~5°C.	Picks up the NW to SE temperature gradient well and shows slight differences between the cooler and warmer urban areas. Underestimates temperatures across the board by 5-10℃ because of sanlc forest landcover. Taking out 5℃ bias shows similar to control values
Upington	Roughly identifies the urban areas with the exception of Southern section. Underestimates temps by 8-18℃ (colder vs warmer urban areas). Similar to observed (3-5℃) in non urban areas apart from water features (~10℃)	Picks up the cooler city vs surroundings, and is very similar to observed in cooler areas, but slightly underestimates city temps in warmer areas by around 4-5℃. Similar to observed (3-5℃ difference) in non urban areas apart from irrigated land and which it overestimates (10+℃)
Vryburg	Roughly identifies the urban extent, but slightly skewed to north. Underestimates temperatures in urban areas by 10-15℃ and slightly overestimates LST's outside (~3℃)	Picks up LST spatial differences well and shows some of the slight differences between urban areas. Slightly underestimates temperatures in warmer urban parts (3-4℃), but is very close to observed in cooler parts of the urban area. Outside urban areas LST's are within 3℃ of observed.

2.2.2 Land Surface Temperature validation

As was seen in the landsat thermal imagery, The LST distribution simulated by the models is highly influenced by the landcover.. This is very apparent across all outputs, with temperature changes showing very similar patterns to landcover changes.

In the *Modis* simulations this tends to mean that the spatial extent of the urban areas are both simplified and under-represented. This is most notable in Kuruman, Pilanesberg and Thohoyandou where only very small sections of the urban or populated areas are actually identified as such. Where urban areas are identified, the modis simulations pick up the cooler city versus rural LST values, but consistently underestimate these values by large margins. For most of the cities this is by at least 10℃ in the cooler urban areas and up to almost 20℃ in the warmer regions.

The *sanlc* simulations pick up the LST spatial patterns very well, but they too tend to underestimate LST values across the warmer areas of cities, but to a far lesser extent. This underestimation is most apparent in the more spread out and less established urban areas, with values between 5 and 10℃ cooler than observed in the warmer parts of Kuruman, Thohoyandou, Pilanesberg and Rustenburg. By comparison, the modis simulations are more accurate in these warmer areas due to them being treated by the model as natural vegetation rather than urban. When it comes to the cooler areas across all 10 cities, they are far better simulated with the sanlc and generally lie within 3℃, apart from Bloemfontein, Thohoyandou and Rustenburg which are closer to 5°C because of a general cold bias in their simulations.

The simulation of the non-urban areas surrounding the cities is very similar between the modis and sanlc datasets, and in general both do well when comparing to the observed values- sitting within 3-5℃ across most of the areas. There are some exceptions to this, most notably in Thohoyandou where the conversion of the sanlc has classified the dominant vegetation as forest, where it would likely do better as the savanna or woody savanna as in modis, leading to an approximate 5°C cool bias across the board. Pilanesberg has a similar situation where the sanlc treats some of the area's as savanna and underestimates LST's slightly (~3℃) while the modis treats it as open shrubland and shows more similar LST's to observed. Rustenburg and Bloemfontein also both show a noticeable cool bias of around 3-5℃ in both modis and sanlc simulations which could be put down to landcover issues or a general underestimation of temperatures on those days. On a smaller scale, water features, croplands and mining areas show large differences in simulations versus observed, with the modis landcover not picking up the majority of these features at all. The sanlc does far better in identifying these areas and in general does well with valuing water features, but can struggle with croplands due to the wide range in properties from well vegetated and irrigated to low vegetated and non-irrigated.

In terms of differentiating between LST's of different urban landcovers, the sanlc simulations show skill in picking up cooler vs warmer urban sections. This is very noticeable in Bloemfontein and Phalaborwa, but can be identified across all study areas. This difference is however less apparent than in the observed LST's, with modeled differences reaching a maximum of around 4℃ while observed values often reach over 5℃ and even up to 10℃.

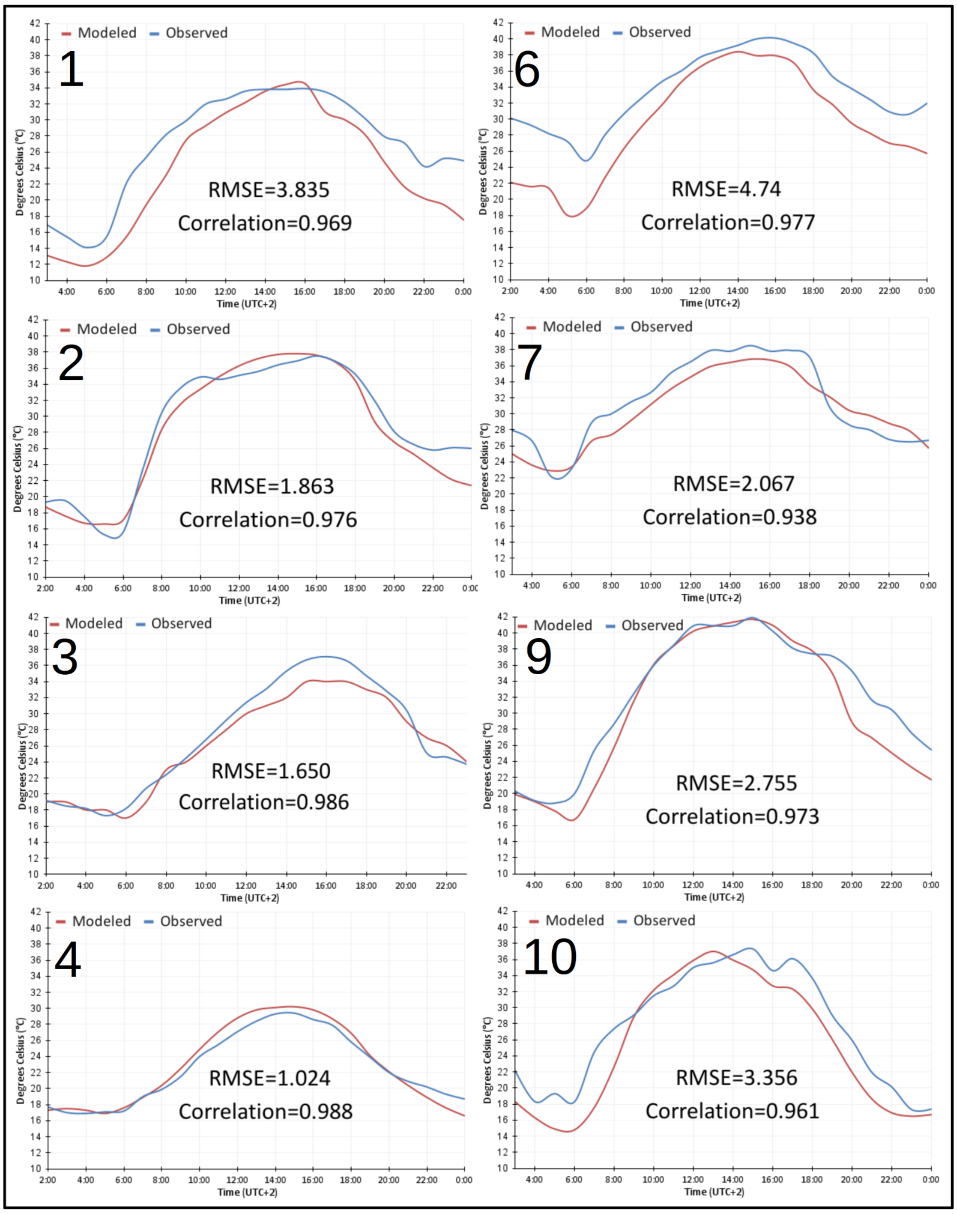


Figure 7. Plots comparing air temperature of WRF control simulations (red) with that of the available location's station data. Station data for location 5- Phalaborwa and location 8- Thohoyandou were not available.

