



SUMMER IN THE CITY: HOT AND GETTING HOTTER

SUMMER IN THE CITY: HOT AND GETTING HOTTER

Alyson Kenward, PhD
Daniel Yawitz
Todd Sanford, PhD
Regina Wang

ABOUT CLIMATE CENTRAL

Climate Central surveys and conducts scientific research on climate change and informs the public of key findings. Our scientists publish and our journalists report on climate science, energy, sea level rise, wildfires, drought, and related topics. Climate Central is not an advocacy organization. We do not lobby, and we do not support any specific legislation, policy or bill. Climate Central is a qualified 501(c)3 tax-exempt organization.

Climate Central scientists publish peer-reviewed research on climate science; energy; impacts such as sea level rise; climate attribution and more. Our work is not confined to scientific journals. We investigate and synthesize weather and climate data and science to equip local communities and media with the tools they need.

Princeton: One Palmer Square, Suite 330 Princeton, NJ 08542

Phone: +1 609 924-3800

Toll Free: +1 877 4-CLI-SCI / +1 (877 425-4724)

www.climatecentral.org

SUMMARY

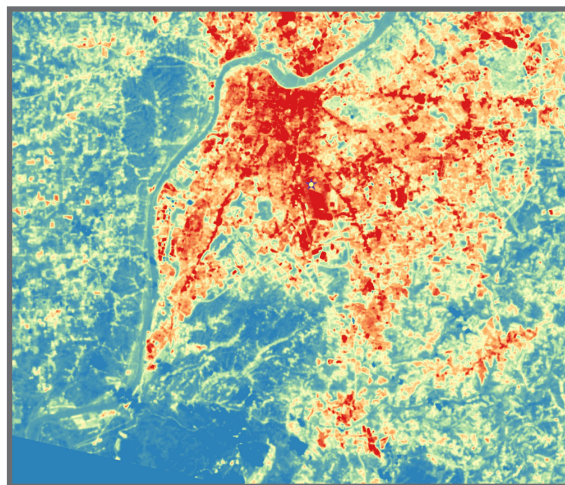
Cities are almost always hotter than the surrounding rural area but global warming takes that heat and makes it worse. In the future, this combination of urbanization and climate change could raise urban temperatures to levels that threaten human health, strain energy resources, and compromise economic productivity.

Summers in the U.S. have been warming since 1970. But on average across the country cities are even hotter, and have been getting hotter faster than adjacent rural areas.

With more than 80 percent of Americans living in cities, these urban heat islands -- combined with rising temperatures caused by increasing heat-trapping greenhouse gas emissions -- can have serious health effects for hundreds of millions of people during the hottest months of the year. Heat is the No.1 weather-related killer in the U.S., and the hottest days, particularly days over 90°F, are associated with dangerous ozone pollution levels that can trigger asthma attacks, heart attacks, and other serious health impacts.

Our analysis of summer temperatures in 60 of the largest U.S. cities found that:

- 57 cities had measurable urban heat island effects over the past 10 years. Single-day urban temperatures in some metro areas were as much as 27°F higher than the surrounding rural areas, and on average across all 60 cities, the maximum single-day temperature difference was 17.5°F.
- Cities have many more searing hot days each year. Since 2004, 12 cities averaged at least 20 more days a year above 90°F than nearby rural areas. The 60 cities analyzed averaged at least 8 more days over 90°F each summer compared to adjacent rural areas.
- More heat can increase ozone air pollution. In 50 of the 51 cities with adequate data, there was a statistically significant correlation between higher daily summer temperatures and bad air quality (as measured by ground-level ozone concentrations). Temperatures are being forced higher by increasing urbanization and manmade global warming, which could undermine the hard-won improvements in air quality and public health made over the past few decades.



Louisville, KY
(urban heat measured by satellite)

-
- In two thirds of the cities analyzed (41 of 60), urbanization and climate change appear to be combining to increase summer heat faster than climate change alone is raising regional temperatures. In three quarters (45 of 60) of cities examined, urbanized areas are warming faster than adjacent rural locations.
 - The top 10 cities with the most intense summer urban heat islands (average daily urban-rural temperature differences) over the past 10 years are:
 - Las Vegas (7.3°F)
 - Albuquerque (5.9°F)
 - Denver (4.9°F)
 - Portland (4.8°F)
 - Louisville (4.8°F)
 - Washington, D.C. (4.7°F)
 - Kansas City (4.6°F)
 - Columbus (4.4°F)
 - Minneapolis (4.3°F)
 - Seattle (4.1°F)
 - On average across all 60 cities, urban summer temperatures were 2.4°F hotter than rural temperatures.

Urban heat islands are even more intense at night. Over the past 10 years, average summer overnight temperatures were more than 4°F hotter in cities than surrounding rural areas.

Several independent studies have shown that urban heat islands (in the U.S., and around the world) do not bias global warming measurements, ruling out the possibility that rising global temperatures have been caused by urbanization alone.

Research suggests that urban planning and design that incorporates more trees and parks, white roofs, and alternative materials for urban infrastructure can help reduce the effects of urban heat islands. But rising greenhouse gas emissions are projected to drive average U.S. summer temperatures even higher in the coming decades, exacerbating urban heat islands and their associated health risks.

CONTENTS

Executive Summary	p3
01 Introduction	p6
02 Urban Heat Islands	p7
03 U.S. Urban Heat Island Analysis	p9
04 Hotter Temperatures and Urban Ozone	p17
05 Conclusions	p20
06 References	p21
07 Methodology	p23
08 Appendix A: Urban Heat Island Rankings	p26
09 Appendix B: Satellite Images	separate PDF
10 Appendix C: Urban Ozone Charts	separate PDF

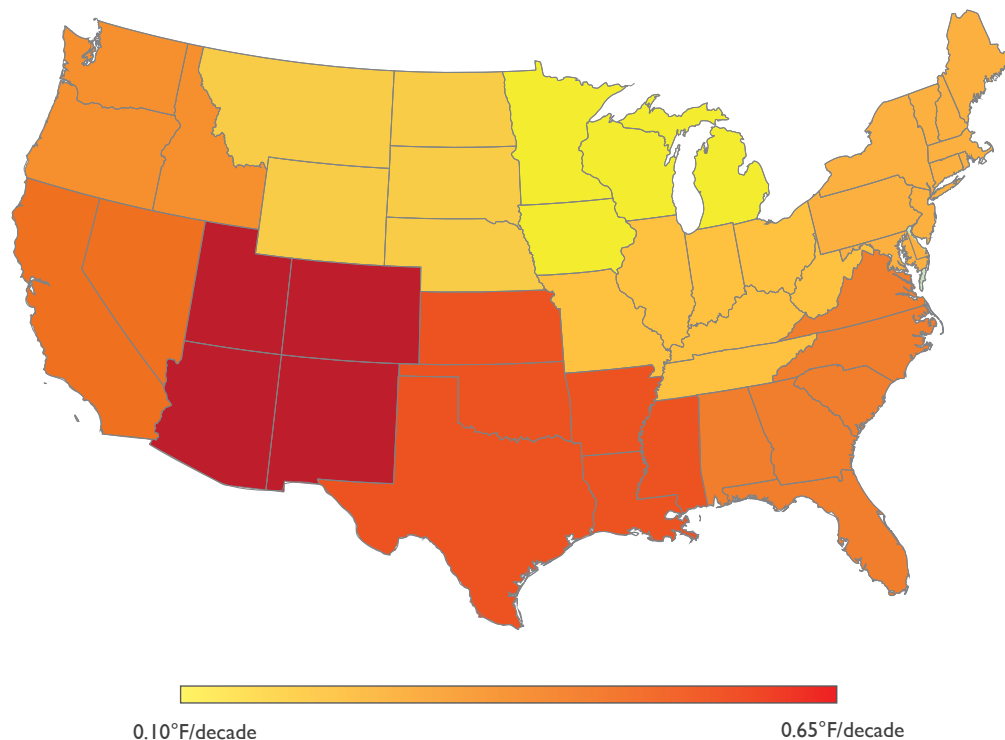
01. INTRODUCTION

Across the U.S., summers have been getting hotter since 1970.¹ On average, summer temperatures have increased at a rate of about 0.4°F per decade over that time, or nearly 2°F overall. But some areas have been warming faster than that, and others more slowly.²

