Quantifying the Effect of Urbanization on U.S. Historical Climatology Network Temperature Records

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INTRODUCTION

Urbanization has long been recognized as having the potential to impact near-surface temperature readings by altering the sensible and latent heat fluxes in affected areas (e.g., *Mitchell*, 1953; *Oke*, 1982; *Arnfield*, 2003). While a number of studies have been undertaken to quantify the impact of the "urban heat island" (UHI) signal on U.S. temperature trends (e.g., *Kukla et al.*, 1986; *Karl et al.*, 1988; *Gallo et al.*, 1999, *Gallo and Owen*, 2002; *Peterson*, 2003; *Peterson and Owen*, 2005) such studies are complicated by factors unrelated to urbanization such as instrument changes and station moves. Here, an analysis is described whose aim is to quantify the potential UHI contribution to U.S. temperature trends by more fully controlling for external factors unrelated to urbanization. A range of UHI assessments is provided by making use of four separate urbanization proxies to differentiate urban and rural station environments in order to help assess the magnitude of uncertainty in quantifying the potential urban signal. In addition, the impact that data homogenization has on the UHI signal is evaluated, particularly with respect to determining whether homogenization is successful at removing urban influences on the temperature record and assessing the potential magnitude of residual urban bias in U.S. Historical Climatology Network (USHCN) version 2 adjusted temperature data (*Menne et al.* 2009).

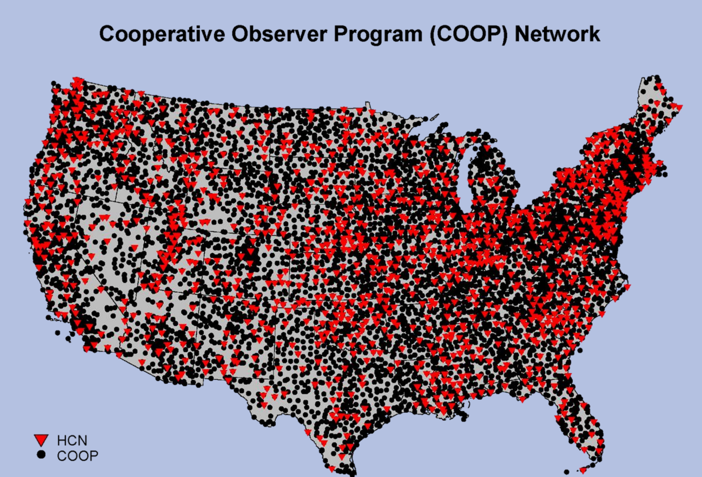

Figure 1. Distribution of U.S. Cooperative (Coop) Observer Network stations in the Conterminous United States (black dots) and the U.S. HCN version 2 sites (red triangles).