2.2.3 Air Temperature validation

The use of a climate model has the major draw of being able to study a huge array of variables. Air temperature is the more common value we as humans are accustomed to using when it comes to heat. It has also been shown to be the more comparable variable when relating to heat related illnesses and deaths (reference). To be able to use the model outputs effectively and trust its simulations, it is important to compare with known values. (Fig. 7)

The diurnal profile of air temperature across all 8 locations has been very well simulated by the model, with correlation values all over 0.96 apart from Rustenburg at 0.938. This shows that the model picks up changes in temperature well and gives a good overall idea of the “shape” of temperature in each location. The air temperature values simulated by the model are also shown to be similar to the observed, with 7 of 8 locations having an RMSE under 4℃. Pilanesberg has a larger RMSE of 4.74℃, with it strongly underestimating the temperatures during the morning and late afternoon, but still doing well during the middle of the day. Newcastle (1.024), Mokopane (1.65), Kuruman (1.863) and Rustenburg (2.067) all show very good estimations of air temperature across the day. What we are most interested in however is the prediction of the hot midday temperatures. Looking at the profiles, one can see that these too are well simulated with 5 of the 8 showing maximum temperatures within 1℃ of the observed, while Pilanseberg (~2℃), Rustenburg (~2℃) and Mokopane (~3℃) show slight underestimations.

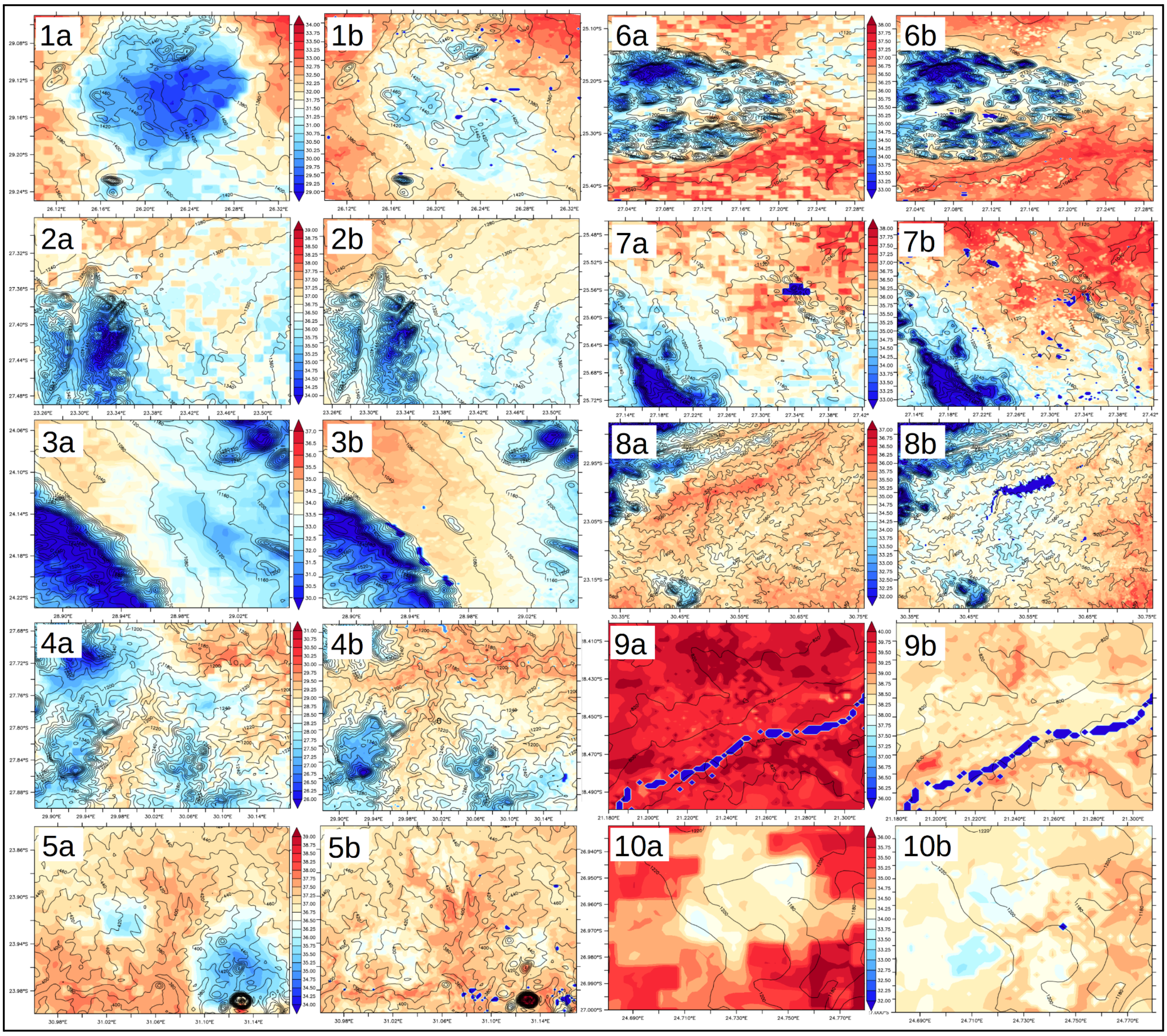


Figure 8. WRF air temperature (T2m) distribution for each study location averaged for the period 10am to 5pm (utc+2) with a) modis simulations b)sanlc converted (control) simulations.

2.2.4 WRF air temperature distribution

The spatial distribution values of T2m across the modis and sanlc scenarios (Fig, 8))is far more similar than for the equivalent LST values (Fig .6). There is however still a very strong correlation between the landcover, LST's and the air temperature. T2m, particularly in the flatter and denser locations (i.e Bloemfontein, Vryburg), shows almost identical general patterns to that seen in the sanlc landcover and the LST's. In the other locations there is still a very noticeable relationship between the variables, but other factors like topography (Mokopane) and water features (Upington) seem to be impacting the distributions more than they previously had. While it is hard to properly validate air temperature distribution without an extensive observational study, these results definitely point towards LST being a useful predictor of T2m as shown in (Oyler et al., 2014), which would give extra validation to using LST variables as a predictor on extreme heat and it's impact on people.

2.2.5 Model skill and limitations

Surface Temperatures. The sanlc simulations show a vast improvement in simulating city scale LST compared to its modis equivalent . This is mostly due to the higher resolution and greater separation of classes, most importantly the separation of urban classes into varying levels of intensity and the subsequent addition of the Urban Canopy model. While the conversion of the sanlc dataset in this manor has been shown not to be a perfect one size fits all, it serves as a very good base to work from, with the ideal situation being that the landcover of each study area is specifically converted for its local properties- i.e in an area like Thohoyandou the natural forest and low intensity urban could be easily converted into woody savanna and a more spread out urban class with less tree cover. In this manner, the UCM characteristics can also be adjusted for each city's specific conditions- buildings and road sizes, vegetation fraction, natural vegetation, albedo of buildings and roofs etc. This would be especially important in differentiating between the low intensity urban classes of the more spread out and less vegetated areas observed in Kuruman, Thohoyandou and Pilanseberg and that of the denser, more vegetated equivalent in Bloemfontein, Vryburg and Upington. These changes could be guided by the results seen in the modis simulations where the urban areas not identified by the landcover dataset actually predicted the LST's of these more spread out, low vegetated areas better than those which were identified as urban in the sanlc dataset.

