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# Remote Sensing-Based Assessment of Urban Heat Island Effects: A Case Study from Three Major Cities of Alabama, USA

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## Abstract

Urban heat island (UHI) effects, and their consequences on urban environments, society, and economies, are intensifying due to continued urban developments and anthropogenic activities. Using Moderate Resolution Imaging Spectroradiometer's (MODIS) MOD11A2 land surface temperature (LST) and land-use/land-cover (LULC) products from National Land Cover Database (NLCD), this research investigated spatio-temporal dynamics of UHI developments over the past two decades (2000-2024), focusing three major cities of Alabama, namely Huntsville, Birmingham, and Mobile. The Madison and Limestone counties, hosting the Huntsville City area, experienced the highest rate of urban expansion over the study period, with a notable increase in newly developed areas. Our findings indicate warming trends over developed areas in general, but more specifically during night-times leading to decreasing diurnal temperature differences and can indicate intensifying UHI effects. These findings also indicate applicability of MODIS LST products for mapping and quantifying UHI effects at local to regional scale studies.

## Keywords

MODIS LST, NLCD LULC, Urban Expansion, UHI Effects

## 1. Introduction

Urbanization has emerged as one of the most transformative human activities on Earth's surface, with significant implications for local climates, environmental sustainability, and human well-being [1]. One of the most prominent and extensively studied consequences of rapid urban development is the Urban Heat Island (UHI) effect. UHI is a phenomenon where urban and suburban areas experience significantly higher temperatures compared to their surrounding rural areas. This temperature difference emerges from a complex interaction of multiple factors that primarily alter how cities absorb, store, and release thermal energy [2]. Cumulative effects of multiple factors such as loss of vegetated areas [3], accumulation of urban materials [4] [5], increasing building density, and anthropogenic heat additions [6] collectively contribute to the formation of UHIs and UHI effects. Intensification of UHIs is a significant concern as the expansion of the developed areas continues in the expense of natural areas. Albedo decrease, heat storage in infrastructure, reduced evapotranspiration, convection variations, and surface energy transfer are primary mechanisms driving UHI intensity [1] [7]. These mechanisms directly relate to LULC changes within urban areas as urban structures often replace natural vegetation with impervious surfaces, leading to increased heat accumulations and elevated surface temperatures.

Remotely sensed data and products are extensively used to map and evaluate UHIs [8] [9] as well as UHI effects [10]. In many previous studies, remote sensing has been applied indirectly, where negative correlations between vegetation indices and LSTs have been utilized to estimate UHI [11] [12]. More recently, direct applications of remote sensing data are developed using remotely sensed LST products as surrogate for air temperature measurements at local to regional scale studies [12]. UHIs are generally classified into two types: canopy urban heat islands (CUHIs) or boundary urban heat islands (BUHIs), which concern temperatures within the canopy layer or boundary layer, respectively; and surface urban heat islands (SUHIs), which estimate the radiative transfer of heat from the surface of different materials.

LST is defined as the radiative skin temperature of the Earth's surface and measures the thermal radiation emitted directly from the ground, vegetation, and built surfaces. Remotely sensed LST data relate directly to the surface energy dynamics and their relationship to the Earth's surface temperatures. For bare soil, LST refers to the soil surface temperature, while over the areas with dense natural or built-up structures (as in vegetated and developed areas), it refers to canopy temperature. For areas with mixed landcover, LST measures combination of both bare earth and surface canopy temperatures. Remotely sensed LST products have become a popular choice in UHI studies [9]. While LST products can be derived using most satellite products, they vary largely in-terms of their spatial and temporal resolutions. Landsat data are finer in spatial resolution and thus are the most popular in investigating UHIs, more specifically at local-scale studies. Landsat-derived LST products, however, suffer from two clear disadvantages: insufficient spatial and temporal coverage for time series analysis over relatively larger areas, and absence of a definite LST product that is readily available [8]. Alternatively, moderate to low resolution LST products such as MODIS LST products, being readily available with high spatial and temporal coverage allowing for long-term trend analyses (rather than a single day investigation), are a popular choice for investigating UHIs in local, regional to global-scale studies [9] [13]-[15].

When investigating UHI effects, ability to distinguish developed and non-developed areas is a critical first step for measuring the temperatures, differences between UHIs and their surrounding non-urban areas [16] [17]. Remotely sensed data are also used extensively in land-use/ land-cover (LULC) classifications at variable spatial scales. In recent times many public domain LULC data have become available from multiple sources. Among others National Land Cover Database (NLCD) LULC products [18] that are derived from Landsat data is a popular choice in studies over the conterminous United States largely due to their finer resolution (30 m), spatial as well as temporal coverage (*i.e.* available for the conterminous United States as annual LULC products).

Despite many previous studies in UHIs reported from around the world, the outcome is ambiguous. Some studies documented the existence of heat islands [16], while some others highlighted the existence of heat sinks [19]. Most UHI studies however, focused large metropolitan areas and thus proper understanding of the UHIs effects, in particular within rapidly developing mid-size cities still remain broadly understudied [9] [16]. According to our knowledge, only a very few studies reported to study UHIs over the state of Alabama and thus, is one such understudied region. Moreover, according to our knowledge, none of the studies from within the region focused on the impacts of LULC changes, nor evaluated long-term trends. In this study, we focused three major, rapidly developing cities of the state of Alabama: Huntsville, Birmingham and Mobile. Our primary goal was to investigate the effects of urban developments (spatial expansion and intensification of developed areas) on UHI developments and their trends over the last two decades. Our specific objectives were to: 1) evaluate urban expansion and trends over the three cities, 2) investigate any trends, and seasonal and diurnal variations in urban surface temperatures, and 3) evaluate how urban expansion and intensification (as reflected in LULC changes) relate to UHI developments (as reflected in remotely sensed LST products).

