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On the reliability of the U.S. surface temperature record

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[1] Recent photographic documentation of poor siting conditions at stations in the U.S. Historical Climatology Network (USHCN) has led to questions regarding the reliability of surface temperature trends over the conterminous United States (CONUS). To evaluate the potential impact of poor siting/instrument exposure on CONUS temperatures, trends derived from poor and well sited USHCN stations were compared. Results indicate that there is a mean bias associated with poor exposure sites relative to good exposure sites; however, this bias is consistent with previously documented changes associated with the widespread conversion to electronic sensors in the USHCN during the last 25 years. Moreover, the sign of the bias is counterintuitive to photographic documentation of poor exposure because associated instrument changes have led to an artificial negative ("cool") bias in maximum temperatures and only a slight positive ("warm") bias in minimum temperatures. These results underscore the need to consider all changes in observation practice when determining the impacts of siting irregularities. Further, the influence of nonstandard siting on temperature trends can only be quantified through an analysis of the data. Adjustments applied to USHCN Version 2 data largely account for the impact of instrument and siting changes, although a small overall residual negative ("cool") bias appears to remain in the adjusted maximum temperature series. Nevertheless, the adjusted USHCN temperatures are extremely well aligned with recent measurements from instruments whose exposure characteristics meet the highest standards for climate monitoring. In summary, we find no evidence that the CONUS average temperature trends are inflated due to poor station siting.

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1. Introduction

[2] Recent photographic documentation of exposure conditions at stations that comprise the U.S. Historical Climatology Network (USHCN) has raised questions regarding the reliability of surface temperature trends in the United States [*Davey and Pielke*, 2005; *Watts*, 2009]. *Watts* [2009], in particular, has speculated that U.S. surface temperature records from the USHCN from the last 30 years or so are likely biased high (warm) thereby artificially enhancing the magnitude of observed temperature trends. This conclusion is based on recent photographic documentation of stations in the USHCN indicating that the widespread installation of the electronic Maximum/Minimum Temperature System (MMTS) and Nimbus-type thermistors, which began in the mid-1980s, often caused measurements to be taken much closer to heated buildings, paved surfaces, and other artificial sources of heat than was likely the case for the thermometers that they replaced: Liquid in Glass (LiG). LiG thermometers were generally housed in wooden Cotton Region Shelters (CRS; also known as Stevenson Screens) that were more easily located further from the buildings where the observers worked or resided. In contrast, the MMTS replacements are attached by cable to an indoor readout device. Limits on the maximum allowable length of cable as well as barriers along the cable pathway (e.g., sidewalks, parking lots) apparently led to the placement of these sensors closer to buildings and other objects that may negatively influence exposure than their CRS predecessors.

[3] Both instrument changes and sensor moves are known to cause shifts in the mean level of a station's temperature series that are unrelated to true variations in the climate signal [*Mitchell*, 1953; *Peterson et al.*, 1998]. The process of removing such nonclimatic artifacts is called homogenization. In essence, homogenization of climate data involves identifying and removing abrupt shifts in station series that are unique to a particular series. The assumption behind such testing is that a spatially isolated and sustained shift in mean level of one station series relative to surrounding station series is artificial, or, at least, likely to have originated from causes other than background variations in weather and climate. This assumption can be verified when a shift in one station time series relative to other correlated series from nearby stations coincides with a known change in observation practice such as a small station move [*Karl and Williams*, 1987]. Unfortunately, station history records are often incomplete. As a result, both documented and undocumented shifts in station series may be present throughout the periods of record within an observing network such as the USHCN.

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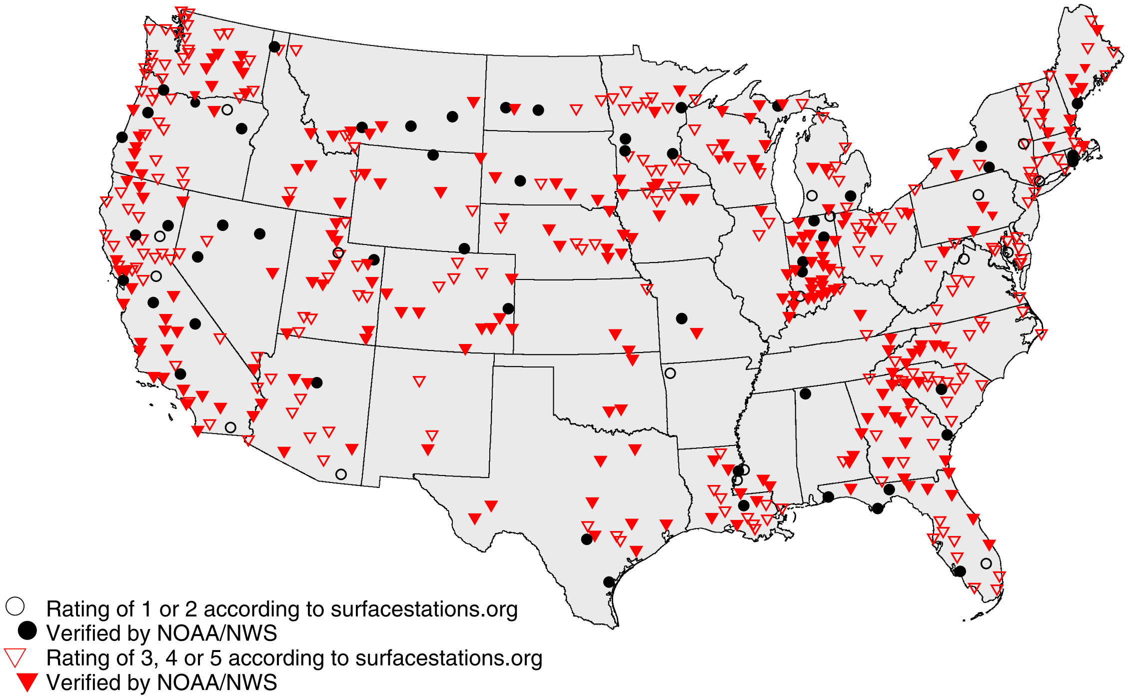

