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Short Communication

Urban and rural temperature trends in proximity to large US cities: 1951–2000

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ABSTRACT: This paper presents a study of urban and rural temperature trends in proximity to the most populous metropolitan areas of the US. As data from urban meteorological stations are typically eliminated or adjusted for use in continental and global analyses of climate change, few studies have addressed how temperatures are changing in the areas most vulnerable to the public health impacts of warming: large cities. In this study, temperature data from urban and proximate rural stations for 50 large US metropolitan areas are analysed to establish the mean decadal rate of change in urban temperatures, rural temperatures, and heat island intensity over five decades. The results of this analysis find the mean decadal rate of change in the heat island intensity of large US cities between 1951 and 2000 to be 0.05 °C and further show a clear division in temperature trends between cities situated in the northeastern and southern regions of the country. Copyright © 2007 Royal Meteorological Society

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1. Introduction

The annual reporting of mean global temperature estimates has become perhaps the most widely publicized and compelling evidence of global climate change in the eyes of the general public. Derived from a large network of meteorological stations distributed across the Earth's surface, these estimates are intended to provide the most reliable assessment of spatially averaged, 'background' rates of climate change that are independent of local scale, human-induced effects on temperature (Quayle *et al*., 1999; Hansen *et al*., 2001). To this end, local scale climate anomalies, such as the urban heat island (UHI) effect, are eliminated from the global temperature record through the removal of urban meteorological stations from the observation network or through the statistical adjustment of temperature measurements obtained by these stations. While the statistical adjustment of urban temperature trends is necessary to accurately gauge background warming rates, an important limitation of this approach is that it fails to accurately reflect rates of warming in the very places where such warming is likely to have the greatest impacts on public health: large cities.

In light of the public health implications of rising temperatures in cities, there is a critical need to regularly assess the degree to which background temperature trends are amplified by urbanization. From the perspective of urban planning, we must gauge the impacts of climate change on both the planetary background and the population foreground to best assess the implications of these changes for human health. While numerous studies have sought to quantify the intensity of the UHI effect in US cities (Arnfield (2003) or Peterson (2003) for extensive overviews), only a handful of studies has focused on rates of change in heat island intensity over time (Kukla *et al*., 1986; Gallo *et al*., 1999; Hansen *et al*., 2001; Kalnay and Cai, 2003), and none has focused solely on the largest population centres.

In response to these observations, this paper presents an analysis of urban and rural temperature trends in proximity to 50 of the most populous cities in US. Specifically, this research addresses the question: How have large metropolitan areas amplified (or moderated) regional background warming rates over the last half century? While previous work has sought to measure the differential between urban and rural temperature trends, this work differentiates itself through its focus on large urbanized areas alone and through its use of meteorological data subjected to the same set of homogeneity adjustments, with the exception of an urban correction, as that employed in widely cited global climate change estimates. Through the pairing of urban and rural stations, as determined through population size and night light analysis, I estimate the mean decadal rate of change in urban and rural temperatures between 1951 and 2000.

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The results of this analysis find the mean rate of warming in large US cities to be approximately 0.5 °C higher per century than within proximate rural areas, an estimate that compares favourably with previous analyses focused on a greater range of city sizes. The results further show a clear division in temperature trends between large cities situated in the northeastern and southern regions of the country and a variable composition of heat island trends in the regions studied.

2. Methodology

Three principal methodological issues must be addressed in measuring urban and rural temperature trends over a multiyear timescale. These include a set of spatial and temporal inhomogeneities in the temperature record of *in situ* meteorological stations, the classification of meteorological stations as urban or rural, and the selection of specific stations for inclusion in a study network. What follows in this section is a brief overview of these issues and a discussion of the specific methods employed in this present study.

2.1. Homogeneity adjustments

A significant challenge in measuring climate trends over the period of a decade or more is the development of a methodologically uniform set of meteorological observations. As discussed in detail by Hansen *et al*. (2001) and Peterson (2003), among others, temperature observations recorded by surface meteorological stations are subject to a set of methodological inconsistencies over time, which have been described collectively as data inhomogeneities. These inconsistencies in the temperature record result from three principal changes, including changes in the location of a station, changes in the time of observation, and changes in the observing instruments. In addition, proximity to urban land uses is also considered to be a source of inhomogeneity in the meteorological record. As almost all of the long-term weather stations in operation in US have experienced one or more of these changes, adjustments to the temperature record (based on station metadata) are necessary to create a more spatially and temporally homogenious set of observations (Peterson, 2003).

