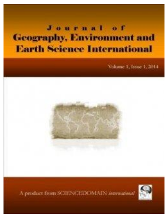

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The Urban Heat Island of San Antonio, Texas, from 1991 to 2010

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Authors' contributions

This work was carried out in collaboration between all authors. Author DCB designed the study, managed the analyses and wrote the first draft of the manuscript. Author MEG managed the mitigation strategies and author SEH performed the statistical analysis. Authors DCB and MEG managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

This study aims to investigate the urban heat island (UHI) effect of San Antonio, Texas (USA), and its temporal changes over the time period 1991-2010. It is an extension of previous work that used historical air temperature data from 1946 to 1990. The study was designed to compare 20 years of daily air temperature records (1991-2010) of San Antonio, Texas (USA), with three small surrounding communities; New Braunfels, Poteet, and Boerne. These towns are all within 50 kilometers of San Antonio and have contemporary temperature records. Temperature differences between San Antonio and the surrounding communities indicate changes in the thermal environment due to urbanization. The results are as follows. The daily UHI intensity in autumn and winter is increasing and decreases in the spring and summer seasons. Autumn is the only season where the daily UHI intensity increased and spring is the only season where it decreased during the years 1991-2010. The results for Poteet and Boerne were generally similar. In June during 1997 to 2010, the daily UHI intensity in San Antonio is increasing at an average rate of 0.8°C/decade relative to New Braunfels. These results are generally consistent with previous studies. A physical

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model of the urban environment is described that is under development to aid in interpreting the results and for city planning. Mitigation strategies as applied to San Antonio are briefly discussed, including green roofs, and urban trees and other natural vegetation. In conclusion, despite mitigating influences, San Antonio continues to have an increasing UHI effect. However, further work is needed to connect to the previous study from 1946 to 1990 and update to the present to strengthen this conclusion.

Keywords: Urban heat island (UHI); historical air temperature measurements; urban heat sources; UHI mitigation; urban environmental models.

1. INTRODUCTION

The migration of people to urban areas over the past centuries has lead to societal benefits and has modified the local environment and ecology in many ways. The USA has experienced substantial urban growth over the past century, resulting in population increases in urban areas from 45.6% in 1910 to 80.7% in 2010 [1]. This trend is expected to continue during the 21st century. This extensive urbanization has led to warmer thermal environments in urban areas, known as "heat islands," where vegetation and surface water cover, which would otherwise reduce surface temperatures through evapotranspiration, have been replaced by buildings and pavements with higher thermal inertias that retain heat. In addition, human activity is a significant heat source where power generation, extensive transportation networks, air conditioning, and others contribute to higher urban temperatures when compared to the rural surroundings. In a large city, air temperatures can be as much as 12°C higher than the nearby rural areas. Consequently, these higher urban temperatures increase energy demand, raise air pollution levels, and cause heat-related illnesses and even death. For example, higher urban temperatures during heat waves can cause heat stroke in vulnerable populations (elderly, infirmed, and infants) and provide conditions suitable for the spread of infectious and vector-borne diseases (malaria, dengue fever, etc.) [2]. As global temperatures continue to rise due to climate change, urban areas are likely to experience more intense, more frequent, and longer heat waves.

The urban heat island (UHI) can be measured directly by air temperatures in the canopy layer using common meteorological stations, and indirectly by surface temperatures using infrared (IR) satellite imagery or by aircraft measurements in the upper atmosphere (boundary layer), although the relationship between these different aspects of heat islands can be complex. Strictly speaking, the UHI refers to the effect on air temperature in the canopy layer. Satellite imagery reveals effects of the surface temperature, the Surface Urban Heat Island (SUHI), that is an important source of heat that influences the air temperature and usually correlates with it. However, there are instances where the UHI and SUHI do not correlate since there are other important heat sources and sinks that affect the air temperature. The SUHI also establishes the two-dimensional spatial extent of heat effects throughout the urban region where air temperatures do not exist. Measurements of air temperature in the boundary layer give an important vertical component to the effects of the UHI.

As urban areas grow to megalopolis sizes, they may actually affect the local climate, instead of only being a perturbation of it. The causes of the UHI can be broadly divided into two classes, active and passive heat sources. Active heat sources include power generation and utilization, heat associated with transportation, air conditioning exhausts, industrial waste heat, fires, and others. Passive sources include impervious cover, pavements, building and housing surface structures, roofing materials, among others [3].

Once a UHI has been established, it is important to understand how it changes with time. To measure its growth (warming) rate, temperature datasets with long time baselines are needed. Warming rates are known to exist and have been well documented for large urban areas world-wide. Previous studies in the USA have shown that warming rates can be as high as 1-3°C/decade [4].

Studies of the UHI are important for several reasons. Power generation demands for cities must be forecast at least a decade in advance due to the long time-scale to build new power plants. It is well known that energy demands are positively correlated to temperature highs (above about 20°C), especially in the summer months, so a few degree increase over that time period due to the UHI is significant. Urban planners need to understand heat island effects so they can include mitigating measures to combat the UHI in their future plans. The “hot air bubble” caused by the UHI effects the local weather and can result in lower rainfall as storms are diverted around the city (e.g., [5,6]). This affects the watershed and also leads to more evaporation of surface water. The UHI may also affect climate change studies since temperatures are gathered in urban areas and need to be calibrated for the UHI. However, this has been disputed by Hansen et al. [7] and Peterson [8] who claim that the influence of urban heat bias on estimates of global surface temperature change is minimal.

