A closer look at United States and global surface temperature change

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Abstract. We compare the United States and global surface air temperature changes of the past century using the current Goddard Institute for Space Studies (GISS) analysis and the U.S. Historical Climatology Network (USHCN) record [*Karl et al.*, 1990]. Changes in the GISS analysis subsequent to the documentation by *Hansen et al.* [1999] are as follows: (1) incorporation of corrections for time-of-observation bias and station history adjustments in the United States based on *Easterling et al.* [1996a], (2) reclassification of rural, small-town, and urban stations in the United States, southern Canada, and northern Mexico based on satellite measurements of night light intensity [*Imhoff et al.*, 1997], and (3) a more flexible urban adjustment than that employed by *Hansen et al.* [1999], including reliance on only unlit stations in the United States and rural stations in the rest of the world for determining long-term trends. We find evidence of local human effects ("urban warming") even in suburban and small-town surface air temperature records, but the effect is modest in magnitude and conceivably could be an artifact of inhomogeneities in the station records. We suggest further studies, including more complete satellite night light analyses, which may clarify the potential urban effect. There are inherent uncertainties in the long-term temperature change at least of the order of 0.1°C for both the U.S. mean and the global mean. Nevertheless, it is clear that the post-1930s cooling was much larger in the United States than in the global mean. The U.S. mean temperature has now reached a level comparable to that of the1930s, while the global temperature is now far above the levels earlier in the century. The successive periods of global warming (1900-1940), cooling (1940-1965), and warming (1965-2000) in the 20th century show distinctive patterns of temperature change suggestive of roles for both climate forcings and dynamical variability. The U.S. was warm in 2000 but cooler than the warmest years in the 1930s and 1990s. Global temperature was moderately high in 2000 despite a lingering La Niña in the Pacific Ocean.

1. Introduction

Analyses of global surface air temperature change are routinely carried out by several groups, including the University of East Anglia [*Jones et al.*, 1999], the Goddard Institute for Space Studies (GISS) [*Hansen et al.*, 1999], and the National Climatic Data Center [*Peterson et al.*, 1998b; *Quayle et al.*, 1999]. Although these different analyses are based on basically the same observations, they provide useful checks because of different ways of handling data problems such as incomplete spatial and temporal coverage, urban influences on station environment, and other factors affecting data quality [*Karl et al.*, 1989, 1994; *Jones*, 1995; *Easterling and Peterson*, 1995; *Peterson et al.*, 1998a]. The differences among the global mean temperature changes from these different analyses are generally small, of the order of 0.1°C [*IPCC*, 1996, 2001; *Hansen et al.*, 1999, Appendix A], but regional differences can be larger.

Hansen et al. [1999] emphasized the difference between their analyzed temperature changes for the contiguous U.S. and the global mean. Specifically, they found a decline of about 0.5°C in the U.S. mean temperature between the early 1930s and the late 1970s, with the greatest cooling in the southeastern U.S., while the global temperature declined only about 0.1°C. Although the contiguous U.S. represents only about 2% of the world area, it is important that the analyzed temperature change there be quantitatively accurate for several reasons. Analyses of climate change with global climate models are beginning to try to simulate the patterns of climate change, including the cooling in the southeastern U.S. [*Hansen et al.*, 2000]. Also, perceptions of the reality and significance of greenhouse warming by the public and public officials are influenced by reports of climate change within the United States.

The GISS analysis of *Hansen et al.* [1999] did not incorporate adjustments to the large subset of the U.S. stations represented by the U.S. Historical Climatology Network (USHCN) which *Karl et al.* [1990] developed from the extensive station metadata available for that network. The current GISS analysis includes time-of-observation and station history adjustments. In addition, the urban adjustment in the GISS analysis has been improved, particularly in those regions where satellite observations allow a more accurate identification of stations that are removed from regions of human development. The purpose of the present paper is to document the changes that have been made in the GISS analysis of surface temperature change subsequent to the documentation of *Hansen et al.* [1999] and to use this new analysis for a closer look at the United States and global temperature change. In section 2 we summarize the source data used in our analyses. In section 3 we illustrate the use of satellite data of *Imhoff et al.* [1997] to identify urban, periurban, and rural stations, and we compare this with the use of population data. In section 4 we illustrate some of the different corrections that enter into the USHCN data adjustments of *Karl et al.* [1990] and provide rationale for the choices made for the GISS global analysis. In section 5 we examine the effects of the various data adjustments. In section 6 we use the current analyses to compare the United States and the global temperature changes.

2. Source Data

The source of the monthly mean station temperatures for the GISS analysis is the Global Historical Climatology Network (GHCN) of *Peterson and Vose* [1997] and updates, available electronically, from the National Climatic Data Center (NCDC). This is a compilation of 31 data sets, which include data from more than 7200 independent stations. One of the 31 data sets is the U.S. Historical Climatology Network (USHCN), which includes about 1200 stations in the United States. The USHCN [*Karl et al.*, 1990; *Easterling et al.*, 1996a] is composed of stations with nearly complete records in the 20th century and with metadata that aid homogeneity adjustments.

The GISS analysis uses the version of the GHCN without homogeneity adjustments, as adjustments are carried out independently in the GISS analysis. The GISS adjustments consist of data quality control and a homogeneity adjustment applied to urban stations. The data quality control, including comparison of each station with its several nearest neighbors, is the same in the current GISS analysis as described by *Hansen et al.* [1999].

The urban adjustment is improved in the current GISS analysis. The urban adjustment of *Hansen et al.* [1999] consisted of a two-legged linear adjustment such that the linear trend of temperature before and after 1950 was the same as the mean trend of rural neighboring stations. In the new GISS analysis the hinge year is a variable chosen to be that which allows the adjusted urban record to fit the mean of its neighbors most precisely. The current GISS analysis also uses satellite measurements of nightlights to identify urban areas and remote stations in the United States (and southern Canada and northern Mexico); only "unlit" stations are used to define homogeneity adjustments. For USHCN stations the time-of-observation and station history adjustments of *Karl et al.* [1990] are applied before the urban adjustment is made.

3. Satellite Light Data

Hansen et al. [1999] attempted to minimize urban influence on the analyzed temperature change by identifying urban stations and adjusting their record such that the long-term trend was the same as the mean of rural neighboring stations. Urban stations were identified from local population data provided as metadata in the GHCN records. Problems with this approach include the fact that the population data were typically two decades old, so it could not describe accurately recent urban development. Also, the effective spatial resolution was poor, as it was not possible to tell whether a station was located in the city center, suburbs, or outskirts of the region with specified population.

As an alternative approach to identifying stations subject to human influence, we test in this paper the use of satellite observations of nighttime light emissions. Specifically, we use observations from a United States Defense Meteorological Satellite taken with a highly sensitive photomultiplier tube [*Imhoff et al.*, 1997]. Observations employed are generally those taken under a new moon to minimize reflected moonlight. A composite of many images is used to eliminate ephemeral light sources such as lightning and fires. The observations were acquired in 1995, so they do a good job of describing current urban development. The same data have been used to quantify the effect of urban development on primary productivity [*Imhoff et al.*, 2000]. The spatial resolution of the data used here is about 2.7 km.

Plate 1 illustrates the night light data. The percent of brightness refers to the fraction of the area-time at which light was detected, i.e., the percent of cloud-screened observations that triggered the sensor. These data are then summarized into three categories (0-8, 8-88, and 88-100%). From empirical studies in several regions of the United States, Imhoff et al. associate the brightest regions (which we designate as "bright" or "urban") with population densities of about 10 persons/ha or greater and the darkest ("unlit" or "rural") regions with population densities of about 0.1 persons/ha or less. As is apparent from Plate 1b, the intermediate brightness category ("dim" or "periurban") may be a small town or the fringe of an urban area. Some of the regions defined as periurban may be a consequence of reflected light from urban areas, bleeding between detectors, navigation errors, and other effects that spread the urban influence [*Imhoff et al.*, 1997]. However, these problems do not prevent us from using the periurban brightness category to identify areas where the likelihood of human influence is greater than in the unlit regions but less than in the bright regions. The average population density in the periurban class is 1 person/ha.

The locations of meteorological stations in four parts of the United States are included in Plate 1b. The color of the station-locating asterisk refers to three categories of population from the GHCN station metadata: blue (less than 10,000), green (between 10,000 and 50,000), and red (greater than 50,000). *Hansen et al.* [1999] referred to these three categories as rural, small town, and urban. Plate 1b reveals that there is not a close correspondence of these three population categories to the three satellite brightness categories. This is shown quantitatively by Table 1, which is an inventory for the USHCN and GHCN stations in the contiguous 48 states with more than 20 years of data. Indeed, most of the "rural" stations of *Hansen et al.* [1999] are classified by the satellite brightness as "periurban."

Only 214 of the USHCN and 256 of the GHCN stations within the United States are in "unlit" areas. Fortunately, because of the large number of meteorological stations in the United States, it is still possible to define area-averaged temperature rather well using only the unlit stations. This is not necessarily true in much of the rest of the world.

4. Modifications to GISS Analysis

The largest changes to the GISS analysis since the publication of *Hansen et al.* [1999] are in the United States, where we take advantage of USHCN adjustments [*Karl et al.*, 1990; *Easterling et al.*, 1996a] and the analysis of satellite night lights by *Imhoff et al.* [1997]. We modify our two-legged urban adjustment procedure globally, but GHCN population data are still used to identify rural stations except in the United States and bordering regions of Canada and Mexico. The significant modifications to the GISS analysis are summarized in this section. Impacts of individual modifications are illustrated in section 4.1.

Some prefatory comments about adjustments to the temperature records are in order. The aim of adjustments is to make the temperature record more "homogeneous," i.e., a record in which the temperature change is due only to local weather and climate. However, caution is required in making adjustments, as it is possible to make the long-term change less realistic even in the process of eliminating an unrealistic short-term discontinuity. Indeed, if the objective is to obtain the best estimate of long-term change, it might be argued that in the absence of metadata defining all changes, it is better not to adjust discontinuities. In that case we would be relying on the fact that absolute temperature calibrations have existed for the past century, and observers were generally aiming to measure the monthly mean temperature for the undisturbed environment at the specified location.

An example relevant to a later discussion is shown in Figure 1 for the temperature change at an urban location. In this figure the "undisturbed temperature" is the temperature change that would have occurred at that location in the absence of local human development. The measured temperature includes an urban warming effect (exaggerated relative to year-to-year variability for clarity), a discontinuity due to the station moving to the city outskirts, and a lesser continued human effect in the suburbs. In this case, if the record is adjusted for the discontinuity (Figure 1b), the adjusted long-term temperature trend is less realistic than the trend of the unadjusted data, as urban warming at two locations has been incorporated into the adjusted record.