Figure 1 illustrates how much summer warming has increased across nine climate regions of the U.S., as defined by the National Climatic Data Center.³ The Southwest has experienced the fastest warming summers, with temperatures increasing at a rate of more than 0.6°F per decade – or more than 2.6°F degrees overall – since 1970. The South (including Texas, Oklahoma, Kansas, Arkansas, Louisiana, and Mississippi), as well as California and Nevada, also saw summer temperatures increase faster than the national average.

This regional summer warming illustrates climate trends averaged over large areas, and includes trends in both urban and rural locations. But on-the-ground temperature records and satellite measurements have illustrated that urban areas tend to be much hotter than their surrounding rural areas. Today, most Americans live in urban environments, and these areas are projected to get even hotter in the coming decades. Higher urban temperatures, in addition to climatic warming trends, can lead to health impacts for hundreds of millions of Americans, particularly during the hottest months of the year.

Figure 1. Regional summer (June-July-August) warming rates since 1970.



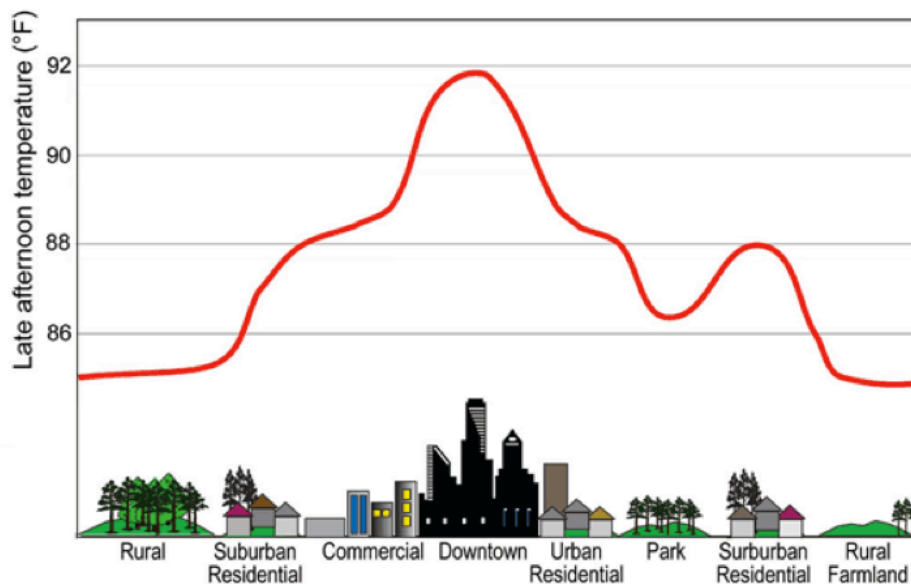
02. URBAN HEAT ISLANDS

The buildings, roads, and other infrastructure that comprise urban environments typically make cities hotter than surrounding rural areas. This condition of a hotter metropolitan area than its surroundings is known as an urban heat island.⁴

In the sunlight, for example, concrete, asphalt, and shingled roofs (which are impermeable and dry) can get much hotter than vegetated areas (which hold more moisture), causing surface temperatures in cities to be several degrees hotter in the midday than in rural areas. After the sun goes down, these same materials release heat more slowly, keeping urban air temperatures higher overnight than in most rural areas, particularly those covered with grasses, plants, and trees. In addition, cities tend to have fewer trees and less vegetation -- whose shade helps keep areas cool -- and more industrial heat sources, including cars and air conditions.

Figure 2 illustrates a typical urban heat island, where temperatures are hottest in the most developed part of a city, and cooler in rural areas.

Figure 2. Urban heat island temperature profile.⁵



The occurrence of urban heat islands has been known for more than 200 years, and dozens of modern studies have investigated urban heat islands (though not all cities have dramatic urban heat islands).⁶ In fact, the attribution of rising global temperatures to higher atmospheric concentrations of greenhouse gases was, for a short time, questioned, because of the high number of temperature stations located in growing urban areas. Several studies have since included urban-specific corrections and evened out variations within a region, and those analyses rule out the possibility that global warming (and, specifically, U.S. temperature rise) is due to urbanization.^{7,8}

03. URBAN HEAT ISLANDS

Against the backdrop of the widespread climatic warming trend, the urban heat island phenomenon potentially poses further risks for people who, by living in cities, may experience even hotter temperatures. Higher urban summer temperatures pose serious health risks from exposure to high levels of ground-level ozone (explored further in Section 4), as well as from heat stress, heat stroke, and higher risks of heart and lung problems.¹ Hotter urban summers can also lead to increased energy demands as more people turn to air conditioners for relief. These higher energy demands have the potential to stress the current electricity grid, particularly at peak electricity times.

Our analysis looks at 60 of the biggest cities in the U.S. (by metropolitan population) to understand how much hotter the urban environments are compared to nearby rural areas, and to study how these temperature differences have been changing since 1970. In addition, we've looked at the relationship between summer temperatures and ground-level ozone concentrations (a major component of air pollution) **to illustrate the risks of future hotter cities to people living there.**

03. U.S. URBAN HEAT ISLAND ANALYSIS


3.1 CITIES ARE HOTTER

To investigate urban heat islands across the U.S., we analyzed temperature data collected from both urban and rural stations between 1970 and 2013. Urban stations with complete data records over this period were identified first, and then paired with three nearby rural stations. For details on station selection, see Methodology (Section 7). This analysis therefore assesses canopy urban heat islands (measuring low-level air temperature, as opposed to ground temperature).

Our analysis found that 57 of the 60 largest cities in the contiguous U.S. exhibited a measurable heat island effect over the past 10 years. Comparing how much hotter cities were to nearby rural areas each summer (June, July and August), on average, over the past 10 years revealed that cities were an average of 2.4°F hotter, although some cities had much higher temperature differences.