In response to the problem of data inhomogeneities, a long-term, geographically distributed, and routinely updated dataset of corrected meteorological observations is available through the U.S. Historical Climatology Network (USHCN). To address the problem of UHI bias, however, meteorological stations in large urbanized regions generally are not included in the USHCN, rendering these data unsuitable for a study of large US cities. In the interest of achieving a more extensive geographic coverage of meteorological observations in US and globally, researchers from the Goddard Institute for Space Studies (GISS) have compiled a database of meteorological stations drawn from the Global Historical Climatology Network (GHCN) that have been adjusted for the estimated effects of urbanization, thus permitting the use of a wider array of stations in the estimation of global and continental trends (Hansen *et al*., 2001). As the GISS database is adjusted for standard inhomogeneities and for urbanization through independent methods, it is available with or without the urban corrections.

This study makes use of the GHCN station data available through GISS that have been corrected for all standard inhomogeneities but have not been adjusted for urbanization. The data obtained for this study can be accessed through the GISS website: http://data.giss.nasa.gov/gistemp/station_data/. This study makes use of the data employing the USHCN corrections and for which observations at the same locations have been combined. These data were not adjusted for urbanization. Specifically, data for urban and rural meteorological stations located within or in proximity to each of 50 large metropolitan regions were obtained for this study. Specific criteria used in the process of station selection are discussed in the following section.

In addition to the artificial inhomogeneities of a change in station location, time of observation, or instrumentation, it should be noted that differences in elevation and latitude between urban and rural stations, referred to as natural inhomogeneities by Peterson (2003), complicate the estimation of differentials in temperature between urban and rural areas at any point in time. Owing to the fact that this study is focused on relative rates of temperature change in urban and proximate rural areas over time, rather than on the magnitude difference between urban and rural observations, no adjustments have been made for differences in elevation or latitude between urban and rural stations, as such linear adjustments would have no effect on relative rates of warming or cooling over time.

2.2. Urban and rural classification

Two principal methods have been used in temperature trend analyses to classify meteorological stations as urban or rural; these include the use of population information from the U.S. Census Bureau and the use of night light intensities recorded by satellite radiometers (Owen *et al*., 1998; Gallo *et al*., 1999; Hansen *et al*., 1999, 2001). The use of a population-based approach is limited in that reliable estimates may be unavailable in various regions of the world and, further, the distribution of population may not always correlate highly with the location of surface infrastructure, such as in the case of a rural airport or a military installation.

To address this issue, Imhoff *et al*. (1997) make use of night light observations obtained through the Defense Meteorological Satellite Program Operational Linescan System (OLS) to categorize areas by land cover class. Recorded by a satellite radiometer with high sensitivity to visible light, the OLS data provide a basis for categorizing land cover as urban, suburban, or rural based on the intensity of night light emitted from the Earth's surface. Hansen *et al*. (2001) make use of these data

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to categorize all GHCN meteorological stations included in the GISS station network by urban land cover class. These classifications assign an 'A' to stations located in dark or unlit areas, a 'B' to stations located in dim areas, and a 'C' to stations located in areas of bright night light.

In this present study, stations are classified as urban or rural based on both population data and the OLS night light rankings provided by GISS. Urban stations are those found within metropolitan areas with populations greater than 700 000 and a night light ranking of C. Rural stations are those found in non-metropolitan areas with populations less than 10 000 and a night light ranking of A. As discussed in the following section, for some cities a minimum number of rural stations was not available in proximity to an urban station. In these instances, proximate stations with a population less than 10 000 and a night light ranking of 'B' were used. Imhoff *et al.* (1997) report that in many instances the level of night light intensity associated with the intermediate or dim ranking was a product of reflected light from urban areas and not necessarily indicative of urbanized land covers. A comparison of results from cities associated with A stations only and those associated with a mix of A and B stations, reported below, found no significant difference in temperature trends. Overall, about one-fifth of the rural stations included in this study were ranked in the B category of night light.