In this idealized case, with an obvious nonclimatic discontinuity, the best solution probably is to adjust for the discontinuity and somehow estimate a correction for urban warming. If available data include a sufficient number of rural stations removed from significant human influence, thus permitting a good urban correction, it should be possible to extract a reasonably homogeneous temperature record. Although actual station discontinuities are seldom as unambiguous as in Figure 1, if there is good metadata defining the existence and nature of station changes, the metadata can permit adjustments for most discontinuities in station histories.

It follows that a necessary concomitant of discontinuity adjustments is an adequate correction for urban warming. Otherwise, if the discontinuities in the temperature record have a predominance of downward jumps over upward jumps, the adjustments may introduce a false warming, as in Figure 1. This might happen, for example, if it is more common for stations to move from population centers toward the suburbs, rather than vice versa.

In this paper, by comparing unlit, periurban and urban stations in the United States, we find evidence for an urban warming effect. However, the effect is rather small, generally less than the uncertainties in a single station record, and we suggest that even this amount could be, at least in part, an artifact of inhomogeneities in station records. We discuss this issue after presenting the data.

4.1. USHCN Adjustments

4.1.1. Time of observation bias. The standard way of calculating the monthly mean temperature in the United States is to define the daily mean as the average of the daily maximum and minimum temperatures and then average the daily means over the month. The preferred 24-hour period would be the calendar day, i.e., from midnight to midnight. However, most observers recording results from maximum-minimum thermometers prefer observing times other than midnight. The time of observation has a systematic effect on the monthly mean temperature [*Mitchell*, 1958], for example, an afternoon 24-hour reading samples the diurnal cycle near its maximum on 2 days. This would not matter much if the time of observation at a given station did not change during the station's history. However, there have been changes of the time of observation by many of the cooperative weather observers in the United States [*Karl et al.*, 1986]. Furthermore, the change has been systematic with more and more of the measurements by United States cooperative observers being in the morning, rather then the afternoon. This introduces a systematic error in the monthly mean temperature change.

Karl et al. [1986] derived a correction for the time-of-observation bias and verified its validity from hourly data available for many U.S. stations. Of course, to apply this correction, it is necessary to have reliable metadata defining all changes of time of observation in the station record. These data generally exist for the USHCN stations and are believed to be reliable [*Karl et al.*, 1990]. The time of observation correction is one of the two substantial adjustments included in the adjusted USHCN data [*Karl et al.*, 1990; *Easterling et al.*, 1996a], as illustrated in section 5 below. This time of observation correction, which is the first in the sequence of adjustments carried out by *Karl et al.* [1990], is included in the current GISS analyses for USHCN stations. Such a correction is not generally required in the rest of the world, because the systematic shift from once a day evening to once a day morning observations which occurs at U.S. cooperative observer stations is not characteristic of most global observations [*Easterling et al.*, 1996b].

4.1.2. Station history adjustments. One difficulty in defining a homogeneous temperature record is caused by changes in the location of the thermometer or the station itself. In most long records, such moves are the rule, rather than the exception, and records of the moves are not generally available. *Easterling et al.* [1996b] note that "in reality, even the most extensive station history files probably do not contain information on all changes at a station … ."

One of the best opportunities to make useful station history adjustments is in the United States. The USHCN stations were selected as locations with nearly complete temperature records for the 20th century, but also because they have reasonably good station history records that permit adjustments for discontinuities [*Karl and Williams*, 1987; *Karl et al.*, 1990]. The impact of the station history adjustments is illustrated in section 5.

4.1.3. Other USHCN adjustments. A systematic discontinuity was introduced by the change from liquid-in-glass thermometers to the maximum-minimum temperature system (MMTS) in the U.S. Cooperative Network [*Quayle et al.*, 1991)]. The effect on the U.S. mean temperatures, as shown, is an order of magnitude smaller than the effect of either the time-of-observation bias or the station history adjustments, but because this correction is well defined, it is included in the USHCN analysis and in the current GISS analysis.

The USHCN analysis [*Karl et al.*, 1990; *Easterling et al.*, 1996a] contains another small adjustment in which missing data, mainly in the period 1900-1910, are filled in by interpolation. The effect is much less than the time of observation and station history adjustments, as illustrated. This adjustment is not included in the GISS analysis, which was designed to minimize the effect of data gaps.

4.2. Urban Adjustment

Urban adjustments are determined after all other adjustments are complete, because of the possible interaction between the estimated urban warming and the other adjustments, as discussed in connection with Figure 1. A prerequisite to determination of urban effects is classification of meteorological stations into categories for which different levels of local human effects could reasonably be anticipated.

We provide one explanatory comment here about the rationale for trying to remove anthropogenic urban effects but not trying to remove regional effects of land use or atmospheric aerosols. Urban warming at a single station, if it were not removed, would influence our estimated temperature out to distances of about 1000 km, i.e., 1 million square kilometers, which is clearly undesirable. This is independent of the method of averaging over area, as even 5000 stations globally would require that each station represent an area of the order of 100,000 square kilometers, an area much larger than the local urban influence. On the other hand, anthropogenic land use and aerosols are regional scale phenomena. We do not want to remove their influence, because it is part of the large-scale climate.

4.2.1. Classification of meteorological stations. Meteorological stations were classified by *Hansen et al.* [1999] as rural, small town, or urban, based on the population estimate provided as metadata in the GHCN record, as in the earlier study by *Easterling et al.* [1997]. This classification was used to identify which stations would be corrected for possible urban warming (adjustments were made only in "urban" areas, i.e., those with a population over 50,000) and also to identify nearby rural stations that could be used to define the magnitude of the adjustment. Problems with this approach include not only the age of the population data and the poor geographical resolution but also the fact that a population of even 10,000 (the division between "rural" and "small town") or less can produce significant local climate effects [*Mitchell*, 1953; *Landsberg*, 1981].

In the current GISS analysis within the United States the long-term temperature trend is based on only the "unlit" stations identified by satellite data, as the long-term temperature trends of the periurban and urban stations are adjusted to match the mean trend of neighboring unlit stations. Only about one quarter of the "small-town" stations are unlit, but this more stringent definition of a rural area still leaves about 250 stations in the United States. As the contiguous United States covers only about 2% of the Earth's area, the 250 stations are sufficient for an accurate estimate of national long-term temperature change, but the process inherently introduces a smoothing of the geographical pattern of temperature change.

This reclassification of stations is carried out here only for the United States and bordering regions in Canada and Mexico, where *Imhoff et al.* [1997] have analyzed brightness data into these three categories. Thus for the rest of the world we continue to use the GHCN population classification of stations to decide which stations should be adjusted.

4.2.2. Urban adjustment. In the prior GISS analysis the time series for temperature change at an urban station was adjusted such that the temperature trends prior to 1950 and after 1950 were the same as the mean trends for all "rural" stations (population less than 10,000) located within 1000 km (with the rural stations weighted inversely with distance). In other words it was a two-legged adjustment with the two legs hinged at 1950 and with the slopes of the two lines chosen to minimize the mean square difference between the adjusted urban record and the mean of its rural neighbors.

The urban adjustment in the current GISS analysis is a similar two-legged adjustment, but the date of the hinge point is no longer fixed at 1950, the maximum distance used for rural neighbors is 500 km provided that sufficient stations are available, and "small-town" (population 10,000 to 50,000) stations are also adjusted. The hinge date is now also chosen to minimize the difference between the adjusted urban record and the mean of its neighbors. In the United States (and nearby Canada and Mexico regions) the rural stations are now those that are "unlit" in satellite data, but in the rest of the world, rural stations are still defined to be places with a population less than 10,000. The added flexibility in the hinge point allows more realistic local adjustments, as the initiation of significant urban growth occurred at different times in different parts of the world.

The urban adjustment, based on the long-term trends at neighboring stations, introduces a regional smoothing of the analyzed temperature field. To limit the degree of this smoothing, the present GISS analysis first attempts to define the adjustment based on rural stations located within 500 km of the station. Only if these stations are insufficient to define a long-term trend are stations at greater distances employed. As in the previous GISS analysis, the maximum distance of the rural stations employed is 1000 km.

This homogeneity adjustment should serve to minimize the effect of nonclimatic warming at urban stations on the analyzed global temperature change. However, as discussed by *Hansen et al.* [1999], it should not be assumed that the adjustment always yields less warming at the urban station or that it necessarily makes the result for an individual urban station more representative of what the temperature change would have been in the absence of humans. Indeed, in the global analysis we find that the homogeneity adjustment changes the urban record to a cooler trend in only 58% of the cases, while it yields a warmer trend in the other 42% of the urban stations. This implies that even though a few stations, such as Tokyo and Phoenix, have large urban warming, in the typical case, the urban effect is less than the combination of regional variability of temperature trends, measurement errors, and inhomogeneity of station records.

5. Effect of Adjustment on Analyzed Temperature

5.1. U.S. Mean Temperature Change

The temperature change averaged over the 48 contiguous United States is shown in Plate 2 for (1) the raw USHCN data, (2) the USHCN data, including all adjustments of *Karl et al.* [1990] and *Easterling et al.* [1996a], and (3) the GISS analysis of GHCN data. The long-term change in the GISS analysis (0.32°C based on the linear trend over 100 years) falls in between the change for the raw USHCN data (0.16°C) and the adjusted USHCN data (0.46°C). The differences can be understood from the adjustments that are made to the raw data.

The impacts of each of the five adjustments contained in the adjusted USHCN data [*Karl et al.*, 1990; *Easterling et al.*, 1996a] are shown in Plate 2. The largest adjustments are the time of observation debiasing and station history adjustment, each of which increases the mean warming over the United States by about 0.15°C over the 100 years. The net of all five adjustments to the USHCN record is a warming of about 0.3°C.

The current GISS analysis incorporates both the time of observation and the station history adjustments (as well as the small maximum/minimum thermometer change adjustment). The rationale is that the metadata defining time-of-observation changes is believed to be good, the adjustment formula is well verified [*Karl et al.,* 1986], and the systematic change of time of observation during the past 30 years is well understood. The station history adjustments are perhaps less certain, and their introduction of warming (Plate 2f) could be, in part, a reflection of a tendency for stations to move away from the population center, which is the phenomenon depicted in Figure 1. However, if there is such a tendency for urban warming, it should be corrected by application of our urban adjustment based on unlit stations.