Most of these cities have also been urban heat islands for decades. In 52 cities, average annual summer temperatures were hotter more than 75 percent of the time since 1970. And nearly half (26 of 60 cities) had average annual summer temperatures that were hotter every year since 1970

The top 10 cities with the largest difference in summer temperatures between their urban and rural stations, on average since 2004, were:

- 
- Las Vegas (7.3°F)
 - Albuquerque (5.9°F)
 - Denver (4.9°F)
 - Portland (4.8°F)
 - Louisville (4.8°F)
 - Washington, DC (4.7°F)
 - Kansas City (4.6°F)
 - Columbus (4.4°F)
 - Minneapolis (4.3°F)
 - Seattle (4.1°F)

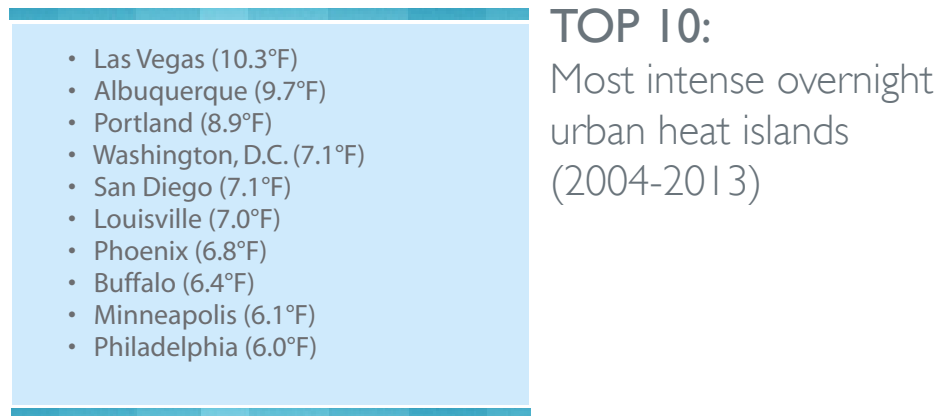
*see Appendix A for all 60 cities

TOP 10:
Most intense
urban heat islands
(2004-2013)

Our analysis also found that urban heat islands were typically even more intense during summer nights. Over the past 10 years, summer nights have been more than 4°F hotter in cities, on average.

03. U.S. URBAN HEAT ISLAND ANALYSIS

The top 10 cities with the most intense summer nighttime urban heat islands over the past 10 years were:



*see Appendix A for all 60 cities

While the difference in average summer temperatures between urban and rural stations ranged from less than 1°F to more than 7°F, the largest single-day differences between urban and rural stations ranged from 9-27°F. Urban-rural temperature differences of at least 20°F were measured at least once in 23 cities.

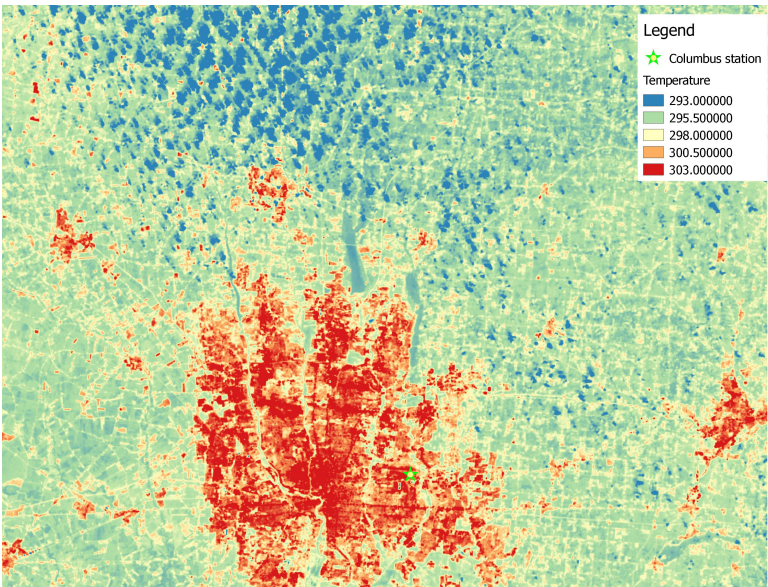
Figure 3 illustrates examples of how significant temperatures difference are between urban and rural environments. These satellite images, taken by NASA's Landsat 8 satellite over the course of 2013 and 2014, show surface temperatures for a single day for each city. Illustrated temperatures were calculated using thermal satellite images. Satellite images for all 60 cities in this analysis are included in Appendix B. These satellite images are included for illustration, but they were not used quantitatively for this report.

In these images, red and orange areas are hotter, while green and blue areas are cooler. The images show that the hottest areas tend to be the most urban locations, including areas with more roads and dense development. These satellite images show that the hottest areas can be as much as 23°F hotter than surrounding rural areas. While the chosen satellite images reflect conditions on a single day (across a range of dates and locations), the temperature differences shown often approached the highest single-day differences calculated between urban and rural stations. Some of this apparent temperature difference between satellite measurements and the historical records used above stems from where temperatures are measured at on-the-ground stations.⁴ Whereas satellites measure actual surface temperature (as a function of the energy reflected and emitted from the earth's surfaces, including cement, roofs, vegetation, or water surfaces), observational temperature records from monitoring stations are typically measured about 5 feet above the ground. Even that short distance accounts for several degrees temperature difference.

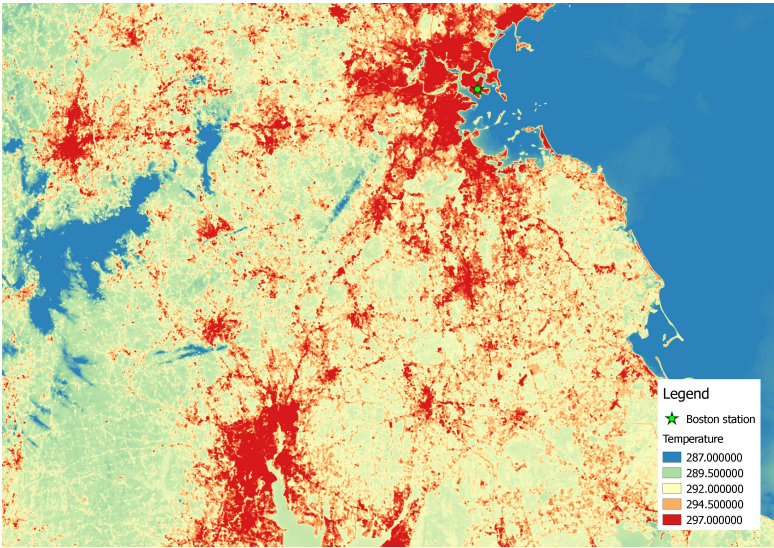
03. U.S. URBAN HEAT ISLAND ANALYSIS

When possible, we have plotted the locations of both urban and rural stations on these satellite images (Figure 3D). In these cases, it is clear that even the designated rural stations are not in the coolest parts of the surrounding rural areas of each major city. The fact that many of these “rural” observation stations are still located within a small town, or close to some development, explains these local hotspots. This potentially offers additional explanation as to why the average differences between urban and rural areas in our above analysis of observational temperature data are not as large as those measured elsewhere by surface temperature satellite imagery.

Figure 3(A-D). Satellite images depicting urban heat islands in land surface temperatures (see Section 7.3 for imaging methods).