2.3. Station selection

As noted above, the central objective of this study is to measure temperature trends in the most highly populated regions of the United States, rather than evenly across a geographic extent. To this end, the 50 most populous US metropolitan regions meeting a set of predetermined criteria were included in the study database. As only a single urban station is available for many large cities through the GHCN-based network compiled by the GISS, all urban trends are represented by the primary airport meteorological station for each region.

The use of airport station data potentially entails both limitations and advantages for a study of this nature. On one hand, most regional airports are not located within or particularly close to the central business district of major metropolitan areas, limiting the ability of these stations to reflect temperature trends in the most intensely developed zones. On the other hand, as the central business districts of most large US cities have failed to capture the lion's share of new metropolitan growth since the 1950s, airport stations may provide a better representation of the change in temperatures as a product of new regional development over time.

To be included in the study database, an urban airport station must have a minimum of 550 of 600 complete months of mean monthly temperature observations between 1951 and 2000, a threshold for missing data that was found to be attainable for 48 of the 50 most populous cities. All urban stations were drawn from metropolitan statistical areas (MSA) with a 2000 US census population of at least 700 000 residents and an OLS night light ranking of C.

For each study area, three rural meteorological stations were selected to represent regional background temperature trends based on three criteria. These included a maximum and minimum distance from the urban station, population and night light thresholds as discussed above, and a minimum of 550 of 600 months of monthly mean temperature observations between 1951 and 2000. Initially, the minimum and maximum distances were set at 50 and 150 km; however, in a limited number of regions, this maximum distance was found to be too restrictive and thus was expanded to 250 km. In many regions, only three rural stations satisfying these criteria could be found; to be methodologically consistent, three rural stations were thus selected for each metropolitan area.

The outcome of this selection process resulted in the inclusion of 50 of the 60 most populous MSAs in US, representing more than 50% of the national population. These metropolitan areas and their respective 2000 populations are presented in Figure 1. Overall, 50 urban stations and 108 rural stations were included in the study database. [In the most densely developed regions of the country, some rural stations satisfied the selection criteria for more than a single metropolitan area, serving to reduce the total number of rural stations included in the study.]

2.4. Analysis

Once constructed, the study database was analysed to estimate the mean decadal rate of change in the temperature differential between urban and rural stations (i.e. the mean change in each region's heat island intensity from year to year, averaged by decade). To do so, monthly mean temperatures were averaged annually for each station. The mean annual temperatures for the three rural stations per city were averaged to derive a regional rural mean. This rural mean was then subtracted from the annual mean for the urban station to derive an estimate of the average UHI intensity in each year between 1951 and 2000. As a final step, the mean annual heat island intensity was subtracted from the heat island intensity of the following year to estimate the annual rate of change in the regional UHI.

The following section presents descriptive statistics on the rate of change in regional UHIs, subnational trends, and the variable patterns through which heat islands were composed over the five decade study period.

3. Results

3.1. Mean decadal trends

The mean decadal change in urban temperatures, rural temperatures, and UHI intensity by city is presented in Figure 2. As illustrated in panel A, the majority of urban stations experienced a warming trend between 1951 and 2000. Thirty-eight of the 50 cities registered