The primary difference between the USHCN and the current GISS adjustments, given that the GISS analysis now adapts the USHCN time of observation and station history adjustments, is the urban adjustment. The GISS urban adjustment, as summarized in Plate 2, yields an urban correction averaged over the United States of about -0.15°C over 100 years, compared with a USHCN urban adjustment of -0.06°C. When only urban stations are adjusted the impact of our adjustment is about -0.1°C on either the USHCN stations (Plate 2j) or on the GHCN stations (Plate 2k) in the United States. When both urban and periurban stations are adjusted, the impact is about -0.15°C.

The magnitude of the adjustment at the urban and periurban stations themselves, rather than the impact of these adjustments on the total data set, is shown in Plate 2l. The adjustment is about -0.3°C at the urban stations and -0.1°C at the periurban stations. In both cases these refer to the changes over 100 years that are determined by adjusting to neighboring "unlit" stations. The adjustments to the periurban stations have a noticeable effect on the U.S. mean temperature because of the large number of periurban stations, as summarized in Table 1.

The larger urban warming adjustment in the GISS analysis than in the GHCN analysis might result from a combination of the phenomenon of Figure 1 and the ability of the satellite "unlit" category of stations to effectively find truly remote locations. However, this interpretation is uncertain, as the procedure of *Karl et al.* [1988] for defining an urbanization correction attempts to extrapolate to zero population. The GISS urban adjustment is dependent upon the accuracy of the temperature records of the unlit stations, so if the station history records and homogeneity adjustments for these stations are inaccurate or incomplete, this could alter the inferred urban warming. We discuss the urban corrections further, after examining them in more detail.

5.2. Geographical Distribution of Temperature Change

The geographical distribution of the temperature change in the United States is shown in Plate 3 for the USHCN data and for the GISS analysis of GHCN data. We first list the principal differences between these two analyses, and then discuss the specific adjustments that created these differences. In section 6 we discuss the climate change itself.

The GISS analysis shows a smaller national mean warming over the past century. This lesser mean warming is due to the larger urban adjustment in the GISS analysis than in the USHCN data. The magnitudes of regional warming and cooling, specifically the warming in the Southwest and the cooling in the Southeast, are less intense in the GISS analysis. This is a result of the smoothing introduced by the urban adjustment process, which defines the long-term trend based on a regional mean of unlit stations.

The geographical distributions of the USHCN and GISS adjustments are shown in Plate 3. The net of all USHCN adjustments (Plate 3, bottom right) is substantial warming at most places except the southern Rocky Mountain region. The USHCN urban adjustment is smoother and negative everywhere, while the GISS urban adjustment (Plate 3), in addition to being larger on the average than the USHCN urban adjustment, is more geographically variable. The USHCN urban correction [*Karl et al.*, 1988] is based on an equation that represents a mean urban warming as a function of population, so it is negative wherever population increased and it peaks in the coastal areas where the population growth was greatest.

The GISS urban adjustment is expected to vary geographically, because it is calculated at each station as a local homogeneity adjustment based on neighboring rural (unlit) stations. Thus it incorporates effects of local meteorological variability as well as local measurement errors and other sources of uncertainty such as unrecorded station history changes. However, the primary reason for the spatial variability in the GISS urban adjustment is the spatial smoothing that occurs in adjusting the long-term trend of the urban and periurban stations to match that of neighboring unlit stations. This causes the end product to be smooth and thus the adjustment must be spatially variable (Plate 3). The smoothing causes the urban adjustment to be positive in the grid boxes that have cooling relative to neighboring grid boxes. Note that the color scale is designed to bring out very small changes; in most grid boxes the urban adjustment and smoothing effect is less than or approximately 0.1°C in 100 years.

We reiterate a caveat that we have discussed elsewhere [*Easterling et al.,* 1996b*; Peterson et al.*, 1998c; *Hansen et al.*, 1999]: the smoothing introduced in homogeneity-adjusted data may make the result less appropriate than the unadjusted data for local studies. In the United States the availability of records from more than 1000 stations with extensive metadata has permitted careful construction of the comprehensive USHCN data set. The high spatial resolution that is possible with this data set is substantially maintained in the adjusted USHCN data set [*Karl et al.*, 1990; *Easterling et al.*, 1996a] by estimating an urban correction based on population data rather than using rural stations at a distance. (A moderate amount of smoothing is introduced in the USHCN data by the station history adjustment but on a scale of, at most, a few hundred kilometers.) Although the mean urban adjustment in the USHCN data set is smaller than that which we estimate in this paper, the difference is only about 0.1°C in 100 years. We suggest that for local or small-scale studies the USHCN data set is the preferable source. The GISS homogeneity-adjusted data set is intended for large-scale, especially global, applications.

5.3. Temperature Change by Station Category

A better feeling for the nature of the temperature adjustments can be obtained by examining the adjustments separately for the unlit, periurban and urban stations defined by satellite observations. Plate 4 shows the principal USHCN adjustments separately for these three station categories. The raw USHCN data at the rural (unlit) stations yields a national cooling of about -0.05°C for 1900-1999, while urban stations warm by 0.25°C and periurban stations fall between these results. Cooling is particularly strong in the southeastern United States at the unlit stations.

The time of observation adjustment reduces the difference between the unlit and the urban stations and reduces the magnitude of the cooling in the southeastern United States. The larger change for unlit stations is presumably because a larger portion of the unlit stations were part of the cooperative observers network, and the cooperative stations were especially subject to a systematic change in time of observation.

The station history adjustment reduces the small-scale variability of the temperature change. This is probably a consequence of the smoothing inherent in using neighboring stations to define the adjusted temperature change where discontinuities were discovered. The station history adjustment introduces a United States mean warming of about 0.2°C for each of the three categories of stations. This suggests that downward jumps, as in Figure 1, predominate in station discontinuities.

The urban adjustment in the USHCN data substantially reduces but does not remove the difference in the magnitude of warming among the station brightness categories. This suggests the possibility that the urban adjustment in the USHCN data set is not complete, but the difference between unlit and urban stations is only 0.08°C.

The strong cooling that exists in the unlit station data in the northern California region is not found in either the periurban or urban stations either with or without any of the adjustments. Ocean temperature data for the same period, illustrated below, has strong warming along the entire West Coast of the United States. This suggests the possibility of a flaw in the unlit station data for that small region. After examination of all of the stations in this region, five of the USHCN station records were altered in the GISS analysis because of inhomogeneities with neighboring stations (data prior to 1927 for Lake Spaulding, data prior to 1929 for Orleans, data prior to 1911 for Electra Ph, data prior of 1906 for Willows 6W, and all data for Crater Lake NPS HQ were omitted), so these apparent data flaws would not be transmitted to adjusted periurban and urban stations. If these adjustments were not made, the 100-year temperature change in the United States would be reduced by 0.01°C.

The 1900-1999 temperature change in the GISS analysis is shown in Plate 4 for the three categories of station brightness. The result for unlit stations is nearly the same as the USHCN data at the point of the station history adjustment, with the main exception being in northern California. The results of the GISS analysis for periurban and urban stations are spatially smoothed, as a consequence of adjusting to the regional mean long-term trend of unlit stations.

Plate 5 shows the difference between the U.S. mean temperature based on periurban, urban, or all three categories of station and the temperature based on only the unlit stations. These results refer to the USHCN and GISS analysis of GHCN data after all adjustments. The results suggest that the periurban and urban stations in the USHCN-adjusted data may still contain an urban warming of as much as 0.1°C in 100 years. Most of this apparent unadjusted warming occurs in the past 35 years.

We are implicitly assuming that urban (local human induced) warming at the unlit stations is negligible. We argue that this warming can be, at most, a few hundredths of a degree Celsius over the past 100 years. Plate 2l shows that the urban adjustment falls from 0.3°C in 100 years at urban stations, which have population densities of greater than 10 persons/ha, to 0.1°C at periurban stations, which have population densities from 0.1 to 10 persons/ha. We suggest below that more quantitative conclusions may become possible if the periurban satellite category can be split into two categories, of say less and more than 1 persons/ha, but the available categories already suggest that the human influence on open air temperature in unlit regions (estimated to have a population less than 0.1 persons/ha) is negligible. This is consistent with other empirical studies of urban influence versus population [*Karl et al.*, 1988; *Mitchell*, 1953; *Landsberg*, 1981].

6. United States and Global Temperature Update

6.1. Mean Anomalies, 1900-2000

The mean U.S. and global surface air temperature anomalies since 1880 are compared in Plate 6, based on the GISS analysis of meteorological station data. The “global” temperature, based on only meteorological station data, excludes much of the ocean area, yet the result differs little when the ocean SST change is incorporated [*Hansen et al.*, 1999], [Plate 3 and Figure 8].

The global mean temperature in the current GISS analysis differs very little from that of *Hansen et al.* [1999] (compare their Figure 4). The only noticeable change is in the 1880s, where the new analysis is several hundredths of a degree cooler. This small change is caused by the inclusion of additional small-town and urban stations in the early part of the record. In our present analysis, in defining the slope of the temperature trend for urban and small town stations, we required that rural neighbors be available for only two thirds of each leg in the two-legged urban adjustment. This permitted use of longer records for stations that were adjusted.

The U.S. mean temperature in the current GISS analysis is about 0.2°C warmer in the past two decades than it was in the analysis of *Hansen et al.* [1999] (compare their Plate A2). This is because the warming introduced by inclusion of time-of-observation and station history adjustments is only partially balanced by cooling caused by a stronger urban adjustment.

The comparison between the United States and the global temperature histories is qualitatively unaffected by the changes in our current analysis. In both the United States and globally, the temperature rose from the late 1800s to 1940, fell between 1940 and 1965, and rose again from 1965 to 2000. The temperature decline between 1940 and 1965 was more than 0.5°C in the United States but only about 0.1°C on the global average. The geographical distribution of the temperature changes for these three periods is illustrated below. The qualitative difference between United States and global temperature changes over the past half century is reproduced in global climate model simulations driven by observed sea surface temperatures [*Hansen et al.*, 2000].

The U.S. annual (January-December) mean temperature is slightly warmer in 1934 than in 1998 in the GISS analysis (Plate 6). This contrasts with the USHCN data, which has 1998 as the warmest year in the century. In both cases the difference between 1934 and 1998 mean temperatures is a few hundredths of a degree. The main reason that 1998 is relatively cooler in the GISS analysis is its larger adjustment for urban warming. In comparing temperatures of years separated by 60 or 70 years the uncertainties in various adjustments (urban warming, station history adjustments, etc.) lead to an uncertainty of at least 0.1°C. Thus it is not possible to declare a record U.S. temperature with confidence until a result is obtained that exceeds the temperature of 1934 by more than 0.1°C.