The UHI also affects air chemistry, increasing air pollution including ozone, since key reaction rates are highly temperature dependent [9]. Anthropogenic activity causes chemical emissions (hydrocarbons, sulfur compounds, NOx compounds, aerosols, etc.) in the urban atmosphere that dissociate and ionize due to solar ultraviolet (UV) radiation. The resulting radicals and ions undergo chemical reactions in the atmosphere, producing many new species and enhancing naturally existing ones. The rates of chemical reactions with low activation energy barriers and the formation of aerosols absorb and re-emit radiation in the IR. Thus, heat radiation is trapped by urban air and creates a positive feedback on the heat island effect and on chemical air pollution [9].

The remainder of this paper is organized as follows: Section 2 gives a brief description of the geographical area included in this study, summarizes previous studies of the UHI of San Antonio, and discusses the temperature database, methodology, and data analysis, including a description of a physical model of the UHI under development; Section 3 presents the results and limitations of the study; including preliminary results from the UHI physical model and mitigation strategies with application to San Antonio; and Section 4 gives conclusions and directions for future studies.

2. METHODOLOGY

2.1 Geographical Area and Studies of the UHI of San Antonio, Texas (USA)

San Antonio is the seventh largest city in the USA with a population of over 1.3 million [1]. It has a variety of vegetation with little polluting industry and as of late 2017, continues to be designated as an attainment city by the US Environmental Protection Agency (EPA) under the federal government’s stricter 2015 air quality standards. For comparison, the Houston metropolitan area and the Dallas-Fort Worth metroplex are listed as non-attainment cities. (Houston and Dallas are the fourth and ninth largest US cities, respectively.) Consequently, San Antonio is less influenced by anthropogenic activity than other major cities. It has experienced rapid growth over the past decades (sixth in population growth among major US cities in 2016) that counters mitigating influences on the UHI, making it an interesting case study.

Past studies of the historical temperature records have established that a UHI exists in San Antonio, Texas (USA). A tentative discovery was made in the preliminary study by Huebner and Boice [10], comparing air temperatures of San Antonio to only one nearby rural site (New Braunfels, TX). Boice et al. [11] made the first definitive detection by using 45 years of air temperature data from 1946 to 1990, comparing San Antonio to three surrounding “rural” communities (New Braunfels, TX; Poteet, TX; and Boerne, TX). These small communities are within about 50 km of San Antonio and have contemporary temperature records. All are part of the San Antonio Metropolitan Area (Greater San Antonio). Fig. 1 shows the location of these sites, forming a nearly equilateral triangle surrounding the city. They all have similar latitudes, elevations, distances from each other, and distances from the Gulf of Mexico coast. Table 1 gives relevant population information about these communities, taken from [1]. San Antonio has remained an Urbanized Area (UA) but crossed over to being a metropolis (population > 1,000,000) during this study. New Braunfels and Boerne show the largest growth with Boerne crossing over from Rural (R) to an Urban Cluster (UC) and New Braunfels leaping from Rural to Urbanized Area. Although being the smallest community with the least growth, Poteet has remained an Urban Cluster, just missing Rural due to its small population. (Definitions of UA, UC, and R are given in the Table 1 notes).

2.2 Data and Analysis

To quantify the urban heat island effect, homogeneous, high-quality daily maximum and minimum air temperature datasets were assembled for San Antonio, Texas, and the three surrounding communities using data from the National Weather Service (NWS) weather station network as archived at the National Climatic Data Center (NCDC) [12]. Upon submission to the NCDC, the data is certified for climate investigations; therefore, quality control of the data was unnecessary since the data from the NWS stations has already been scrutinized as part of standard NCDC procedures. The typical precision of the temperature measurements is 0.3°C.

As noted by Peterson [8], there are many limitations of the historical temperatures resulting in data inhomogeneities. Biases between station measurements can exist (such as, equipment differences, changes in instrumentation and location, sampling, data recording methods, station microclimate, etc.) and are typical causes of data inhomogeneities. Modernization of the NWS during the early 1990s resulted in the introduction of Automated Surface Observing System (ASOS) instrumentation. For a few years at the beginning of our study, prior to the implementation of ASOS systems, the time of day for manually reading Maximum/Minimum Temperature Systems was selected to be 8am at each station. With the implementation of the ASOS systems, all time of observations were synchronized automatically. Therefore, adjustments for time-of-observation bias were not necessary in our datasets. Site location and instrument exposure issues have been addressed by the NWS.

Urban encroachment may affect stations that were formerly in appropriate locations. Airport locations and general urbanization are the most important sources of problems with historical temperature records. The authors are aware of these limitations and strived to minimize their effects. The only major influence on the San Antonio record of which the authors are aware was a relocation of the station from a site near a newly constructed parking lot at the airport to a grassy field on the airport's property in 1997. This move shows up in the temperature data as a cooler measurement by a few degrees. For this preliminary report, the authors choose to keep the original historical data, knowing that the observed warming trends would be underestimated due to this relocation. Using historical meteorological weather data has limitations but when properly addressed, these data have been used in many past studies to establish the existence of a UHI and its intensity.