Though the model's sanlc based simulations are not fully accurate in estimating LST values across all the areas, it shows very good skill in representing their spatial distribution. It is therefore assumed that this can provide a useful base or control to test the impact of changes in the sanlc dataset's urban characteristics on these LST's.

Air Temperatures. The validation of 8 locations modeled T2m with the observed stationair temperature showed very good results, especially in simulating the hottest parts of the day. It can therefore be expected to provide useful information regarding changes in this variable under the two landcover change scenarios.

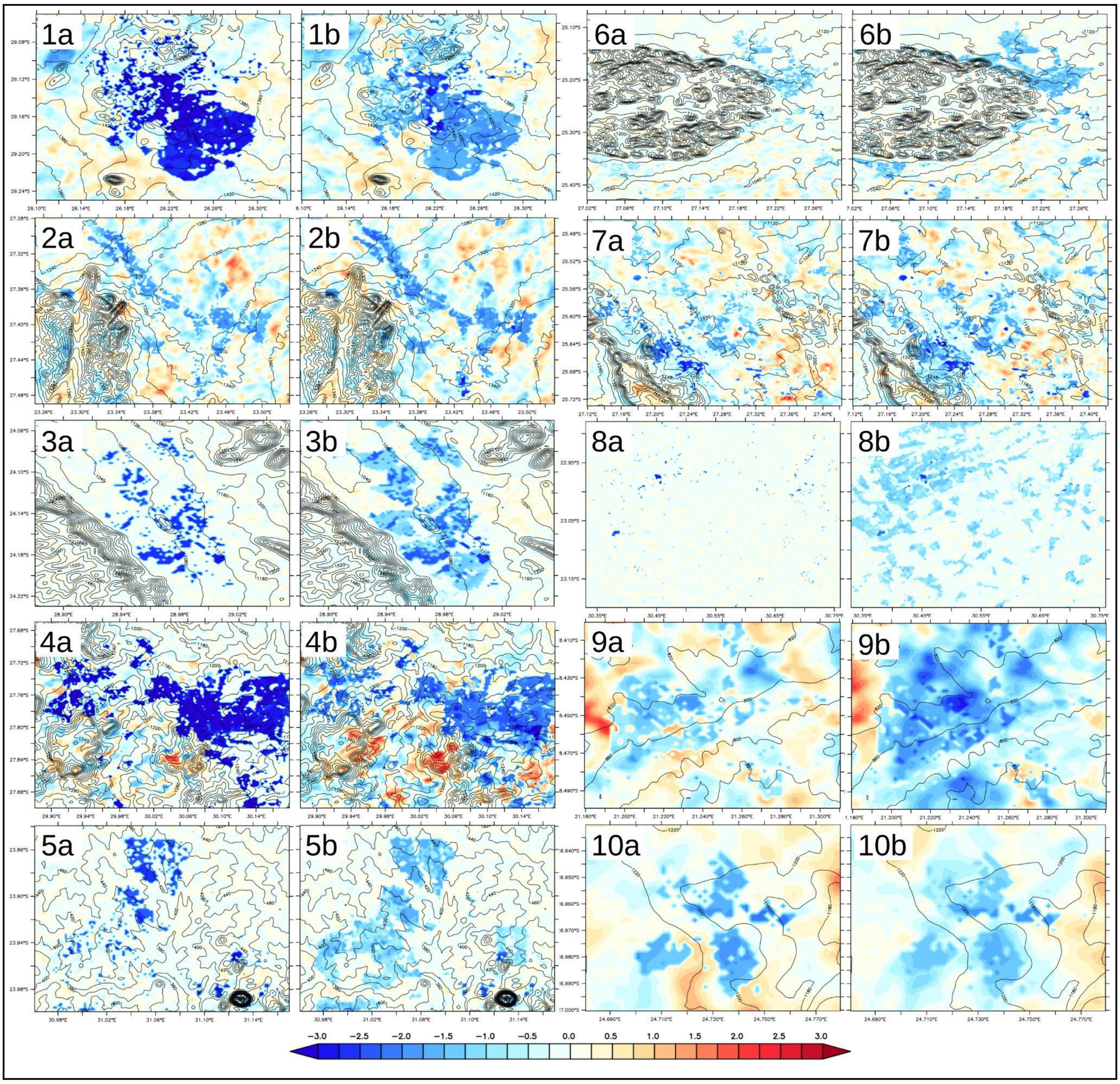


Figure 9.. Difference in LST between WRF experiments and control for each study area averaged across the period 10am to 5pm. a) urban fraction scenario b) roof albedo scenario

2.3 Heat adaptation scenarios

2.3.1 LST's

The change in both Urban fraction and roof albedo have cooling effects across the board, but these vary in intensity depending on location and landcover type.

Trees. The cooling through changes in urban fraction is as expected far greater in areas that were previously classified as having few trees (high-intensity urban and commercial/industrial which both had an initial 10% cover) than in low-intensity urban which already had 40% tree cover). This cooling averages ~3℃ across these less vegetated areas and is very prominent in the larger, denser cities of Bloemfontein and Newcastle. Apart from Thohoyandou, the other cities also all show noticeable cooling, but across less of the areas, or to a slightly lesser extent. Thohyandou only shows cooling in the small industrial sections as the landcover across most of the remaining area is already low-intensity (40% cover).

Albedo. Cooling due to increased roof reflectance shows similar patterns to that of trees, with it again related to the urban landcover type, but less so. This relationship occurs because the larger roofs of industrial areas and the denser nature of high-intensity urban means these both have greater overall roof coverage meaning greater potential for increase in albedos and subsequent greater cooling ability than the lower intensity, more spread out urban class. For most of the study areas, this cooling is around 2℃ across the urban extent, with slightly stronger cooling (~2-3℃) in higher intensity urban and industrial areas and less in the lower intensity (~1-2℃).

