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Uneven Decadal Warming of a Desert Metropolis: Municipality-Resolved Summer Surface Temperature Trends and Their Vegetation and Albedo Controls Across Greater Phoenix, Arizona (2013–2023)

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Abstract

Greater Phoenix is among the most intensively studied urban heat environments in the world, yet it is usually treated as a single thermal unit, which hides the fact that its constituent municipalities can follow different, and sometimes opposite, thermal paths over time. Here we present a municipality-resolved assessment of summertime daytime surface temperature change and its land-surface controls across the Greater Phoenix metropolitan area using Landsat 8 imagery for the summers (June–August) of 2013 to 2023. We retrieve land surface temperature (LST), surface albedo and the normalized difference vegetation index (NDVI) from summer composites; quantify the decadal trend in summer maximum LST for individual municipalities with linear regression, the Mann–Kendall test and the Theil–Sen slope; map the endpoint change in average, maximum and minimum LST alongside the change in albedo, greenness and a surface thermal-anomaly (urban heat island, UHI) index; and attribute the warming pattern to its land-surface controls through pixel-wise correlation and standardized regression. Six of the seven municipalities examined warmed in summer maximum LST over the decade, at rates up to about $+3^{\circ}\text{C}$ per decade, while one municipality in the northwest (Peoria) cooled slightly; the metropolitan mean warmed at approximately $+1.6^{\circ}\text{C}$ per decade. Only Scottsdale’s increase is statistically significant at $p < 0.05$ over this short record, so it is the consistency of the positive sign across municipalities, rather than any single trend, that carries the signal. The attribution is unambiguous: the spatial pattern of warming is governed by vegetation change (change in LST versus change in NDVI, $r = -0.54$, $p < 0.001$) and not by surface reflectivity, whose independent effect collapses to near zero once vegetation is accounted for (standardized $\beta_{\text{NDVI}} = -0.54$ versus $\beta_{\alpha} = -0.01$). The analysis shows that a sub-metropolitan, multi-variable reading of freely available satellite data provides heat information, and a defensible driver, at the scale at which an arid city actually manages heat.

Keywords: land surface temperature; urban heat island; arid cities; NDVI; surface albedo; land-cover change; Mann–Kendall; Landsat; Greater Phoenix

1 Introduction

Cities alter the surface energy balance, a phenomenon that has been known and studied for many years and can lead to higher temperatures in urban areas (Oke, 1982). With increasing urbanization and background temperatures, it is becoming increasingly important to understand the location, timing and drivers of urban heat. Satellite thermal remote sensing is a valuable tool for this purpose as it provides spatially continuous observations of land surface temperature (LST) and captures the large temperature differences that exist within urban areas (Weng et al., 2004; Zhou et al., 2019). The surface urban heat island (SUHI), which is based on LST rather than air temperature, has been extensively studied in various cities around the globe (Peng et al., 2012; Imhoff et al., 2010).

The Greater Phoenix region of Arizona has long been an important location for urban climate studies. The region is situated in the Sonoran Desert and has been the subject of research for over 20 years, including studies on the energetics of the heat island (Brazel et al., 2000), the impact of urban form and land cover (Buyantuyev & Wu, 2010), and the effectiveness of various adaptation strategies (Chow et al., 2012; Middel et al., 2014; Georgescu et al., 2014). This extensive body of work provides a solid foundation, but it also means that simply showing that Phoenix is hot or is getting hotter does not necessarily provide new insight. The more useful question is how warming differs across the metropolitan region. Greater Phoenix is made up of the diverse municipalities of Phoenix, Mesa, Tempe, Chandler, Gilbert, Glendale, Peoria, Scottsdale, Paradise Valley, Cave Creek and Tolleson. These municipalities differ in built density, vegetation, development history and water use. Studies that consider the metropolitan area as a whole or that compare an urban core with its rural surroundings may therefore overlook differences that are directly relevant to municipal planning. Uneven development, infill, and greening across the region mean that neighbouring municipalities can experience different temperature trends, and some may even experience cooling while others experience warming. These differences, however, have rarely been quantified systematically at the municipal level.

It is equally important to understand how these changes occur. If a region experiences a temperature change over time, this change can be associated with changes in two land-surface properties that can be modified through urban development: surface reflectivity (albedo) and vegetation greenness (typically measured by the Normalized Difference Vegetation Index or NDVI). Albedo is the fraction of incoming solar radiation reflected rather than absorbed, whereas vegetation can affect surface temperature through shading and evapotranspiration (Yuan & Bauer, 2007; Middel et al., 2014). The relative importance of these properties is not always obvious in an arid climate like Phoenix. Changes in albedo may not always lead to the cooling effect expected from conventional urban climate assumptions, and the effect of vegetation may be influenced by local land cover and water availability. It is therefore important to understand how these properties relate to observed temperature changes to move beyond mapping heat toward understanding which land-surface changes are most relevant for adaptation.

We address these questions in this study using Landsat 8 data from the summer seasons of 2013–2023, processed in Google Earth Engine (Gorelick et al., 2017). We analyze summertime daytime LST, albedo and NDVI and calculate the trend in summer maximum LST for each municipality using linear regression, the Mann–Kendall test and the Theil–Sen slope. Changes in average, maximum and minimum LST are also mapped, as are changes in albedo, vegetation greenness and a surface thermal-anomaly index. Finally, the relationships between temperature change and land-surface properties at the pixel scale are analyzed to determine which properties are most closely associated with the observed

warming and cooling patterns. This study does not simply confirm that Greater Phoenix is warming, but also offers a sub-metropolitan-level evaluation of the spatial distribution of warming, differences in warming among municipalities, and the land-surface properties associated with these spatial patterns. The method can be applied to other desert cities with limited detailed urban climate monitoring, using freely available satellite data and a reproducible workflow.