To facilitate comparisons with the previous study [11], the authors followed the same methodology to analyze the extended datasets from 1991 to 2010. The absolute historical temperature trends were investigated for San Antonio and the three surrounding communities. Using the T_{max} and T_{min} primary data, several derived quantities were determined including the temperature range [$T_{range} = (T_{max} - T_{min})$] and the mid-range temperature [$T_{mid\text{-}range} = (T_{max} + T_{min})/2$]. (Many researchers report $T_{mid\text{-}range}$ as the mean daily temperature (T_{mean}) but that is not statistically accurate.) The authors will refer to $T_{mid\text{-}range}$ as simply the daily temperature (T_{daily}) since it does represent an average of sorts.

To investigate the UHI intensity (UHII), differences in the temperatures of San Antonio and the three surrounding communities were computed following the standard definition of the UHII [UHII = $T_{urban} – T_{rural}$]. By taking temperature differences, any long-term, climatic influences are minimized. Due to their proximity, the microclimates of the comparative regions should be relatively similar to San Antonio and to each other. The authors adopted monthly (and annual) averages of T_{daily}, T_{min}, and T_{max} to minimize random errors in the datasets. In addition to calculating UHII using T_{daily} differences, the authors have also calculated differences in T_{max} and T_{min} between San Antonio and the surrounding rural communities. Many researchers have labelled these quantities as the "daytime UHI" and "nighttime UHI." Although these are not strictly measurements of the UHII, they are nevertheless important for understanding diurnal effects of heating and cooling processes that affect the UHI so they have been included in this study. The analysis was carried out with extreme care since there are small gaps in the data.

After calculating the UHII using each comparison rural community, standard linear least squares techniques were used to quantify the temporal UHII growth rates. The mean UHII growth rate was obtained by averaging the results from each community.

The authors also binned the temporal data by monthly and seasonal averages (summer is defined as June through August, autumn is September through November, etc.) to look for long-term seasonal trends, as well as diurnal trends. Using astronomically defined seasons (i.e., spring is from vernal equinox to summer solstice, etc.), the results were not significantly different from the simplified definition mentioned above.