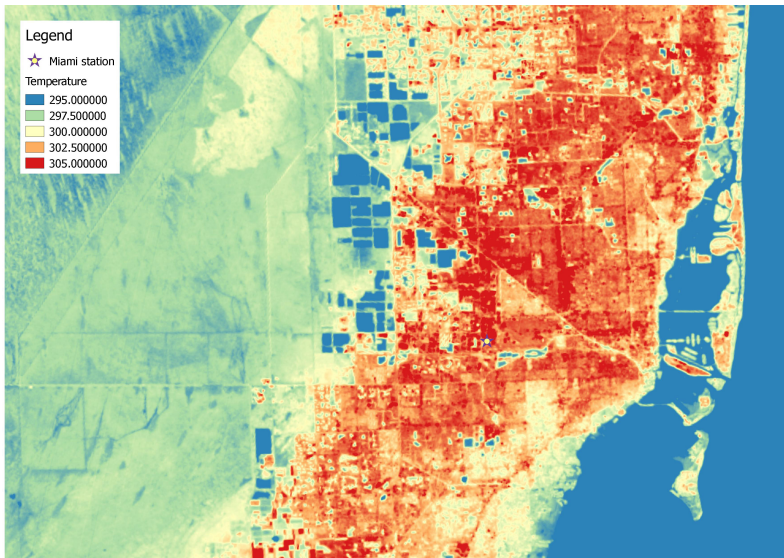


(A) Columbus, Ohio

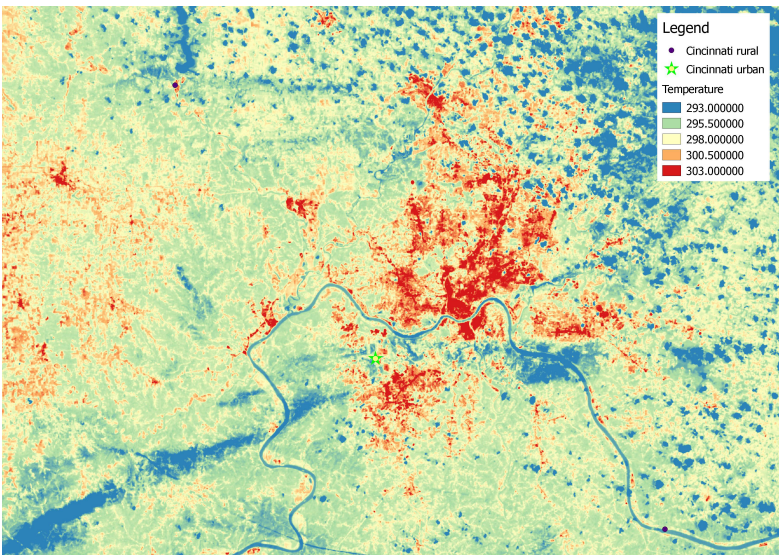


(B) Boston

03. U.S. URBAN HEAT ISLAND ANALYSIS



(C) Miami, Fla.



(D) Cincinnati, Ohio

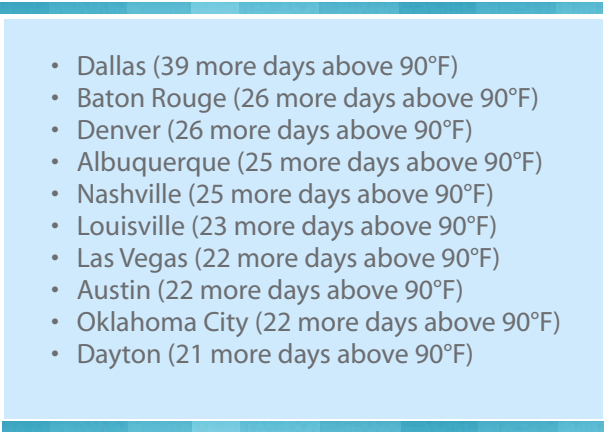
03. U.S. URBAN HEAT ISLAND ANALYSIS

3.2 CITIES HAVE MORE VERY HOT DAYS

Our analysis of 60 U.S. cities also found that cities tend to have many more extremely hot days each year, on average, than nearby rural areas. Over the past 10 years, cities had an average of at least 8 more days over 90°F each summer, compared to nearby rural areas.

There were 47 cities where temperatures exceeded 90°F more frequently in the cities than in nearby rural areas, and there were 23 cities where urban stations exceeded 90°F at least 10 days more each year, on average, than their rural counterparts.

The top 10 cities where temperatures exceeded 90°F more frequently at urban stations than rural stations were:

- 
- Dallas (39 more days above 90°F)
 - Baton Rouge (26 more days above 90°F)
 - Denver (26 more days above 90°F)
 - Albuquerque (25 more days above 90°F)
 - Nashville (25 more days above 90°F)
 - Louisville (23 more days above 90°F)
 - Las Vegas (22 more days above 90°F)
 - Austin (22 more days above 90°F)
 - Oklahoma City (22 more days above 90°F)
 - Dayton (21 more days above 90°F)

TOP 10:

Most days above 90°F compared to nearby rural areas

Of the 60 cities we analyzed, 11 averaged 10 or more days above 100°F each year at their urban stations, and among these 11 cities, temperatures exceeded 100°F an average of 7 more times each year than in nearby rural areas.

Las Vegas, for example, had an average of 79 days above 100°F each year over the past 10 years, which is 29 days more than in rural areas outside the city. And both Dallas and Austin, Texas, had 18 more days above 100°F each year than in their rural areas between 2004-2013

03. U.S. URBAN HEAT ISLAND ANALYSIS

3.3 CITIES ARE GETTING HOTTER FASTER

The difference between urban and surrounding rural temperatures is also widening. In 45 of the 60 cities we studied, temperatures have been rising in urban areas faster than in the surrounding rural areas, since 1970.

The top 10 cities where urban average summer temperatures are heating up faster than rural temperatures, since 1970, are:

- Columbus (0.84°F per decade)
- Minneapolis (0.77°F per decade)
- Baltimore (0.66°F per decade)
- Louisville (0.65°F per decade)
- St. Louis (0.64°F per decade)
- Wichita (0.60°F per decade)
- Birmingham (0.58°F per decade)
- New Orleans (0.56°F per decade)
- Des Moines (0.56°F per decade)
- Oklahoma (0.55°F per decade)

TOP 10:

Cities with fastest-growing urban heat islands

*see Appendix A for all 60 cities

Among these 10 cities, urban summer temperatures increased an average of 0.64°F per decade faster than in the surrounding rural areas since the 1970s.

Just as most cities experience more intense urban heat island effects in overnight temperatures, similar trends are seen in how much faster urban areas are warming overnight compared to surrounding rural areas. In Las Vegas, for example, summer overnight temperatures have, on average, been increasing 0.95°F per decade faster since 1970 at the urban station than in rural areas outside the city. And in Albuquerque, since 1970 summer nights have been warming 0.93°F per decade faster at the urban station than in nearby rural areas.

03. U.S. URBAN HEAT ISLAND ANALYSIS

The top 10 cities where urban summer overnight temperatures are heating up faster than rural temperatures, since 1970 are:

- Las Vegas (0.95°F per decade)
- Albuquerque (0.93°F per decade)
- New Orleans (0.82°F per decade)
- Minneapolis (0.81°F per decade)
- Norfolk (0.78°F per decade)
- Birmingham (0.66°F per decade)
- Jacksonville (0.65°F per decade)
- Philadelphia (0.64°F per decade)
- Louisville (0.61°F per decade)
- St. Louis (0.61°F per decade)

TOP 10:

Cities with fastest-growing overnight urban heat islands

*see Appendix A for all 60 cities

Most cities are not only getting hotter faster than surrounding rural areas, but they have also warmed faster than their surrounding climate region, since 1970. Of the 60 cities analyzed, 41 have seen summers get hotter faster than has been typical for their climate region over that time. And 12 cities have seen summers warm at least twice as fast as the average rate for their region.