2 Study Area and Data

2.1 Study area

The study area is the Greater Phoenix metropolitan region of central Arizona, in the Sonoran Desert, roughly between 33° and 34° N and 111.5° and 112.5° W (Fig. 1). It consists of eleven municipalities linked by an extensive network of highways and suburban areas in a relatively flat, arid basin bordered by mountain ranges and desert preserves. Trend and attribution analyses focus on the seven municipalities with continuous, areally sufficient Landsat coverage across all eleven summers—Phoenix, Mesa, Tempe, Chandler, Scottsdale, Gilbert and Peoria; the remaining incorporated areas appear on the change maps for spatial context but are not analysed as individual series. The climate is hot and dry, with very high surface temperatures in the summer, mild winters and low, strongly seasonal rainfall, which is associated primarily with winter frontal systems and the North American monsoon. Rapid and uneven urban growth, coupled with an already extreme thermal environment, makes Greater Phoenix an important and challenging setting in which to investigate land use, surface energy balance and urban heat.

2.2 Satellite data and preprocessing

All analyses are based on Landsat 8 Collection 2 Level-2 surface reflectance and thermal products (30 m resolution) (Roy et al., 2014), accessed and processed through Google Earth Engine (Gorelick et al., 2017). A clear-sky seasonal composite was created for every summer season (1 June to 31 August) between 2013 and 2023. The scene quality-assessment band was used for cloud and shadow masking prior to compositing, so that only clear-sky pixels were used for the seasonal mean. Observations taken throughout the summer minimize the effect of any particular acquisition date and provide a more consistent seasonal representation for each year. The LST and albedo endpoint comparisons use 2013 and 2023, while the NDVI and UHI endpoint comparisons use 2013 and 2022. The implications of this small difference in the analysis periods are discussed in the limitations.

3 Methods

The overall workflow is summarised in Fig. 2.

3.1 Land surface temperature retrieval

LST was retrieved using the NDVI-threshold emissivity approach (Sobrino et al., 2004; Jiménez-Muñoz & Sobrino, 2003; Weng et al., 2004). NDVI was computed from the near-infrared and red bands,

$$\text{NDVI} = \frac{B5 - B4}{B5 + B4}, \quad (1)$$

the fractional vegetation cover followed Carlson & Ripley (1997),

$$F_v = \left(\frac{\text{NDVI} - \text{NDVI}_{\min}}{\text{NDVI}_{\max} - \text{NDVI}_{\min}} \right)^2, \quad (2)$$

surface emissivity was estimated as $\varepsilon = 0.986 + 0.004 F_v$, and LST was obtained from the brightness temperature T_B (Kelvin),

$$\text{LST } (^{\circ}\text{C}) = \frac{T_B}{1 + (0.00115 T_B / 1.4388) \ln \varepsilon} - 273.15. \quad (3)$$

For each summer, the minimum, maximum and mean LST were retained for every municipality.

3.2 Surface albedo

Broadband albedo was estimated from the narrowband Landsat 8 reflectances using the coefficients of Liang (2001),

$$\alpha = \frac{0.356 B_2 + 0.130 B_4 + 0.373 B_5 + 0.085 B_6 + 0.072 B_7 - 0.0018}{1.016}. \quad (4)$$

3.3 Vegetation greenness

NDVI is used both in the LST retrieval process and as an independent indicator of vegetation greenness. In this arid urban area, NDVI is mainly associated with irrigated vegetation, and changes over the decade indicate greening or vegetation loss.

3.4 Decadal trend analysis

The summer maximum LST series were analyzed for trends for each municipality using three complementary methods: an ordinary least-squares linear slope (with R^2 and p), the Mann–Kendall test for trend significance (Mann, 1945; Kendall, 1975), and the Theil–Sen estimator for a robust estimate of trend magnitude (Sen, 1968). The Mann–Kendall test does not require a distributional assumption and is robust to outliers, while the Theil–Sen slope is less sensitive to individual anomalous years. Significant trends were defined as $p < 0.05$, and marginally significant trends were defined as $p < 0.10$. The same procedure was followed for the metropolitan-mean series. This is important because an eleven-year record allows trends to be estimated with a stated level of confidence, which is not possible with a two-point difference.

3.5 Attribution of warming to its land-surface controls

Heat storage and release by the land surface are major controls on warming.

The spatial patterns of warming were associated with changes in land-surface properties (LST, albedo and NDVI) between the endpoint composites (2013 and 2023 for LST and albedo; 2013 and 2022 for NDVI and UHI) by calculating the change in each parameter at the pixel level. The change in LST was then related to changes in the two predictors. The Pearson correlation and ordinary least-squares slope of ΔLST against $\Delta\alpha$ and ΔNDVI are reported separately, along with a standardized multiple regression:

$$\Delta\text{LST} = \beta_0 + \beta_\alpha \Delta\alpha^* + \beta_N \Delta\text{NDVI}^* \quad (5)$$

Both predictors are z-scored in this regression to allow comparison of their coefficients and to determine the effect of each predictor while holding the other constant. The analysis was performed over the metropolitan domain at 100 m resolution, the native thermal resolution.

4 Results

4.1 Decadal trend in summer maximum surface temperature

The annual summer maximum LST values are presented in Table 1, the fitted trends are shown in Fig. 3, and the trend statistics are summarized in Table 2. Six of the seven municipalities examined—Phoenix, Mesa, Tempe, Chandler, Scottsdale and Gilbert—show a positive trend in summer maximum surface temperature over the decade, while Peoria, in the northwest, shows a declining trend. Warming is strongest in the southeastern valley, reaching approximately $+3.1^\circ\text{C}$ per decade in Tempe and $+2.6^\circ\text{C}$ per decade in Chandler based on the linear slopes. The metropolitan-mean series warms at approximately $+1.6^\circ\text{C}$ per decade. Phoenix, despite recording the highest absolute summer maximum LST ($\text{LST}_{\max} \approx 57.9^\circ\text{C}$), has an essentially flat linear trend of -0.3°C per decade.