Figure 1. USHCN exposure classifications according to surfacestations.org (circles and triangles). Solid symbols are in agreement with independent assessments by NOAA National Weather Service Forecast Office personnel. Ratings are based on criteria similar to those used to classify U.S. Climate Reference Network stations. In this analysis, ratings 1 and 2 are treated as “good” exposure sites; ratings 3, 4, and 5 are considered “poor” exposure sites. Source: “V1.05 USHCN Master Station List.” (Note this file was downloaded from http://www.surfacestations.org in June 2009, but is indicated as having been updated on 18 April 2008. A more complete set of USHCN station classifications as referenced by *Watts* [2009] was not available for general use at the time of this analysis.)

[4] In version 2 of the USHCN temperature data [*Menne et al.*, 2009], the apparent impacts of documented and undocumented inhomogeneities were quantified and removed through automated pairwise comparisons of mean monthly maximum and minimum temperature series as described by *Menne and Williams* [2009]. In addition, version 2 temperature data were also debiased for changes in the time of observation [*Karl et al.*, 1986], which have contributed to an artificial, systematic “cooling” in the average conterminous United States (CONUS) temperature data [*Schaal and Dale*, 1977; *Hansen et al.*, 2001; *Vose et al.*, 2003], especially since 1950.

[5] The general impacts of these nonclimatic artifacts on historic CONUS temperature trends are discussed by *Menne et al.* [2009]. Here we address more specifically the potential impact that poor thermometer exposure conditions may have had on trends over the past 30 years. In brief, we use recent information about siting characteristics to derive maximum and minimum temperature trends from stations that have good instrument exposure and compare them to trends based on records from stations with poor exposure. The impact of shifts in temperature associated more generally with the transition from LiG/CRS measurements to the MMTS/Nimbus sensors (hereafter referred to as CRS and MMTS, respectively) is also discussed in light of the recently available information regarding the apparent degradation in exposure characteristics caused by this widespread instrument change. Finally, mean annual CONUS temperatures obtained from the USHCN data are compared to analogous temperatures (see section 4) derived from the U.S. Climate Reference Network (USCRN), a new network whose siting characteristics meet the highest standards for instrument exposure.

2. Methods

[6] The exposure characteristics of a subset of USHCN stations have been classified and posted to the Web by the organization surfacestations.org based on rating factors specified for the USCRN [*Climate Reference Network*, 2002; *Leroy*, 1999]. Note that the rating system used for the USCRN and retrospectively applied to the USHCN is more restrictive than long-accepted standards used in the siting of U.S. Cooperative Observer Network stations (and therefore the USHCN), especially in terms of the allowable distance to a building or other obstruction. For this reason, a reasonably well-sited station by Cooperative Observer standards may be assigned a moderately poor rating according to USCRN standards. Nevertheless, to evaluate the potential impact of exposure on station siting, we formed two subsets from the five possible USCRN exposure types assigned to the USHCN stations by surfacestations.org, and reclassified the sites into the broader categories of “good” (USCRN ratings of 1 or 2) or “poor” exposure (USCRN ratings of 3, 4 or 5). The geographic distribution of stations that fall into the two categories is shown in Figure 1 (note that just over 40% of the 1218 total