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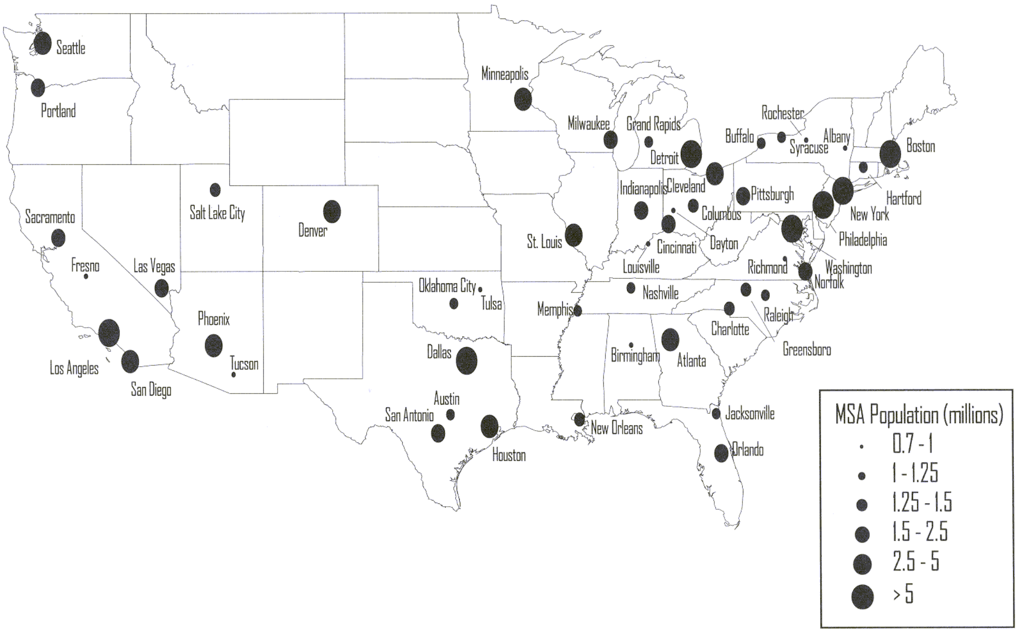

Figure 1. Metropolitan areas included in the study and the U.S. census 2000 population for each MSA.

a warming trend averaging 0.30 °C ($t = 6.19$; $p < 0.01$) per decade, while 12 cities registered a cooling trend averaging −0.14 °C ($t = -4.33$; $p < 0.01$) per decade. Regionally, clusters of cooling can be seen in the northeast, Florida, and in three of four cities in California. The most rapidly warming cities tend to be found in the southern and upper midwestern sections of the country.

Panel B of Figure 2 indicates that an equal number of cities registered a cooling trend in their rural reference stations but with variance in the regional distribution of these trends. For 38 of 50 cities, rural reference stations experienced an average warming trend of 0.24 °C ($t = 6.48$; $p < 0.01$) per decade, while 12 of 50 stations experienced a cooling trend of −0.13 °C ($t = -3.94$; $p < 0.01$) per decade. Panel B also indicates that many cities found to have warmed during this 50 year period are paired with rural stations that have experienced an average cooling trend, serving to further enhance an increase in heat island intensity during this period.

Panel C illustrates the mean decadal change in the urban and rural temperature differential during the study period. Across all 50 cities, the mean decadal change in urban temperatures between 1951 and 2000 was found to be 0.20 °C ($t = 4.26$; $p < 0.01$), while the mean decadal change in rural temperatures was found to be 0.15 °C ($t = 4.04$; $p < 0.01$). The mean decadal growth in UHI intensity between 1951 and 2000 was thus found to be 0.05 °C ($t = 1.71$; $p < 0.05$).

Twenty-nine of 50 cities experienced a mean decadal increase in heat island intensity of 0.19 °C ($t = 7.31$; $p < 0.01$), while 21 of 50 cities experienced a mean decadal reduction in heat island intensity of −0.14 °C ($t = -6.26$; $p < 0.01$). Interestingly, a regional clustering of diminishing heat islands was found in the northeastern US and in parts of the Ohio River Valley, while heat island intensity was found to be generally increasing throughout the southern US, with the exception of two cities in Florida.

3.2. Composition of heat island trends

The pairing of urban and rural meteorological stations facilitates an assessment of the composition of heat island trends. As illustrated in Figure 2, a divergence in urban and rural temperatures over time can result from a number of different patterns, including an elevated rate of warming in urban areas relative to rural areas, a suppressed rate of cooling in urban areas relative to rural areas, and a warming trend in urban areas accompanied by a cooling trend in rural areas. Figure 3 illustrates the composition of both positive and negative heat island trends found across the 50 metropolitan areas included in the study.