The statistical significance of these trends requires careful interpretation. Over the eleven-year record, which exhibits considerable interannual variability, only Scottsdale shows a significant Mann–Kendall trend at $p < 0.05$ ($\tau = 0.51$, $p = 0.046$), while Tempe shows a marginally significant trend ($\tau = 0.45$, $p = 0.071$). The remaining trends, including the metropolitan mean, are not individually significant. Therefore, the more robust finding is not any single trend line, but the consistent pattern of positive trends across six of the seven municipalities. The relatively short record limits the statistical power to detect trends in individual municipalities, so a lack of significance should not be interpreted as evidence that warming is absent.

Table 1: Summer maximum LST ($^\circ\text{C}$) by municipality and year, corresponding to Fig. 3.

City	'13	'14	'15	'16	'17	'18	'19	'20	'21	'22	'23
Phoenix	59.5	58.0	55.5	57.0	56.0	59.0	59.5	60.0	54.5	61.0	56.5
Mesa	54.0	54.0	54.0	54.5	54.0	55.0	56.5	56.5	53.0	56.5	54.5
Tempe	53.5	56.0	56.0	58.5	57.0	57.5	59.5	59.5	56.5	58.0	57.5
Chandler	55.5	57.5	51.5	59.5	56.0	55.0	59.5	60.0	56.0	59.0	56.5
Scottsdale	53.0	51.5	55.0	55.5	55.0	55.0	55.5	56.0	53.5	56.0	55.5
Peoria	49.0	50.0	49.0	50.0	50.0	48.5	49.5	52.0	47.5	51.0	46.5
Gilbert	50.5	54.5	54.0	58.0	56.5	54.0	56.0	56.0	53.5	56.5	54.5

4.2 Spatial pattern of decadal LST change

The average, maximum and minimum LST change maps for 2013–2023 (Fig. 4) reveal that warming has been spatially non-uniform. Surface temperature has increased in most areas, with the largest increases in average LST occurring in southwestern Phoenix and portions of the southeastern valley. The change in maximum LST shows a generally similar pattern, while the change in minimum LST is more variable, ranging from approximately -5 to $+2^\circ\text{C}$. In contrast to the dominant warming pattern, substantial cooling is observed in the northwest, around Peoria and Cave Creek, where average LST decreased by

Table 2: Decadal trend in summer maximum LST by municipality: linear (OLS) and Theil–Sen slopes ($^{\circ}\text{C decade}^{-1}$), Mann–Kendall τ and p , and the series mean. Significance: * $p < 0.05$, † $p < 0.10$, ns otherwise.

City	OLS	Theil–Sen	MK τ	MK p	sig.	Mean ($^{\circ}\text{C}$)
Tempe	+3.1	+3.3	0.45	0.071	†	57.2
Chandler	+2.6	+1.9	0.24	0.347	ns	56.9
Scottsdale	+2.5	+2.0	0.51	0.046	*	54.7
Gilbert	+2.0	+1.0	0.13	0.636	ns	54.9
Mesa	+1.5	+1.7	0.38	0.144	ns	54.8
Phoenix	+0.3	+1.3	0.11	0.696	ns	57.9
Peoria	−0.9	−1.0	−0.09	0.752	ns	49.4
Metro mean	+1.6	+1.4	0.28	0.273	ns	55.1

more than 4.5°C in some areas. The spatial pattern is consistent with the municipality-based trends: the northwestern cooling region is associated with Peoria, the only municipality with a negative trend, while the southeastern warming is associated with the municipalities showing the strongest positive trends.

4.3 Change in surface albedo and vegetation

Albedo and vegetation changed over the decade.

Two land-surface properties changed considerably over the decade. Surface albedo decreased across most of the urbanized metropolitan region (Fig. 5). The central and southern districts had relatively high-albedo surfaces (0.2–0.4) in 2013, while by 2023 the distribution had shifted toward lower albedo values (0.15–0.3), especially in Phoenix, Glendale, Scottsdale and Paradise Valley. Several rapidly developing southeastern municipalities (Tempe, Gilbert and Mesa) experienced a decrease in vegetation greenness (Fig. 6) between 2013 and 2022, consistent with the conversion of vegetated land to impervious urban cover. The northwestern region associated with cooling retained relatively high greenness. These two changes are described here as observations; which of them is more closely related to the observed warming is explored in Section 4.5, and the outcome is not necessarily what would be expected from conventional surface-climate assumptions.

4.4 Change in the surface thermal-anomaly (UHI) index

The surface thermal-anomaly maps (Fig. 7) indicate that the extent of the strongest positive anomaly (warmer than the regional average) increased from 2013 to 2022, becoming larger and more spatially continuous in Phoenix, Peoria, Scottsdale and portions of Glendale. Areas near the regional average temperature in 2013 shifted toward higher relative temperatures by 2022, reflecting the strengthening of the surface heat pattern observed in the LST change maps.

4.5 Attribution: vegetation, not albedo, governs the warming

Vegetation is more strongly associated with the observed warming than albedo. The pixel-wise relationships between decadal LST change and changes in the two land-surface properties are used to identify factors associated with the warming pattern, with vegetation emerging as the stronger predictor. Across the metropolitan domain, the change in LST is moderately and negatively correlated with the change in

NDVI (Pearson $r = -0.54$, $p < 0.001$; OLS slope -19.6°C per unit NDVI): areas that lost vegetation tended to warm, while areas that gained vegetation tended to cool (Fig. 8, right; Table 3). In contrast, the change in albedo is only weakly correlated with the change in LST, and the correlation is positive rather than the expected negative relationship ($r = +0.15$, $p < 0.001$; slope $= +16.7^\circ\text{C}$ per unit albedo; Fig. 8, left). Vegetation retains nearly all of the explanatory power ($\beta_{\text{NDVI}} = -0.54$) when both predictors are included in a standardized regression, while albedo adds almost no independent signal ($\beta_{\alpha} = -0.01$). The two predictors collectively account for approximately 29% of the spatial variance in decadal LST change, with most of the explanatory power associated with vegetation (Table 3). In short, albedo provides little additional explanatory information beyond vegetation change.