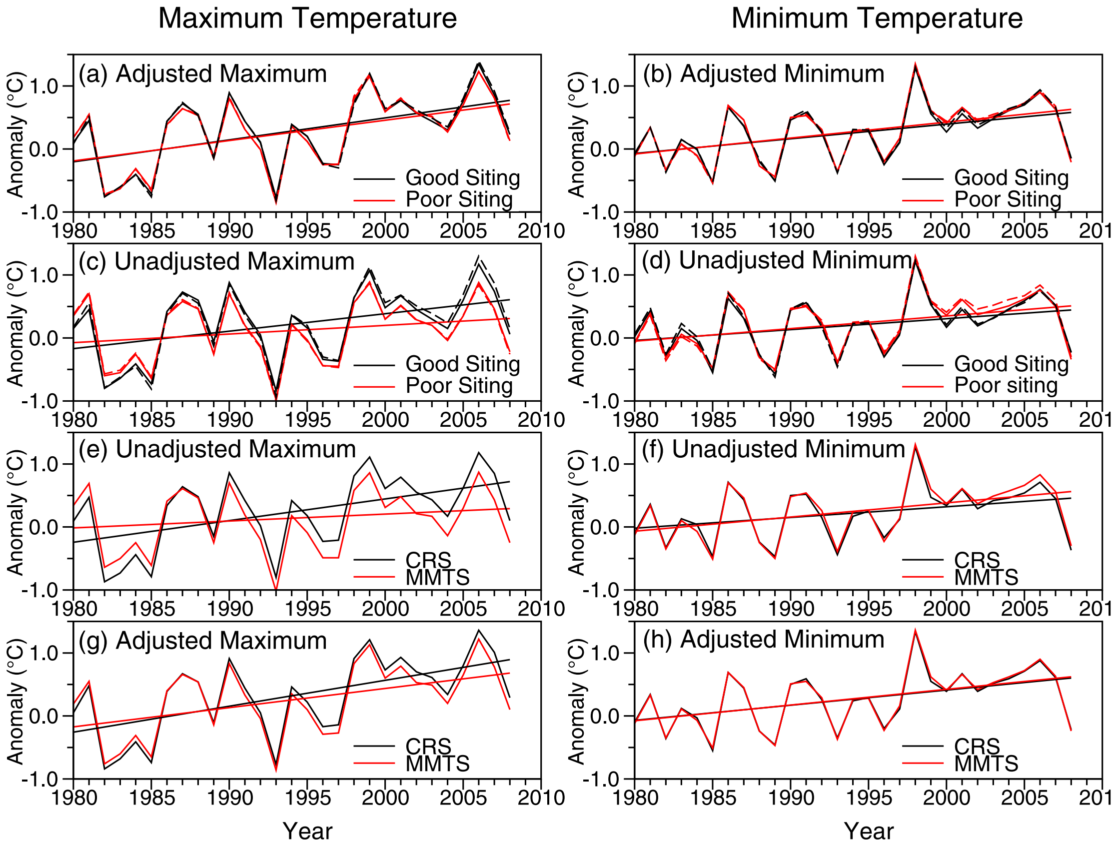

Figure 2. Annual average CONUS maximum and minimum temperature anomalies (with respect to the 1971–2000 mean) calculated using (a) maximum and (b) minimum adjusted (homogenized) temperatures from good and poor exposure sites (dashed lines are based on the set of stations whose ratings were verified by NOAA NWS; see Figure 1); (c) maximum and (d) minimum unadjusted temperatures from good and poor exposure sites (dashed lines are based on the set of stations whose ratings were verified by NOAA NWS; see Figure 1); (e) maximum and (f) minimum unadjusted temperatures from CRS and MMTS sites; and (g) maximum and (h) minimum adjusted (homogenized) temperatures from CRS and MMTS sites.

USHCN Version 2 sites had available ratings). Figure 1 also indicates which of the surfacestations.org station ratings are in agreement with recent, independent assessments by NOAA National Weather Service Forecast Office personnel.

[7] The two types of stations were then treated as separate subnetworks for calculating different estimates of the average annual CONUS maximum and minimum temperatures. Such estimates were calculated using both the unadjusted and adjusted (homogenized) monthly temperatures. Specifically, the unadjusted and adjusted monthly station values were converted to anomalies relative to the 1971–2000 station mean. The anomalies were then interpolated to the nodes of a 0.25° × 0.25° latitude-longitude grid using the method described by *Willmott et al.* [1985], separately for the good and poor exposure stations. Finally, the interpolated maximum and minimum temperature anomalies were grid box area weighted into a mean anomaly for the CONUS for each year as shown in Figure 2. In total, four time series of the CONUS maximum and minimum temperature anomalies were generated using the combinations of unadjusted and adjusted USHCN temperature data from good and poor exposure sites. To aid in distinguishing the differences between the CONUS estimates, annual differences between the various estimates are shown in Figure 3.

[8] Notably, only 71 USHCN stations fall into the good exposure category, while 454 fall into the poor category. Fortunately, the sites with good exposure, though small in number, are reasonably well distributed across the country and, as shown by *Vose and Menne* [2004], are of sufficient density to obtain a robust estimate of the CONUS average (see their Figure 7). This is because the number of spatial degrees of freedom in the surface temperature field across the CONUS is much smaller than the number of USHCN stations [e.g., *Wang and Shen*, 1999]. We note also that only about 30% of the good exposure sites currently have the newer MMTS-type sensors compared to about 75% of the poor exposure locations. For this reason, we also generated CONUS annual average temperatures by subsetting the USHCN into stations with MMTS versus those with CRS sensors, again using both adjusted and unadjusted data. In this case, the subsets are drawn from the full set of stations in the network, not just those for which exposure characteristics have been classified. Annual CONUS temperature estimates stratified by instrument type are also provided in Figure 2,