## 2. Methods

### 2.1. Study Area

This study was conducted in four counties, hosting three major cities of the state of Alabama, namely Madison and Limestone counties, hosting the city of Huntsville, Jefferson county, hosting the city of Birmingham, and Mobile county, hosting the city of Mobile. Our study units in this study were the county areas. Madison and Limestone counties are located along the northernmost state boundaries, sharing the northern boundaries with the state of Tennessee (**Figure 1**). Among them the Madison county occupies about 801.6 square miles of land area [20], while Limestone county occupies about 563.4 square miles of land area [21]. Jefferson county is located south of the Madison and Limestone counties and occupies about 1111.6 square miles of land area [22]. Mobile county is one of the southernmost counties and is a coastal county, sharing the western boundary with the state of Mississippi, occupying about 1229.4 square miles of land area [23]. Huntsville city area within the Madison and Limestone counties is known to be the fastest growing urbanized area within the state of Alabama and this growth is expected to continue [24]. Birmingham experienced the rapid developments with expansion of developed areas from 1988 to 2004 [25] [26]. Mobile is located on the banks of several rivers. More interestingly, the population of Mobile decreased by 2.7% from 1990 to 2010, while during this same time its metropolitan area expanded spatially [26].

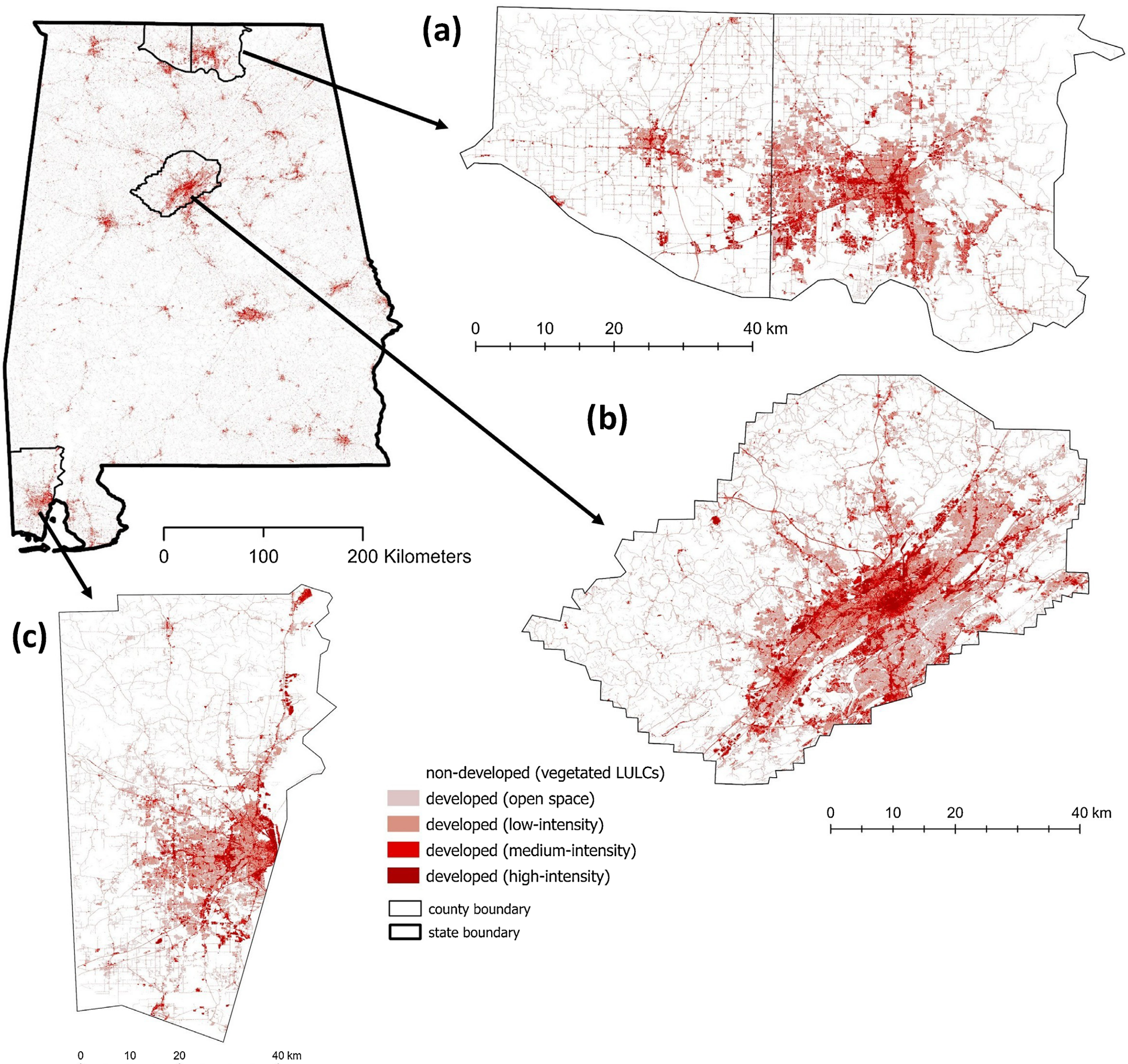


Figure 1. Map of the study areas: Location of Madison and Limestone (a), Jefferson (b) and Mobile (c) counties within the State of Alabama hosting three city areas: Huntsville, Birmingham and Mobile, respectively. Developed LULCs mapped using 2024 NLCD annual LULC products are displayed to illustrate the intensity of development within each study area.

## 2.2. Data

Annual LULC products from NLCD were obtained from the Multi Resolution Landcover Consortium (MRLC) data archives. Data were available at 30m resolution for the conterminous USA for the calendar years 2000 to 2024. NLCD LULC products map varying intensities of developed areas as developed-open space, -low intensity, -medium intensity, and -high intensity areas (LULC classes 21, 22, 23, & 24, respectively). These LULC products were used to map and classify varying intensities of developed areas within each study areas. Satellite-based LST data (8-day composites) from the Moderate Resolution Imaging Spectroradiometer's (MODIS) MOD11A2 product archives were available for the same years. County boundaries data were obtained from US Census Tiger Line products.

## 2.3. Data Processing and Analyses

Data processing and analyses including statistical analyses were performed primarily using Python language (version 3.13) in Spyder IDE (version 6.0.7) and ArcGIS Pro (version 3.6). Preliminary processing involved reprojection of the data to bring all products into a common coordinate reference system. LULC data from NLCD were available in Albert Equal Area Projection (datum WGS 84), while MODIS LST data were available in geographic coordinate reference system (WGS 84). All vector data (county and city boundaries) were available in UTM, Alabama State Plane reference system. Thus, all data were brought into a common coordinate reference system by re-projecting NLCD and vector data to match the coordinate reference system of MODIS LST data.