Table 3: Attribution of the decadal LST change to its land-surface controls (pixel-wise, 100 m, over the metropolitan domain). Standardized β are from the joint two-predictor regression; the model explains about 29% of the spatial variance in ΔLST .

Predictor	Pearson r	OLS slope ($^\circ\text{C unit}^{-1}$)	Std. β
ΔNDVI	-0.54^{***}	-19.6	-0.54
Δalbedo	$+0.15^{***}$	$+16.7$	-0.01

*** $p < 0.001$. Joint model $R^2 \approx 0.29$.

4.6 A coherent picture across all datasets

Taken together, the four datasets support a consistent interpretation. The municipality-based trends and LST change maps agree on the overall direction of temperature change, with cooling in the northwest and warming in the southeastern municipalities. The vegetation and albedo change maps show where land-surface conditions have changed, while the pixel-wise attribution analysis identifies which of these changes is more closely associated with the observed warming: vegetation loss rather than albedo decline. Phoenix provides an important exception in the temporal record. Despite having the highest absolute summer temperatures and experiencing a visible decline in albedo, it shows an essentially flat trend. One possible explanation is that its already dense, built-out urban core has limited capacity for further warming associated with land-cover change, while the warming front of the metropolitan area is concentrated in expanding suburban municipalities rather than the mature core. In the northwest, where vegetation was largely retained, neither greenness nor temperature increased substantially. Overall, the datasets consistently indicate that suburban expansion onto previously vegetated or irrigated land, and the associated loss of vegetation, is a plausible proximate driver of the spatial pattern of surface warming.

5 Discussion

The analysis here focuses on the internal structure of warming in the region, rather than the average warming of the metropolitan area, and three key results stand out.

Warming is uneven, and no municipality is uniform: six of the seven municipalities show warming in summer maximum LST, while the change maps show both intensifying hotspots in southeastern Phoenix and the southeastern valley, and a coherent cooling zone in the northwest around Peoria and Cave Creek. Peoria is the only municipality with a cooling trend. This spatial variability is important because heat management in the region is carried out at the municipal and sub-municipal levels through

zoning, shade and tree programmes, cool-roof and cool-pavement policies, and landscape water allocation. The metropolitan mean can mask the variations that are relevant to decisions made by individual municipalities. The northwestern cooling is especially important: localised surface cooling is achievable even in a warming desert metropolis, and identifying and expanding these areas could be as important for policy as mapping hotspots.

Only Scottsdale is significant at $p < 0.05$, while Tempe is marginally significant over the eleven-year record; the other municipal trends and the metropolitan mean are not individually significant. This is consistent with what is expected from a short and variable record, rather than evidence against warming. The consistency of positive trends across six of the seven municipalities, as well as their agreement with the spatial change maps and the distribution of greenness, is more convincing than any single p -value. Extending the record beyond 2023 and pooling the municipal series would improve statistical power and is considered a logical next step rather than a limitation that undermines the present result.

The pattern is more strongly associated with vegetation than reflectivity, and this is where our result is consistent with the literature. The attribution focuses on vegetation change, and the pixel-wise result supports this: areas that lost vegetation tended to warm, while areas that gained vegetation tended to cool. The relationship between surface temperature and vegetation abundance is similar to that found by Weng et al. (2004) in their urban heat island study, and NDVI has been shown to be as good as, or better than, impervious-surface measures in predicting surface urban heat (Yuan & Bauer, 2007). Buyantuyev & Wu (2010) related the spatial distribution of surface temperature to vegetation and land cover in Phoenix, and vegetation and shade-based interventions have been demonstrated to reduce local temperatures in the metropolitan area (Middel et al., 2014; Georgescu et al., 2014). Our further result, that albedo has little independent explanatory power when vegetation is controlled for, and that its raw relationship with temperature is positive, is consistent with the behaviour of arid environments, in which bright bare desert is hot while darker vegetated cover is cool, and in which urban areas can appear cooler than their surroundings during the day (Imhoff et al., 2010). We therefore do not consider the widespread albedo decrease in Fig. 5 to be the direct cause of warming, but rather a correlate of the land-cover transition associated with warming. The policy-relevant change for daytime surface heat is vegetation and irrigated canopy, rather than surface brightening alone, which the data suggest would provide little additional cooling benefit in this region.

Several limitations should temper the interpretation. The joint model accounts for 29% of the spatial variance in decadal LST change, leaving most of the pixel-scale variability to be explained by other factors not represented here, such as impervious expansion not captured by NDVI, surface moisture, built form, and noise associated with differencing two summers. Albedo, NDVI and UHI comparisons are made between two endpoint composites: the NDVI and UHI endpoints (2022) are one year earlier than the LST and albedo endpoints (2023). The attribution is correlational rather than causal because vegetation, albedo, impervious cover and land use co-vary.