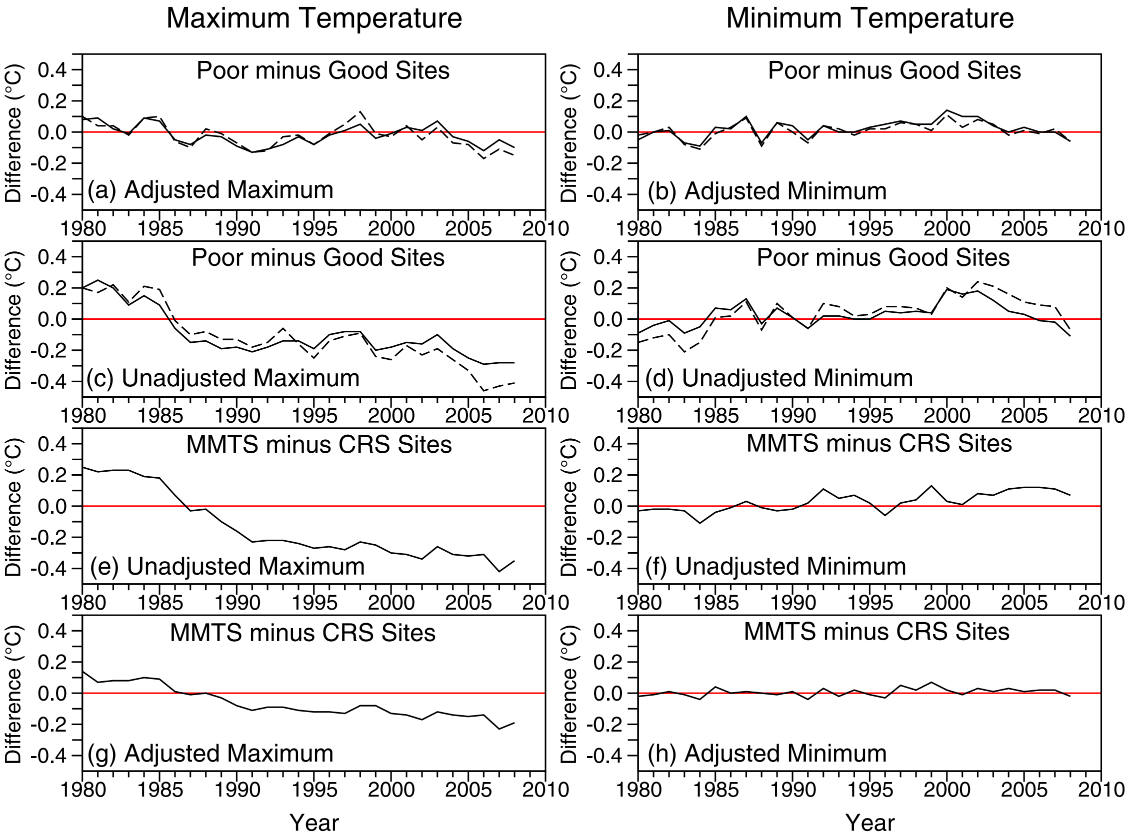

Figure 3. Average difference between maximum and minimum temperature anomalies (with respect to the 1971–2000 mean). (a) maximum and (b) minimum adjusted (homogenized) CONUS mean from poor exposure sites minus analogous mean from good exposure sites (dashed lines are based on the set of stations whose ratings were verified by NOAA NWS; see Figure 1); (c) maximum and (d) minimum unadjusted CONUS mean from poor exposure sites minus analogous mean from good exposure sites (dashed lines are based on the set of stations whose ratings were verified by NOAA NWS; see Figure 1); (e) maximum and (f) minimum unadjusted CONUS mean from MMTS sites minus analogous mean from CRS sites; and (g) maximum and (h) minimum adjusted (homogenized) CONUS mean from MMTS sites minus analogous mean from CRS sites.

and the differences between the MMTS and CRS averages are likewise shown in Figure 3.

[9] Figures 2 and 3 depict values since 1980 to highlight the period of widespread instrument changes and possible degradation of exposure characteristics. For reference, the current distribution of CRS and MMTS instrument types in the USHCN is shown in Figure 4. Although the USHCN is dominated by MMTS sensors, as in the case of the "good" exposure sites, the 218 CRS sites are reasonably well distributed and therefore also sufficient to calculate a robust average annual CONUS temperature according to *Vose and Menne* [2004].

3. Results and Discussion

[10] Figures 2a and 2b indicate that there is close agreement between the annual average CONUS anomalies from good and poor exposure sites when monthly maximum and minimum temperatures are adjusted for inhomogeneities. As shown in Table 1, the average CONUS trend since 1980 is nearly the same when calculated using adjusted data from good or poor exposure sites. In contrast, when calculated from unadjusted values, the CONUS average maximum trend is significantly smaller from the poor exposure sites relative to the trend from good exposure sites (see also Table 1). As shown in Figure 3c, this significant difference in trend arises primarily during the mid and late 1980s, the period when about 60% of USHCN sites converted from CRS to MMTS.