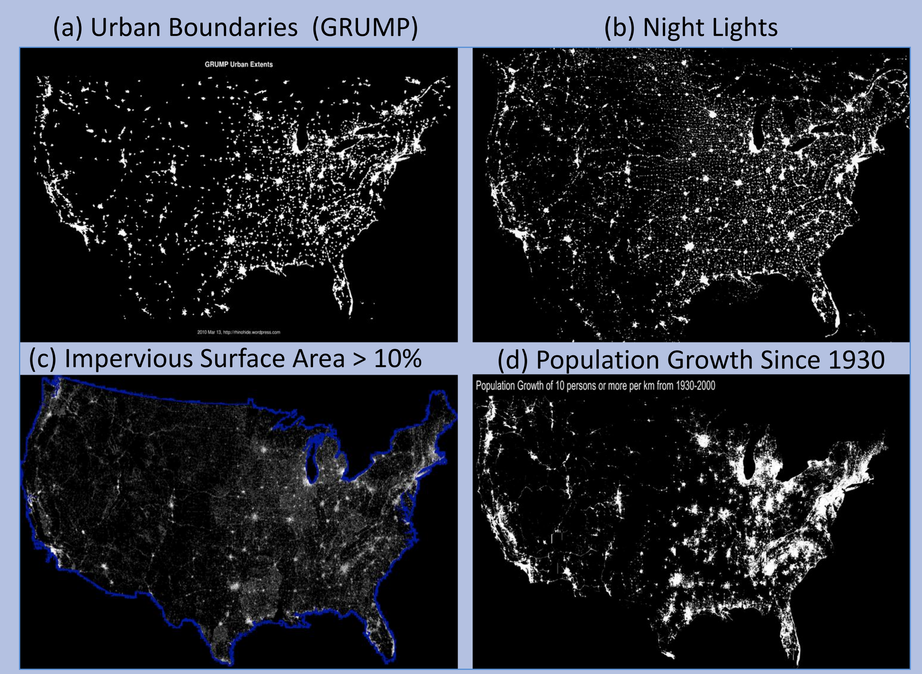

Figure 2. Datasets used to classify the Coop and USHCN stations:
(a) Global Rural-Urban Mapping Project (GRUMP): http://sedac.ciesin.columbia.edu/gpw/documentation.jsp
(b) Global Radiance Calibrated Nighttime Lights data-set year 2006, satellite F16: http://www.ngdc.noaa.gov/dmsp/download_radcal.html
(c) Gridded 1 km Population Estimates for the Conterminous U.S., 1930-2000: http://www.ncdc.noaa.gov/oa/climate/research/population/popdata.html
(d) Global Distribution and Density of Constructed Impervious Surfaces: http://www.ngdc.noaa.gov/dmsp/download_global_isa.html

Table 1. Number of USHCN stations classified by urbanity for each urbanity proxy (Figure 2). Note that four stations could not be classified using the ISA urbanity proxy due to dataset limitations.

Classification	Urban Boundaries (GRUMP)	Nightlights	Impervious Surface Area >10%	Population Growth
Number of Rural Stations	608	978	857	685
Number of Urban Stations	610	240	357	533

METHODS

The conterminous U.S. (CONUS) has some of the most dense, publically available digital surface temperature data in the world with over 7000 Cooperative Observer (Coop) Network Program stations reporting daily maximum and minimum temperature for at least 10 of the network's 120-plus year history. A subset of 1218 stations, generally those with long records, comprises the USHCN (Figure 1; *Menne et al.* 2009). This highly sampled surface temperature field allows for the comparison of subsets of station data in a manner that avoids inherent biases due to changes in spatial coverage. The Coop Program also maintains accurate geolocational information on the present location of observing stations, with coordinates expressed in degrees, minutes and seconds (roughly 30 meter accuracy) available for most stations. This also allows for the accurate indexing of Coop stations against high-resolution georeferenced datasets that are useful to delineating urban and non-urban areas (Figure 2; Table 1). We use four such datasets to classify station locations as well as two different but complimentary methods to compare urban and rural station temperatures: station pairing and spatial gridding. The station pairing method is used to control for differences in instrument type and the gridding approach is used to control for the non-uniform distribution of stations across the conterminous U.S. In brief, these methods were carried out as follows:

Station pairing

- Take all permutations of urban and rural station pairs within 160 km (100 miles) of each other with the same sensor type (and for those that converted to the Maximum/Minimum Temperature System (MMTS), pair only those with transition dates within 5 years of each other)
- Perform a weighted regression of urban-rural pair anomaly differences by unique urban station

Spatial gridding

- Assign each station to a 2.5°x3.5° latitude/longitude grid
- Average rural and urban anomalies separately by grid cell and create a CONUS-weighted average series
- Regress urban-rural differences against date using an AR(1) process to correct for autocorrelation
- (To generate Figure 4, the anomalies were interpolated to a 0.25°x0.25° grid before averaging as in *Menne et al.*, 2009)

Urban-rural differences for mean monthly maximum and minimum temperatures were then calculated using four different versions of the USHCN version 2 monthly temperature data (results for minimum temperatures are presented here). The four versions were used to help quantify the magnitude of the UHI in the underlying raw (unhomogenized) data, to isolate the impact of data homogenization on the UHI signal, and to evaluate impact/need of applying the specific UHI correction used by NASA's Goddard Institute for Space Studies (GISS; Hansen et al. 2010) over and above homogenization. The dataset versions include:

1. Time of observation-only adjusted data (called TOB)—raw data differences are also summarized in Fig. 4;
2. Adjusted USHCN version 2 (TOB + pairwise homogenization adjustments; v2);
3. Adjusted version 2 data with the GISS UHI correction (Hansen et al. 2010; TOB + pairwise homogenization + GISS UHI adjustments; v2+step2)
4. Adjusted version 2 data produced by running the pairwise homogenization algorithm using (a) neighboring series classified only as rural (v2-rural neigh); and, (b) neighboring series classified only as urban (v2-urban neigh).