6 Conclusions

We evaluated summertime daytime land-surface temperature change and related land-surface controls across the Greater Phoenix municipalities using Landsat 8 satellite imagery for the summers of 2013–2023. Summer maximum surface temperature increased in six of the seven municipalities studied, at

rates of up to approximately $+3^{\circ}\text{C}$ per decade, and decreased slightly in the seventh, Peoria. The metropolitan mean increased by approximately $+1.6^{\circ}\text{C}$ per decade. The overall pattern, rather than any single municipal trend, is most important, and only Scottsdale's trend is statistically significant over this short period. The spatial change maps corroborate this pattern, showing widespread warming alongside a coherent northwestern cooling region. The pixel-wise attribution shows that vegetation change is the stronger predictor of this spatial pattern (ΔLST versus ΔNDVI , $r = -0.54$), while surface albedo contributes little additional explanatory power once vegetation change is included. Phoenix's warming rate was low, despite its highest absolute temperatures, which is consistent with an established, densely built-up urban core and warming concentrated in expanding suburban areas. The results also highlight the potential for satellite monitoring to provide more than just information about urban heat, by identifying associated land-surface changes at a scale relevant to urban management using freely available data and tools. In this region, the results suggest that vegetation change is more strongly associated with daytime surface heat than surface reflectivity. Further research should incorporate a comprehensive decadal time series and extend the framework to include nighttime and air-temperature measurements.

Declarations

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Ethics approval. Not applicable.

Consent to participate. Not applicable.

Consent for publication. Not applicable.

Data availability. All satellite data used in this study are publicly available through the USGS and Google Earth Engine data catalogues, including Landsat 8 Collection 2 Level-2 products.

Author contributions. Md Rayhan conceived the study, processed and analysed the data, prepared the figures, and wrote and revised the manuscript. The author read and approved the final manuscript.

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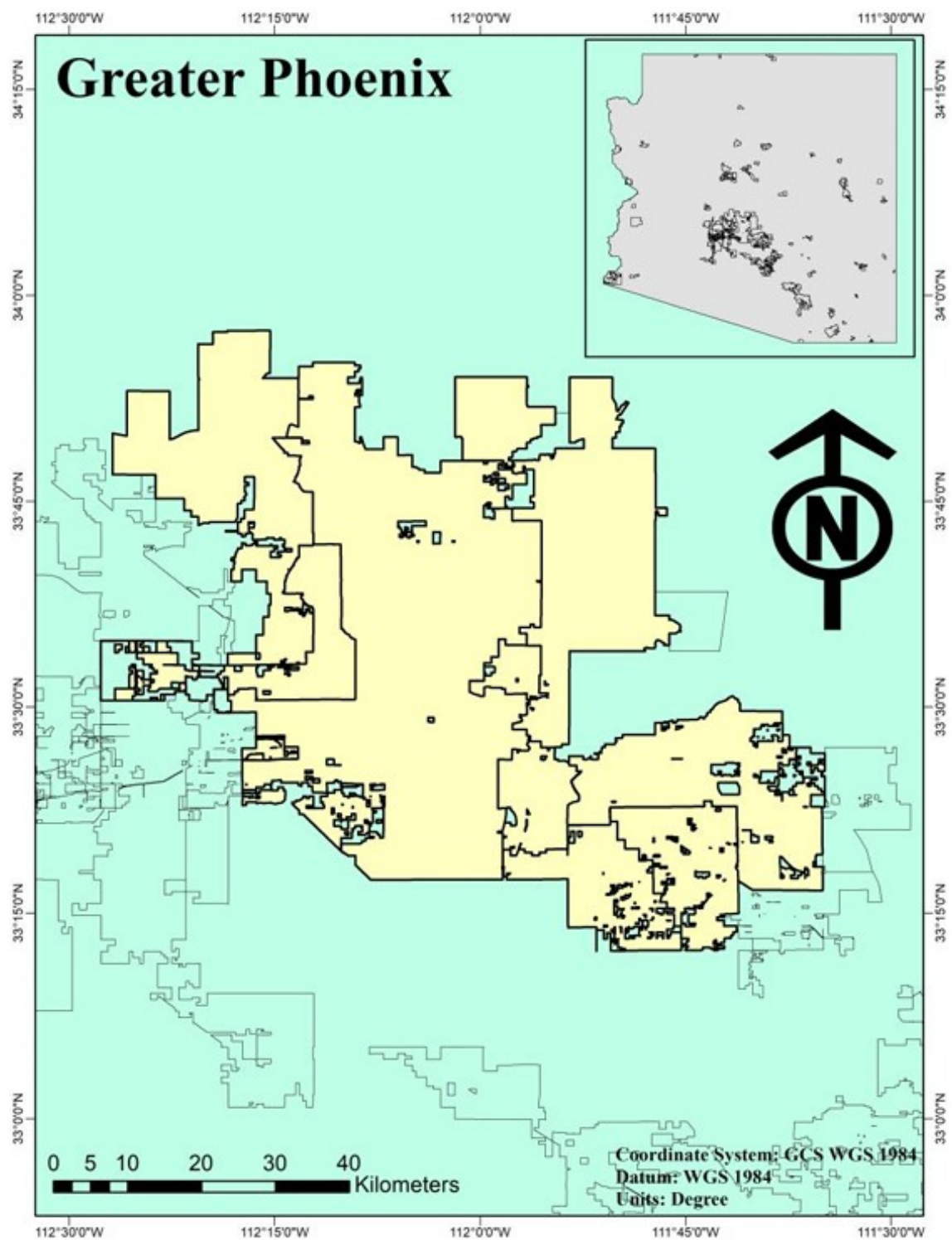


Figure 1: Study area: the municipalities of Greater Phoenix within the Sonoran Desert of central Arizona.