[11] Given that the poor exposure sites are predominately equipped with MMTS sensors, the shift toward lower maximums relative to good exposure sites is not necessarily unexpected and is, in fact, consistent with previous investigations into the impact of the MMTS on USHCN temperature series [*Quayle et al.*, 1991; *Hubbard and Lin*, 2006; *Menne et al.*, 2009]. These studies have shown that the MMTS sensors, on average, record lower daily maximums than their CRS counterparts, and, conversely, somewhat higher daily minimums (thus leading to a reduced diurnal temperature range). Such a signal is evident in the differences in mean annual CONUS temperatures derived from sites with CRS sensors versus those with MMTS sensors as shown in Figures 2e and 2f and Figures 3e and 3f. Notably, the unadjusted CONUS minimum temperature trend from good

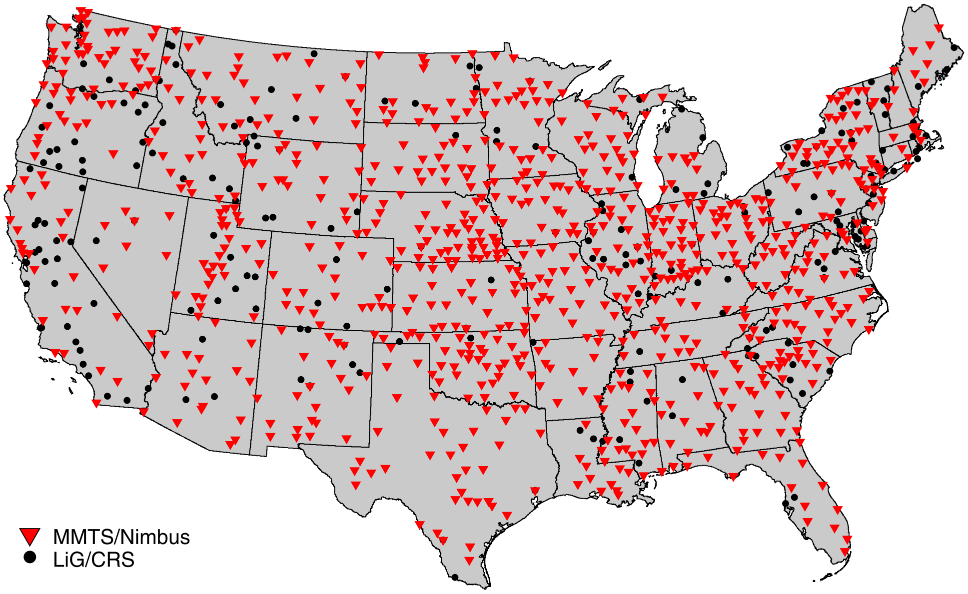

Figure 4. Current distribution of MMTS/Nimbus and LiG/CRS sites in the USHCN. Source: NOAA National Climatic Data Center MultiNetwork Metadata System.

and poor exposure sites as well as from CRS and MMTS sites show only slight differences in the unadjusted data. These small differences, however, do not accurately reflect the complete impact of the MMTS on minimum temperatures because many observers also switched from afternoon to morning observation times since 1980. Basically, the gradual changeover in time of observation throughout the network led to an artificial “cooling” of both the CONUS average maximum and minimum temperatures coincident with the transition to the newer MMTS sensors. The time of observation bias in the USHCN, therefore, has amplified the impact of the changeover to MMTS on maximum temperatures, but mitigated the impact of the instrument change on minimum temperatures as shown in Table 1 (see also Figures 4 and 7 of *Menne et al.* [2009]).

[12] It is important to note that changes in instrumentation, station moves or other changes in the circumstances behind temperature measurement have not occurred simultaneously at all stations. This makes it possible to estimate the relative and specific impact of changes at individual stations. As noted above, the timing and magnitude of shifts in the USHCN version 2 temperature data were identified using the pairwise comparison procedure described by *Menne and Williams* [2009]. This procedure both identifies the timing of relative shifts in temperature series and provides an estimate of the magnitude of each shift using correlated series from nearby stations that the procedure determined were homogeneous during the period before and after the shift in question. The magnitude of all shifts (documented and undocumented) identified in USHCN monthly temperature series is shown in Figure 5 (see also Figure 6 of *Menne et al.* [2009]). Figure 5 provides additional evidence of the preference for negative shifts in maximum temperatures and positive shifts in minimum temperatures (relative to the prior mean levels) during the concentrated period of transitions to the MMTS in the mid to late 1980s regardless of any role coincident changes in exposure may have played [see also *Hubbard and Lin*, 2006].