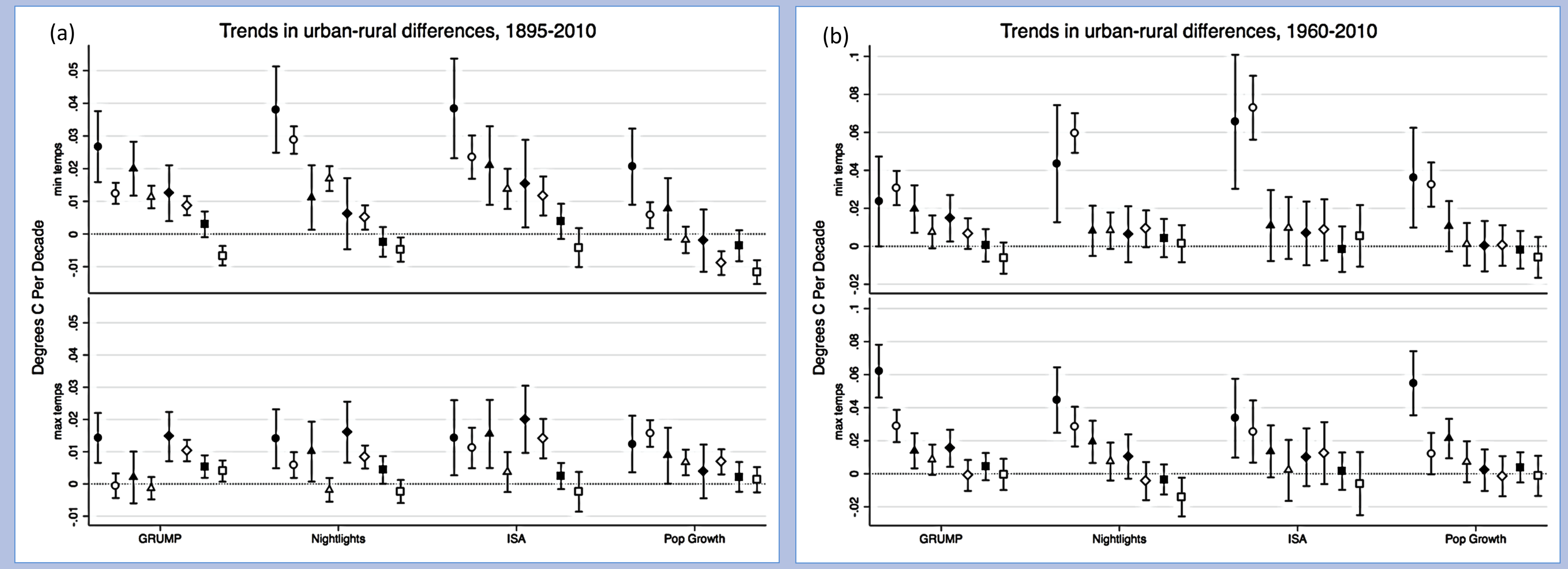

Figure 3. Trends and 95% confidence intervals in urban-rural differences by proxy type for the periods (a) 1895-2010 and (b) 1960-2010.. Circles represent TOB adjusted data, Triangles represent version 2.0 data adjusted using rural neighbors only (v2-rural neigh), Diamonds represent version 2.0 homogenized data (v2), and Squares represent version 2.0 homogenized data with additional UHI corrections using NASA GISS's "Step 2" method. Solid shapes show results from the station pair method, and hollow shapes show results from the spatial gridding method.