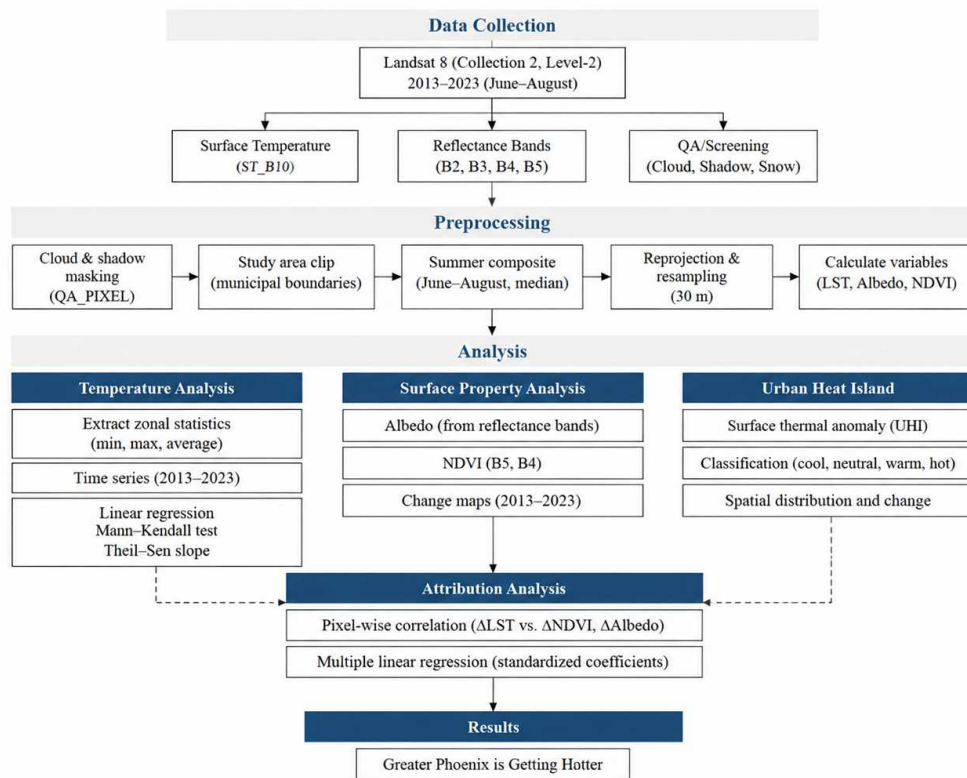


Figure 2: Methodology: Landsat 8 summer composites are processed in Google Earth Engine and R/GIS to derive LST (minimum, maximum, mean), albedo, NDVI and a surface thermal-anomaly (UHI) index, which are then compared over time, across municipalities, and against one another.

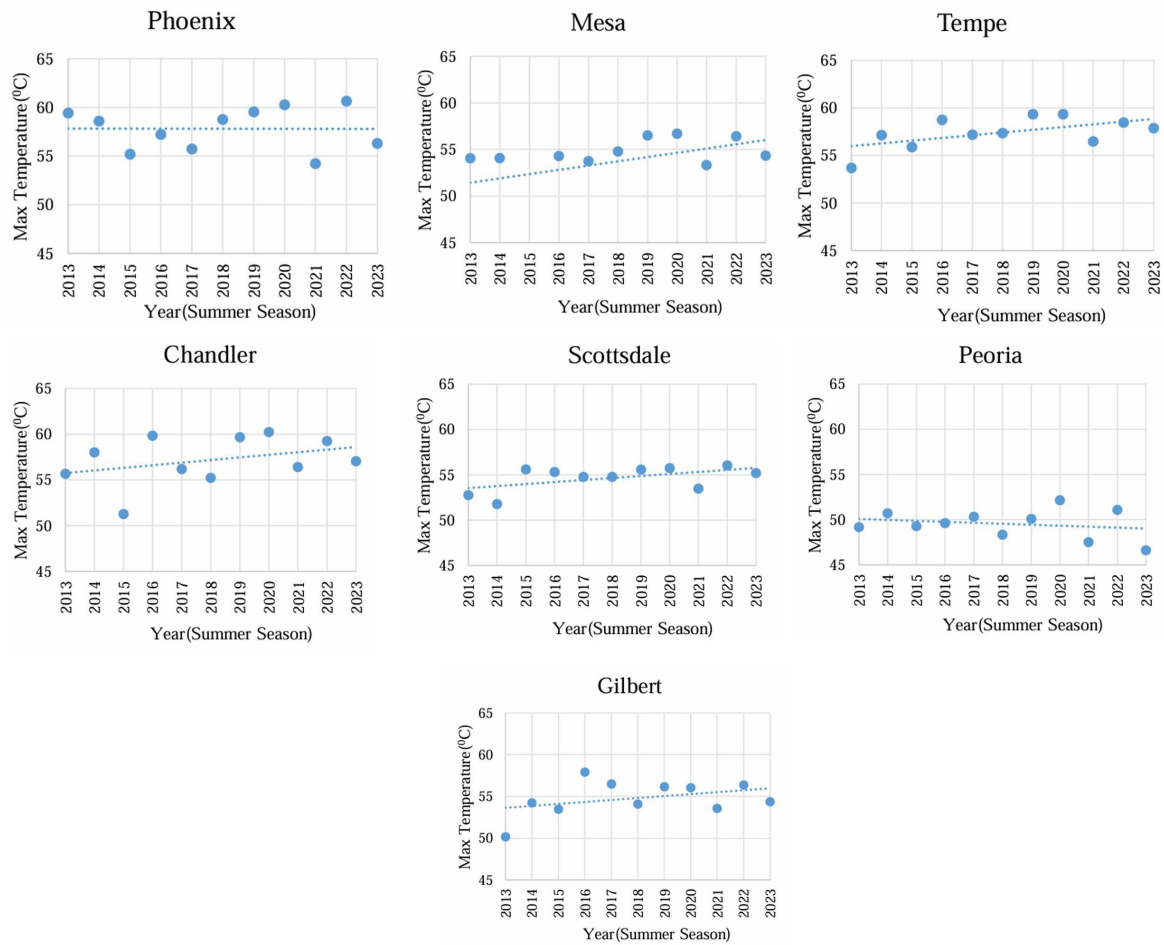


Figure 3: Summer-season maximum land surface temperature by municipality, 2013–2023, with fitted linear trends. Six municipalities warm; Peoria declines.