### 2.3.1. Reclassification of NLCD Data

Among all the NLCD defined categories, developed LULCs (NLCD classes 21 - 24) were combined and were considered as urbanized/developed areas. All other LULC classes, except open water class (NLCD Class 11), were considered non-developed areas. Open water areas were entirely excluded from this study and thus, our area estimates represent only the land extents within each study area (county/s). Accordingly, the different stages/intensities of the developed and the non-developed areas were further reclassified into three categories:

*Category I*: where all the intensities of the developed areas were maintained as their respective different classes, and the rest were set to "no data". This dataset was particularly useful to extract the total land extents and LSTs for different intensities of urbanization.

*Category II*: where all the individual stages/intensities of the developed areas were grouped into one single class (total developed areas), and the rest were set to "no data". This dataset was useful to extract the total areas occupied by the urbanized areas.

*Category III*: where all the non-developed areas were grouped into one single class (total non-developed areas), and the rest were set to "no data". This dataset was useful to extract the total areas occupied by the non-developed/natural areas.

All category I-III datasets were then used to extract developed vs non-developed extents within each county using county boundaries datasets as the set boundaries for each of the study sites.

#### 2.3.2. Estimates of Urban Intensification Variations and Trends

The degree of urbanization for each county was estimated as the relative proportion of the developed land extents within each county using Equation 1. Developed land extents were estimated as the total number of pixels mapped as NLCD developed LULCs (Classes 21 - 24) while the total land extent of each county was derived as the cumulative of all LULCs excluding open water (NLCD class 11).

$$A_c = \frac{A_u}{A_t}\% \quad [1]$$

where, $A_c$ represents the relative proportions of developed areas within each county, while $A_u$ and $A_t$ are the total land extents of developed LULCs, and cumulative land extents covered by all LULCs (excluding open water - NLCD class 11) within each county, respectively.

Area estimates were performed for separately for each of the developed LULCs and for each year and study site separately using Category I NLCD products. These estimates were used to evaluate urban intensification trends within each of the study sites. Similarly, trends in urban expansion were evaluated by estimating $A_c$ for all developed LULCs derived from Category II NLCD products ($A_U$ in Equation 1 was replaced by the cumulative area of all developed LULCs). Urban intensification trends for different intensities of urbanization as well as for overall urbanization were evaluated based on these area estimates and using Mann-Kendall ($\tau$) test. Additionally, spatial extents of the developed areas were mapped using Category II products to evaluate spatial expansion of the urban areas within each study area.

#### 2.3.3. LST Extraction and Analyses

In this study, UHI effects were evaluated by defining UHIs based on the measurable differences in surface temperatures between developed areas and their surrounding non-developed areas. Surface temperatures were derived using MODIS bi-weekly LST products that were available separately for day and nighttime. Our focus in this study was to evaluate UHI effects during extreme conditions, analyses were restricted for the summer and winter months only. Thus, summer and winter day and nighttime LST products were derived by combining all bi-weekly composites over the summer (June, July & August) and winter months (December of the current year, and January and February of the following year). For example, winter LSTs for 2000 were derived using 8-day composites of December of 2000, and January and February of 2001.

LST data from MOD11A2 products are already pre-processed for quality check and cloud contaminated pixels and extensively validated [27]. Thus, in this study, no further pre-processing was applied. However, pixel-based raster calculations were performed on all LST products to re-scale and convert LST values that were available in Kelvin into degree Celsius following the process described in the product guide [27]. Surface temperatures over developed LULCs and their non-developed/vegetated surroundings were then evaluated by overlaying annual LULC products with respective MODIS LST products and by defining spatial boundaries as the respective county boundaries of each study area. While this process tabulated all LST descriptive statistics for each of the study areas, LULC category, season, year and time (day- and night-time) separately, only the LST averages were evaluated for a fair representation of all pixel values classified for each LULC category. To avoid any mixed pixel conditions and to account for any mis-match between differently sized pixels of LST and NLCD products, no-data pixels were defined in all NLCD products (NLCD Categories I - III). Thus, derived LST statistics represented only the pixels that were completely covered by developed or non-developed areas only.

In this study, we also evaluated diurnal temperature differences over all LULCs (developed and non-developed) for each year and during both seasons. Diurnal temperature differences were estimated as the LST differences between day and nighttime using Equation 2.

$$\Delta T = T_{daytime} - T_{nighttime} \quad [2]$$

where, $\Delta T$ is diurnal temperature difference and $T_{daytime}$ and $T_{nighttime}$ are day and nighttime LSTs respectively, calculated as the average over all pixels classified for each LULC. $\Delta T$ were calculated for each of the season, year, and study area separately for different intensities of developed LULCs, as well as for non-developed LULCs.

Seasonal average LST statistics (daytime, nighttime, day-night difference) of each of the study area and during each season were then evaluated for temporal trends in LSTs using Mann-Kendall ($\tau$) test.

## 3. Results

### 3.1. Spatial Variations and Rates of Urban Expansion among Three Study Areas

Analysis of the NLCD data revealed continuous expansion of developed areas across all study sites but at varying rates. Highest rates of urban expansion reported over the Madison and Limestone counties that host Huntsville city area followed by Jefferson, and Mobile counties hosting Birmingham and Mobile city areas, respectively (**Figure 2(a)**). While urban expansion predominantly occurred through the conversion of vegetated land covers (**Figure 2(b)**), the relative proportion of developed land extents varied significantly among the study areas. Our results indicate that over the past two decades, total land extent of the developed areas within Madison-Limestone counties has increased by 7% (from 17.7% in 2000 to 24.7% in 2024). Within Jefferson and Mobile counties rates of change in developed areas were 3.5% and 3.2%, respectively.

Based on our visual interpretations of the NLCD LULC data, within the Madison-Limestone county areas these conversions were evident with larger areas of agricultural fields converting into sub-urban areas to accommodate growing needs of rapidly expanding populations in particular in the southwest boundaries of the city (**Figure 3**) where most of the new developments were introduced within the last 1 - 2 decades [28].