RESULTS

Figure 3 summarizes the urban minus rural trend differences for all data set versions. Figure 3(a) indicates that the USHCN unhomogenized (TOB-only adjusted) data contain significant urban warming signals ($p < 0.05$ for linear trend fit) over the period from 1895 to present in minimum temperatures according to all urban classification and comparison methods. Urban minus rural station trends in minimum temperature range between 0.05 and 0.5 C per century in minimum for the 1895-2010 period for the unhomogenized data depending on the classification and comparison method (e.g. station pairing or spatial gridding). There is also evidence of a significant urban signal in the unhomogenized data during the past 50 years (Fig. 3(b)), with urban-rural difference trends of between 0.2 and 0.6 C per century across all urbanity proxies for the period 1960-2010. This large urban warming signal does not appear to be a result of any correlation between instrument changes and urban form because it occurs with a similar magnitude in both the station pairing method (which controls for instrument type) and the spatial gridding method (which does not).

The urban warming signal over both century and half-century timeframes is larger in the more restrictive urban classifications—Nightlights and ISA—that contain relatively few urban stations, and are smaller in the classifications—GRUMP and Population Growth—that contain a more even split between urban and rural designations. The station pairing method often shows significantly larger urban warming than the spatial gridding method; however, the pairing method does not account for the potential biases related to the spatial distribution of the station pairs. As shown in Figure 4, the rural-urban differences are even larger in the raw minimum temperatures than in the TOB-adjusted data especially for the period since 1950 when time-of-observation changes were prevalent. However, this difference is not likely driven by any physical phenomena related to UHI. Rather it likely reflects a higher frequency of time of observation changes at non-urban stations. By comparing the minimum trends of rural stations to those of all USHCN stations, we can use the spatial gridding method to estimate the extent to which overall CONUS minimum temperature trends over the past century are driven by the urban warming signal. By this estimate, the unhomogenized minimum temperature data from rural USHCN stations yields trends that are between 10 and 20 percent smaller on average over the period 1895-2010 period than the trends from the full USHCN network. This difference decreases to between about 5 and 8 percent during the last 50 years.

The Pairwise Homogenization Algorithm (*Menne and Williams,* 2009; PHA) significantly reduces the difference between urban and rural minimum temperature trends according to all analysis methods and station classifications. This is particularly true over the 1960-2010 period, where none of the proxies classification methods indicated significant urban warming in the minimum temperatures. The station pairing method suggests some residual urban signal before 1960, but this residual signal is small in the spatial gridding method for all proxies after 1930 (Figure 4). Applying the NASA GISS "Step 2" urban-correction procedure has essentially no impact on homogenized USHCN version 2 trends since 1930, but effectively removes the residual urban-rural temperature trend differences for years before 1930 according to all four urban proxy classifications.

The differences between urban and rural station minimum temperature trends suggest that homogenization can remove much and perhaps nearly all (since 1930) of the urban signal without requiring a specific UHI correction. However, the trends in rural station minimum temperatures are slightly higher in the homogenized minimum temperature data than in the TOB-only adjusted data. One possible reason for this is that the PHA is appropriately removing inhomogeneities caused by station moves or other changes to rural stations that have had a net negative impact on the CONUS average bias (e.g., many stations now classified as rural were less rural in the past since they moved from city centers to airports or waste water treatment plants). Another possibility is that homogenization is causing nearby UHI-affected stations to homogenize some rural station series in a way that transfers some of the urban warming bias to the temperature records from rural stations. In such a case, a comparison of the homogenized data between rural and urban stations would then show a decreased difference between the two by removing the *appearance* of an urbanization bias without actually removing the bias itself. As described in the next section, an experiment was conducted to help determine the relative merits of these two explanations.