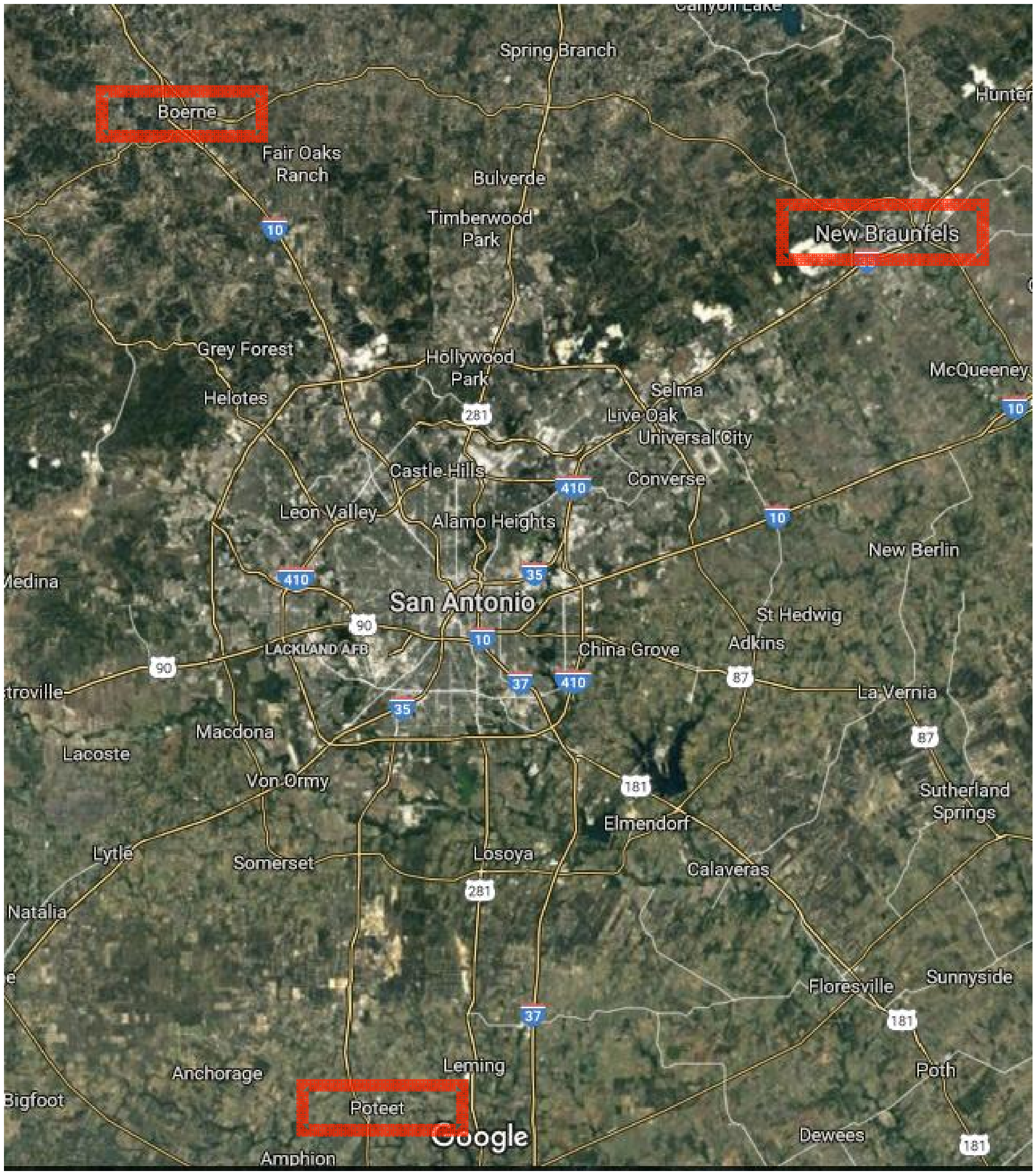

Fig. 1. Location of San Antonio and the surrounding communities in this study. (Courtesy Google Maps)

Table 1. Populations of San Antonio and surrounding communities in this study[a]

City	US Census Bureau population (1990)	US Census Bureau population (2010)	Population growth from 1990 to 2010	Population density [mi^{-2}][b] (1990)	Population density [mi^{-2}][b] (2010)	Distance from San Antonio City Center [km]
San Antonio	999,290	1,327,407	32.8%	2168 (UA)	2880 (UA)	•
New Braunfels	27,803	57,740	107.7%	626 (R)	1316 (UA)	51 (NE)
Boerne	4699	10,471	122.8%	810 (R)	1088 (UC)	48 (NW)
Poteet	3028	3260	7.7%	1781 (UC)	1918 (UC)	48 (S)

[a]Source - US Census Bureau [1]; [b]Communities are classified according to the US Census Bureau as an Urbanized Area (UA; population >50,000 and population density >1000/mi^2), Urban Cluster (UC; 2500 < population < 50,000 and population density >1000/mi^2), or Rural (R; population <2500 or population density <1000/mi^2)

Two primary weather characteristics affect urban heat island development: wind and cloud cover. In general, urban heat islands form during periods of calm winds and clear skies, because these conditions maximize the amount of solar energy reaching urban surfaces and minimize the amount of heat that can be convected away. Conversely, strong winds and cloud cover suppress urban heat islands. The authors acknowledge these effects of frontal weather on UHI magnitude, but no corrections for weather could be made since this information is not included in the NCDC records.

Changes have occurred in the “rural” areas used in this study. As shown in Table 1, New Braunfels and Boerne have grown since the original study at a higher rate than San Antonio, Poteet at a lower rate than San Antonio, and all continued to grow during the current timeline (1991-2010). Indeed, rapid growth has occurred in San Antonio along the corridors connecting to Boerne and to New Braunfels, less so in the direction to Poteet. At some point in large-scale urban development, heat islands must be considered as defining local and regional climate rather than being just a perturbation on that climate. The authors note that San Antonio hasn’t graduated into this megalopolis category at this time.

Stewart [13] has systematically reviewed the methodology in modern UHI literature. He developed nine criteria of experimental design and communication to critically assess methodological quality in heat island studies. The present study is found to pass the three critical criteria (adherence to the conceptual model, operational definitions, and site representativeness), two of the three desirable criteria (site metadata and number of replicants), and a somewhat essential criterion (data collection synchronicity). This places the present study in the top tier, meaning that UHI estimates are acceptable. The reader is referred to [13] for more details concerning these criteria.

The concept of Local Climate Zones (LCZ) has been introduced to facilitate the comparison of urban temperature measurements for UHI studies [14]. There are 17 LCZ classes, urban built types numbered 1 to 10 and rural natural types with letters A to G. Each class is based on the local physical and thermal properties of the urban and rural sites. San Antonio exhibits all built types (LCZ 1-LCZ 10) but a larger proportion of LCZ 5 (open mid-rise) and LCZ 6 (open low-rise) and a deficiency of LCZ 3 (compact low-rise) and LCZ 4 (open high-rise) [15]. The surrounding rural areas are mostly LCZ A (dense trees) in the north and east, LCZ B (scattered trees) and LCZ D (low plants) in the south, and LCZ D in the west [15]. New Braunfels appears to be similar to San Antonio, containing mostly LCZ 6 followed by LCZ 5. The Boerne and Poteet sites have a high proportion of LCZ A/B and LCZ B/D, respectively. These LCZ classes are useful for investigations of the land surface temperatures obtained by IR satellite imagery for San Antonio’s SUHI [15].

It must be kept in mind that the temperature readings were taken from a single weather station in each community. In San Antonio this was at the international airport, an area with paved parking lots, long runways, many buildings, and much traffic. To gain more insight into the nature of the UHI in San Antonio, a grid of temperature stations needs to be established to measure the temperature distribution within this major US city. Links to San Antonio’s SUHI with high spatial resolution will be important also.