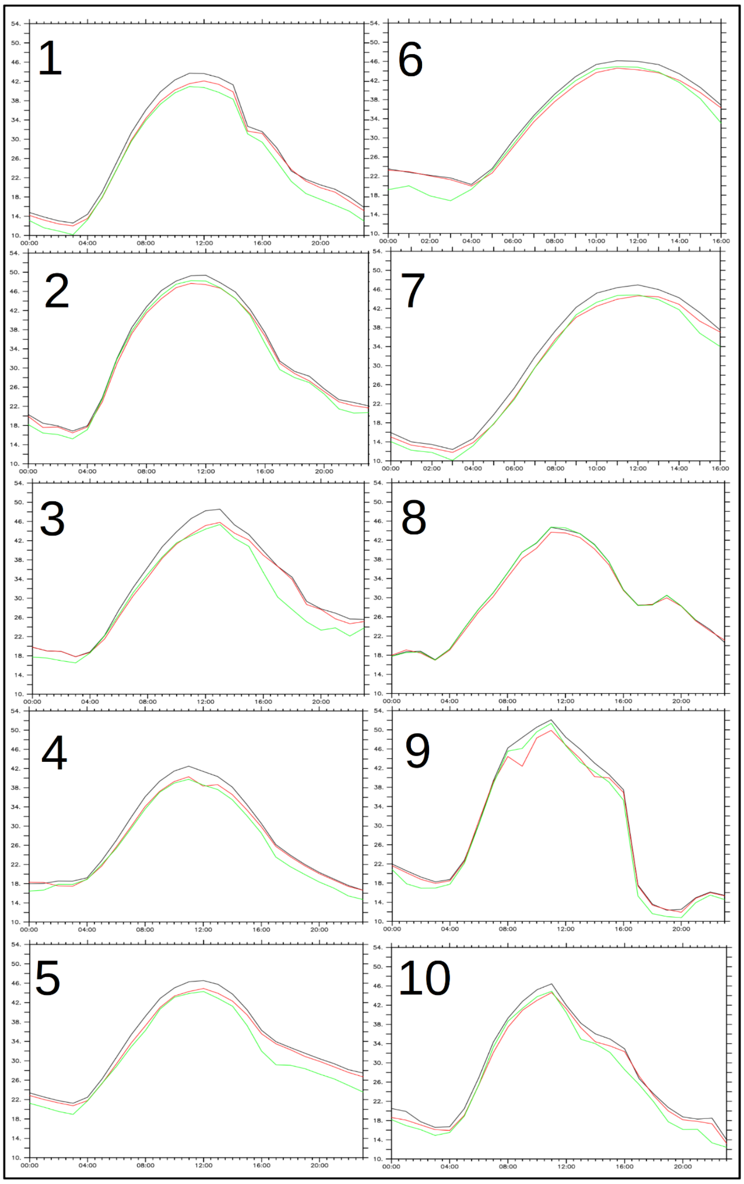


Figure 10.. Plots comparing the LST's of WRF's sanlc control (black), urban fraction scenario (green) and roof albedo scenario (red) simulations.

Diurnal profile. The cooling effectiveness of the methods on LST also shows a strong diurnal or temporal cycle. The cooling by trees is present across entire days, but is most prominent during the midday hours (11am to 4pm) and during the night (8pm through to 5am), reaching up to and over 4℃ during these times. This trend is present to some extent across all the study areas bar Thohoyandou where the landcover did not change. The increased albedo scenario shows the same midday peak cooling, also reaching up to 4℃ in places but lasting slightly shorter than the tree peak (11am to 3pm). The rest of the day shows very slight cooling and then the night-time hours show little to no effect on temperature, illustrating albedo's reliance on direct sun reflectance for cooling.

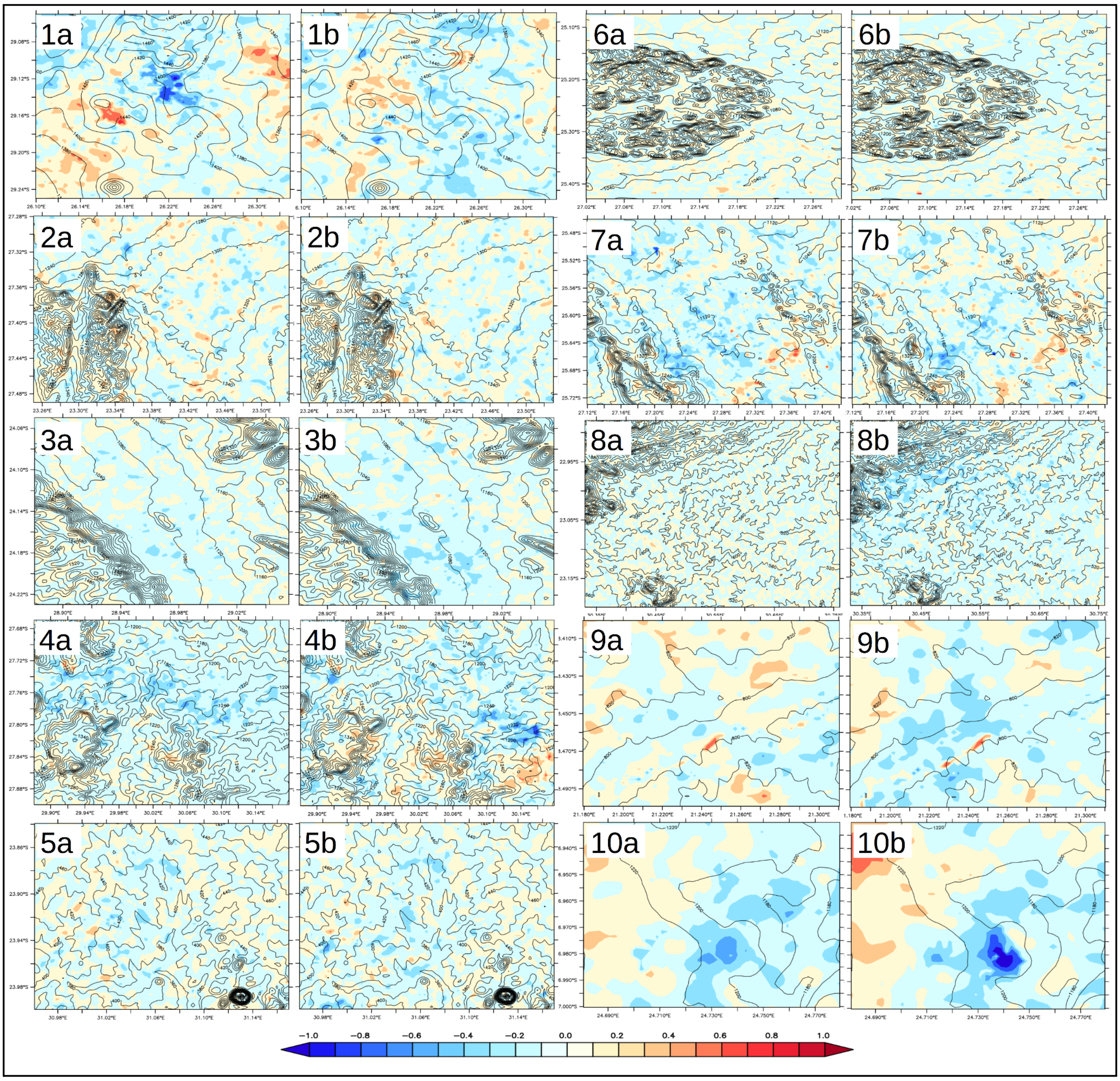


Figure 11.. Difference in LST between WRF experiments and control for each study area averaged across the period 10am to 5pm. a) urban fraction scenario b) roof albedo scenario

2.3.2 Air Temperatures

There is a noticeable relationship in the distribution of air temperature change with that seen in LST change distribution, particularly in Newcastle and Rustenburg. The study areas of Mokopane, Phalaborwa, Thohoyandou, Upington and Vryburg also show similar patterns of change to those of LST's while Bloemfontein and Kuruman show little obvious relationship to LST. The cooling is as expected far less than that seen with surface temperatures, with the more fluid air temperatures not as directly dependent on landcover type, bur this cooling is still observed across all areas to some level. In most locations, the effect of albedo change versus tree cover change is very similar and larger cooling occurs for both scenarios in parts of Newcastle (~0.5-1℃), Rustenburg (~0.4-0.7℃) and Vryburg (~0.4-1℃). The increased tree scenario in Bloemfontein also shows a small section of cooling around 1℃, but given its location, this seems likely to be driven more by other factors like topography than the change in landcover.

While the values of air temperature differences are minimal compared to surface temperatures, small changes in this variable have been shown to have significant impacts on human health and mortality. A review of urban albedo'a impact on temperature by (Santamouris and Fiorito, 2021) estimated that for every 1℃ drop in temperature on hot days, there is a decrease in heat related deaths by approximately 20%.