This analysis shows that 40% of the large cities studied experienced what can be categorized as a traditional warming pattern during this period, with urban stations warming more rapidly than rural stations. An additional 14% experienced urban warming accompanied by rural cooling, also contributing to a growth in heat island intensity over time. In a handful of regions (4%), both rural and urban stations cooled during this period, with urban stations cooling less rapidly and registering an increase in the positive differential in urban and rural trends per decade.

Importantly, 42% of the metropolitan areas studied experienced a reduction in heat island intensity between 1951 and 2000. In 22% of all cities, rural stations warmed more rapidly, on average, than urban stations. Rural warming was accompanied by urban cooling in 14% of the sampled cities, and urban areas cooled more rapidly than rural areas in 6% of the cities. As noted above, while

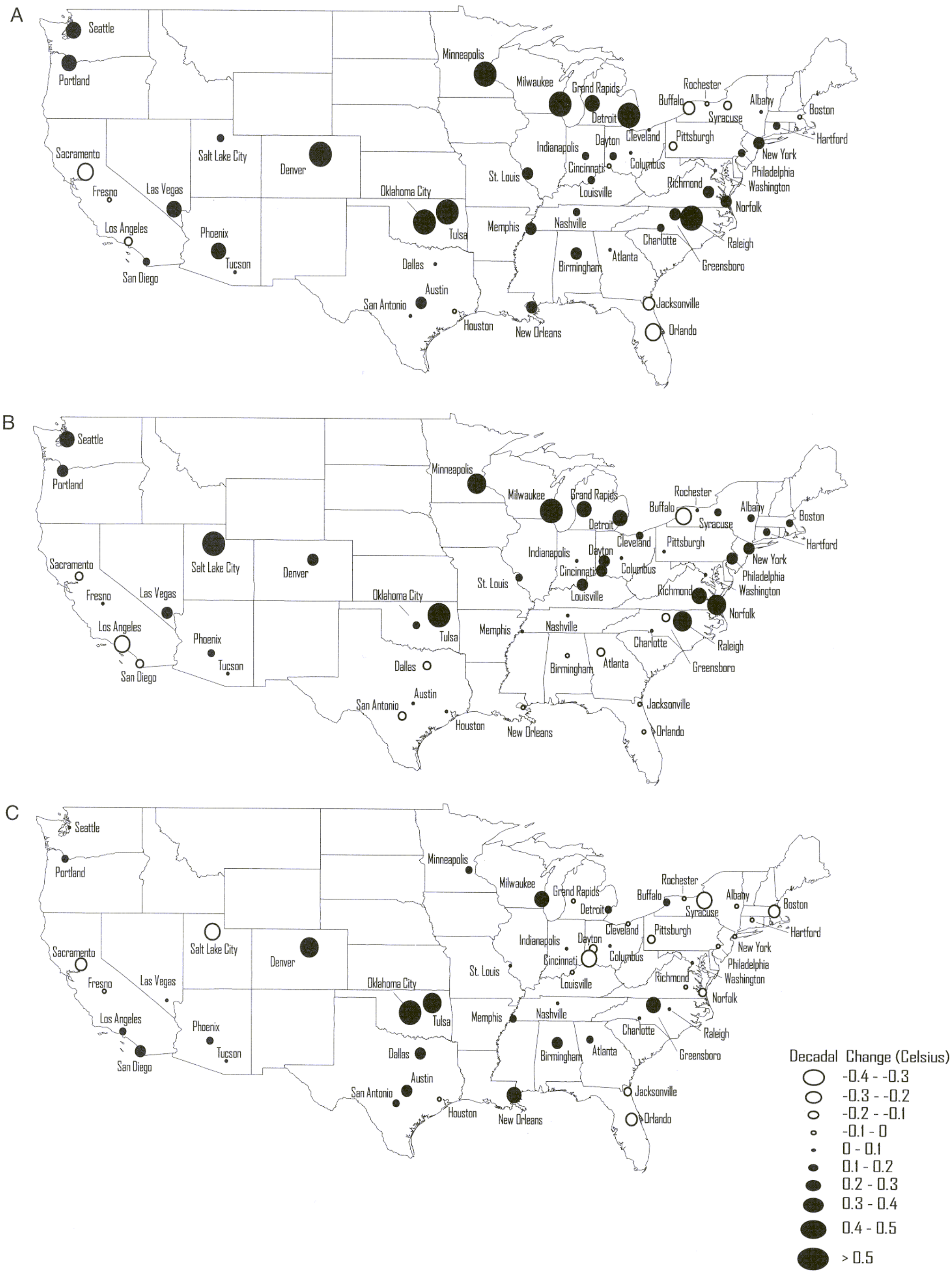

Figure 2. Mean decadal temperature change between 1951 and 2000. Panel A presents the mean decadal change of urban stations; panel B presents the mean decadal change of rural stations; and panel C presents the mean decadal change in heat island intensity. Black circles denote warming trends; open circles denote cooling trends.

only 58% of the sampled cities experienced an increase in heat island intensity during this period, the average magnitude of this increase was about 1.4 times as great as the average reduction experienced by cities in which UHI intensity was found to have diminished over time.

4. Discussion and conclusions

The results of this study compare favourably with other long-term, time-series analyses of urban and rural temperature trends. While the finding of a mean decadal differential between urban and rural temperatures of 0.05 °C is higher than that found in previous, comparable analyses, this present study is the first to focus exclusively on large cities, which have been shown to exhibit more intense heat islands than less populous cities (Oke, 1976; Karl *et al*., 1988). In their analysis of urban and rural temperature trends employing a similar but larger dataset, Hansen *et al*. (2001) report a mean decadal differential in urban and rural temperatures of 0.015 °C. On the basis of an OLS method in selecting urban and rural stations, Gallo *et al*. (1999) find a differential in the mean rate of warming between urban and non-urban stations