2.3 The Urban Environmental Model (UEM) for Studying the UHI

A physics-based model to study the UHI, called the Urban Environmental Model (UEM), has been initiated [9]. In addition to studying increasing temperatures and directly connecting the SUHI and upper atmosphere effects to the UHI, the goal of UEM is to have a general tool for investigating a variety of important issues facing modern cities. These include air quality, especially the effects of the UHI on ozone concentration; changes in the local meteorology (winds, humidity, clouds) due to a hot "bubble" of air over the city; relationships of the UHI to ground and surface water; and long-range city planning strategies to mitigate the negative effects of the UHI. The Regional Atmospheric Modeling System (RAMS, version 6 released in 2009) [16], a mesoscale meteorological computer simulation, was selected for modification. Mesoscale, meteorological models successfully simulate the transport and deposition of air pollution, so accounting for urban air pollution chemistry with meteorology is an important step because many chemical reactions are sensitive to air temperature. A change of a few degrees can greatly affect reaction rates and, in turn, the concentrations of pollutants. A computer code developed to study chemical reactions in the atmospheres of comets [17] has been modified to include urban air pollution chemistry, and coupling to RAMS has begun. The interaction of sunlight with the atmosphere is necessary since many air pollutants, including aerosols, absorb and re-emit radiation in the infrared as heat; trapping hot urban air and creating a positive feedback on the UHI and on air pollutants. Conversely, strong winds dissipate pollutants and urban heat. Additional modifications to RAMS have been made. The soil model was adapted to include urban "soil" and "vegetation" classes along the lines of the LCZ concept, urban parameters such as heat capacity, thermal diffusivity, thermal conductivity, moisture capacity, hydraulic conductivity, soil porosity, surface albedo, emissivity for long-wave radiation (heat), and surface roughness have been included. The inclusion of internal heat sources to simulate anthropogenic activity (vehicles, air-conditioners, power plants, etc.) in the city has been added.

3. RESULTS AND DISCUSSION

In this section, the authors briefly summarize the results from their extensive study and give a few illustrative examples. Table 2 contains monthly average temperatures of San Antonio compared to New Braunfels (as a representative "rural" area) during the years from 1991 to 2010. It can be seen that the daily UHI in the summer months (June through August) exhibits an increasing trend, similar to the daytime UHI while nighttime UHI decreases during these months. In turn, the daily, daytime, and nighttime UHI in the autumn months (September through November) generally show an increasing trend. Table 3 lists the average seasonal temperature differences between San Antonio and New Braunfels. The seasonal daily UHI in autumn and winter is increasing and decreases in the spring and summer seasons. Daytime UHI in summer, autumn, and winter is increasing, whereas the nighttime UHI is decreasing during this time period. Autumn is the only season where the daily, daytime, and nighttime UHI increased and spring is the only season where they all decreased during the years 1991-2010. Comparisons with Poteet were generally similar to the results for New Braunfels. Table 4 contains monthly average temperatures of San Antonio compared to Boerne. In contrast to the results from New Braunfels, the daily UHI exhibits mostly decreasing trends (increasing trend only for the months of February, June, and August). Daytime UHI shows an increasing trend only for the months of February, March and June, while it decreases during all other months. The nighttime UHI in all months except August shows a decreasing trend. It is noted that these trends for Boerne were all small and could reverse within their standard errors. Fig. 2 shows the differences of the average temperatures in June between San Antonio and New Braunfels during 1997 (when the weather station was moved) to 2010 for the daily, daytime, and nighttime measurements. Fig. 3 presents the trendlines for the temperature data shown in Fig. 2. It shows that the daily UHI at the San Antonio International Airport is increasing at an average rate of 0.8°C/decade, whereas the daytime UHI is increasing 1.6°C/decade and the nighttime UHI remained relatively constant. The UHI growth rates from the previous study [11] are included for comparison.

Table 2. Average monthly temperature differences between San Antonio & New Braunfels, 1991 - 2010

Month	Average maximum temperature difference (°C)	Trend of daytime UHI from 1991 to 2010	Average daily temperature difference (°C)	Trend of daily UHI from 1991 to 2010	Average minimum temperature difference (°C)	Trend of nighttime UHI from 1991 to 2010
Jan	0.3	Decreasing	1.2	Decreasing	2.1	Decreasing
Feb	0.9	Increasing	1.6	Increasing	2.2	Increasing
Mar	0.3	Decreasing	1.2	Decreasing	2.0	Decreasing
Apr	0.4	Decreasing	1.0	Decreasing	1.6	Decreasing
May	0.5	Decreasing	1.1	Decreasing	1.6	Decreasing
Jun	0.5	Increasing	1.0	Increasing	1.4	Decreasing
Jul	0.3	Increasing	0.8	Increasing	1.3	Decreasing
Aug	0.3	Increasing	1.0	Increasing	1.7	Decreasing
Sep	0.1	Increasing	0.9	Increasing	1.7	Increasing
Oct	0.5	Decreasing	1.4	Decreasing	2.2	Increasing
Nov	0.1	Increasing	0.8	Increasing	1.4	Increasing
Dec	0.7	Increasing	1.4	Increasing	2.0	Increasing

Table 3. Average seasonal temperature differences between San Antonio & New Braunfels, 1991 - 2010