The temperature anomaly in the United States in the GISS analysis for 2000 through November is about 0.8°C. This is unusually warm, but it is very unlikely that the U.S. temperature in 2000 will exceed the levels of 1934 or 1998.

The global temperature anomaly for 2000 through November is 0.37°C, which is well below the maximum of 1998. Nevertheless, if we consider the fact that 2000 should have felt the maximum influence of the present long-lived La Niña (see below), it is clear that 2000 was an unusually warm year.

6.2. Multidecadal Temperature Change

Plate 7 examines the 20th century temperature change by dividing the period successively into one, two, and three parts. The full 100-year period, 1900-1999, has the best chance of averaging out fluctuations associated with phenomena such as the Southern Oscillation and the Arctic Oscillation. Division into two half-century periods has merit, because knowledge of climate forcings and details of climate change, including internal ocean and tropospheric temperature changes, is much better in the second half century, and thus this period is being extensively studied with global climate models. Division into three periods also has merit, because it allows an independent study of the periods of global warming (1900-1940), global cooling (1940-1965), and global warming (1965-1999). This division into the three periods of global temperature change perhaps has a better chance of separating different mechanisms of climate change.

Over the full century, warming is remarkably widespread and rather uniform. As shown in Plate 7, the warming is about 0.4°C in the tropics, 0.6°C at middle latitudes, and 0.5°C on global average for the 100 years. In the Northern Hemisphere extratropics, the warming is about twice as large in the cool season as in the warm season.

Note that the 100-year temperature change in the North Polar region and at high latitudes in the Southern Hemisphere is uncertain, and indeed, we suspect that our illustrated temperature change in those regions understates the warming of surface air. The reason for this belief is the realization that mean temperature changes at those latitudes are predominantly associated with changes in sea ice area. If an area of sea ice is replaced by open water, the local change of surface air temperature is exceptionally large because of the loss of insulating effect of the sea ice. Such large surface air temperature changes are captured in climate models but not in empirical studies in which the temperature changes of ocean areas are based on either estimated SST changes or extrapolations from measurements on coastal land areas. (The temperature index in Plate 7 uses sea surface temperatures for ocean areas, but where no SST data exist, the 1200 km smoothing radius in the GISS analysis extends the influence of meteorological stations over the ocean. Note that the GISS analysis is available with the option of either 1200 km or 250 km smoothing.)

The division into two 50-year periods illustrates that the temperature change over the full period is not the sum of the changes in the subperiods. Because of the drop of global temperature around 1950 the sum of the linear changes over the two subperiods is substantially larger than the linear 100-year change.

The map for 1900-1950 reveals a cooling in the El Niño region of the tropical Pacific Ocean. Thus the strong warming in that region during the last half century, generally associated with an increase of the frequency and intensity of El Niños, results in only a modest warming in that region over the full century. Indeed, the warming in the El Niño region over the full century is no larger than the warming over the full ocean. This empirical context suggests that the recent apparent increase in the intensity of El Niños may be only natural variability in that region superimposed on a global warming trend.

The large warming in central Asia in 1950-1999 is an inviting target for analysis that has proved difficult to simulate in climate models [*Folland et al.*, 1998]. *Shindell et al.* [1999] conclude that simulating the observed trend of the Arctic Oscillation [*Thompson and Wallace*, 1998], which strongly influences Asian temperature, requires a model that fully represents the upper atmosphere. Perhaps the most realistic simulation of Asian warming is that of *Russell et al.* [2000], which is obtained with a coupled ocean-troposphere model where the Northern Hemisphere pattern of surface air temperature change is associated with a cooling of the North Atlantic Ocean. In all these models the climate changes are driven by observed greenhouse gas increases. Interpretation of the 1950-1999 temperature change should bear in mind observed changes in the previous half century. Plate 7 reveals that the central Asia region cooled over 1900-1950, a time when greenhouse gases and global temperature were also increasing, albeit at lesser rates than in 1950-1999. Note also that the Asian warming over the full 100 years is not particularly large. If it were concluded that part of the Asian warming in 1950-1999 is the recovery phase of an unforced oscillation, then there would be less need to seek a large forced response in the most recent 50 years.

We suspect that it may be more fruitful to study the division of the century into the three periods that coincide with the global temperature swings, as shown on the right-hand side of Plate 7 with zonal means shown in Plate 7. In the period 1900-1940, strong Arctic warming and some central Asian cooling stand out, with the largest changes in the cool season. These patterns are the mirror image of the dynamical patterns in 1870-1900, which are illustrated by [*Hansen et al.* (1999), Plate 5]. The period 1900-1940, in addition, has a pervasive global warming. One might speculate that this warming is at least in part a response to greenhouse gas and solar forcings [*Lean et al.*, 1995], both of which are believed to have been positive in that period.

The period 1940-1965 reverts to cooling in the Arctic with warming in central Asia, as in 1870-1900. There is a rather general global cooling in 1940-1965, even though the global mean cooling is only -0.1°C. One might speculate that a negative climate forcing could have contributed to this cooling, because it is approximately this period when aerosols had their best chance to compete with greenhouse gases as a climate forcing. Specifically, the increase of aerosol forcing depends on the rate of growth of fossil fuel use, which peaked in this period [*Hansen et al.*, 2000]. Also, some correspondence has been noted between spatial patterns of aerosols and the temperature change [*Karl et al.*, 1995]. However, it is also possible that fluctuations in ocean heat transport, perhaps unforced, could contribute to such multidecadal climate swings. In an ensemble of coupled atmosphere-ocean simulations, *Delworth and Knutson* [2000] found that by chance, one member of the ensemble yielded global cooling in approximately this period despite a positive trend of the net climate forcing.

The period 1965-1999 is remarkable both in the pervasiveness and in the rate of global warming. This is the period in which warming intensified in the El Niño region of the Pacific Ocean, but the Indian, Atlantic and Arctic Oceans also warmed. Over land areas there was intense warming over northwest North America and central Asia, but all of the continents warmed except Antarctica. The period 1965-1999 is the time when increasing greenhouse gases yielded their strongest climate forcing [*Hansen et al.*, 1998]. In this period the aerosol climate forcing may have changed relatively little, because the growth rate of fossil fuel use decreased to about 1%/year [*Hansen et al.*, 2000], and even this small increase would have been mitigated by efforts in some countries to reduce the sulfur content of fuels. It thus seems highly probable that the rapid global warming in this period is the response to a strong net positive climate forcing. The fact that the warming is largest in high latitudes of the Northern Hemisphere and larger in the cool season than in the warm season (Plate 7) is consistent with expectations from climate models. The minimal warming in the ocean around Antarctica is consistent with coupled ocean-atmosphere simulations [*Manabe et al.*, 1990; *Russell et al.*, 2000].

Our speculations here on climate change mechanisms are only intended as an indication of possible uses of the temperature data. Quantitative interpretations need to be made with the help of comprehensive global modeling and examination of many other climate diagnostics in addition to the patterns of surface temperature change.

6.3. Recent Temperature Anomalies

The annual mean temperature anomalies for 2000 are shown in Plate 8. Ocean temperatures are SSTs of *Reynolds and Smith* [1994]. North America and Eurasia were very warm in 2000, despite a moderately strong La Niña in the Pacific Ocean.

The seasonal temperature anomalies for each of the past 3 years are shown in Plate 8 to place the 2000 anomalies in recent context. The strong El Niño, which was present at the beginning of 1998, faded during that year as it was replaced by a La Niña that apparently peaked in the winter of 2000. The La Niña had almost disappeared by August 2000 but strengthened somewhat by November 2000 (monthly temperature anomalies are available at www.giss.nasa.gov/data/update/gistemp).

The United States has been unusually warm in each of the past three winters (1997-1998, 1998-1999, 1999-2000). However, it should not be assumed that this will continue to be the case. Although global warming has increased the probability of a season being warmer than normal, continental winter temperatures on a regional spatial scale are highly variable. Four of the 10 cool seasons (November-April) in the 1990s were cooler than normal, i.e., cooler than the 1951-1980 mean, in the United States, and six were warmer than normal [*Hansen et al.* (1999), Plate 9a].

Global mean temperature is much more predictable than the U.S. temperature. The seasonal mean temperature anomalies of 0.28°-0.44°C in the past seven seasons are probably a trough of global temperature associated with the La Niña. *Hansen et al.* [1999] argue that the background global temperature has risen to at least 0.5°C relative to 1951-1980, which would imply that the temperature should reach that magnitude in 2001 and a still higher level in conjunction with the next El Niño. These expectations are based on the inference that the increasing climate forcings of recent decades have left the planet with a radiation imbalance of 0.5-1.0 W/m^2 [*Hansen et al.*, 1997], thus causing a continuing tendency toward further heating.

7. Discussion

We emphasize in this paper our continuing attempts to minimize nonclimatic factors in analyses of global temperature change. It should be noted, however, that these uncertainties and adjustments are generally moderate in size in comparison with either the global or the regional temperature changes during the past century. For example, the uncertainties and the adjustments in the analyses do not have a notable qualitative effect on the climate variations discussed in section 6.

We find evidence of local human effects ("urban warming") even in suburban and small-town surface air temperature records. This evidence is based on comparison of temperature trends of urban, periurban, and unlit stations in the United States, with the stations classified according to nighttime brightness observed by satellite. We believe that this evidence is suggestive of a significant urban effect within the United States, but it requires further investigation.

One reason to be cautious about the inferred urban warming is the possibility that it could be, at least in part, an artifact of inhomogeneities in the station records. Our present analysis is dependent on the validity of the temperature records and station history adjustments at the unlit stations. T. Peterson (manuscript in preparation, 2001) has carried out recent detailed studies of urban and neighboring rural stations, concluding that urban warming is negligible. This conclusion is consistent with comparisons of global temperature change based on all stations and rural stations only [*Peterson et al.*, 1999; *Hansen et al.*, 1999].

We suggest two possible improvements to the current GISS analysis that may shed more light on the urban warming issue. Both of these require substantial additional work with satellite nighttime brightness data. First, it would be useful to break the periurban category of brightness into two categories. The periurban category, in the United States, corresponds to population densities ranging from about 0.1 persons/ha to 10 persons/ha. More than 50% of the meteorological stations are in periurban brightness regions, so there should be a sufficient number of stations to populate two subcategories that divide at, say, 1 person/ha. With the resulting four brightness (and population) categories it should be possible to obtain a reasonably good empirical determination of urban warming as a function of population density. If warming increases monotonically with brightness (population density), the inferred urban effect would be more convincing.