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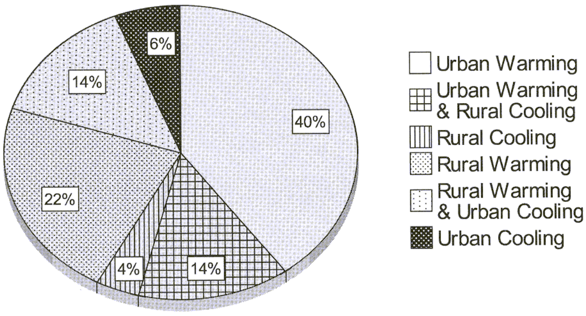

Figure 3. Percentage of MSAs experiencing various warming and cooling trends between 1951 and 2000. Urban (rural) warming denotes regions in which urban (rural) temperatures were increasing more rapidly than rural (urban) temperatures. Urban warming and rural cooling denotes regions in which urban stations experienced an increase in temperatures, while rural stations experienced a reduction in temperatures. Rural (urban) cooling denotes regions in which rural (urban) temperatures decreased more rapidly than urban (rural) temperatures. Rural warming and urban cooling denotes regions in which rural stations experienced an increase in temperatures, while urban stations experienced a reduction in temperatures.

of 0.026 °C per decade. In each case, a magnitude difference between the observed trends and those reported herein reasonably may be explained by the inclusion of less populous cities than this present study.

Kalnay and Cai (2003) reported an enhancement in mean temperatures due to land use change of 0.035 °C per decade across a large number of urban and rural stations; however, as these data were not adjusted for standard inhomogeneities, the effect of urban areas may be overestimated (Vose *et al*., 2004). Likewise, a study of 34 urban and rural station pairs performed by Kukla *et al*. (1986) found a differential of 0.12 °C per decade but also failed to adjust for all standard inhomogeneities, which may explain the finding of a larger urban effect than this present analysis.

The results of this analysis suggest a wide variance in the temperature trends of large US cities that is not well captured by any single measure of change. While the most populous US cities were found to have warmed more rapidly than proximate rural stations on average, a significant number of urban stations was found to have warmed less rapidly or cooled more rapidly than paired rural stations between 1951 and 2000. For those cities experiencing growth in heat island intensity over time, the mean rate of growth was found to be about four times greater (almost 2 °C per century) than the mean for all cities, suggesting a substantial enhancement of background warming rates over time. In addition, the composition of heat island formation, both negative and positive, was found to be highly variable as well.