2.3.3 Albedo versus Trees

Both the scenarios consistently produce cooling across the study areas, with little differences between the maximum midday cooling we are most interested in. For this reason, choosing one method over the other would likely come down to how well they can be implemented in the specific study areas. Tree's in real life take many years to be effective cooling mechanisms, and also come with a significant burden on water resources in these hot, dry environments. Many of these study areas have also been shown to be vulnerable to cold related mortality during winter and by adding trees- this could actually negatively impact mortality. On the other hand, trees also provide ecosystem services- reducing carbon dioxide and soil erosion and producing fruit. Changing roof albedo is a comparatively simpler/more immediate strategy, with all it needing is a good coat of paint or a slight change in building material

2.3.4 Limitations

The first issue with these specific experiments is that they are based on an LST control map which has already been shown to underestimate temperatures in urban areas. To produce more accurate results, the sanlc landcover map and the WRF-UCM model setup first need to be adjusted for each location to create a more representative map. The next is that model based changes in landcover are great in theory, but the implementation and scale of proposed changes is always different on the ground and so are the actual effects. Combining ground measurements and actual physical changes in land cover would be a great addition to test the effectiveness of the model and provide better information to simulate.

3. Conclusions

The study has managed to successfully map city-scale changes in temperature distributions and identify areas within these that are most susceptible to hot extremes. The method of combining both thermal imagery and climate model simulations has provided information that is both spatially and temporally continuous and which can be manipulated to understand how heat in cities could change under different scenarios. The addition of the converted sanlc landcover dataset has been shown to have great potential in improving the simulations of surface temperatures in cities. If minor adjustments are made based on a specific study areas characteristics, it is thought that this could reproduce surface temperatures to within 1-2℃ across a city area, providing a great framework for future studies in South Africa.

The information produced in the study has emphasised the existence of significant thermal inequality in South African cities. LST differences of up to 10℃ between wealthier, well forested houses and bare informal settlements have been observed, showing again how the people least equipped to deal with extreme heat, are also the ones most exposed to it. What the study has also shown though, is the potential of cities to become refuges from extreme heat. Both LST's and air temperatures have consistently illustrated significantly lower temperatures over large parts of the urban areas compared with their rural surroundings. This is likely as a result of the study areas being situated in environments which do not naturally support major "cool vegetation" growth on their own, and so the human impact has actually increased this vegetation coverage over the areas. What one could gain from this, is that adaptation measures have already been proven to work and now by focusing on improving the areas which do still experience more extreme temperatures, we can create liveable cities. To do this though, one needs to implement solutions that are both suited for the specific location and which are also sustainable in the long term.

4. References

Artis DA, Carnahan WH. 1982. Survey of emissivity variability in thermography of urbanareas. Remote Sens Environ. 12(4):313–329.

Ayanlade, A., Aigbiremolen, M.I. and Oladosu, O.R. (2021) "Variations in urban land surface temperature intensity over four cities in different ecological zones," Scientific Reports, 11(1). Available at: https://doi.org/10.1038/s41598-021-99693-z.

Chand, P.K., Murthy, P., 2008. Climate change and mental health. Regional Health Forum, pp. 43–48.

Chen, Dong & Wang, Xiaoming & Thatcher, Marcus & Barnett, Guy & Kachenko, Anthony & Prince, Robert. (2014). Urban vegetation for reducing heat related mortality. Environmental pollution (Barking, Essex : 1987). 192. 10.1016/j.envpol.2014.05.002

D'Amato, G. et al. (2013) "Climate change, air pollution and extreme events leading to increasing prevalence of allergic respiratory diseases," Multidisciplinary Respiratory Medicine, 8(1), p. 12. Available at: https://doi.org/10.1186/2049-6958-8-12.

Ebi KL, Capon A, Berry P, Broderick C, de Dear R, Havenith G, Honda Y, Kovats RS, Ma W, Malik A, Morris NB, Nybo L, Seneviratne SI, Vanos J, Jay O. Hot weather and heat extremes: health risks. Lancet. 2021 Aug 21;398(10301):698-708. doi: 10.1016/S0140-6736(21)01208-3. PMID: 34419205.

Engelbrecht, F. 2019. Green Book – Detailed Projections of Future Climate Change over South Africa. Technical report, Pretoria: CSIR

Han J, Liu S, Zhang J, et al. The impact of temperature extremes on mortality: a time-series study in Jinan, China. BMJ Open 2017;7:e014741. doi:10.1136/bmjopen-2016-014741

Ho, H., Knudby, A., Xu, Y., Hodul, M., Aminipouri, M., 2016. A comparison of urban heat islands mapped using skin temperature, air temperature, and apparent temperature (Humidex), for the greater Vancouver area. Sci. Total Environ. 544, 929–938 Ho et al., 2016 https://doi.org/10.1016/j.scitotenv.2015.12.021

Ihlen, V. (2019) Landsat 8 Data Users Handbook, Landsat 8 Data Users Handbook | U.S. Geological Survey. Available at: https://www.usgs.gov/media/files/landsat-8-data-users-handbook (Accessed: October 29, 2022).

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA. Doi:10.1017/9781009157896.

Jagarnath, M., Thambiran, T. and Gebreslasie, M. (2020) "Heat stress risk and vulnerability under climate change in Durban Metropolitan, South Africa—identifying urban planning priorities for adaptation," Climatic Change, 163(2), pp. 807–829. Available at: https://doi.org/10.1007/s10584-020-02908-x.

Jandaghian, Z., Akbari, H., 2018. The effects of increasing surface reflectivity on heat-related mortality in Greater Montreal Area. Canada. Urban Climate. 25, 135–151.

Kusaka, H. Kondo, Y. Kikegawa, and F. Kimura, 2001: A simple singlelayer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. Bound.-Layer Meteor., 101, 329-358

Kusaka, H. and F. Kimura, 2004: Coupling a single- layer urban canopy model with a simple atmospheric model: Impact on urban heat island simulation for an idealized case. Journal of the Meteorological Society of Japan, 82, 67-80

Jandaghian, Z., Akbari, H., 2018. The effects of increasing surface reflectivity on heat-related mortality in Greater Montreal Area. Canada. Urban Climate. 25, 135–151. https://doi.org/10.1016/j.uclim.2018.06.002-

Oyler, J.W. et al. (2014) "Creating a topoclimatic daily air temperature dataset for the conterminous United States using homogenized station data and remotely sensed land skin temperature," International Journal of Climatology, 35(9), pp. 2258–2279. Available at: https://doi.org/10.1002/joc.4127.

Rinner C, Hussain M. Toronto's Urban Heat Island—Exploring the Relationship between Land Use and Surface Temperature. Remote Sensing. 2011; 3(6):1251-1265. https://doi.org/10.3390/rs3061251

Sinclair S& Pegram, Geoffrey. (2009). A comparison of ASCAT and modelled soil moisture over South Africa, using TOPKAPI in land surface mode. Hydrology and Earth System Sciences Discussions. 14. 10.5194/hessd-6-7439-2009.

Santamouris, M., Paolini, R., Haddad, S., Synnefa, A., Garshasbi, S., Hatvani-Kovacs, G., et al., 2020. Heat mitigation technologies can improve sustainability in cities. An holistic experimental and numerical impact assessment of urban overheating and related heat mitigation strategies on energy consumption, indoor comfort, vulnerability and heat-related mortality and morbidity in cities. Energy Build. 217
Skamarock WC, Klemp JB. 2008. A time-split nonhydrostatic atmospheric model for weather research and forecasting applications.Journal of Computational Physics. 227(7): 3465–3485, doi: 10.1016/j.jcp.2007. 01.037.