Second, the satellite brightness analysis could be extended to the rest of the world, preferably with the four-category resolution. It is not expected that the brightness-population relation deduced for the United States would be valid in other parts of the world. However, we anticipate that nighttime brightness would have a useful positive correlation with energy use and with human impacts on local temperature, indeed, it may be a more appropriate variable than population.

Finally, we note that if such empirical relations for the human influence on local temperature are developed, it would be possible to apply these adjustments locally, as an alternative to the present urban adjustment that employs rural stations up to 500 or 1000 km away. This approach would preserve maximum spatial resolution of anomalies, in contrast to the regional smoothing in the current GISS analysis. Both approaches have merit (the current method minimizes small scale noise), however, so it may be appropriate to make available results of both methods.

The current GISS analysis of surface air temperature change is available at www.giss.nasa.gov/data/update/gistemp. The data set can also be obtained via ftp at ftp@giss.nasa.gov. The previous analysis [*Hansen et al.*, 1999] continues to be available at the GISS web site, but it is not updated each month as the new analysis.

Acknowledgments. We thank John Christy, Phil Jones, David Parker, Simon Scott, Dian Seidel, and three anonymous referees for helpful comments on our draft manuscript, and Eleni Palmos for desktop typesetting. The USHCN data are available from the NCDC web site at www.ncdc.noaa.gov/ol/climate/research/ushcn/.

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Received January 9, 2001; revised May 23, 2001; accepted June 7, 2001.

Paper number 2001JD000354
0148-0227/2001JD000354.0900

Figure Captions

Figure 1. (a) Schematic illustration of a temperature record at a site experiencing urban warming and a station move from the urban center to the urban outskirts. (b) The temperature record adjusted for the discontinuity has a stronger warming trend than that in the undisturbed environment.

Plate 1. (a) Night light area-time coverage based on defense meteorological satellite data [*Imhoff et al.*, 1997]; (b) three categories of area-time average brightness: blue, unlit or rural; pale green, dim or periurban; yellow, bright or urban. Blue, green, and red asterisks mark meteorological stations for which the GHCN metadata indicate populations of less than 10,000, between 10,000 and 50,000, and greater than 50,000, respectively.

Plate 2. (a) Surface air temperature anomaly relative to 1951-1980 averaged over the contiguous 48 United States for the USHCN data [*Easterling et al.*, 1996a] and for the GISS analysis of GHCN data; (b) effects of the adjustments in the USHCN analysis [*Easterling et al.*, 1996a] averaged over the contiguous 48 U.S., (c) effects of the homogeneity adjustments in the GISS analysis on the U.S. mean temperature. In Plate 2C the normalized effect is obtained by multiplying the effect of a station category (urban or periurban) on the full data set by the ratio of the total number of stations over the number of stations in that category.

Plate 3. (a) Surface air temperature change for 1900-1998 based on local linear trends for USHCN data and for the GISS analysis of GHCN data; (b) effect of individual adjustments of *Easterling et al.* [1996a] to the USHCN data; and (c) effect of GISS homogeneity adjustments on USHCN and GHCN data. The number in the top right-hand corner refers to the mean over the contiguous 48 states.

Plate 4. (a) Surface air temperature change for 1900-1998 at successive levels of USHCN adjustments (successive rows) as divided into station categories (columns); and (b) GISS analysis of GHCN data for the three station categories.

Plate 5. Difference between the U.S. mean surface air temperature based on particular categories of stations and the temperature based on only the unlit stations. (a) USHCN data and (b) GISS analysis of GHCN data.

Plate 6. (a) Annual and 5-year running-mean surface air temperature for the contiguous 48 United States relative to the 1951-1980 mean; and (b) global annual and 5-year running-mean surface air temperature based on the meteorological stations.

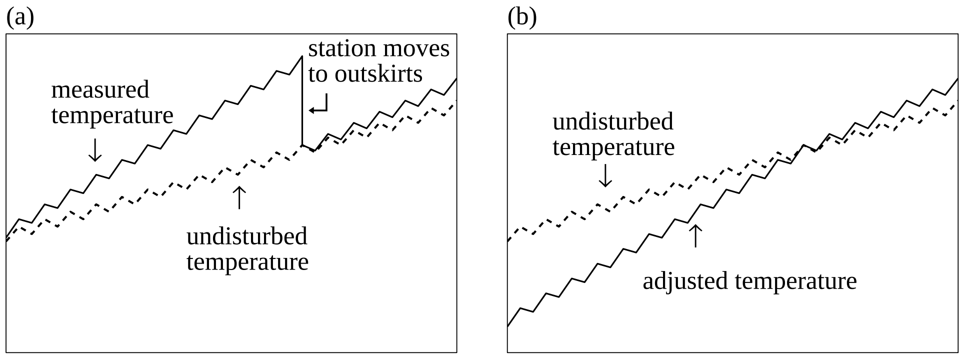
Plate 7. (a) Change of surface temperature index for different periods based on local linear trends using surface air temperature change over land and SST change over the ocean [*Rayner et al.*, 1996] (and updates), and (b) zonal-mean annual, warm season, and cool season temperature change for the full century and for three subperiods.

Plate 8. (a) Year 2000 temperature anomalies (presently only January-November) for the United States (250 km smoothing) and for the globe (1200 km smoothing); and (B) global seasonal anomalies for the past 3 years. The data over the ocean are SSTs of *Reynolds and Smith* [1994].

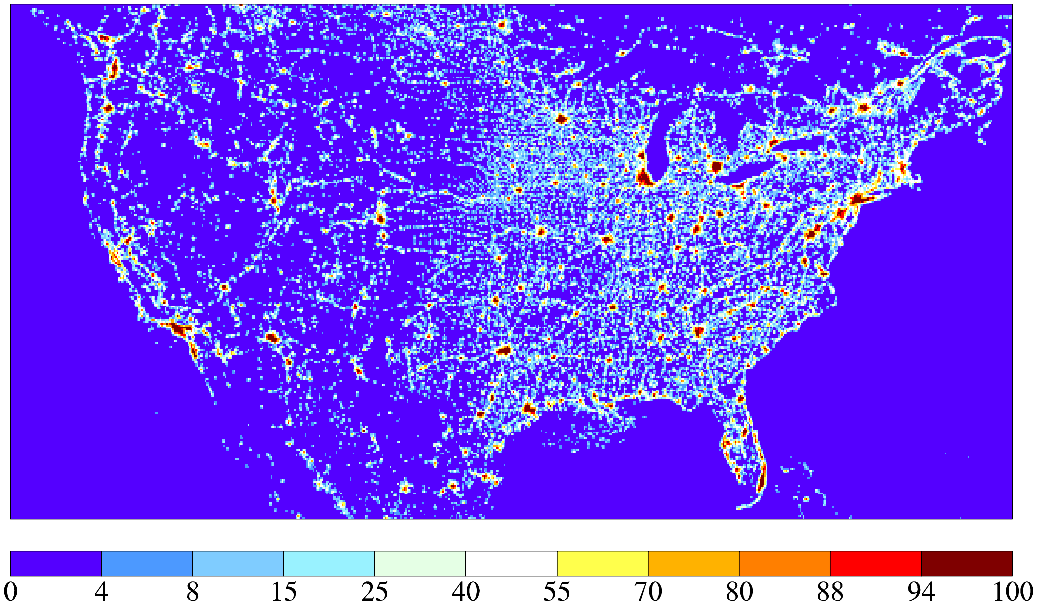
Table 1. Inventory of USHCN and GHCN Meteorological Stations According to Categories of Population (in GHCN Metadata) and Night Brightness Observed by Satellite.[a]

USHCN					GHCN				
	<10,000	10,000-50,000	>50,000	Total		<10,000	10,000-50,000	>50,000	Total
Unlit	214	9	0	223	Unlit	256	16	0	272
Dim	548	128	14	690	Dim	613	196	60	869
Bright	58	151	99	308	Bright	73	207	291	571
Total	820	288	113	1221	Total	942	419	351	1712

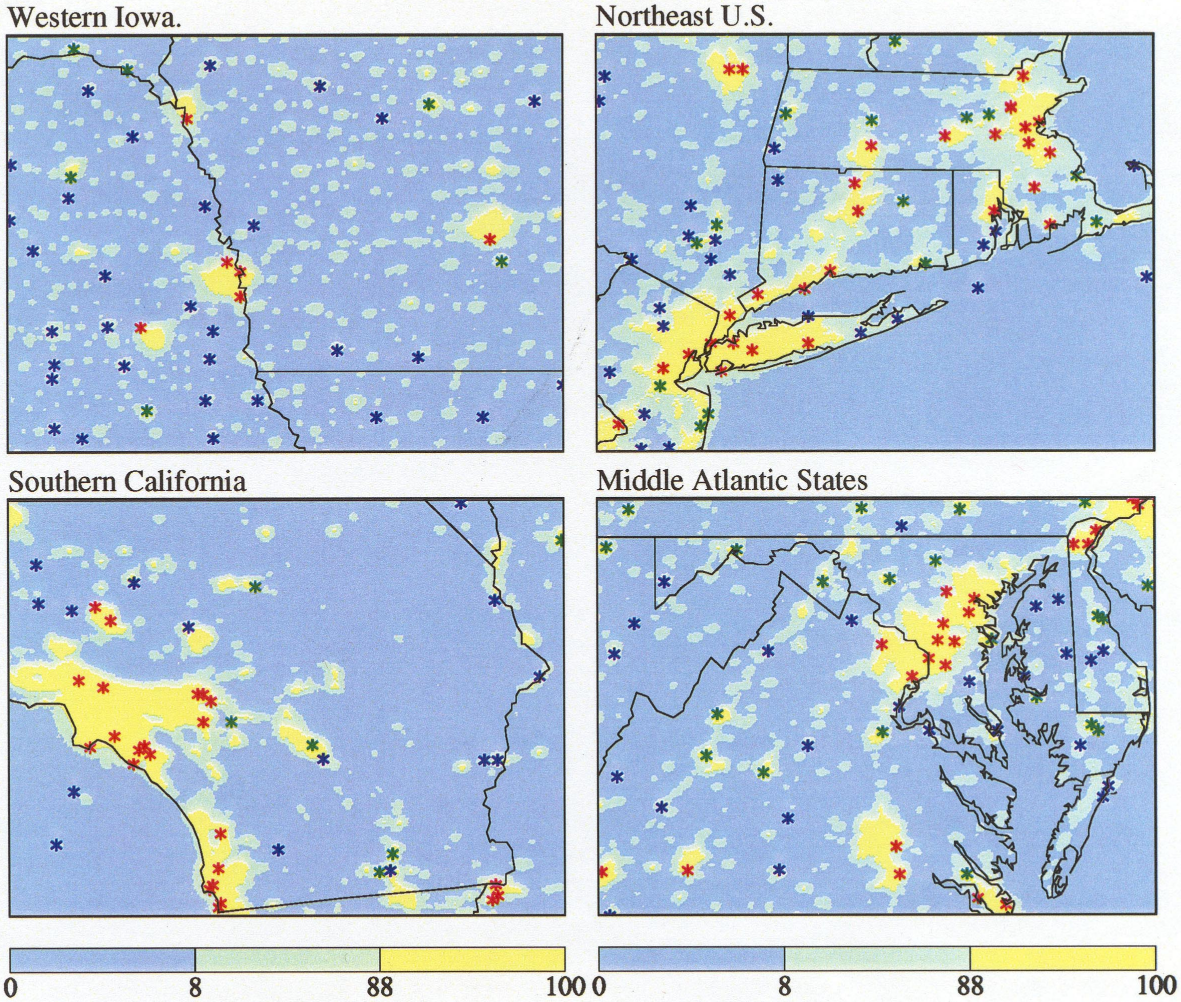
[a] USHCN stations are a subset of GHCN. Only stations with at least 20 years of temperature data are included.