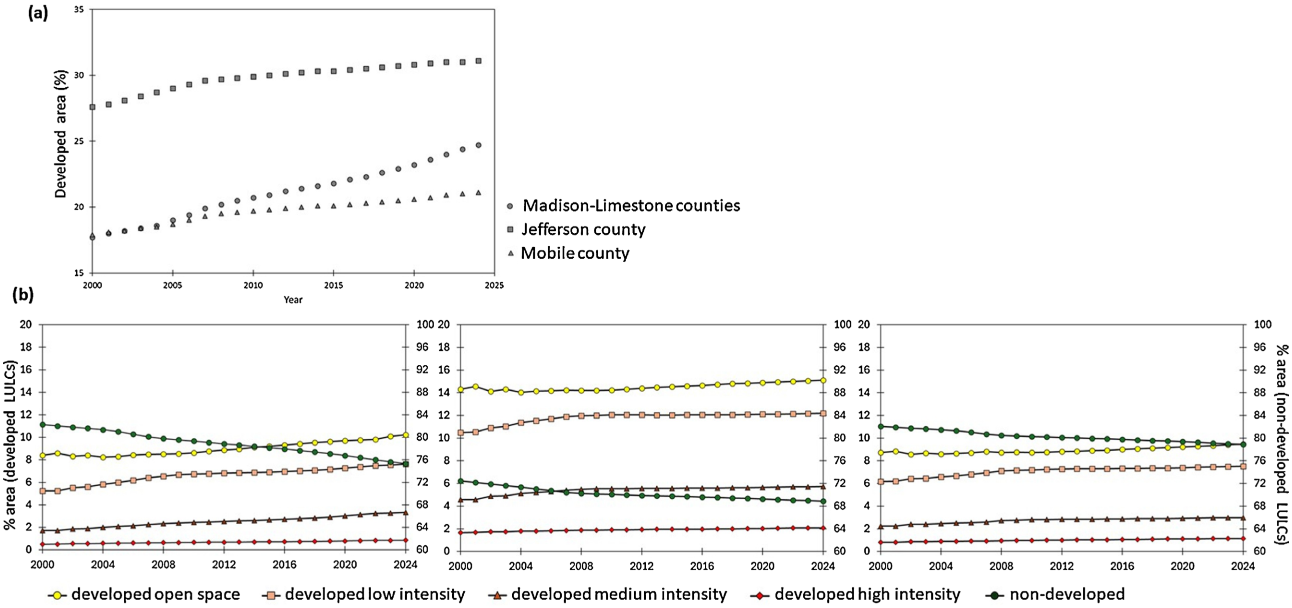


**Figure 2.** Relative expansion of the urban areas among the three study sites during the study period: (a) Total land extents of the developed areas (all developed LULCs) as a percentage of the total land extent within each study area, and (b) percentage land extents classified into different stages of urban intensification within Madison-Limestone counties (left), Jefferson county (middle) and Mobile county (right). All land extents were derived using NLCD LULC products (annual).

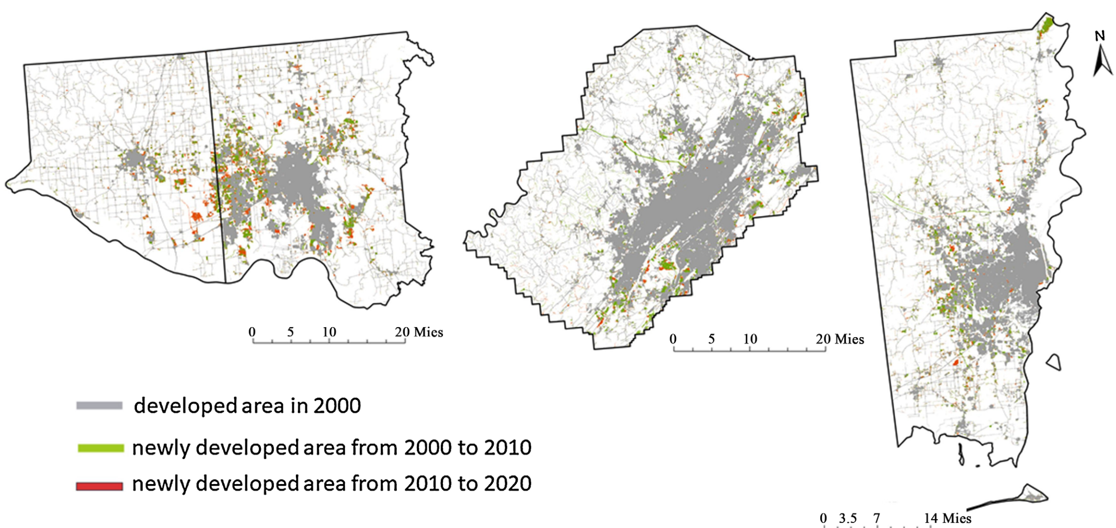


**Figure 3.** Relative expansion in urban areas within the three study areas mapped using NLCD annual LULC data of 2000, 2010 and 2020 over Madison-Limestone counties (left), Jefferson county (middle), and Mobile county (right) hosting Huntsville, Birmingham & Mobile city areas, respectively.

## 3.2. Urban Expansion Trends

Our results revealed significant ($p = 0.01$) trends of urban expansion across all three sites and for all developed LULCs at the expense of non-developed areas (**Table 1**). These results also align well with what we observed in the urban expansion maps (**Figure 3**). We observed relatively high values of the Mann-Kendall statistic along with very high statistical significance of the results ($p = 0.01$) for all developed LULCs while non-developed areas revealed strong negative trends.

**Table 1.** Mann-Kendall statistics from LULC change trend analysis.

| LULC | Mann-Kendall statistic | | |
| --- | --- | --- | --- |
| | Madison-Limestone counties | Jefferson county | Mobile county |
| Developed-open space | 0.9* | 0.8* | 0.9* |
| Developed-low intensity | 1.0* | 0.9* | 1.0* |
| Developed-medium intensity | 1.0* | 1.0* | 0.9* |
| Developed-high intensity | 1.0* | 0.9* | 0.9* |
| Non-developed | −1.0* | −1.0* | −1.0* |

*significant at 99% CI.