[13] Moreover, Table 1 provides evidence that a positive bias has not simply been transferred from poorly sited stations

Table 1. Linear Trends in CONUS Average Annual Temperatures Since 1980 Computed From Various Subsets of the USHCN Monthly Temperature Records[a]

	Fully Adjusted	Unadjusted	Adjusted for Time of Observation Bias Only
		Maximum Temperature	
Good exposure	0.35 (±0.11) [*0.37 (±0.11)*]	0.28 (±0.11) [*0.32±0.12)*]	0.32 (±0.11)
Poor exposure	0.32 (±0.11) [*0.32 (±0.11)*]	0.14 (±0.11) [*0.12 (±0.11)*]	0.23 (±0.11)
LiG/CRS	0.41 (±0.11)	0.34 (±0.11)	0.41 (±0.11)
MMTS/Nimbus	0.30 (±0.11)	0.11 (±0.10)	0.19 (±0.11)
		Minimum Temperature	
Good exposure	0.23 (±0.08) [*0.23 (±0.08)*]	0.17 (±0.09) [*0.15 (±0.09)*]	0.24 (±0.09)
Poor exposure	0.25 (±0.09) [*0.26 (±0.09)*]	0.20 (±0.09) [*0.24 (±0.09)*]	0.30 (±0.09)
LiG/CRS	0.23 (±0.09)	0.17 (±0.09)	0.22 (±0.09)
MMTS/Nimbus	0.25 (±0.09)	0.22 (±0.09)	0.32 (±0.09)

[a] Trends are °C/decade with ± one standard error from least squares estimate in parenthesis. Values in brackets and italics are calculated from the subset of USHCN stations with consistent ratings between those classified by surfacestations.org and NOAA’s National Weather Service.

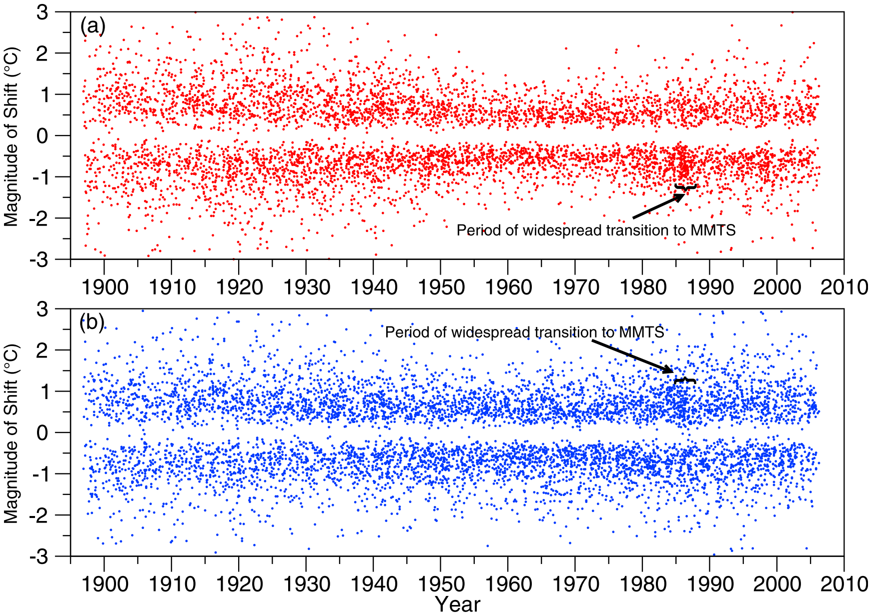

Figure 5. Magnitude and timing of shifts identified in USHCN version 2 (a) mean monthly maximum and (b) mean monthly minimum temperature series [*Menne et al.*, 2009]. A negative (positive) value indicates that the change led to a decrease (increase) in the mean level of the series relative to preceding values.

to well sited stations during the pairwise adjustment procedures. This is because nearly all of the artificial bias at the good exposure (and at LiG/CRS) sites is accounted for by the time of observation bias adjustment, which is applied independently of the *Menne and Williams* [2009] pairwise adjustments and does not require any comparisons between station series. In other words, there is almost no impact of the pairwise adjustments on the well sited and LiG/CRS temperature series after the TOB adjustments have been applied. In contrast, the temperature series from poorly sited and MMTS stations are significantly impacted by the pairwise adjustments since these adjustments address artificial shifts in the temperature series caused by the switch to electronic thermistors that collectively had a negative impact on maximum temperature observations and a positive impact on minimum temperatures.

[14] The lack of very small magnitude shifts in Figure 5 is a consequence of adjusting only those shifts that were statistically significant according to the pairwise comparison procedure. However, the average of all unadjusted MMTS transitions is about −0.1°C for maximum temperature series and about +0.025°C for minimum temperature series. The adjustments for the impact of the MMTS on maximum temperature series in the USHCN version 2 data set are therefore somewhat inadequate, as reflected in Figures 2g and 3g. In fact, contrary to there being a positive (warm) bias as might be suggested by the exposure conditions at MMTS sites, there appears to be a residual, artificial negative bias in adjusted maximum temperatures (and little to no residual bias in adjusted minimum temperatures). In short, the "under-adjustment" in maximum temperatures is a consequence of using site-specific adjustments for the MMTS in the version 2 release as opposed to a network-wide, fixed adjustment as in version 1 [*Quayle et al.*, 1991]. Overall, the version 2 under-adjustment appears to be somewhat smaller than the network average over-adjustment for the MMTS in version 1 discussed by *Menne et al.* [2009].