3.4 URBAN HEAT ISLAND VARIATIONS

Our analysis shows that most cities are hotter, and are getting hotter faster than rural areas. Urban heat island trends for all 60 cities, including how much hotter average city summers are, and how much faster they are warming, are included in Appendix A. Although these urban heat islands vary in intensity, there are only a few cities we analyzed where urban temperatures are cooler than at nearby rural temperature stations. This overwhelming identification of urban heat islands across the contiguous U.S. shows that people living in cities are experiencing hotter summers.

Several of the metropolitan areas with weak urban heat islands are coastal cities. This means the rural stations chosen for comparison were not evenly distributed around the perimeter of the city. Previous research has found measured urban heat islands to be less intense for coastal cities, particularly when rural stations are relatively inland,⁹ though in some cities water-front skyscrapers are thought to prevent this coastal ventilation.¹⁰ Moreover, urban heat islands were previously shown to be intensifying more rapidly in southern parts of the country, compared to the Northeast.¹¹

03. U.S. URBAN HEAT ISLAND ANALYSIS

While this analysis did not reveal regional or population-based trends in urban heat island intensity or rates of change, previous studies have examined how land-use change and city location influence urban heat islands.

Surface temperature analysis has found that cities with more developed surfaces (including more cement, asphalt, etc) tend to be hotter than their nearby rural areas. However, desert cities -- where rural land area tends to have much less vegetation than in other regions -- were often an exception.¹² And in general, cities in more forested regions, including many Northeastern and Northwestern cities, as well as Atlanta, Charlotte, N.C., and Memphis, Tenn. tended to have the most dramatic differences between urban and rural temperatures. More recent research suggests that urban heat islands are largely influenced by the surrounding climate, and the humidity in particular; cities in more humid climates tend to be much hotter during the day than nearby rural areas, whereas urban heat islands are relatively less intense in drier climates.¹³ Though many of the urban heat islands found in our analysis fit the trends explained in previous work, not every city follows these tendencies. This may be because of some aspects of our methodology, including the focus on canopy UHI versus surface temperature UHI, and the focus on a single, often airport-based, urban station.

04. HOTTER TEMPERATURES AND URBAN OZONE

Summertime heat in U.S. cities can lead to increased ground-level ozone concentrations. While ozone is a beneficial component of Earth's upper (stratospheric) atmosphere in shielding some of the Sun's harmful radiation, at the Earth's surface ozone is hazardous to human health, contributing to increased incidents of lung inflammation, asthma attacks, and other respiratory problems, particularly in children and young adults. Currently, the Environmental Protection Agency's (EPA) national air quality standard for ground-level ozone concentrations is set at 0.075 parts per million (ppm), based on evidence that higher levels of ozone are dangerous for human health.¹⁴

Ozone is not released directly into the air, instead forming from other common pollutants (including nitrogen oxides (NO_x), volatile organic compounds (VOCs), and carbon monoxide) in the presence of sunlight and heat. It is the main component of smog, and studies have shown that hotter temperatures correlate with higher ozone levels.^{15,16} Other meteorological factors, including cloud cover and cyclone frequency, are also believed to influence ozone air pollution episodes.¹⁷

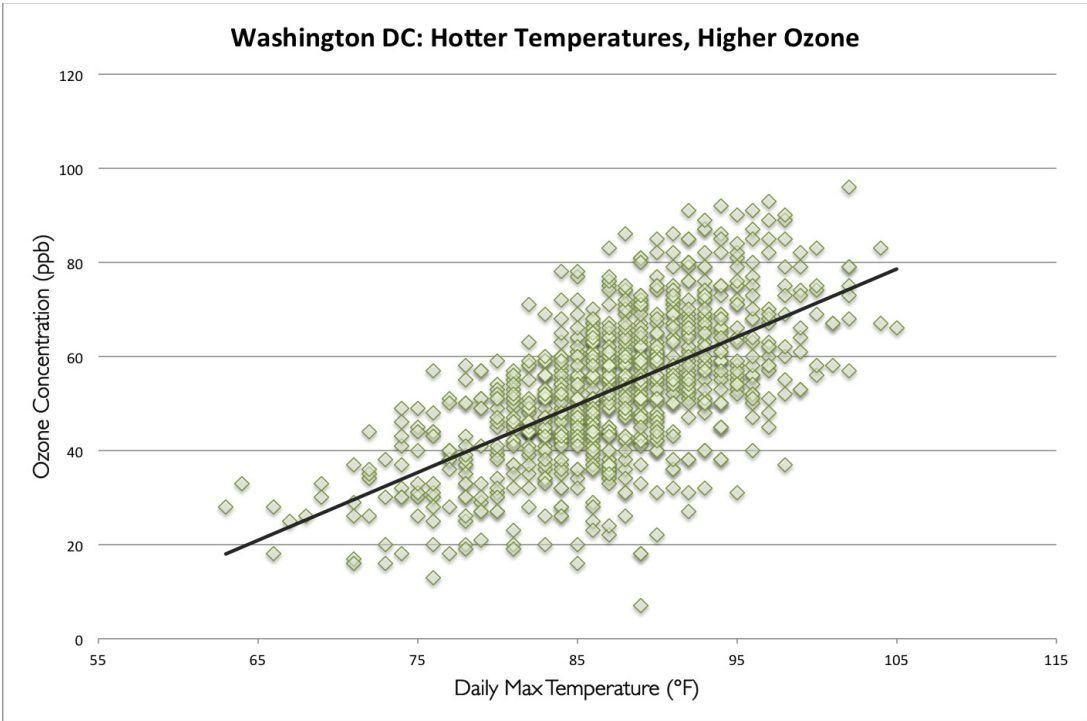
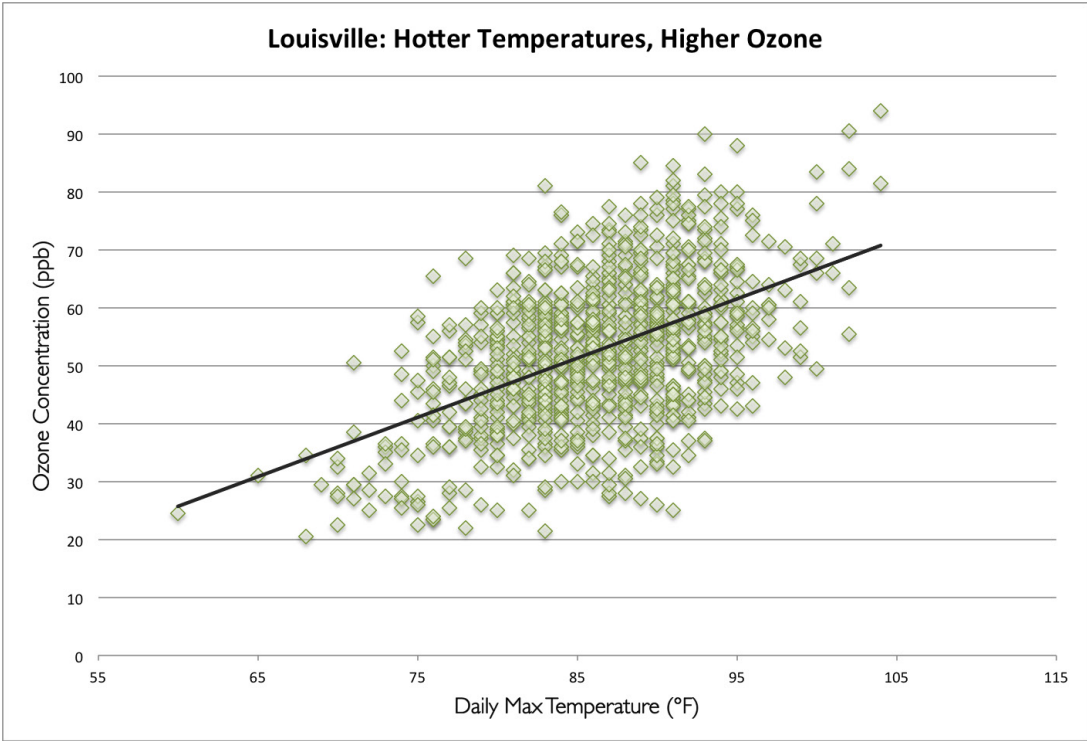
The U.S. Clean Air Act has helped reduce emissions and overall concentrations of many pollutants in the U.S., but day-to-day air quality – including ozone levels – is also weather-dependent. On average, the number of days exceeding the EPA ozone standard each year in the Northeastern U.S. has decreased by 20, since 1980.¹⁸ However, our analysis of the temperature dependence of ozone in 60 U.S. cities also shows that increasingly hotter summers have the potential to elevate average ozone concentrations even as emissions of ozone-forming pollutants are decreasing.