Season	Average maximum temperature difference (°C)	Trend of daytime UHI from 1991 to 2010	Average daily temperature difference (°C)	Trend of daily UHI from 1991 to 2010	Average minimum temperature difference (°C)	Trend of nighttime UHI from 1991 to 2010
Winter	0.5	Increasing	1.3	Increasing	2.1	Decreasing
Spring	0.4	Decreasing	1.0	Decreasing	1.6	Decreasing
Summer	0.2	Increasing	0.9	Decreasing	1.5	Decreasing
Autumn	0.4	Increasing	1.2	Increasing	1.9	Increasing

Table 4. Average monthly temperature differences between San Antonio & Boerne, 1991 - 2010

Month	Average maximum temperature difference (°C)	Trend of daytime UHI from 1991 to 2010	Average daily temperature difference (°C)	Trend of daily UHI from 1991 to 2010	Average minimum temperature difference (°C)	Trend of nighttime UHI from 1991 to 2010
Jan	1.6	Decreasing	2.6	Decreasing	3.6	Decreasing
Feb	1.7	Increasing	2.5	Increasing	3.2	Decreasing
Mar	1.5	Increasing	2.6	Decreasing	3.6	Decreasing
Apr	1.2	Decreasing	2.2	Decreasing	3.1	Decreasing
May	1.7	Decreasing	2.2	Decreasing	2.6	Decreasing
Jun	1.5	Increasing	2.0	Increasing	2.4	Decreasing
Jul	1.6	Decreasing	2.0	Decreasing	2.4	Decreasing
Aug	1.0	Decreasing	1.9	Increasing	2.7	Increasing
Sep	1.3	Decreasing	2.1	Decreasing	2.9	Decreasing
Oct	1.3	Decreasing	2.3	Decreasing	3.3	Decreasing
Nov	1.0	Decreasing	2.1	Decreasing	3.1	Decreasing
Dec	1.8	Decreasing	2.5	Decreasing	3.1	Decreasing

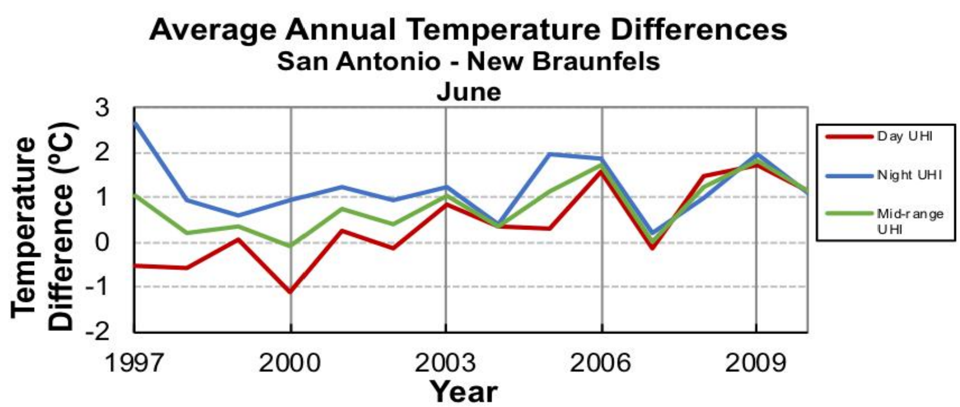

Fig. 2. Comparison of the average annual daytime UHI (red line), daily UHI (green line), and nighttime UHI (blue line) in June for San Antonio (compared with New Braunfels), during the years 1997 to 2010

3.1 Comparison with Previous UHI Studies

Boice et al. [11] found that the daily UHI intensity of San Antonio, relative to the surrounding communities, was increasing at a rate of about 0.5°C/decade, compared with 0.8°C/decade in the present study. The nighttime UHI was increasing at a rate of about 0.3°C/decade, being most pronounced in the summer months. Similar effects were found in the daytime UHI in the winter months, increasing at an average rate of about 0.6°C/decade. Using the same methodology, the authors were interested to see if these trends continued past 1990 up to 2010 in the present study. Compared with the authors' previous study [11], it can be seen that the warming trend of the daily UHI in winter and autumn, as well as the daytime UHI in winter and summer, has continued up to 2010. However, the trend in the nighttime UHI in the summer months has reversed as shown in Fig. 3, from warming prior to 1990 to cooling afterwards up to 2010. The authors are not certain of the cause of this reversal but it may be due to the growing heat island in New Braunfels since its population (and population density) has more than doubled since the previous study [11]. Changes in New Braunfels' LCZ to more urban classes, like San Antonio, is also a likely cause for the reversal as well as the relocation of San Antonio's meteorological station that resulted in cooler temperature measurements. In addition, cooling rates at night determine the nighttime UHI intensity, cooling faster in rural regions. Heat is slowly released from urban infrastructure at night due to higher thermal inertia. The UHI is most intense in the nighttime or pre-dawn hours and in winter months. Anthropogenic heat typically is not a concern in rural areas and during the summer. In the winter, though, and year round in dense, urban areas, anthropogenic heat can significantly contribute to UHI formation.