(a)
measured temperature
station moves to outskirts
undisturbed temperature
(b)
undisturbed temperature
adjusted temperature

(a) Nightlight Coverage (%) at 0.1° x 0.1° Resolution



(b) Unlit, Peri-urban and Urban Regions at 30" x 30" Resolution

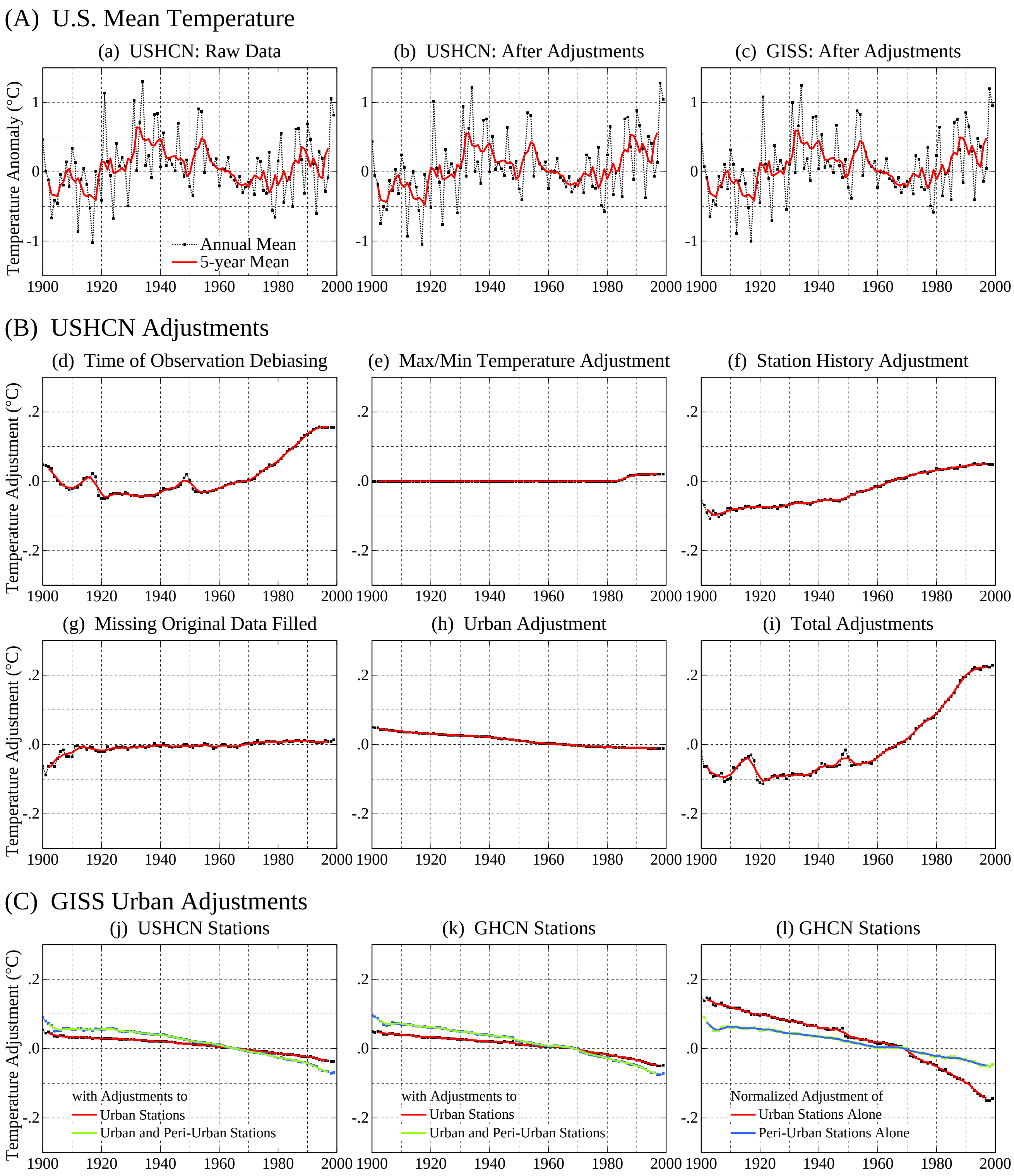


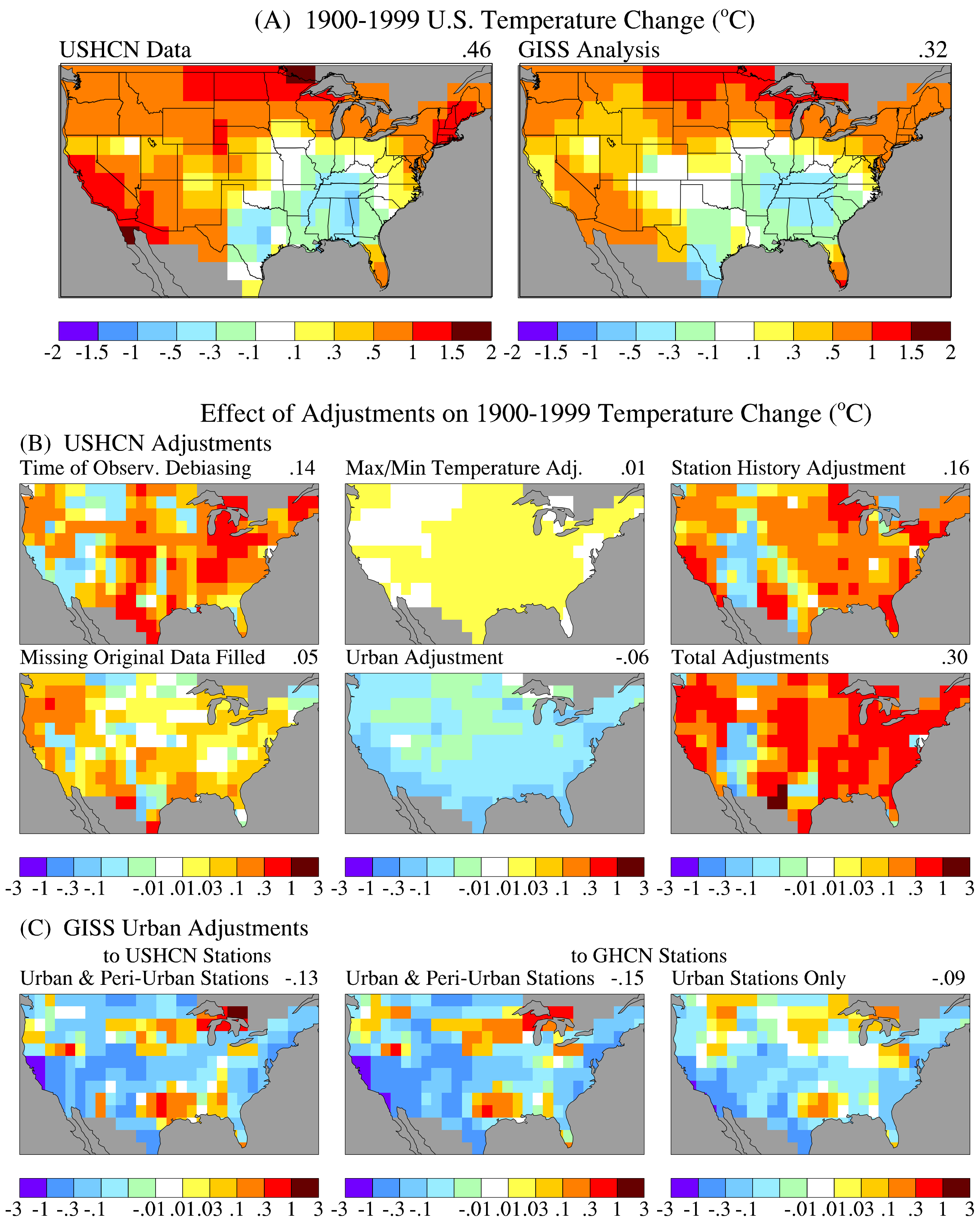
Western Iowa.

Northeast U.S.