Figure 4 illustrates examples (Louisville and Washington, D.C.) of the temperature dependence of ozone concentration from four of the cities from the urban heat island analysis above. Similar graphs for all 60 cities are illustrated in Appendix C. Each graph shows the relationship between the urban ozone concentrations and maximum temperature for each summer day (June-July-August) over the years designated on each graph.

These plots show that as urban temperatures increase, ground-level ozone concentrations also tend to increase (statistically significant linear correlation). Furthermore, the highest ozone levels typically occur among the hottest days of the year. While each city varies in the magnitude of the temperature-ozone correlation (likely driven by location-specific influences such as population, traffic, industrial density, and other weather factors), 51 of the 52 cities with adequate air quality data showed a statistically significant correlation between daily summer temperatures and ground level ozone concentrations. Forty-five cities showed correlations of at least 0.5 parts per billion per degree Fahrenheit.

04. HOTTER TEMPERATURES AND URBAN OZONE

Figure 4. Ground-level ozone increases as summer air temperatures increase



04. HOTTER TEMPERATURES AND URBAN OZONE

While the current air quality standard for ozone is 0.075 ppm, some EPA scientists recommend this standard be lowered to 0.06 ppm to further protect children from damaging ozone levels. The World Health Organization recommends an even lower standard of 0.053 ppm.¹⁹

The above analysis shows that these ozone standards are already surpassed regularly in most large U.S. cities, particularly during hot summer days. As temperatures continue to rise as projected, particularly if emissions trends continue unabated for several decades, average summer highs could be 2-5°F hotter by 2050, and 6-10°F hotter by 2100. These hotter summers have the potential to roll back some of the recent reductions of ozone levels that have resulted from clean air legislation, and may increase the number of premature deaths related to ground-level ozone.^{1,16} The EPA predicts that future climate change could both lengthen the ozone season (the time during which ground-level ozone standards are most frequently exceeded) and lead to an increase in average summer ozone concentrations of 2-8 ppb.²⁰

This “climate change penalty” could offset some of the benefits of emissions controls that have helped decrease ozone air pollution. Projections of ozone concentrations across the U.S. through 2050 (using a moderate emissions scenario) show that future climate change could degrade air quality in some regions of the U.S., and particularly in the Northeast and the Midwest.²¹ As temperatures continue to warm, even stricter NO_x controls will be needed to achieve the same levels of ozone reductions.

05. CONCLUSIONS

Our analysis of 60 large U.S. cities found that nearly all cities are hotter than their nearby rural areas, and in most cases, these cities are also getting hotter faster. During the summer, these urban heat islands have hotter days, and much hotter nights, and tend to have many more extremely hot days each summer.

Urban heat islands can have serious health effects for hundreds of millions of people. In the cities we examined, hotter summer temperatures correlated with higher ozone pollution, and the hottest days of the year often saw ozone levels exceed the safe standard established by the U.S. Environmental Protection Agency.

It is difficult to quantify how much urbanization and climate change each contribute to today's urban heat islands in the U.S., because each city has a unique and constantly-changing urban landscape and because climate change is regionally sensitive. Yet, it is clear that the combination of continued urbanization and climate change are going to make cities even hotter, threatening the 80 percent of Americans who live in urban environments.

06. REFERENCES

- (1) Melillo, J. M., T. C. Richmond, and G.W. Yohe, Eds. **2014**. "Climate Change Impacts in the United States: The Third National Climate Assessment." U.S. Global Change Research Program.
- (2) Climate Central. **2014**. "Summer's Here and So Is the Heat." <http://www.climatecentral.org/news/u.s.-seeing-red-as-temperatures-rise-17574>. June 19, 2014.
- (3) T. R. Karl and W. J. Koss. **1984**. "Regional and National Monthly, Seasonal, and Annual Temperature Weighted by Area, 1895-1983." Historical Climatology Series 4-3, National Climatic Data Center, Asheville, NC.
- (4) U.S. Environmental Protection Agency. **2008**. "Urban Heat Island Basics, in Reducing Urban Heat Islands: Compendium of Strategies." <http://www.epa.gov/heatisland/resources/pdf/BasicCompendium.pdf>.
- (5) Adapted from *Climate Change Impacts and Adaptation: A Canadian Perspective*, Edited by D. S. Lemmen and F. J. Warren. Ottawa, ON: Climate Change Impacts and Adaptation Program, Natural Resources Canada, **2004**.
- (6) Steward, I.D. **2011**. "A systematic review and scientific critique of methodology in modern urban heat island literature." *Int. J. Climatol.* 31(2): 200-217.
- (7) Hansen, J., R. Ruedy, M. Sato and K. Lo. "Global Surface Temperature Change." *Rev. Geophys.* 48, RG4004.
- (8) Wickham, C., R. Rohde, R. A. Muller, et al. **2013**. "Influence of Urban Heating on the Global Temperature Land Average using Rural Sites Identified from MODIS Classifications." *Geoinfor Geostat: An Overview* 1:2.
- (9) Sakakibara, Y. and K. Owa. **2005**. "Urban-rural temperature differences in coastal cities: influence of rural sites." *Int. J. Climatol.* 25:811-820.
- (10) Wong, M.S., J. Nichol, and E. Ng. **2010**. "A study of the 'wall-effect' caused by proliferation of high-rise buildings using GIS techniques." *Landscape and Urban Planning.* 102: 245-253.
- (11) Stone, B. Jr. **2007**. "Urban and rural temperature trends in proximity to large US cities: 1951-2000." *Int. J. Climatol.* 27:1801-1807.
- (12) Imhoff, M. L., P. Zhang, R. E. Wolfe and L. Bounoua. **2010**. "Remote sensing of the urban heat island effect across biomes in the continental USA." *Remote Sens. Environ.* 114: 504-513.
- (13) Zhao, L., X. Lee, R. B. Smith and K. Oleson. **2014**. "Strong contributions of local background climate to urban heat islands." *Nature.* 511: 216-219.