Sa National Land-cover datasets (2020) SA National Land-Cover Datasets | Environmental Geographical Information Systems (E-GIS). Available at: https://egis.environment.gov.za/sa_national_land_cover_datasets (Accessed: November 2, 2022).

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker D, Duda MG, Huang X-Y, Wang W. (2008) A description of the Advanced Research WRF version 3. NCAR Technical Note No. NCAR/TN/u2013475, Boulder, CO.

Sobrino JA, Jimenez-Mu~noz JC, Paolini L. 2004. Land surface temperature retrieval fromLANDSAT TM 5. Remote Sens Environ. 90(4):434–440.

Soltanzadeh, I., Bonnardot, V., Sturman, A., Quénol, H. and Zawar-Reza, P. (2016). Assessment of the ARW-WRF model over complex terrain: the case of the Stellenbosch Wine of Origin district of South Africa. Theoretical and Applied Climatology, 129(3-4), pp.1407-1427.

Scovronick, N. et al. (2018) "The association between ambient temperature and mortality in South Africa: A Time-series analysis," Environmental Research, 161, pp. 229–235. Available at: https://doi.org/10.1016/j.envres.2017.11.001.

South Africa: High resolution population density maps + demographic estimates -. Available at: https://ckan.africadatahub.org/pt_PT/dataset/f116ce54-41d1-4ebb-82ab-85a265d50adc/resource/6aeb2d41-f32d-441e-9d2e-23ce89d25141?inner_span=True&activity_id=c7bc7934-bf0e-4d8f-b156-07ddbadcf3c2 (Accessed: October 27, 2022).

Tewari, Mukul et al. "Coupled WRF/Unified Noah/Urban-Canopy Modeling System." (2007).
UCM

Local weather forecast, news and Conditions, Weather Underground. Available at: https://www.wunderground.com/ (Accessed: October 2, 2022).

Weng Q, Lu D, Schubring J. 2004. Estimation of land surface temperature-vegetation abun-dance relationship for urban heat island studies. Remote Sens Environ. 89(4):467–483.

Zhang J, Liu S, Han J, et al. Impact of heat waves on nonaccidental deaths in Jinan, China, and associated risk factors. Int J Biometeorol 2016;60:1367–75.

5. Appendix

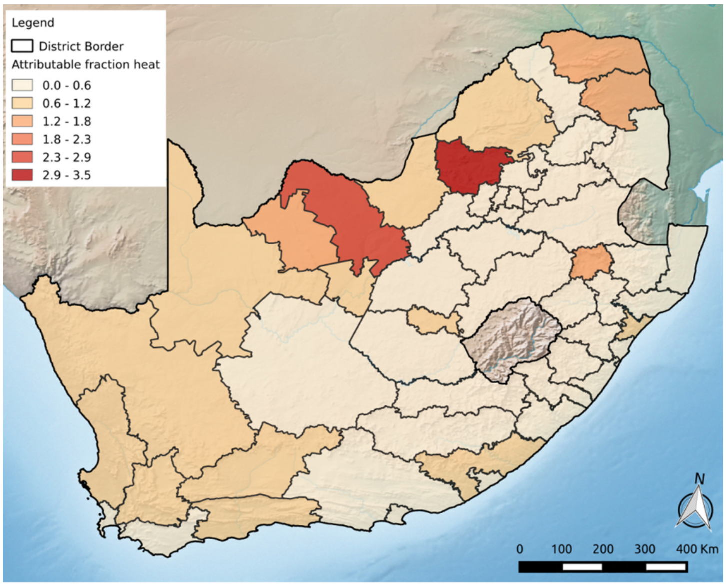


Figure A1. Map of #deaths attributable to extreme heat (Santamouris et al,.2020)

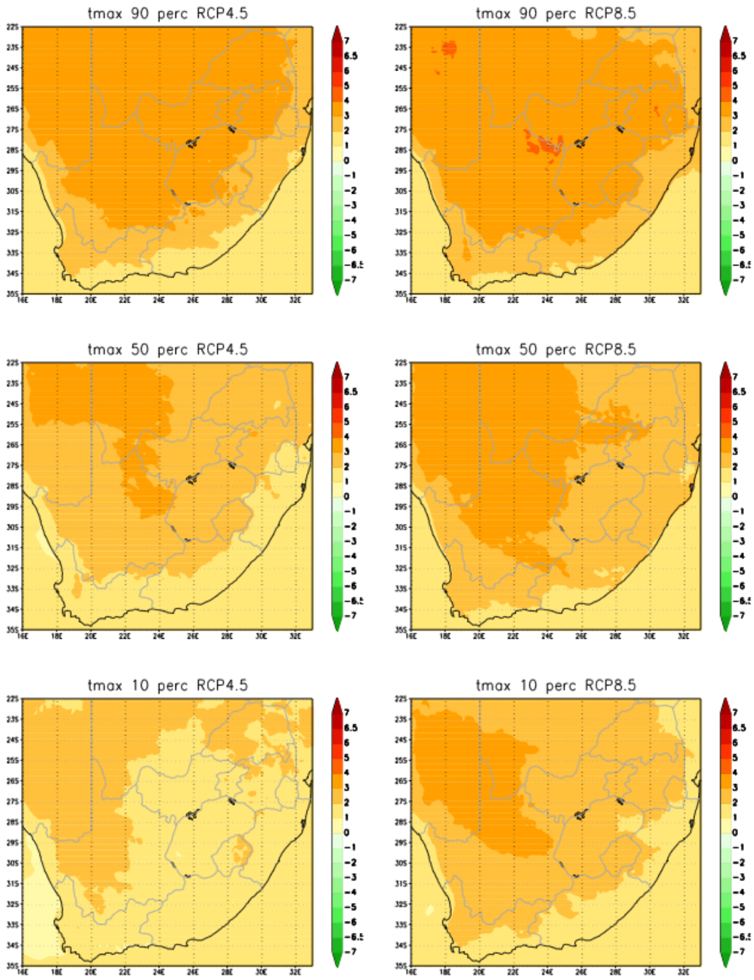


Figure A2
Maps of projected temperature increase over South Africa undit different warming scenarios (Engelbrecht 2019)