Previously, we found that San Antonio's UHI (compared with New Braunfels) showed an increase in all four seasons and even for every month [11]. These trends held true for the comparison with Poteet as well. Similar trends are seen in comparisons with Boerne but the magnitudes are smaller, there are larger temperature fluctuations in the data, and some months showed no change at all. This may be due to the higher elevation of Boerne (about 700 meters above sea level in the Texas "Hill Country"), more rural LCZ classes and microclimate; whereas San Antonio, New Braunfels, and Poteet all have similar elevations (about 200 meters above sea level). Using a typical lapse rate for moist air, Boerne is expected to be about 3-4°C cooler than San Antonio due to their altitude difference. This is consistent with the nighttime but not the daytime temperatures.

Xie et al. [18] established the two-dimensional spatial extent of San Antonio's SUHI by measurements of surface temperature from 2002 to 2005, using daily satellite images from the Moderate Resolution Imaging Spectroradiometer (MODIS/Aqua, Earth Observing System PM satellite) and related it to the UHI [6].

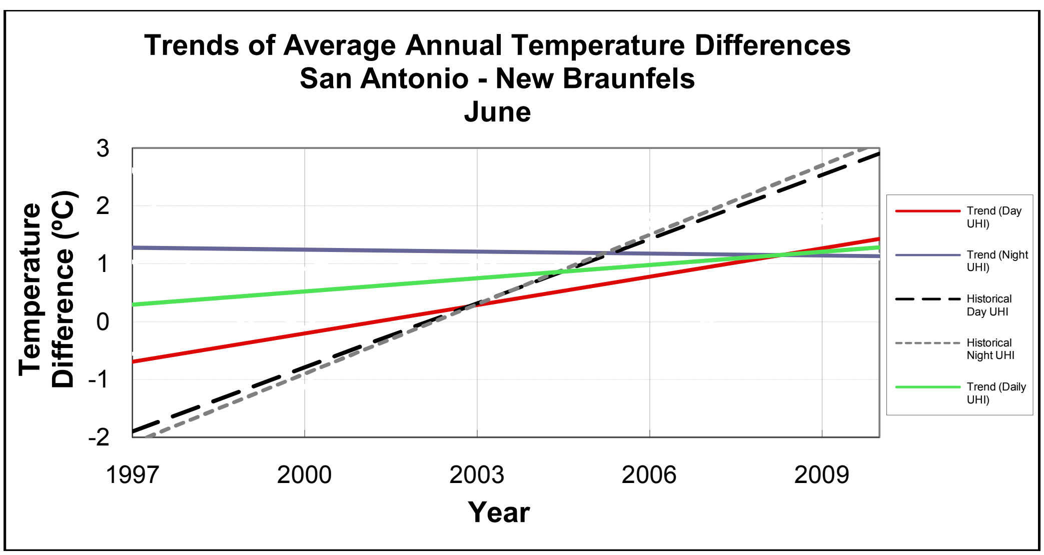

Fig. 3. Comparison of trendlines for the average annual daytime UHI (red line), daily UHI (green line) and nighttime UHI (blue line) in June for San Antonio (compared with New Braunfels), using standard linear least squares fits, during the years 1997 to 2010. Historical trendlines for the daytime and nighttime UHI (black and grey dashed lines, respectively) have been added for comparison with [11]

Both daytime and nighttime data were used. During the daytime, downtown San Antonio was found to be about 6-8°C higher than the average area temperature and 8-12°C higher than surrounding rural areas. During the nighttime, the effect lessened with downtown San Antonio about 4-5°C warmer than the average temperature and 6-7°C warmer than rural areas. They also found several “hot spots” away from downtown but still within the city. The time baseline of this study has been extended to 2008, finding similar results [6,19].

Previous UHI studies in the USA show different trends in urban-rural temperature differences [20]. They found that prior to 1999, the mean warming rate was 0.65°C/century while the mean difference varied between 0.015 to 0.31°C/decade. From 1951 to 2000, it decelerated to 0.05 to 0.19°C. The results of this study for the San Antonio metropolitan area show a much larger warming trend than the US average in the daily UHI (0.8°C/decade) from 1997 to 2010. However, this value falls within the range of 1-3°C/decade found by the US EPA study [4]. They are also in line with [21] that compared summer air temperature measurements for 60 of the largest US cities, including San Antonio, with three surrounding rural communities from 1970 to 2013. They found that summer maximum (minimum) temperatures in San Antonio were on average +1.1°C (+1.2°C) warmer and grew at a rate of 0.28°C/decade (summer daytime UHI) and 0.06°C/decade (summer nighttime UHI). The nighttime UHI remained relatively unchanged in this study, similar to the US average.

3.2 Preliminary Results from the Urban Environmental Model (UEM)

Preliminary results from the UEM show the development of a heat island, in general agreement with measured UHI temperatures. The UEM can be used to study the effects of passive and active heat sources since preliminary results show that (1) dark-colored urban surfaces (low albedo) mainly increase the daytime surface temperature, as more sunlight is absorbed and retained and a modest convective cell is formed in the air above the hot surface and (2) anthropogenic heat release has little effect on surface temperature, but is very effective in increasing wind speed and vertical convection. Active anthropogenic heat sources (e.g., air conditioners, vehicle exhausts, etc.) are deposited directly into the urban air at a height above the surface and mix rapidly with the existing air. The model results show that the heated air rises, enhancing vertical convection with higher wind speeds, with little effect transported downward to the surface.