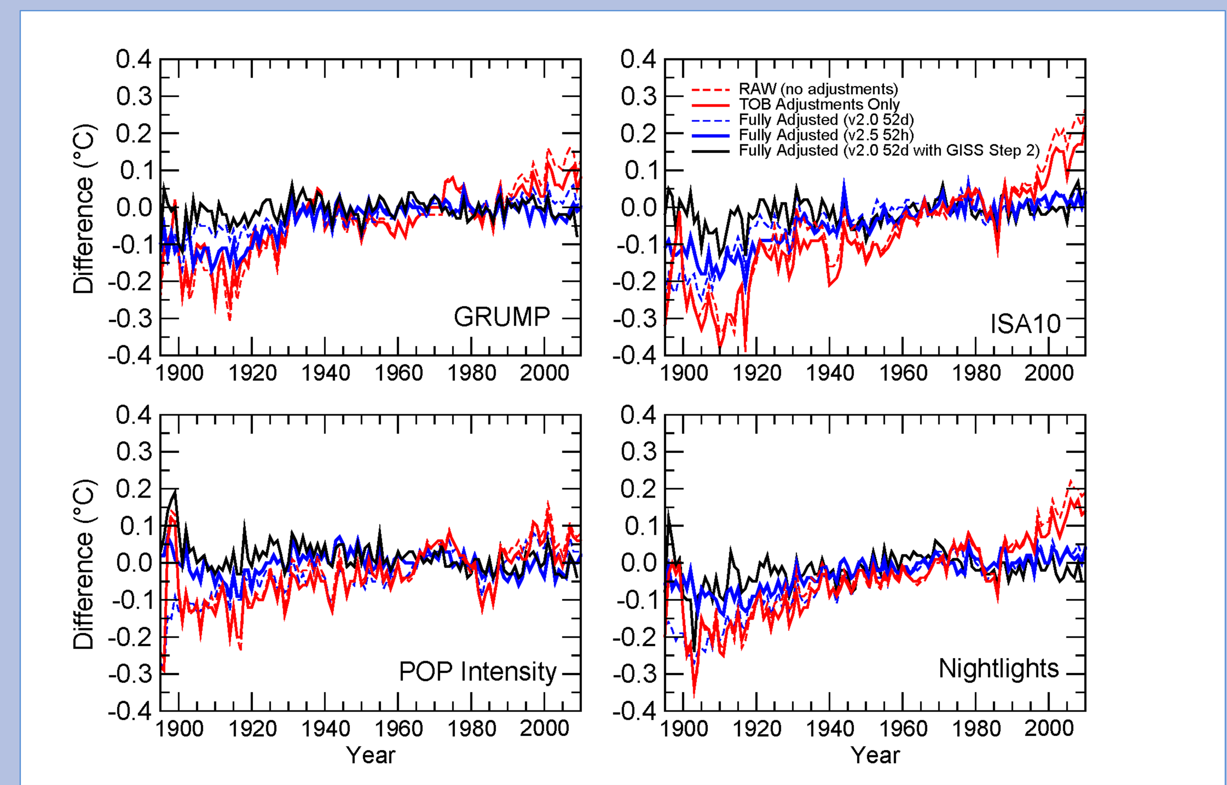

Figure 4. CONUS average urban and rural minimum temperature differences for five different versions of the USHCN station data and four different station classifications. The five different dataset versions are "Raw" (no bias adjustments-dashed red); TOB-only adjusted (solid red); v2 fully adjusted data homogenized using the pairwise algorithm version "52d" (dashed blue); fully adjusted v2 data homogenized using the pairwise algorithm version "52h" (solid blue); and fully adjusted v2 data homogenized using algorithm version "52d" with the NASA GISS (GISTEMP) "Step 2" UHI correction.

HOMOGENIZATION USING URBAN-ONLY AND RURAL-ONLY NEIGHBORS

The PHA was run separately allowing only rural- and only urban-classified Coop stations to be used as neighbors in calculating the PHA corrections for USHCN stations. In Figure 5, the spatially averaged U.S minimum temperature anomalies for rural stations are shown for four different datasets: the unhomogenized (TOB-adjusted only); the version 2 (all-Coop-adjusted; v2) data; the homogenized dataset adjusted using only urban coop stations. The large difference in the trends between the urban-only adjusted and the rural-only adjusted datasets suggests that when urban coop station series are used exclusively as reference series for the USHCN some of their urban-related biases can be transferred to USHCN station series during homogenization. However, the fact that the homogenized all-coop-adjusted minimum temperatures are much closer to those with rural-station-only adjustments than the urban-only adjustments suggests that the bleeding effect is likely small in the USHCN version 2 dataset. This is presumably because there is a sufficient number of rural stations available for use as reference neighbors in the Coop Network to allow for the identification and removal of UHI-related impacts on the USHCN temperature series. Nevertheless, it is instructive further examine the rural-only and urban-only adjustments to assess the consequences of using these two subsets of stations as neighbors in the PHA.