In combination, these two findings – a wide disparity in both the magnitude and composition of urban warming trends – suggest that, from a planning perspective, strategies designed to mitigate heat island formation over time should be expected to produce variable results by city. In light of this finding, urban planners and public health officials concerned about the amplification of background warming through the UHI effect should conduct region-specific analyses to better understand the magnitude and composition of local warming or cooling trends, and to develop strategies best tailored to the region.

Also significant to the field of planning and public health is the degree to which large urbanized areas may be amplifying background rates of warming attributed to global scale climate change. If the rural warming trends observed through this analysis are assumed to represent background warming rates in these regions (0.15 °C per decade), then the finding of a mean decadal increase in heat island intensity of 0.05 °C suggests background rates of warming are being amplified by a factor of one-third across all cities in the study. For the 29 cities experiencing an increasing trend in urban warming between 1951 and 2000, the rural rate of warming is 0.12 °C per decade and the urban rate is 0.31 °C per decade, yielding a mean decadal rate of increase in heat island intensity of 0.19 °C. For these regions, the amplification of background warming rates through heat island formation is about 150%. This finding suggests that planners and public health officials in large cities should be prepared to manage changes in temperature potentially well in excess of those forecast by the Intergovernmental Panel on Climate Change (IPCC).

Despite the study's focus on the distribution of warming with respect to human rather than physical geography, the existence of subnational trends in urban warming or cooling over time is apparent from the results illustrated in Figure 2. A t-test for the difference in means between the mean decadal rate of heat island change in seven contiguous states in New England and the North Atlantic regions of the country (14 cities) and seven contiguous states in the south and southeastern US (12 cities) was found to be significant ($t = 5.90$; $p < 0.01$), indicating a difference in both the magnitude and direction of urban warming between these regions. The regional differences presented in Panel A of Figure 2 are consistent with the findings of Hansen *et al*. (2001), which show a predominance of warming among northeastern rural stations during the 20th Century, accompanied by a predominance of cooling among southern rural stations. However, Hansen *et al*. do not measure unadjusted urban trends by region, which are needed to further support the finding of subnational divisions in heat island trends.

The results of this analysis are limited in at least two important respects. First, urban temperature trends are indicated by a single meteorological station located at each city's largest airport. As discussed above, the use of airport data may be advantageous in better representing the change in urban temperatures due to land development during this period, which tended to be situated in areas outside of the central business district; but a single meteorological station, regardless of location, is an incomplete representation of temperature change across a large geographic zone. Future analyses thus could be improved though the availability of additional urban meteorological stations.

A second important limitation to this work is the use of a number of rural meteorological stations assigned a night light classification of B, a classification characterized as 'dim' by Hansen *et al.* (2001) and potentially indicative of suburban land covers. To assess the degree to which such stations fail to accurately reflect rural conditions, and thus may serve to bias estimates of rural temperature change, the average rate of change in UHI intensity between regions including a mix of rural stations classified as A and B and those only employing rural stations classified as A was compared to test the hypothesis of no difference in the means. The results of a t-test suggested that the null hypothesis could not be rejected, indicating a non-significant difference in the mean temperature trends between these two groupings of cities ($t = 0.56$; $p > 0.05$). Nonetheless, the use of rural stations associated with dim night light holds the potential to reduce the mean differential in rates of change between urban and rural stations and thus should be considered when evaluating the results of this study.

In summary, the objective of this study was to measure long-term trends in heat island intensity in the most heavily populated areas of US. Typically adjusted or eliminated from periodic analysis of climate trends, urban meteorological observations serve as the most direct window onto how climate is changing in proximity to the human population and, as such, provide important information for policy makers charged with protecting public health in cities. Through an analysis of urban and rural temperature trends in 50 of the most populous US cities between 1951 and 2000, a mean decadal difference in urban and rural temperatures of 0.05 °C was found, suggesting an amplification of background warming rates of 0.5 °C per century in large US cities. This finding differs from previous analyses of urban warming rates, which have indicated smaller increments per century, and suggests that, if recent trends continue, some large cities could experience a rate of warming well beyond the range projected by the global climate change scenarios of the IPCC.

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