### 3.3. Seasonal Variations in LST

In general, MODIS-derived LST variations over developed as well as non-developed LULCs reported the expected general pattern of inter-annual fluctuations with a few relatively warmer and cooler years during our study period (**Figure 4**).

### 3.4. LST Trends

Our results did not reveal statistically significant trends ($p = 0.05$) in the daytime LSTs for either summer or winter seasons. However, increasing trends were observed in summer night-time LSTs over all study areas with highly significant trends ($p = 0.01$) in Mobile county area. Winter nighttime LSTs also showed significant increasing trends ($p = 0.05$) over the study period for all developed LULCs, except for developed high-intensity areas in Mobile county. Madison and Limestone counties exhibited moderately significant increasing trends ($p = 0.10$), while results for Jefferson county were ambiguous (**Table 2**).

### 3.5. Diurnal Temperature Differences ($\Delta T$) and Trends

Diurnal temperature differences ($\Delta T$) were evaluated based on the differences in time series of seasonal average day and nighttime LSTs over all LULCs and during both seasons. Our results reported significant differences ($p = 0.05$) in $\Delta T$s among the different LULCs over all study sites during summer. During wintertime, this difference was significant over Madison-Limestone counties and Jefferson county areas but were not significant over the Mobile county area. Moreover, across all study sites and during both seasons diurnal temperature differences were highest over the developed high-intensity areas and were lowest over the non-developed/vegetated areas (**Figure 5**).

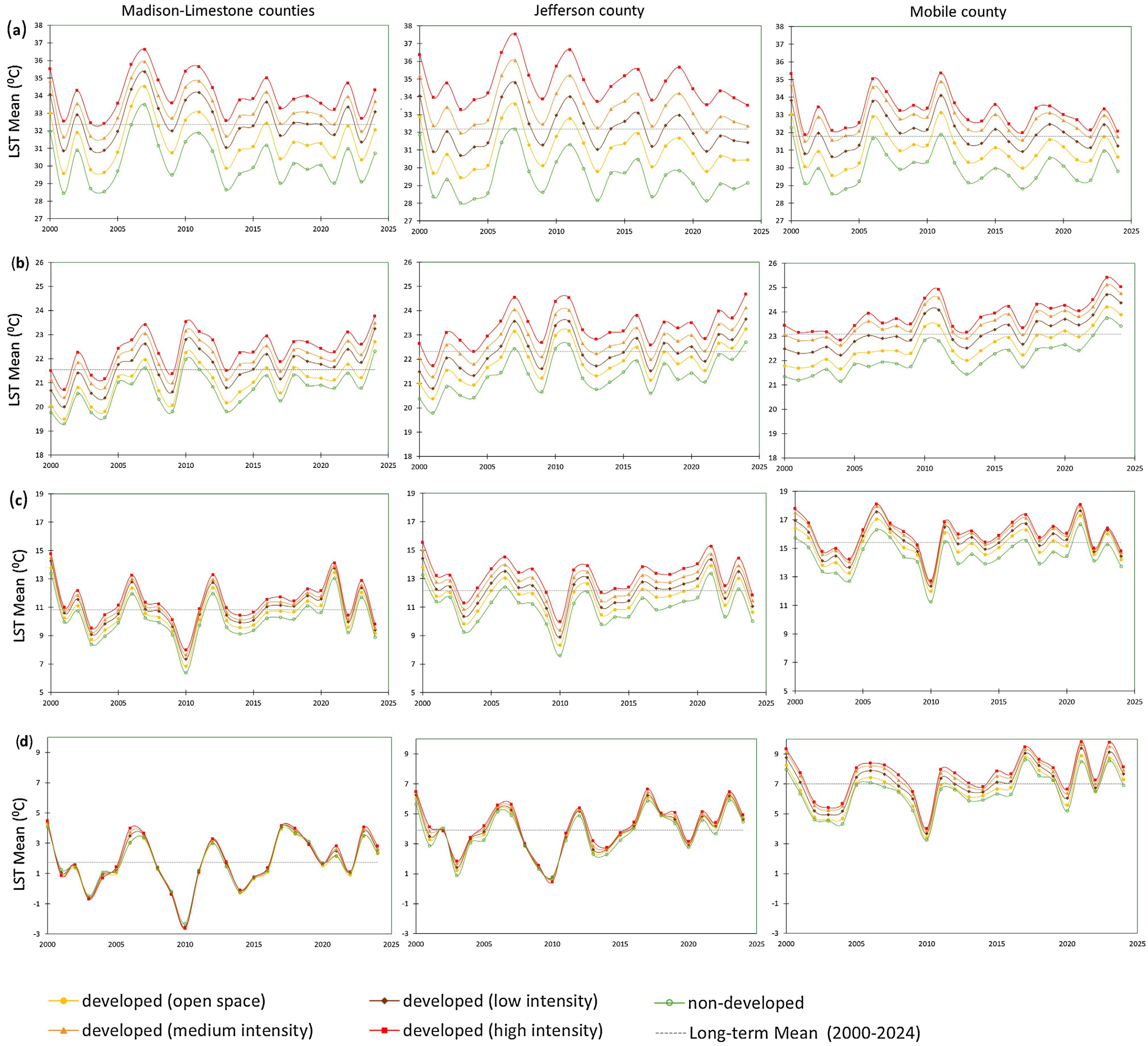


**Figure 4.** Seasonal and diurnal variations of LSTs over developed and non-developed areas. Seasonal average LSTs in ˚C were estimated as the mean of all pixel values of each LULC and are shown for a) summer daytime, b) summer nighttime, c) winter daytime & d) winter nighttime over Madison-Limestone counties (left), Jefferson county (middle) & Mobile county (right).