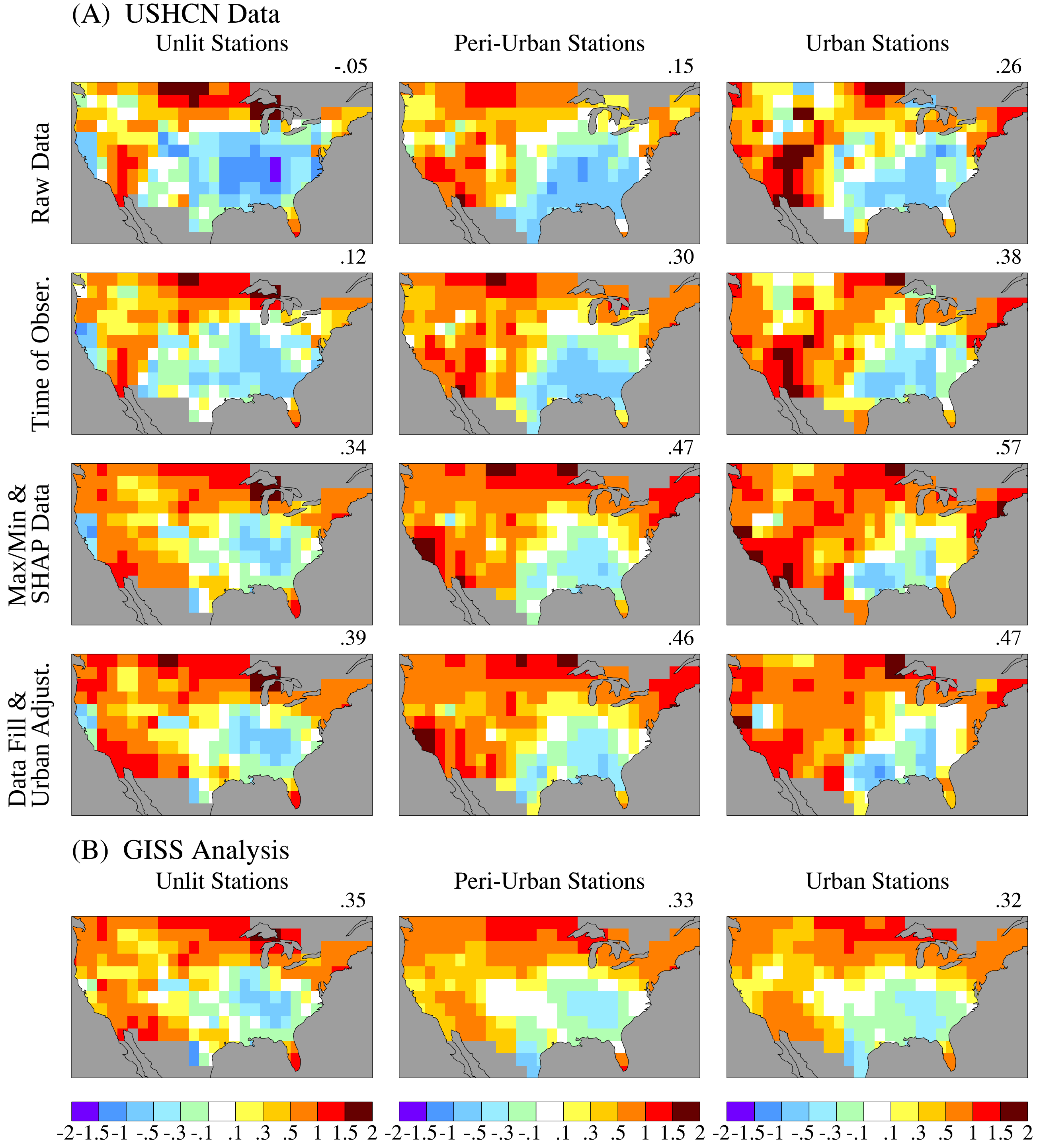
Southern California

Middle Atlantic States

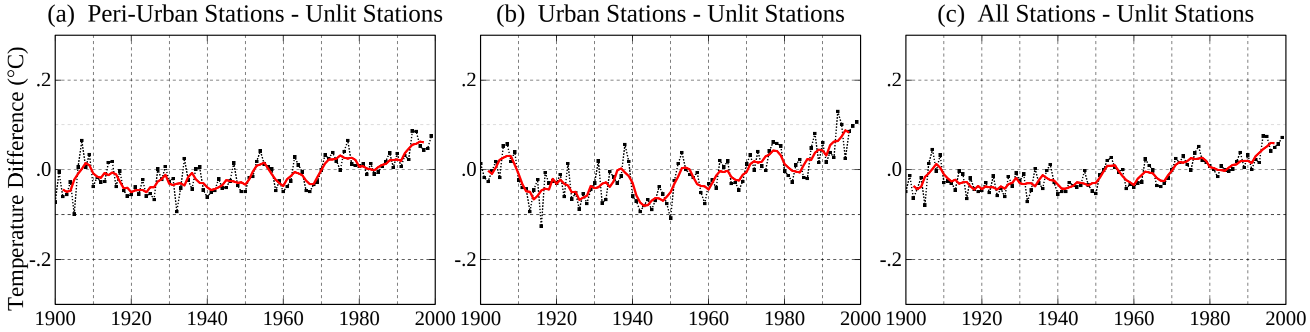

(A) U.S. Mean Temperature
(a) USHCN: Raw Data
(b) USHCN: After Adjustments
(c) GISS: After Adjustments
Temperature Anomaly (°C)
1
0
-1
Annual Mean
5-year Mean
1900
1920
1940
1960
1980
2000
(B) USHCN Adjustments
(d) Time of Observation Debiasing
(e) Max/Min Temperature Adjustment
(f) Station History Adjustment
(g) Missing Original Data Filled
(h) Urban Adjustment
(i) Total Adjustments
Temperature Adjustment (°C)
.2
.0
-.2
(C) GISS Urban Adjustments
(j) USHCN Stations
(k) GHCN Stations
(l) GHCN Stations
with Adjustments to
Urban Stations
Urban and Peri-Urban Stations
Normalized Adjustment of
Urban Stations Alone
Peri-Urban Stations Alone


(A) 1900-1999 U.S. Temperature Change (°C)
USHCN Data .46
GISS Analysis .32
-2 -1.5 -1 -.5 -.3 -.1 .1 .3 .5 1 1.5 2
-2 -1.5 -1 -.5 -.3 -.1 .1 .3 .5 1 1.5 2
Effect of Adjustments on 1900-1999 Temperature Change (°C)
(B) USHCN Adjustments
Time of Observ. Debiasing .14
Max/Min Temperature Adj. .01
Station History Adjustment .16
Missing Original Data Filled .05
Urban Adjustment -.06
Total Adjustments .30
-3 -1 -.3 -.1 -.01 .01 .03 .1 .3 1 3
-3 -1 -.3 -.1 -.01 .01 .03 .1 .3 1 3
-3 -1 -.3 -.1 -.01 .01 .03 .1 .3 1 3
(C) GISS Urban Adjustments
to USHCN Stations
to GHCN Stations
Urban & Peri-Urban Stations -.13
Urban & Peri-Urban Stations -.15
Urban Stations Only -.09
-3 -1 -.3 -.1 -.01 .01 .03 .1 .3 1 3
-3 -1 -.3 -.1 -.01 .01 .03 .1 .3 1 3
-3 -1 -.3 -.1 -.01 .01 .03 .1 .3 1 3

1900-1999 U.S. Temperature Change (°C)