4. Independent Verification of Recent USHCN Annual Temperatures

[15] The USCRN provides new and independent insight into the CONUS air temperature signal. Each of 114 stations at 107 locations (some stations were installed as nearby pairs) is equipped with very accurate instruments in a triplicate configuration so that each measurement can be checked for internal consistency. The station site selection and engineering, as well as the management of data and metadata, are designed to fulfill the recommendations of the Climate Monitoring Principles [*Karl et al.*, 1995] that were adopted by the National Research Council (NRC) in 1999 [*NRC*, 1999]. Since the network was commissioned in 2004, it has grown from 40 stations distributed across the United States to 114, with 100 stations observing a full year of data in 2008 (the locations of USCRN stations are shown in Figure 6). While neither 40 nor 100 stations are a large number, statistical analyses of existing stations indicate that the CONUS annual air temperature average is well represented in either case, as long as the stations are well distributed at each stage of network deployment [*Vose and Menne*, 2004]. Therefore, five useful years of annual CONUS average air temperatures are available from the USCRN to compare to USHCN version 2 adjusted temperature data.

[16] USCRN and USHCN version 2 air temperature measurements cannot be directly compared in raw form, as air temperature is measured by an instrument aspirated by a fan in the case of USCRN, and primarily by natural ventilation in USHCN. Instead, a regression-based method was developed to estimate air temperature normals for each USCRN station using observations from the surrounding Cooperative

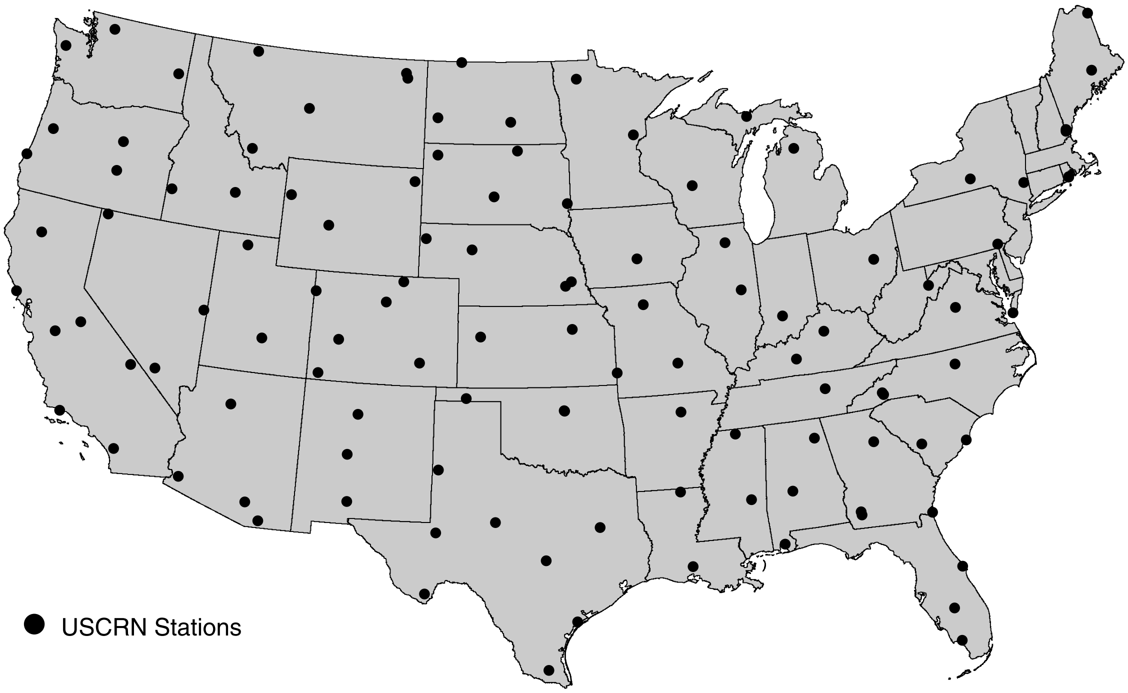

Figure 6. Locations of USCRN stations.

Observer Network as described by *Sun and Peterson* [2005]. Subtracting the estimated normals from the monthly USCRN air temperatures then produces a time series of monthly air temperature departures from normal that are compatible with the predecessor observation technology used throughout the USHCN, but with year-to-year variations that are independent of the USHCN. The USCRN anomalies generated in this fashion were then interpolated to a grid and an average CONUS value was calculated in the same manner described in section 2.