Initial results are encouraging and further development of the UEM continues. The LCZ concept will be integrated into the surface boundary conditions. The resulting three-dimensional, time-dependent model will be used to investigate important issues in modern cities at the mesoscale level (e.g., effects of building and paving materials, park lands, and patterns of urban growth on heat island intensity; as well as their effects on the concentration of ground-level ozone and other urban air pollutants). The UHI effects on air pollution are a particularly important issue for San Antonio, especially as they relate to ozone concentration. San Antonio is currently in compliance with US EPA ozone regulations; however, it is close to being classified as an ozone non-attainment city, which can lead to serious impacts on quality of life and the economy. Of course, microscale effects are below the resolution of the UEM and would need to be considered separately, perhaps by a nested code.

3.3 Mitigation Strategies and San Antonio

After establishing the intensity and extent of a UHI, strategies can be employed to mitigate its effects. There is an extensive literature proposing urban strategies that have been compiled by the US EPA [4]. They broadly fall into three categories: green/white/cool roofs, cool pavements, and urban trees and vegetation. Alternatively, [22] identify trees, shrubs and grass, use of high albedo materials in external building surfaces, and urban inland water bodies, as effective measures to mitigate the UHI. Shahmohamadi et al. [23] review measures to reduce the UHI to achieve a better energy consumption balance including appropriate landscaping, exterior surface materials of buildings, and promoting natural ventilation. The reader is referred to the literature for more details.

The authors discuss specific ecological measures that have positive feedbacks on the UHI that have been largely overlooked. Increasing onsite stormwater capture by building and retrofitting the urban core to include urban trees (in tree wells where open space isn't available), rain gardens and green roofs (planted with native plants suited for the amount of water they will naturally receive), and cisterns (directed into planted areas), will increase water availability for plants and potable water use in the dense urban core. This allows more planting, using native plants that use less water, to increase evapotranspiration, CO_2 uptake to mitigate CO_2 emissions, and provides more ground cover, cooling the dense urban core. In addition, vegetated roofs decrease albedo, absorbing more solar heat, but cool buildings by adding an insulating layer, allowing the building to use less energy for cooling or heating.

In San Antonio, these mitigating factors are addressed in San Antonio's planning efforts to guide the city toward smart, sustainable growth in the coming decades, called SA Tomorrow Comprehensive Plan [24]. These include launching an urban heat island mitigation program in priority areas to address opportunities for new and existing developments to minimize their contribution to the UHI. The UHI program encourages the use of cool roofs, tree plantings, shade structures, and others to mitigate the impact of extreme heat, decreased air quality, and the related health impacts. It calls for evaluating and assessing existing parking space requirements and alternative modes of transportation since minimum parking requirements create excess parking and impervious cover that contribute to the UHI and excessive stormwater runoff. Also proposed is a science-based assessment of the impact of increased impervious cover and determining if development standards are needed to address the UHI.

4. CONCLUSION AND FUTURE DIRECTIONS

High-quality, homogeneous, daily maximum and minimum air temperature datasets were developed covering the years, 1991 to 2010, to examine the magnitude and growth rate of the urban heat island for San Antonio, Texas. The approximate magnitude of the mean annual air temperature of the urban heat island (+1.1°C) is sufficiently large to affect a broad array of physical and environmental systems in San Antonio. The greatest intensities are at night and in the winter months due to larger cooling rates in the rural areas. The mean seasonal daily UHII in autumn and winter is increasing but decreases in the spring and summer seasons. The UHI results in June for San Antonio and New Braunfels from 1997 to 2010 indicate that its intensity is growing at a rate of 0.8°C/decade. These new results show a larger warming trend in the daytime hours than the US average. This is clearly due to the rapid population growth and densification of San Antonio during the study duration. The results for the nighttime hours remained relatively unchanged, similar to the US average. The reason for this may be related to the rapid growth of the comparison "rural" areas and changes in their LCZ to more urban classes. Compared with the authors' previous study of San Antonio's UHI from 1945 to 1990 [11], it can be seen that the warming trend of the daily UHII in winter and autumn has continued and its growth rate has increased from 0.5 to 0.8°C/decade. Despite mitigating influences, San Antonio continues to have an increasing UHI effect.

Future directions of this work will be to continue the UHI study by updating the air temperature database from 2011 to the present, formally linking this new work to previous studies, and a detailed investigation of the historical data including any changes in the location, technology, and collection methodology of the meteorological stations. This will result in the most comprehensive study of San Antonio's UHI over a timeline from 1945 to present. Correlations with other urban properties (e.g., population, LCZ, impervious cover, power usage, transportation, water utilization, etc.) will be sought using modern GIS techniques. The development of the UEM will continue with collaborations with experts in satellite imagery and mitigation effects. The goal is to develop an important tool for city planning and aid in implementation of the SA Tomorrow vision.

NOTE

On 18 July 2018, the US EPA designated San Antonio's air quality in marginal nonattainment, making studies of its UHI and mitigation even more relevant.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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