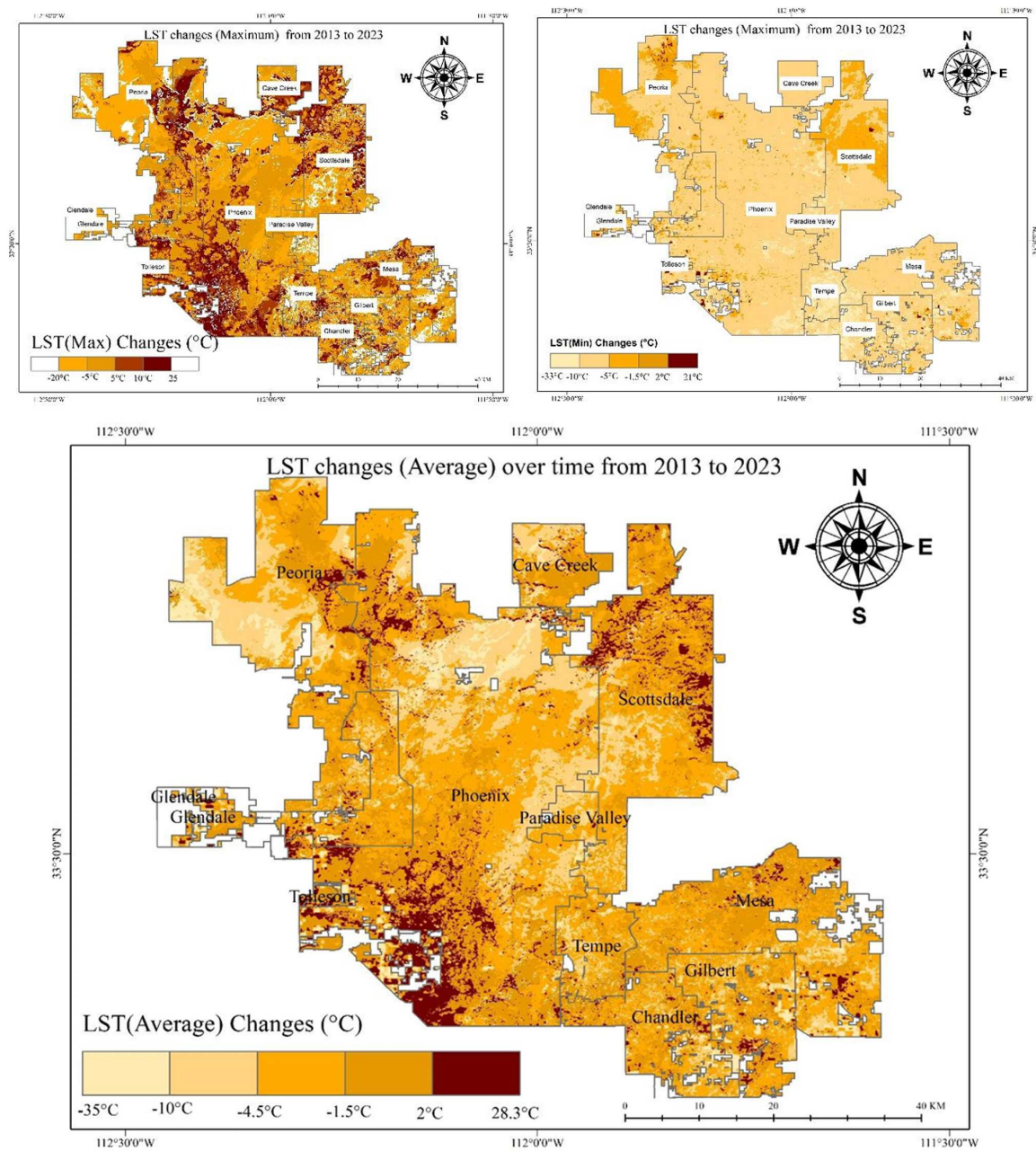


Figure 4: Change in summer LST between 2013 and 2023 across Greater Phoenix: average (main panel), maximum and minimum. Warming dominates, with localised cooling in the northwest.

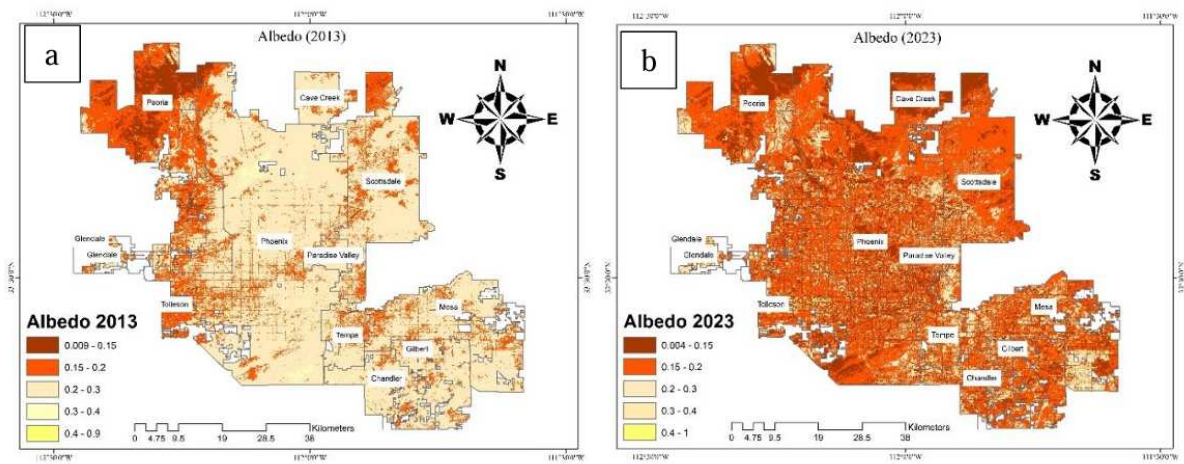


Figure 5: Surface albedo in 2013 (a) and 2023 (b). Albedo declined across much of the built-up area.