**Table 2.** Mann-Kendall statistics from LST trend analysis.

| | LULC | Mann-Kendall statistic | | |
|---|---|---|---|---|
| | | Madison-Limestone counties | Jefferson county | Mobile county |
| Summer day time | Developed-open space | 0.04 | 0.01 | 0.09 |
| | Developed-low intensity | 0.06 | 0.01 | 0.06 |
| | Developed-medium intensity | 0.01 | −0.08 | −0.04 |
| | Developed-high intensity | 0.01 | −0.13 | −0.08 |
| | Non-developed | 0.02 | −0.04 | 0.09 |

Continued

| | | | | |
|---|---|---|---|---|
| Summer nighttime | Developed-open space | 0.31** | 0.34** | 0.64*** |
| | Developed-low intensity | 0.33** | 0.31** | 0.59*** |
| | Developed-medium intensity | 0.30** | 0.30** | 0.57*** |
| | Developed-high intensity | 0.30** | 0.29** | 0.55*** |
| | Non-developed | 0.30** | 0.34** | 0.60*** |
| Winter day time | Developed-open space | 0.17 | 0.17 | 0.12 |
| | Developed-low intensity | 0.17 | 0.18 | 0.10 |
| | Developed-medium intensity | 0.16 | 0.17 | 0.07 |
| | Developed-high intensity | 0.16 | 0.18 | 0.06 |
| | Non-developed | 0.14 | 0.09 | 0.09 |
| Winter nighttime | Developed-open space | 0.25* | 0.27* | 0.33** |
| | Developed-low intensity | 0.26* | 0.25* | 0.33** |
| | Developed-medium intensity | 0.25* | 0.22 | 0.29** |
| | Developed-high intensity | 0.25* | 0.24 | 0.30** |
| | Non-developed | 0.25* | 0.25* | 0.30 |

*, **, and *** indicate significant trends at 90%, 95% and 99% CI, respectively.

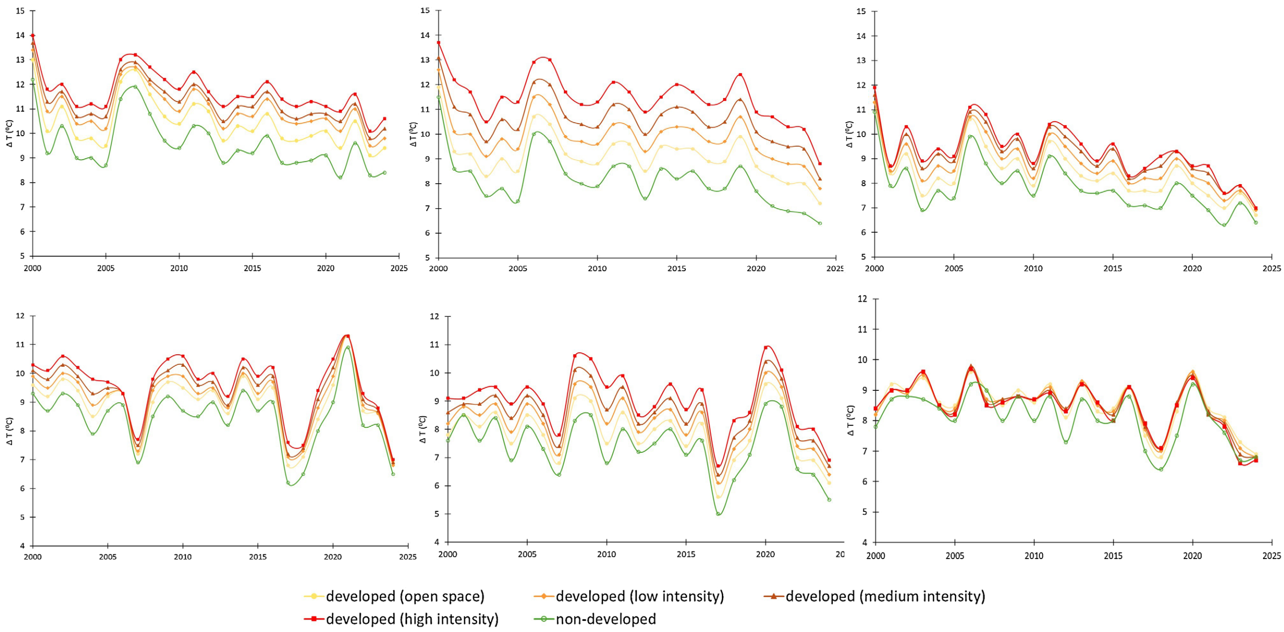


**Figure 5.** Diurnal temperature variations ($\Delta T$) among developed and non-developed LULCs over Madison-Limestone (left), Jefferson (middle) and Mobile (right) counties during summer (a) and winter (b) seasons.

Overall, during summertime, diurnal temperature differences reported decreasing trends across all counties. Moreover, across all counties, decreasing trends in $\Delta T$ during summer were highly significant and stronger as compared to the trends observed in winter (Table 3).

Table 3. Mann-Kendall statistics from $\Delta T$ trend analysis.

| | LULC | Mann-Kendall statistic | | |
|---|---|---|---|---|
| | | Madison-Limestone counties | Jefferson county | Mobile county |
| Summer | Developed-open space | −0.34** | −0.32** | −0.44*** |
| | Developed-low intensity | −0.37*** | −0.33** | −0.44*** |
| | Developed-medium intensity | −0.39*** | −0.35** | −0.45*** |
| | Developed-high intensity | −0.41*** | −0.38*** | −0.42*** |
| | Non-developed | −0.36*** | −0.38*** | −0.43*** |
| Winter | Developed-open space | −0.16 | −0.24* | −0.43*** |
| | Developed-low intensity | −0.20 | −0.24* | −0.42*** |
| | Developed-medium intensity | −0.20 | −0.25* | −0.40*** |
| | Developed-high intensity | −0.21 | −0.24* | −0.41*** |
| | Non-developed | −0.15 | −0.28* | −0.38*** |

*, **, and *** indicate significant trends at 90%, 95% and 99% CI, respectively.

Moreover, decreasing trends observed in diurnal temperature differences during the summer season, revealed strong correlations to the observed trends in urban expansion estimated using spatial expansion of the developed land extents (**Figure 6**). Across all study sites diurnal temperature differences were decreasing over time as the proportions of developed land extents increased.