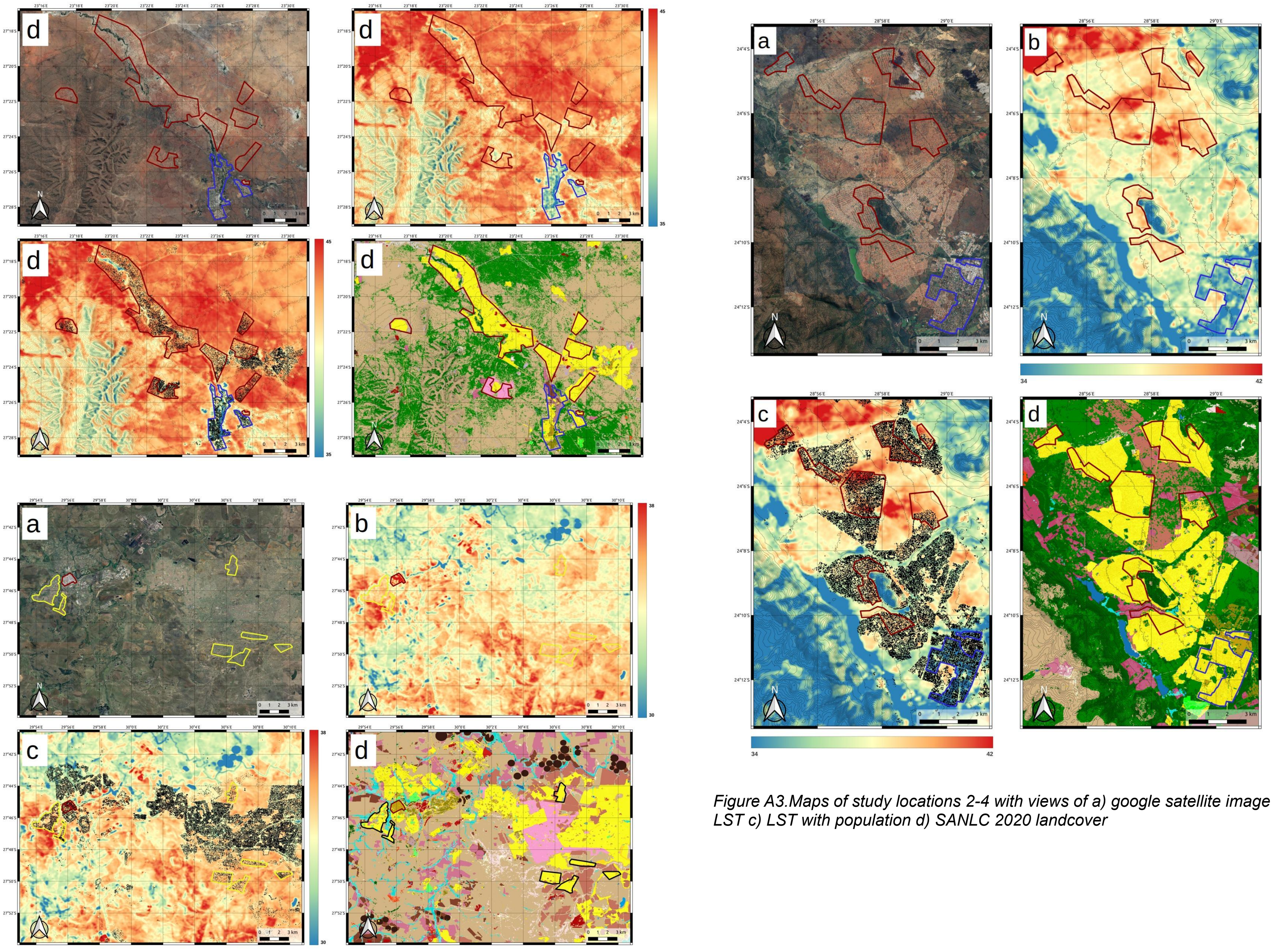
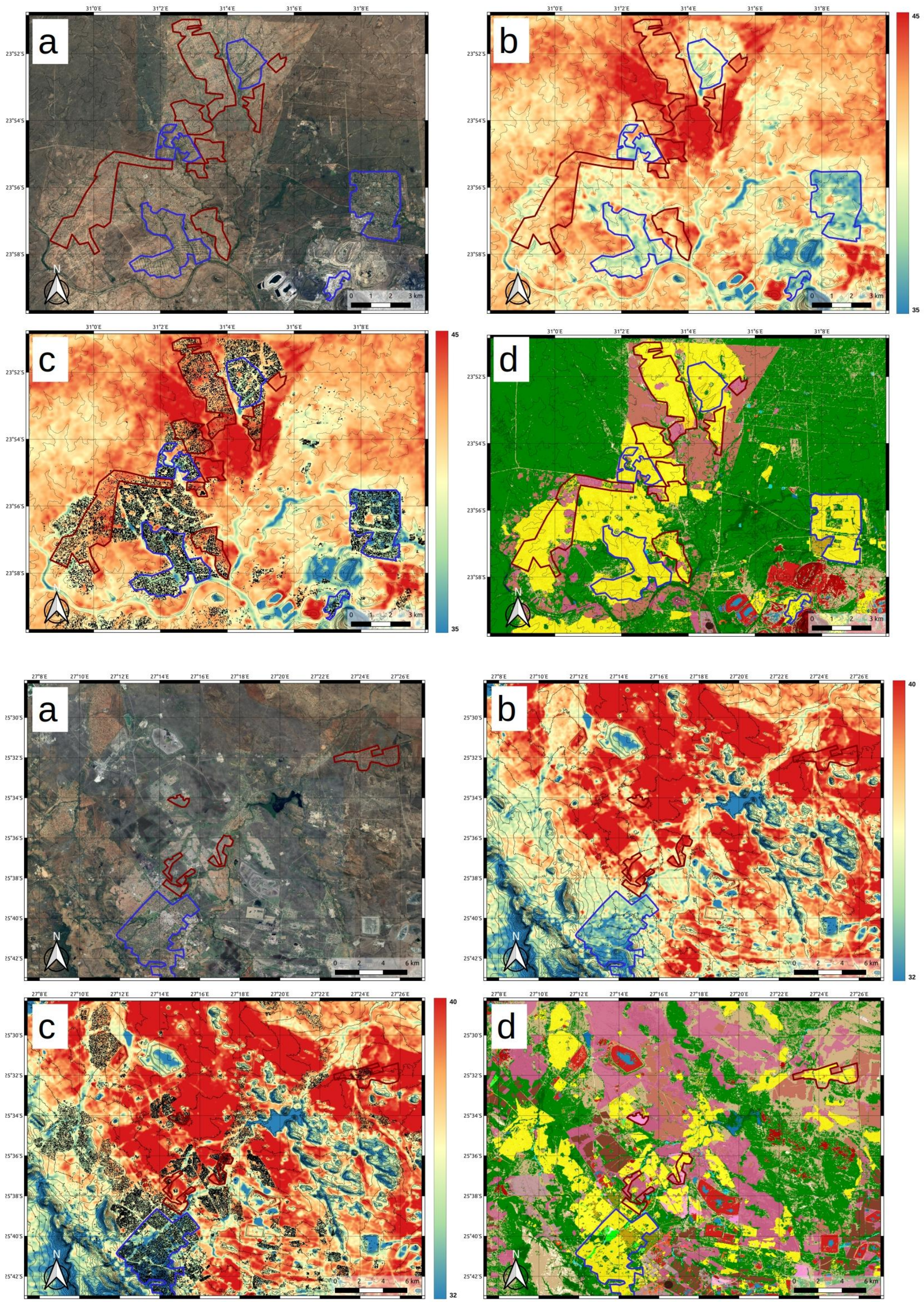


Figure A3.Maps of study locations 2-4 with views of a) google satellite image b) LST c) LST with population d) SANLC 2020 landcover