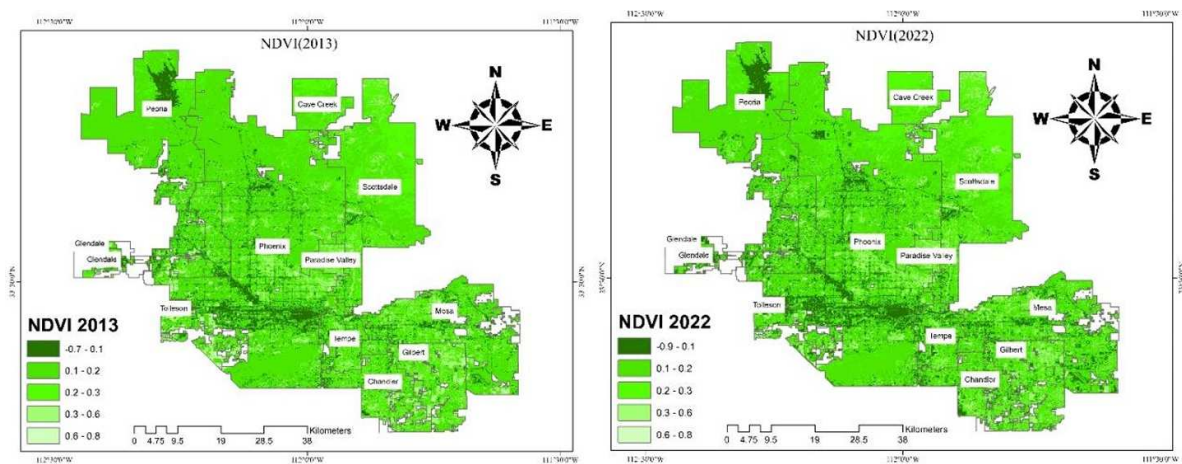


Figure 6: NDVI in 2013 and 2022. Vegetation greenness declined in several rapidly developing south-eastern municipalities.

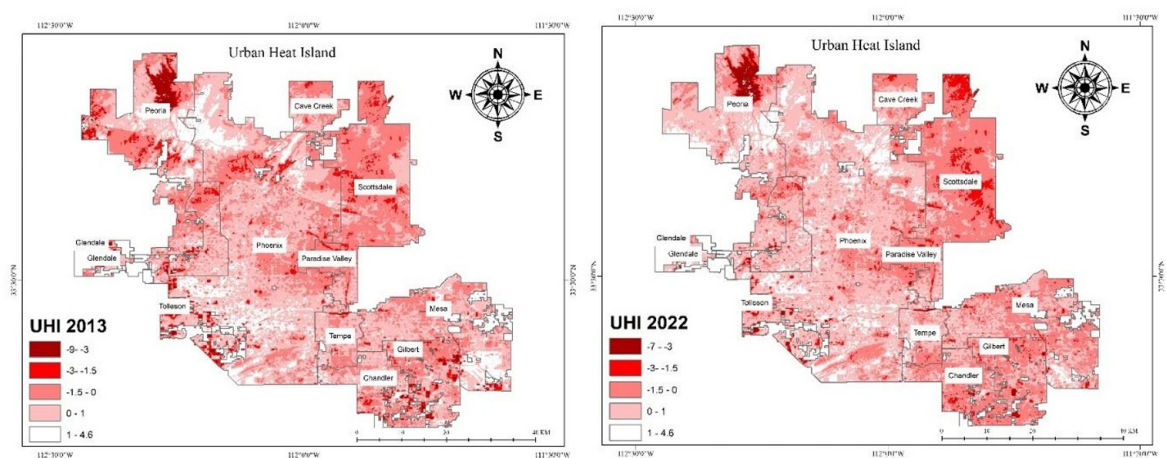


Figure 7: Surface thermal-anomaly (UHI) index in 2013 and 2022. The warmest-anomaly class expanded over the period.

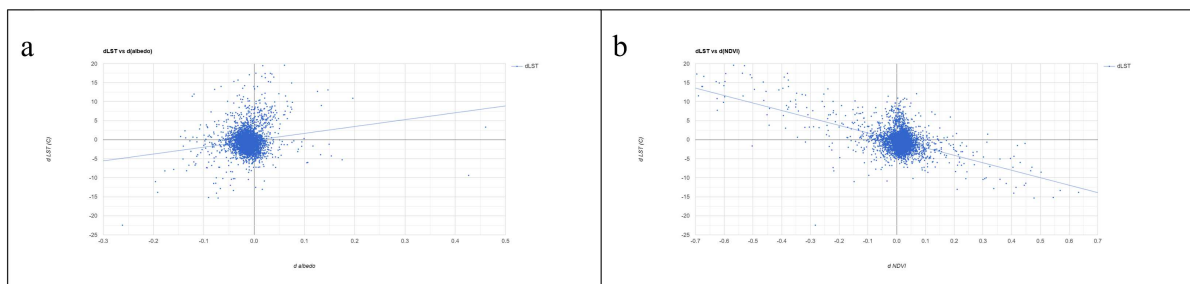


Figure 8: Pixel-wise relationship between the 2013–2023 change in summer LST and the change in surface albedo (left) and NDVI (right). LST change is weakly and positively related to albedo change but moderately and negatively related to NDVI change.