## 4. Discussion

### 4.1. Spatial Variations and Rates of Urban Expansion among Three Study Areas

Our estimates of urban expansion based on NLCD LULC data indicate a steady expansion of the developed areas throughout the study period with 0.2% to 0.5% of the total land area converted into developed land cover during each year with rapid developments starting around 2004 and over the more recent years from 2021. Urban expansion within Jefferson and Mobile county areas reported similar trends with most developments occurred prior to 2007/2008 with approximately 0.2% - 0.3% of the total land area converted to developed land covers during each year but then slowing down to 0.1% per year rate. These estimates align with recent reports indicating rapid urban developments in Huntsville and surrounding areas [25] [26]. Specifically, rapid expansion occurred during the early 2000s, urban expansion rates declined during COVID-19 pandemic, and increased again during post-pandemic [28]. Most urban developments in Jefferson and Mobile county areas reported during early 2000 [29] [30]. Urban developments within the Jefferson county hosting Birmingham city area stand out clearly in-terms of intensified urban developments (**Figure 2(a)**) with nearly one third of the county's total land area mapped as developed areas (31.1% and 35.1% of the total

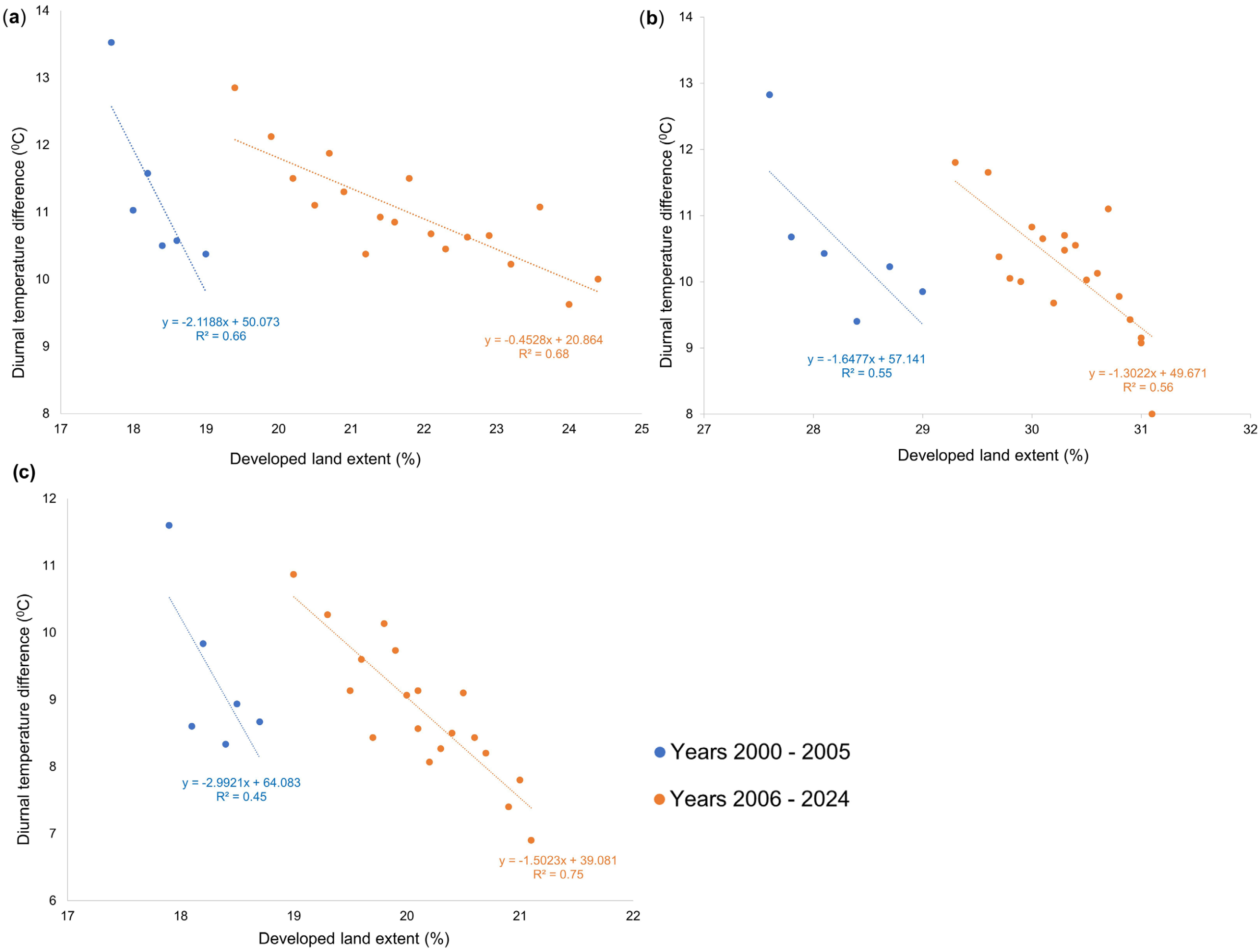


**Figure 6.** Diurnal temperature differences during the summer season plotted against percentage of developed land extents within each study site over Madison-Limestone counties (a), Jefferson county (b) and Mobile county (c).

land area was classified as developed in 2000 and 2024, respectively). Within the two other areas this percentage remains relatively low (as of 2024, 24.7% and 21.1% of total land area within Madison-Limestone and Mobile county areas were mapped as developed LULCs respectively, Figure 2(a)) leaving a relatively larger proportion of the land extents still covered by vegetated areas.

Land cover conversions within developed areas showed similarities among the three study sites with the least expansion in the developed high intensity areas and the largest expansion in developed low intensity areas across all three study areas. For example, within this study period, over the Madison-Limestone county area the total percentage of the developed low intensity areas increased from 5.9% to 8.5% reporting nearly 2.7% of the total land area converted into developed-low intensity areas. Similarly, within Jefferson and Mobile county areas, nearly 1.7% and 1.4% of the total land area was converted into developed-low intensity areas. Within the Madison-Limestone county area, much of the area is also converted into developed open space (~2.1% of the total land area converted into developed open space). Collectively these landcover conversions reflect urban expansion at the loss of vegetated and non-developed areas.

### 4.2. Urban Expansion Trends

Based on our area estimates for each of the LULC areas (developed & non-developed—Categories I & III), urban expansion trends were quantified using Mann-Kendall statistic ($\tau$). Positive values of the Mann-Kendall statistic indicate increasing trends over time, while negative values indicate decreasing trends. Our results revealed increasing trends of urban expansion across all three sites and for all developed LULCs at the expense of non-developed areas (**Table 1**). These findings also align well with what we observed in our urban expansion maps (**Figure 3**). Relatively high values of the Mann-Kendall statistic along with very high statistical significance of the trends ($p = 0.01$) indicate steady growth of the urban areas over the study period while strong negative values reported for the non-developed areas indicate the loss of natural areas over time.