07. REFERENCES

- (14) U.S. Environmental Protection Agency. **2012**. "National Ambient Air Quality Standards" <http://www.epa.gov/air/criteria.html>.
- (15) Dawson, J. P., P. J. Adams, and S. N. Pandis. **2007**. "Sensitivity of ozone to summertime climate in the Eastern USA: a modeling case study." *Atmos. Environ.*, 41, 1494-1511
- (16) Perera, E. M. and T. Sanford. **2011**. "Climate change and your health: Rising temperature worsening ozone pollution." Union of Concerned Scientists.
- (17) Leibensperger, E. M., L. J. Mickley, and D. J. Jacob. **2008**. "Sensitivity of U.S. air quality to mid-latitude cyclone frequency and implications of 1980-2006 climate change." *Atmos. Chem. Phys.* 8: 7075-7086.
- (18) Jacob, D. J. and D. A. Winner. **2009**. "Effect of climate change on air quality." *Atm. Env.*, 43, 51-63.
- (19) World Health Organization. **2005**. "WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide, and sulfur dioxide. Global update 2005." World Health Organization.
- (20) U.S. EPA. **2009**. "Assessment of the Impacts of Global Change on Regional U.S. Air Quality: A Synthesis of Climate Change Impacts on Ground-Level Ozone (An Interim Report of the U.S. EPA Global Change Research Program). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-07/094F.
- (21) Wu, S. L., L. J. Mickley, E. M. Leibensperger, D. J. Jacob, D. Rind, and D. G. Streets. **2008**. "Effects of 2000-2050 global change on ozone air quality in the United States." *J. Geophys. Res.*, 108: D06302.

ACKNOWLEDGEMENTS

Special thanks to Brian Stone Jr. (Georgia Tech) for discussions about urban and rural station selection and for sharing station selections from his previous publications. Thanks to Marshall Shepherd and Neil Debbage (University of Georgia) for thoughtful comments and feedback on the analysis and report.

07. METHODOLOGY

STATION SELECTION

Temperature data is drawn from the Applied Climate Information Systems database (ACIS), which itself draws on data from NOAA/NCDC's Global Historical Climatology Network (GHCN).

For each of the 60 cities we studied, a single urban station was identified as being closest to downtown and having a continuous temperature record for the period 1970-2013. In many cases, this was the city's airport station.

The use of a city's airport station has both limitations and advantages. Airports generally lie outside of the downtown urban core, so they may not be geographically representative of the temperature trends within the city. For this reason, some other UHI analyses incorporate more urban stations in their analysis. However, airports share some of the key characteristics of a city that contribute to the urban heat island effect: impervious surfaces that retain heat, low levels of vegetation, and limited evapotranspiration. The thermal satellite imagery of a city, its airport, and the surrounding rural area confirms that the surface temperature of an airport tends to track closely with the surface temperature downtown. More importantly, airport monitoring stations tend to be highly regulated and, within any given region, they tend to offer the most consistent temperature record over several decades

For each city, we compared urban station data to rural temperatures in the surrounding climate. The background signal was determined using data from nearby GHCN stations located outside the city. Following the methodology established by Stone¹⁰ "rural" stations were identified by three criteria: distance from the city, population size, and the level of light emitted from the land surface at night (as measured by satellite radiometers. See Hansen et al. (2001) for a discussion). More specifically, rural stations were required to: (a) be between 50km and 250km from the urban center, (b) lie in an area with a population of less than 10,000 (as determined by the U.S. Census), and (c) lie in dim, dark, or unlit land areas at night. As per Stone's methods, three rural stations were chosen for each city, and in most cases, temperature trends were averaged over these three stations (more details on temperature analysis below). An additional criterion for rural stations was included in order to control for differences in elevation and climate. To qualify as an appropriate "rural" station, two out of the three stations must lie within the same terrestrial eco-region (as defined by the World Wildlife Foundation) as the urban station, and all three stations must lie within the same biome. As with urban stations, each rural station also contained a continuous temperature record from 1970-2013. These restrictions on rural station selection excluded three major U.S. metropolitan centers from this analysis: San Francisco, San Jose, and Salt Lake City.

TEMPERATURE ANALYSIS

Three temperature variables were analyzed: average summer (June-August) daily temperature, average summer daily maximum temperature, and average summer daily minimum temperature.

07. METHODOLOGY

Urban summer temperature change trends were measured according to linear trends in average summer daily temperatures from 1970-2013 at the urban station. This was compared to regional summer temperature trend analyses previously published by Climate Central.

The current extent of the urban heat island in each of the 60 cities was identified by measuring the differential in average summer daily temperatures for each year from 2004-2013, averaging over that 10-year period. Cities were identified as having an urban heat island if this 10-year average bias was positive. Similarly, the extent of overnight urban heat islands was measured as the average 10-year (2004-2013) bias in average summer low temperatures.

Urban heat island temperature trends were measured as linear trend in the annual bias of average summer daily temperatures from 1970-2013.

SATELLITE THERMAL IMAGERY

These images represent the “at-satellite brightness temperature” of the land, measured by NASA’s Earth-facing Landsat satellite, in degrees Kelvin. “At-satellite brightness temperature” is an estimate of land surface temperature based on the wavelengths of radiation that are emitted and reflected up from the earth’s surface. “At-satellite brightness temperature” varies slightly from actual brightness temperature, because it does not account for how much radiation is emitted by the atmosphere between the land and the satellite, and does not account for how different surfaces (vegetation, water, pavement, etc) emit different amounts of radiation. However, “at-satellite brightness temperature” is often close enough to actual land surface temperature that it can be used to visualize the vast differences in temperature over large areas of land.

At-satellite brightness temperature is calculated from the raw Landsat data band 10, which measures thermal infrared radiation of wavelengths between 10.60 - 11.19 microns. We calculated this difference using the formula:

$$T = 1321.08 / (\ln(774.89 / L\lambda) + 1)$$

where: T = At-satellite brightness temperature (K); $L\lambda$ = Top-of-atmosphere spectral radiance (Watts/(m^2 * (spectral radiance) * μm))

And top-of-atmosphere spectral radiance is given by the formula:

$$L\lambda = .00033420 * Q_{cal} + 0.10000$$

where: $L\lambda$ = Top-of-atmosphere spectral radiance (Watts/(m^2 * (spectral radiance) * μm));
 Q_{cal} = Quantized and calibrated standard product pixel values (DN) of the Landsat data

07. METHODOLOGY

URBAN OZONE ANALYSIS

Ozone data was obtained through AirData (<http://www.epa.gov/airquality/airdata/>), which provides access to U.S. EPA air quality data from outdoor monitors across the United States. For each city, daily maximum 8-hour ozone concentrations were obtained for each meteorological summer day (June-July-August) from 2004-2013, wherever available. Only data from urban stations was included, leading to the exclusion of 9 of the 60 cities, which lacked urban ozone measurements in the past 10 years. For cities with multiple urban stations, data from the station with the most complete continuous record was used. If multiple stations had complete records from 2004-2013, daily data was averaged across these stations.