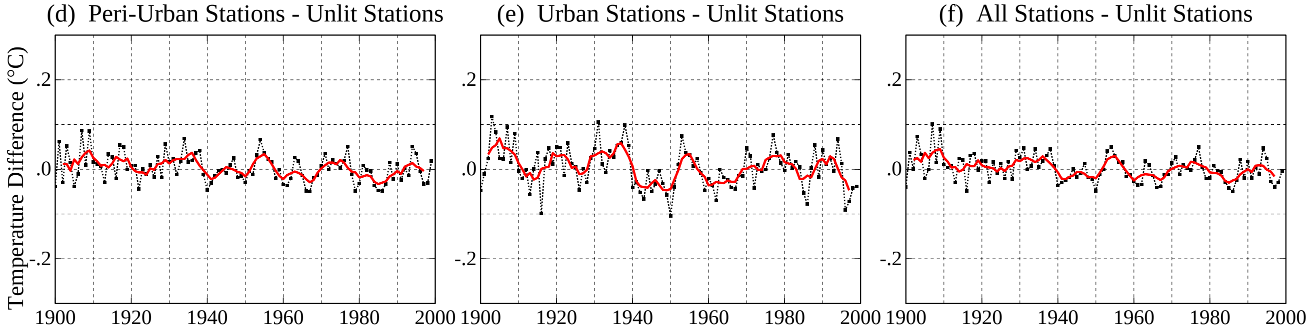
(A) USHCN Data: After Adjustments


(a) Peri-Urban Stations - Unlit Stations

(b) Urban Stations - Unlit Stations

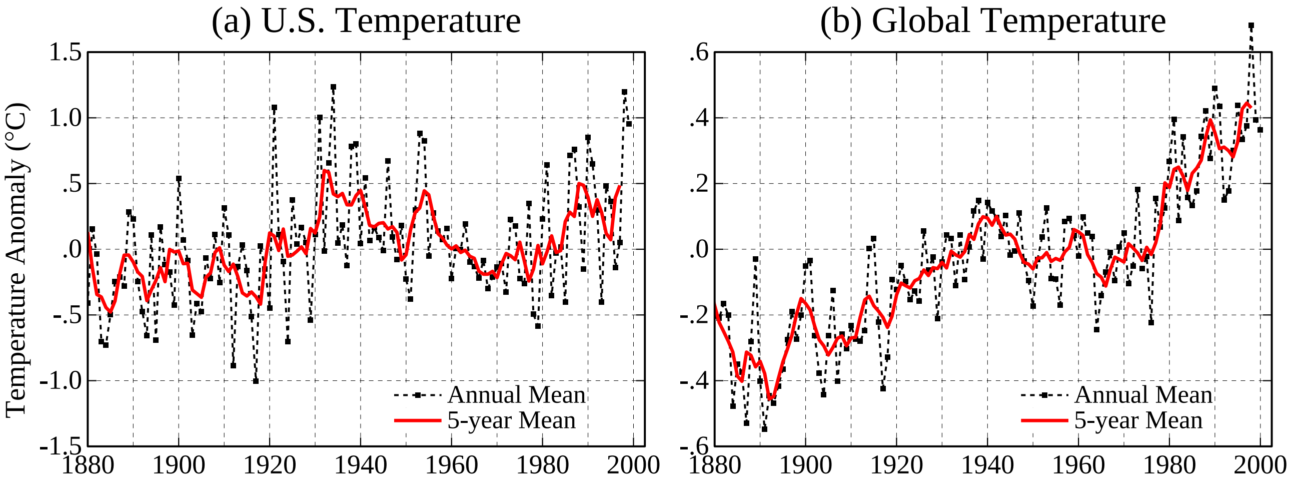
(c) All Stations - Unlit Stations

(B) GISS Analysis: After Adjustments

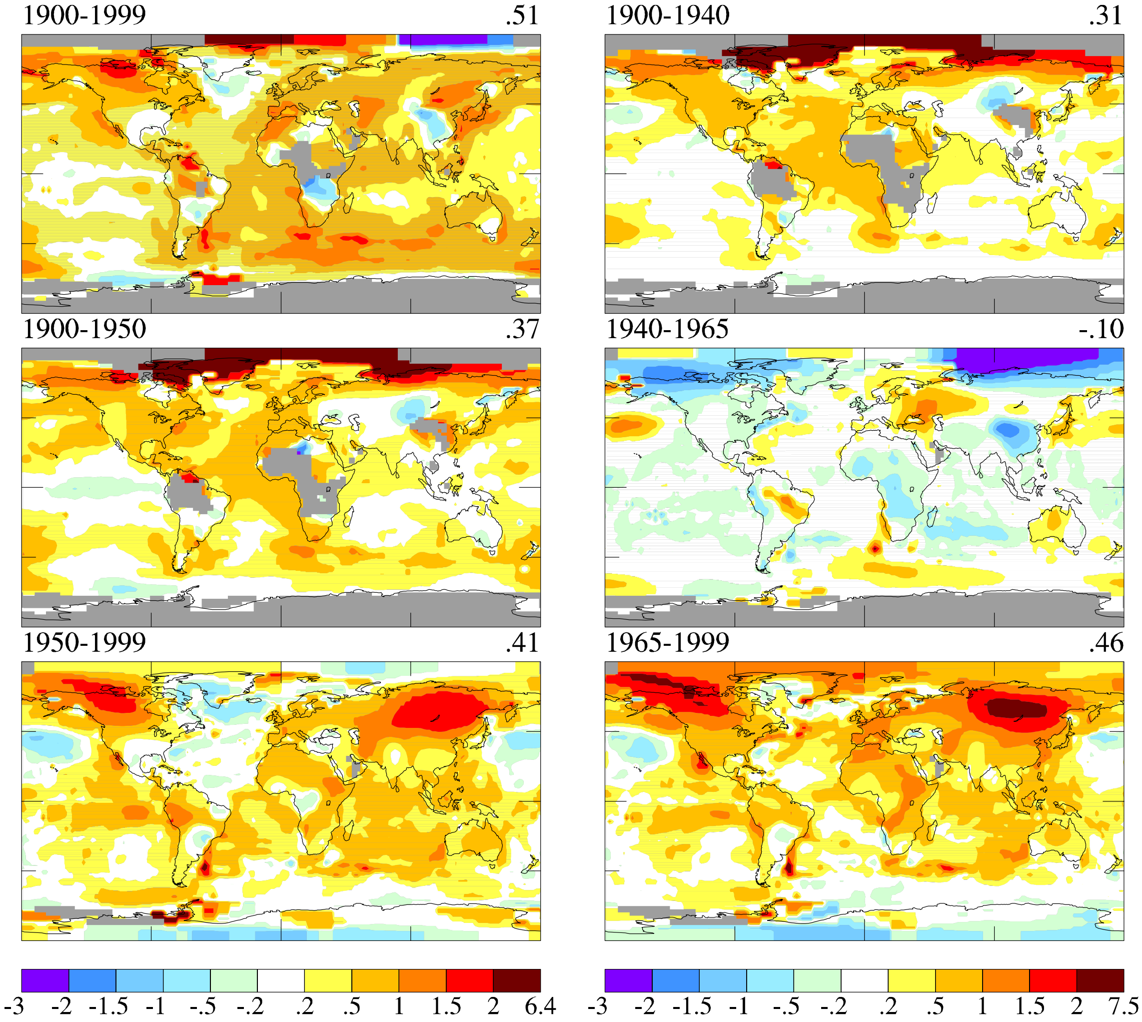

(d) Peri-Urban Stations - Unlit Stations

(e) Urban Stations - Unlit Stations

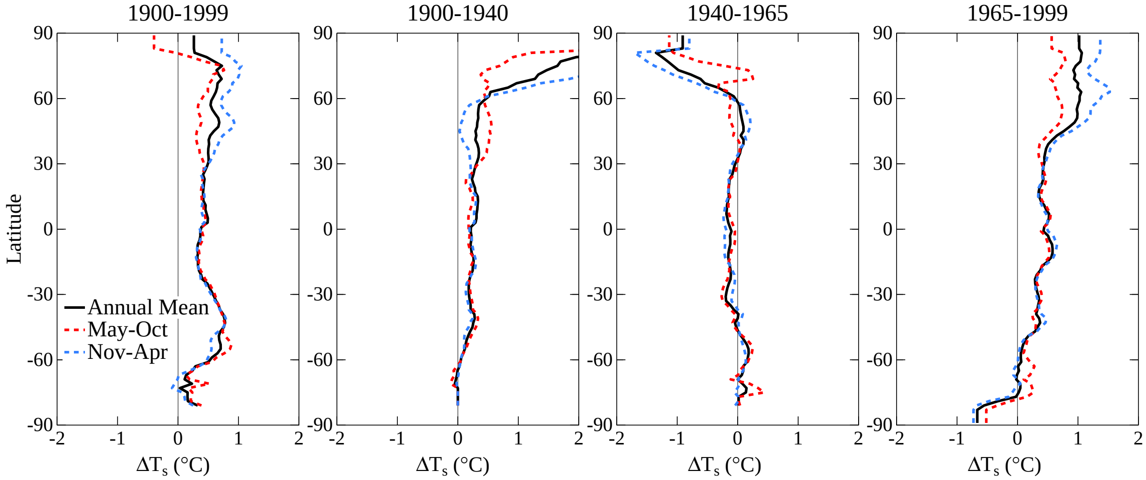
(f) All Stations - Unlit Stations

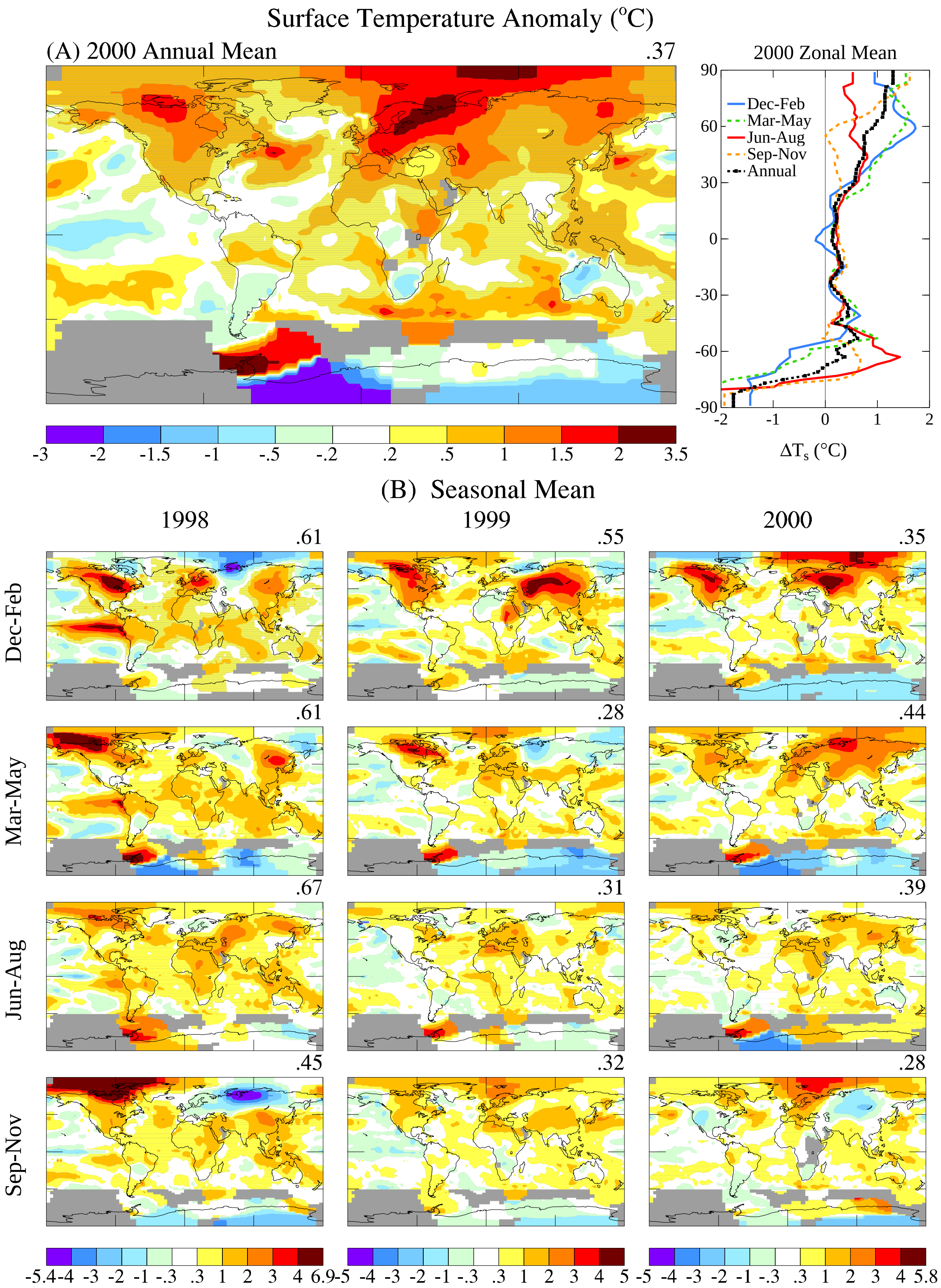

(a) U.S. Temperature
(b) Global Temperature
Temperature Anomaly (°C)
1.5
1.0
.5
.0
-.5
-1.0
-1.5
.6
.4
.2
.0
-.2
-.4
-.6
1880
1900
1920
1940
1960
1980
2000
Annual Mean
5-year Mean

(A) Surface Temperature Change (^{o}C)



(B) Zonal Mean Surface Temperature Change




Surface Temperature Anomaly (°C)
(A) 2000 Annual Mean
.37
-3
-2
-1.5
-1
-.5
-.2
.2
.5
1
1.5
2
3.5
2000 Zonal Mean
90
60
30
0
-30
-60
-90
-2
-1
0
1
2
Dec-Feb
Mar-May
Jun-Aug
Sep-Nov
Annual
ΔTs (°C)
(B) Seasonal Mean
1998
1999
2000
Dec-Feb
Mar-May
Jun-Aug
Sep-Nov
.61
.55
.35
.61
.28
.44
.67
.31
.39
.45
.32
.28
-5.4 -4 -3 -2 -1 -.3 .3 1 2 3 4 6.9
-5 -4 -3 -2 -1 -.3 .3 1 2 3 4 5
-5 -4 -3 -2 -1 -.3 .3 1 2 3 4 5.8