### 4.3. Seasonal Variations in LSTs

In this study we evaluated seasonal variations in urban temperatures as recorded in MODIS-derived LSTs during summer and winter seasons and among the three study areas. These two seasons were selected for a better comparison between extreme weather conditions. Selection of these three areas also allows us to compare UHI effects across varying levels of urban intensification as well as along the north-south gradient capturing natural climate variations due to geographic location. Both day- and night-time LSTs were evaluated to capture diurnal variations in urban temperatures in comparison to their adjacent landscapes that are still occupied by vegetated land covers as a measure of UHI intensities.

Summer average LSTs clearly reflected heat waves including two events of 2007 and 2021 with clear above average temperatures over all LULCs (developed as well as non-developed). Further, relative warming of the developed LULCs were reflected in MODIS-derived mean LSTs (**Figure 4**). As expected, elevated surface temperatures over the developed LULCs (as compared to their surrounding vegetated areas) were observed across all study sites and during both day- and night-times of summer as well as during daytimes of winter. Significantly ($p = 0.05$) higher LSTs over all developed LULCs as compared to their non-developed LULCs were reported during both day- and night-times of the summer. Similar LST variations were observed during winter daytime, but with relatively weak UHI developments. These results corroborate with the basic concept of UHI effect that temperatures over urbanized areas are higher than natural (non-developed/vegetated) areas [31]-[33]. Similar findings of weak UHIs have been reported from previous studies as well [34] [35]. During winter, anthropogenic energy balance dominates the energy cycle due to weak incoming solar radiation [36]. Even during winter daytime, indirect irradiance of solar energy that is available for a relatively a shorter period of time accumulates lesser heat than during summer [35]. Conversely, winter nights get longer time to radiate the energy and have better cooling than summer. These phenomena can collectively explain relatively lower LST differences between developed and non-developed LULCs and thus weak UHI developments during summer as well as during winter daytimes as compared to winter night-times. During winter night-times, slight variations in LSTs were observed among developed and non-developed areas across all study sites.

Mobile County, a coastal region situated in a relatively warmer part of the state, exhibited distinct behavior by revealing elevated LSTs even during winter nighttime. These findings may indicate increasing possibilities for stronger UHI developments and intensified UHI effects in the coastal county's developed areas even during the winter.

As expected, across all study areas, the magnitudes of the elevated surface temperatures between developed and non-developed areas were highest during summer daytimes and thus indicate potential for intensified UHI effects during relatively warmer time periods (*i.e.* heat waves).

### 4.4. Diurnal Temperature Differences ($\Delta T$) and LST Trends

Based on the trends that we observed in LSTs, it appears that increasing trends in urban expansion in the expense of developed/ vegetated surfaces (as reflected in increasing trends in developed LULC extents and decreasing trends in non-developed LULC extents) can have possible contributions towards increasing trends in LSTs over our study areas. Elevated heat accumulations over developed areas resulting from increasing impervious surfaces and urban structures in the expense of natural/ vegetated surfaces have been documented previously as well [37].

Observed trends in $\Delta T$s are primarily due to increasing trends in nighttime LSTs along with no evident trends in daytime LSTs (**Figure 4** & **Table 2**). On average, during the two decades the diurnal temperature differences during summer decreased by about 2˚C - 3˚C. Moreover, observed trends in diurnal temperature differences appear to closely relate to the observed changes in urban developments and was evident in our results from regression analyses between diurnal temperature differences and proportions of developed land extents within each study sites (**Figure 6**). During the study period, across all three sites urban expansion continued over the study period (**Figure 2**, **Figure 3** & **Figure 6**), while diurnal temperature differences decreased (**Figures 5** & **Figure 6**). Decreasing trends in diurnal temperature differences were primarily due to the increasing LSTs while no clear trends were evident in daytime LSTs (**Table 2**). These findings indicate potential impacts of urban expansion in the expense of non-developed/ vegetated areas on urban micro-climates. More specifically, these findings indicate the possibility of elevated surface temperatures over developed areas even within mid-size cities, predominantly during the nighttime. Elevated surface temperatures can be attributed to lack of cooling effects of vegetated surfaces in general [38] and more specifically during nighttime. These findings also indicate the increasing possibilities for intensified UHI effects during relatively warmer conditions (as in summer/heat waves).

## 5. Conclusions

With rapid growth of urbanization, urban heat island (UHI) effect is a growing concern. This study primarily aimed to investigate the growth of urbanization in four counties of Alabama, namely Madison and Limestone counties, Jefferson county and Mobile county hosting three major cities: Huntsville, Birmingham, and Mobile respectively. We evaluated spatial variations and trends in UHI developments as reflected in satellite derived LST products from MODIS. Analysis of NLCD data revealed continuous urban expansion across all study sites, albeit at varying rates. The highest rates of urban expansion were observed in Madison and Limestone counties (hosting Huntsville city area), followed by Jefferson county (hosting Birmingham city area) and Mobile county (hosting Mobile city area). Spatial expansion of the developed areas was clearly evident in the urban expansion maps. The least expansion in the developed high intensity areas and the largest expansion in developed low intensity areas were observed across all three study areas. Highest rates of urban expansion reported over the Madison and Limestone counties that host Huntsville city area followed by Jefferson, and Mobile counties hosting Birmingham and Mobile city areas, respectively. With increasing urbanization, increasing trends in nighttime temperatures were reported across all study areas and during summer as well as winter seasons with relatively stronger trends during summer. As a result, diurnal temperature differences, quantified as the difference between time series of seasonal average daytime and nighttime temperatures, reported decreasing trends during summer as well as winter seasons but with highly significant trends during summer. Our findings also indicate potential impacts of urban expansion (in the expense of non-developed/vegetated areas) on urban surface temperatures possibly leading to elevated LSTs during the nighttime. These findings indicate the increasing possibilities for intensified UHI effects during relatively warmer conditions as in summer and during heat waves.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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