Figure 6(a) shows the cumulative impact of the adjustments using the rural-only and urban-only stations as neighbors to the USHCN. In this example, the impermeable surface extent was used to classify the stations. The cumulative impacts are shown separately for adjustments that are common between the two runs (i.e., adjustments that the PHA identified for the same stations and dates) versus those that are unique to the two separate urban-only and rural-only reference series runs. In the case of both the common and unique adjustments, the urban-only neighbor PHA run produces adjustments (solid red line-common and dashed red line line-unique) that are systematically larger (more positive) than the rural-only neighbor run (solid green line-common and dashed green line-unique). The magnitude of the resultant systematic bias for the adjustments common to both algorithm versions is shown in black. The reason for the systematic differences is likely that UHI trends or undetected positive step changes pervasive in the urban-only set of neighboring station series are being aliased onto the estimates of the necessary adjustments at USHCN stations. This aliasing from undetected urban biases becomes much more likely when all or most neighbors are characterized by such systematic errors.

Figure 6(b) provides a similar comparison of the rural-only neighbor PHA run and the all-Coop (true v2) neighbor run. In this case, the adjustments that are common to both the rural-only and the all-Coop neighbor runs have cumulative impacts that are nearly identical. This is evidence that, in most cases, the Coop neighbors that surround USHCN stations are sufficiently "rural" to prevent a transfer of undetected urban bias from the neighbors to the USHCN station series during the homogenization process. In the case of the adjustments that are unique to the separate runs, the cumulative impacts suggest that the less dense rural-only neighbors are missing some of the negative biases that occurred during the circa 1930 to 1950 period, which highlights the disadvantage of using a less dense station network. In fact, the all-Coop neighbor v2 dataset has about 30% more adjustments than the rural-only neighbor PHA run.

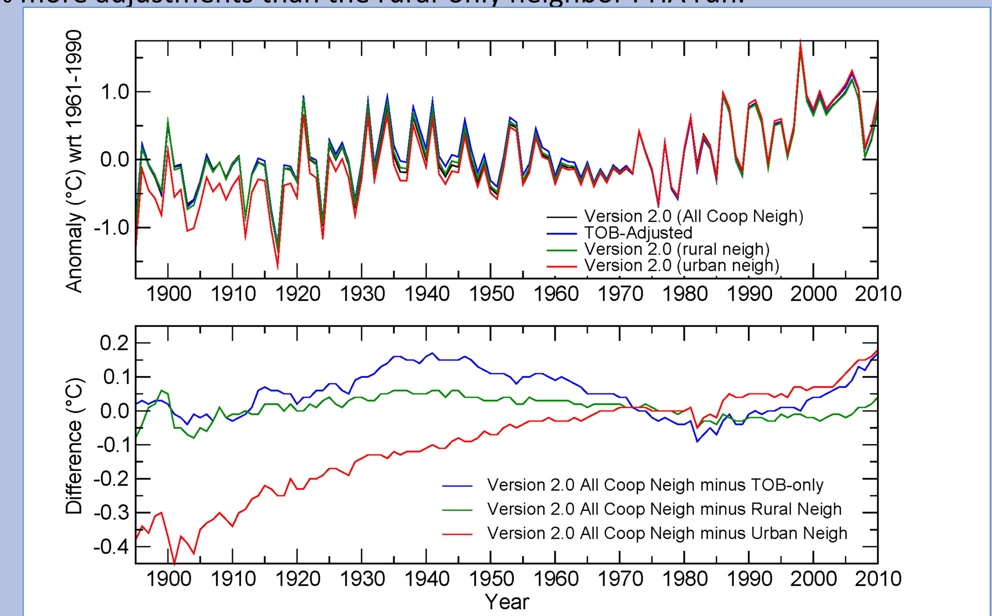

Figure 5. Comparison of spatially gridded minimum temperatures for the TOB-only adjusted USHCN data, v2 USHCN data (homogenized using all Coop station series as reference series), USHCN data homogenized using series from Coop stations only classified as rural according to the impervious surface method, and USHCN data homogenized using series from Coop stations only classified as urban (according to the impervious surface method). Top Panel: CONUS average anomalies for the four versions of the USHCN data. Bottom Panel: the differences between the USHCN v2 data homogenized with all Coop station series, and data adjusted only for the tob-bias (blue); data homogenized using only rural station series (green); and, data homogenized using only urban station series (red).