Daily maximum temperature data was drawn from ACIS from the nearest station with a complete record for 2004-2013, typically the airport station. For each city, daily ozone concentration was then plotted against daily maximum temperature for each summer day. The relationship between ozone concentration and daily maximum temperature was measured as a linear trend, and the p value of the trend was assessed for statistical significance at the .05 level.

08. APPENDIX A

Table A1. Average Summer Temperature Urban Heat Island Rankings

City	Temperature Difference (°F)	City	Temperature Difference (°F)
Las Vegas	7.3	Chicago	2.2
Albuquerque	5.9	Pittsburgh	2.1
Denver	4.9	Knoxville	2.0
Portland	4.8	Syracuse	2.0
Louisville	4.8	Atlanta	2.0
Washington, D.C.	4.7	San Antonio	2.0
Kansas City	4.6	Raleigh	1.8
Columbus	4.4	Columbia	1.7
Minneapolis	4.3	Miami	1.7
Seattle	4.1	Tulsa	1.6
St. Louis	4.0	Wichita	1.6
Philadelphia	3.8	Providence	1.6
Albany	3.8	Tampa	1.4
Dallas	3.8	Milwaukee	1.4
Detroit	3.8	Houston	1.3
Nashville	3.6	Grand Rapids	1.3
Memphis	3.4	Dayton	1.3
Phoenix	3.2	Boston	1.3
Richmond	3.1	Birmingham	1.2
Boise	3.1	Baton Rouge	1.2
Des Moines	2.9	Cincinnati	0.9
Buffalo	2.9	Austin	0.9
Baltimore	2.7	Norfolk	0.8
Rochester	2.7	Allentown	0.7
New York	2.7	Indianapolis	0.6
Hartford	2.5	Oklahoma City	0.5
Cleveland	2.5	Tucson	0.4
Los Angeles	2.4	Sacramento	-0.4
Jacksonville	2.4	San Diego	-0.6
New Orleans	2.2	Charlotte	-1.4

08. APPENDIX A

Table A2. Average Summer Overnight (Minimum) Temperature Urban Heat Island Rankings

City	Temperature Difference (°F)	City	Temperature Difference (°F)
Las Vegas	10.3	Atlanta	3.9
Albuquerque	9.7	Milwaukee	3.9
Portland	8.9	Des Moines	3.7
Washington, D.C.	7.1	Albany	3.5
San Diego	7.1	Knoxville	3.5
Louisville	7.0	Chicago	3.4
Phoenix	6.8	Houston	3.3
Buffalo	6.4	Pittsburgh	3.3
Minneapolis	6.1	Raleigh	3.3
Philadelphia	6.0	Boston	3.2
New York	5.7	Tulsa	2.9
Los Angeles	5.7	Syracuse	2.8
Boise	5.6	Hartford	2.7
Denver	5.6	Indianapolis	2.7
Kansas City	5.6	Columbia	2.5
Detroit	5.2	Baton Rouge	2.5
Dallas	5.2	Tucson	2.4
Columbus	5.2	Norfolk	2.4
St. Louis	5.2	Providence	2.4
Rochester	5.0	Birmingham	2.4
Seattle	4.8	San Antonio	2.1
Memphis	4.8	Wichita	2.1
Richmond	4.6	Cincinnati	2.0
Jacksonville	4.6	Grand Rapids	1.9
Miami	4.5	Oklahoma City	1.8
Nashville	4.3	Dayton	1.6
New Orleans	4.2	Allentown	1.2
Baltimore	4.0	Sacramento	-0.4
Tampa	4.0	Austin	-0.7
Cleveland	3.9	Charlotte	-1.0

08. APPENDIX A

Table A3. Summer urban heat island intensity change rankings

City	Warming Rate (°F per decade)	City	Warming Rate (°F per decade)
Columbus	0.84	Hartford	0.16
Minneapolis	0.77	Buffalo	0.16
Baltimore	0.66	Indianapolis	0.15
Louisville	0.65	Tampa	0.12
St. Louis	0.64	Memphis	0.12
Wichita	0.60	Austin	0.11
Birmingham	0.58	Tucson	0.10
New Orleans	0.56	Columbia	0.09
Des Moines	0.56	Baton Rouge	0.08
Oklahoma City	0.55	Kansas City	0.07
Philadelphia	0.53	Syracuse	0.06
Jacksonville	0.53	Seattle	0.05
San Antonio	0.51	Sacramento	0.05
Raleigh	0.46	Phoenix	0.04
Atlanta	0.43	Norfolk	0.03
Cleveland	0.43	Knoxville	0.00
Washington, D.C.	0.42	Portland	0.00
Milwaukee	0.40	Nashville	-0.03
Tulsa	0.37	Cincinnati	-0.12
Grand Rapids	0.37	Charlotte	-0.13
Houston	0.34	Providence	-0.14
Pittsburgh	0.33	Dayton	-0.15
Las Vegas	0.31	Rochester	-0.15
Dallas	0.26	Allentown	-0.20
Richmond	0.24	Albany	-0.23
Boise	0.24	New York	-0.34
Chicago	0.23	Boston	-0.44
Detroit	0.22	Denver	-0.62
Albuquerque	0.20	Los Angeles	-0.62
Miami	0.20	San Diego	-0.74

08. APPENDIX A

Table A4. Summer overnight urban heat island intensity change rankings

City	Warming Rate (°F per decade)	City	Warming Rate (°F per decade)
Las Vegas	0.95	Tulsa	0.21
Albuquerque	0.93	Sacramento	0.20
New Orleans	0.82	Portland	0.17
Minneapolis	0.81	Dallas	0.17
Norfolk	0.78	Columbia	0.15
Birmingham	0.66	Rochester	0.15
Jacksonville	0.65	Tucson	0.11
Philadelphia	0.65	Milwaukee	0.11
Louisville	0.63	San Antonio	0.10
St. Louis	0.61	Providence	0.02
Columbus	0.61	Syracuse	0.00
Wichita	0.60	Baton Rouge	-0.01
Richmond	0.58	Miami	-0.03
Grand Rapids	0.55	Los Angeles	-0.15
Hartford	0.54	San Diego	-0.17
Oklahoma City	0.53	Detroit	-0.18
Baltimore	0.51	Boston	-0.18
Des Moines	0.47	Seattle	-0.19
Boise	0.46	New York	-0.20
Washington, D.C.	0.42	Knoxville	-0.28
Indianapolis	0.41	Memphis	-0.30
Cleveland	0.36	Kansas City	-0.31
Raleigh	0.35	Nashville	-0.32
Phoenix	0.34	Cincinnati	-0.38
Chicago	0.33	Albany	-0.40
Buffalo	0.30	Dayton	-0.46
Houston	0.30	Charlotte	-0.57
Pittsburgh	0.25	Allentown	-0.67
Tampa	0.24	Austin	-0.67
Atlanta	0.21	Denver	-1.30