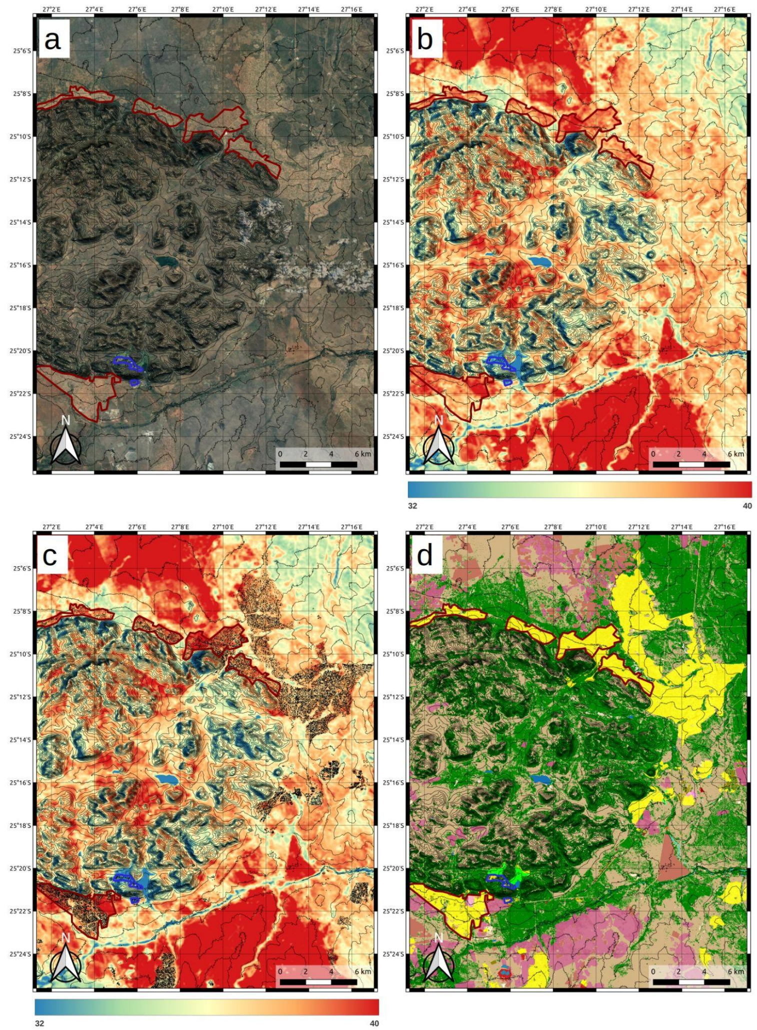
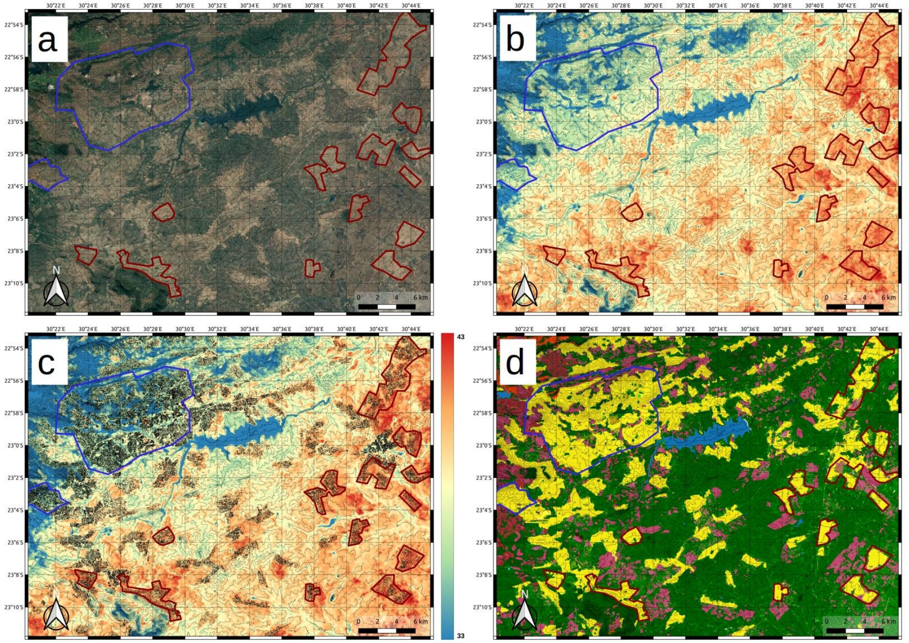
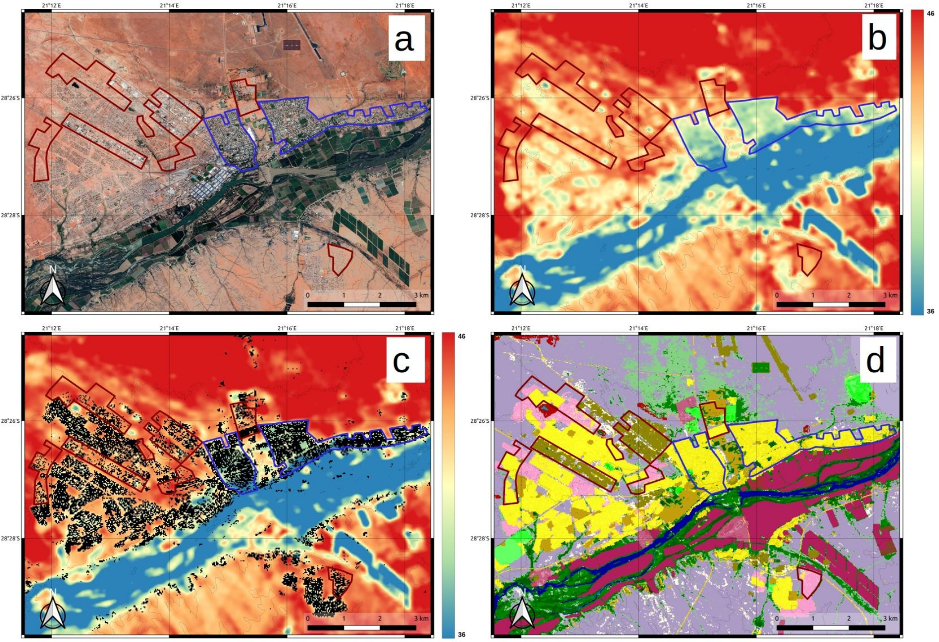


Figure A4 .Maps of study location 5-7 with views of a) google satellite image b) LST c) LST with population d) SANLC 2020 landcover





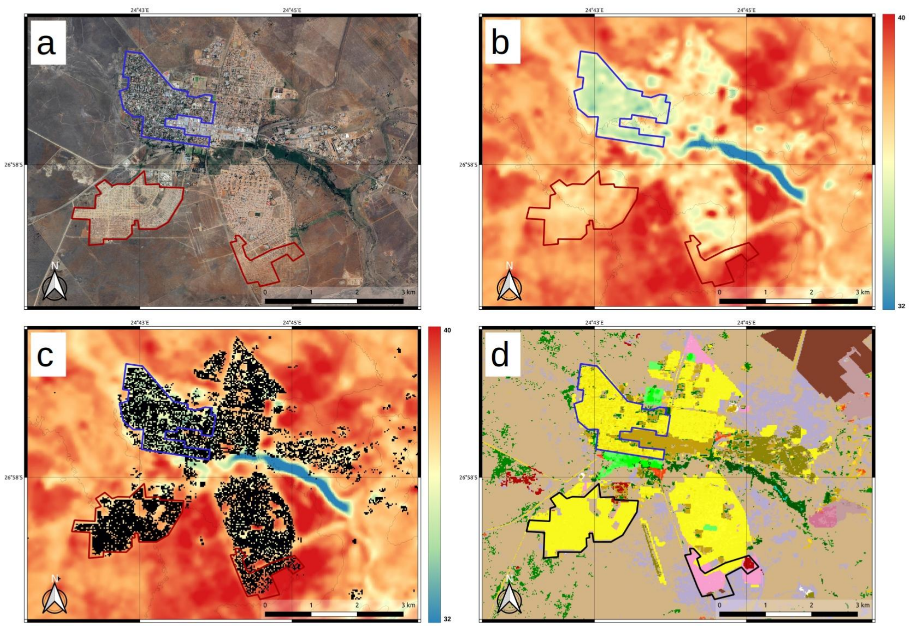


Figure A5. Maps of study location 8-10 with views of a) google satellite image b) LST c) LST with population d) SANLC 2020 landcover