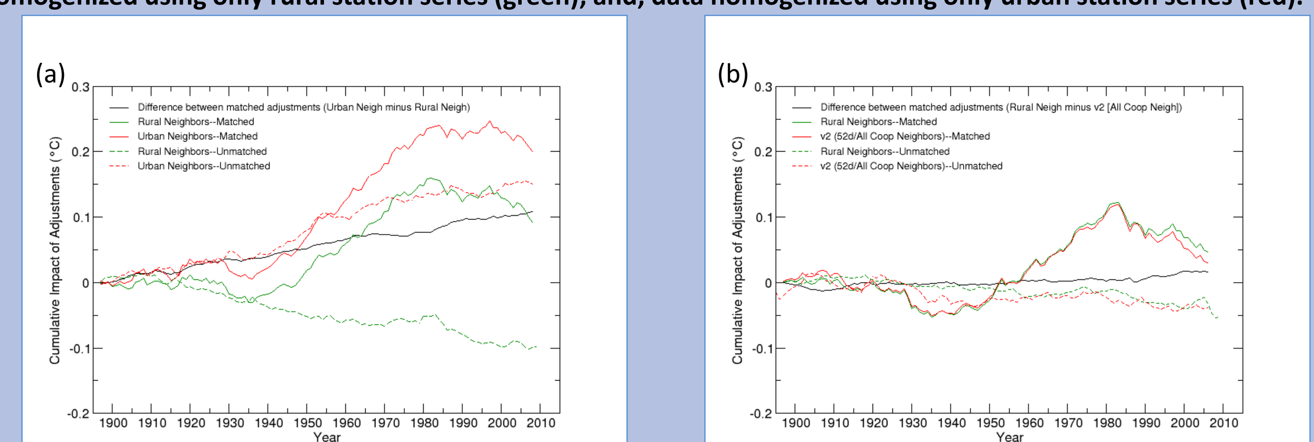

Figure 6. (a) Cumulative impact of PHA-derived adjustments using Coop station reference series classified as urban only (red lines) and as rural only (green lines) according to the impermeable surface area (ISA10) classification method. The impact of the adjustments that are common to both datasets are shown as solid lines and those that are unique are shown as dashed lines.
(b) Cumulative impact of PHA-derived adjustments using all Coop station series as reference series-v2-"52d" (red lines) and classified as rural only (green lines) according to the impermeable surface classification method. The impact of the adjustments are common to both datasets are shown as solid lines and those that are unique are shown as dashed lines.

CONCLUSION

According to all four proxy measures used to identify station environments that are currently urban, there is consistent evidence that urban stations have a systematic bias relative to rural stations throughout the USHCN period of record. This bias has led to an apparent urban warming signal in the unhomogenized data that accounts for approximately 10 to 20 percent of total rise in USHCN minimum temperatures averaged over the CONUS for the period since 1895, and 5 to 8 percent of the rise over the past 50 years. This quantification of urban bias can now be used along with previous assessments of other sources of bias (time of observation, location and instrument changes) to form a more comprehensive assessment of bias in the U.S. surface temperature record. Homogenization of the monthly temperature data via NCDC's Pairwise Homogenization Algorithm (PHA) removes the majority of the apparent urban bias, especially over the last 50 to 80 years. Moreover, results from the PHA using the full set of Coop station series as reference series and using only those series from stations classified as rural are broadly consistent, which provides strong evidence that the reduction of the urban warming signal by homogenization is a consequence of the real elimination of an urban warming bias present in the raw data rather than a consequence of simply forcing agreement between urban and rural station trends through a spreading of the urban signal to series from nearby stations.

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