[17] As shown in Figure 7, the USCRN CONUS air temperature departures for 2004–2008 are extremely well aligned with those derived from the USHCN version 2 temperature data. For these five years, the r^2 between the 60 monthly USCRN and USHCN version 2 anomalies is 0.998 and 0.996 for the maximum and minimum temperatures, respectively,

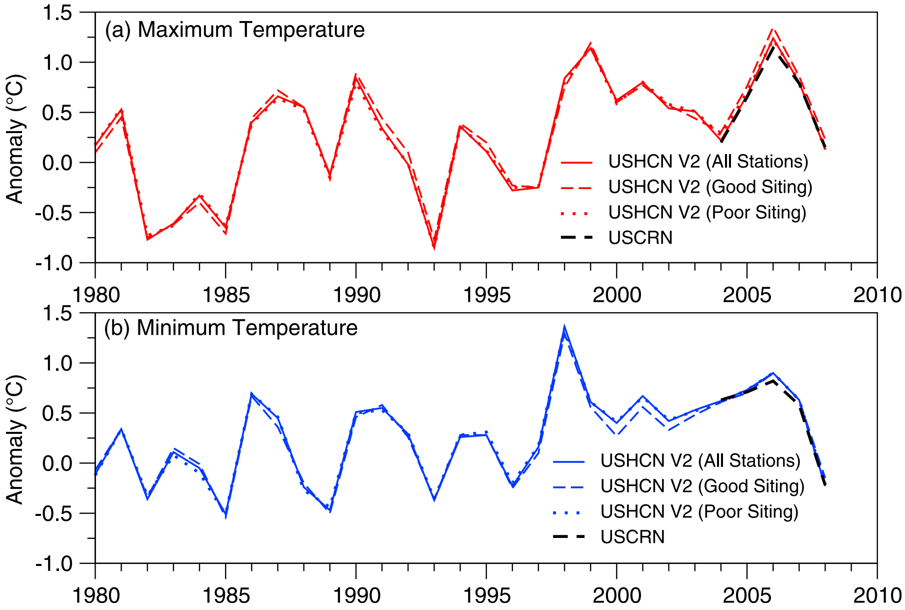

Figure 7. Comparison of the CONUS average annual (a) maximum and (b) minimum temperatures calculated using USHCN version 2 adjusted temperatures [*Menne et al.*, 2009] and USCRN departures from the 1971–2000 normal. Good and poor site ratings are based on surfacestations.org as in Figure 1.

with a mean annual bias for both variables of −0.03°C in the USCRN data relative to USHCN version 2. This finding provides independent verification that the USHCN version 2 data are consistent with research-quality measurements taken at pristine locations and do not contain spurious trends during the recent past even if sampled exclusively at poorly sited stations. While admittedly this period of coincident observations between the networks is rather brief, the value of the USCRN as a benchmark for reducing the uncertainty of historic observations from the USHCN and other networks will only increase with time.

5. Conclusion

[18] Given the now extensive documentation by surfacestations.org [*Watts*, 2009] that the exposure characteristics of many USHCN stations are far from ideal, it is reasonable to question the role that poor exposure may have played in biasing CONUS temperature trends. However, our analysis and the earlier study by *Peterson* [2006] illustrate the need for data analysis in establishing the role of station exposure characteristics on temperature trends no matter how compelling the circumstantial evidence of bias may be. In other words, photos and site surveys do not preclude the need for data analysis, and concerns over exposure must be evaluated in light of other changes in observation practice such as new instrumentation.

[19] Indeed, our analysis does provide evidence of bias in poor exposure sites relative to good exposure sites; however, given the evidence provided by surfacestations.org that poor exposure sites are predominantly MMTS sites, this bias is consistent with previously documented changes associated with the widespread conversion to MMTS-type sensors in the USHCN. Moreover, the bias in unadjusted maximum temperature data from poor exposure sites relative to good exposure sites is, on average, negative while the bias in minimum temperatures is positive (though smaller in magnitude than the negative bias in maximum temperatures). The adjustments for instrument changes and station moves provided in version 2 of the USHCN monthly temperature data largely account for the impact of the MMTS transition, although an overall residual negative bias remains in the adjusted maximum temperature series. Still, the USHCN adjusted data averaged over the CONUS are well aligned with the averages derived from the USCRN for the past five years.

[20] The reason why station exposure does not play an obvious role in temperature trends probably warrants further investigation. It is possible that, in general, once a changeover to bad exposure has occurred, the magnitude of background trend parallels that at well exposed sites albeit with an offset. Such a phenomenon has been observed at urban stations whereby once a site has become fully urbanized, its trend is similar to those at surrounding rural sites [e.g., *Boehm*, 1998; *Easterling et al.*, 2005]. This is not to say that exposure is irrelevant in all contexts or that adherence to siting standards is unimportant. Apart from potentially altering the degree to which a station's mean value is representative of a region, poor siting in the USHCN may have altered the nature of the impact of the MMTS transition from what it would have been had good siting been maintained at all stations. Moreover, there may be more subtle artifacts associated with siting characteristics such as alterations to the seasonal cycle. Classification of USHCN exposure characteristics as well as observations from the very well sited USCRN stations should prove valuable in such studies. Nevertheless, we find no evidence that the CONUS average temperature trends are inflated due to poor station siting.

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