Estimation of the impact of land-surface forcings on temperature trends in eastern United States

Eugenia Kalnay,[1] Ming Cai,[2] Hong Li,[1] and Jayakar Tobin[1]

Received 3 August 2005; revised 21 September 2005; accepted 7 November 2005; published 24 March 2006.

[1] We use the ''observation minus reanalysis'' difference (OMR) method to estimate the impact of land-use changes by computing the difference between the trends of the surface temperature observations (which reflect all the sources of climate forcing, including surface effects) and the NCEP-NCAR reanalysis surface temperatures (only influenced by the assimilated atmospheric temperature trends). This includes not only urbanization effects but also changes in agricultural practices, such as irrigation and deforestation, as well as other near-surface forcings related to industrialization, such as aerosols. We slightly correct previous results by including the year 1979 within the satellite decades and by excluding stations in the West Coast of the United States. The OMR estimate for surface impact on the mean temperature is similar to that obtained using satellite observations of night light to discriminate between rural and urban stations, with regions of large positive and negative trends, in contrast with the urban corrections based on population density, which are uniformly positive and much smaller. The OMR seasonal cycle results suggest that the impact of the greenhouse gases dominates in the winter, whereas it appears that the impact of surface forcings dominates in the summer. The impact of the USHCN adjustments for nonclimatic trends in the observations does not affect the geographical distribution of the OMR trends. The effect of using a model with constant CO_2 in the reanalysis, the use of other reanalyses, and the possible use of the reanalyses to correct for nonclimatic jumps in the observations are also discussed.

Citation: Kalnay, E., M. Cai, H. Li, and J. Tobin (2006), Estimation of the impact of land-surface forcings on temperature trends in eastern United States, *J. Geophys. Res.*, *111*, D06106, doi:10.1029/2005JD006555.

1. Introduction

[2] Trends of surface temperature on the timescale of decades are due to either natural climate variability or to anthropogenic factors, so that their attribution is quite difficult [e.g., *Intergovernmental Panel on Climate Control* (*IPCC*), 2001]. Furthermore, two of the most important anthropogenic activities that impact climate, the increase of greenhouse gases, and near-surface forcings such as changes in the land surface physical properties and aerosols, generally (but not always) tend to produce surface warming so that their impacts are also difficult to separate. The impacts of changes in land use have generally been regarded as ''noise'' compared to the impacts of increases of greenhouse gases, but recent studies [e.g., *Pielke*, 2001; *Pielke et al.*, 2002; *Kalnay and Cai*, 2003; *Zhou et al.*, 2004; *Marshall et al.*, 2004; *Lim et al.*, 2005] suggest that the impact of widespread land-use changes could be larger and should not be ignored.

[3] Until recently, urbanization effects on climate trend were ''corrected'' by comparing observations in cities/suburbs with those in surrounding rural areas and attributing the difference in trends to urbanization [*Karl et al.*, 1988]. The key to these methods has been to classify meteorological stations as urban or rural using either population data [*Easterling et al.*, 1997] or satellite measurements of night lights [*Gallo et al.*, 1999; *Hansen et al.*, 2001]. The estimated average urban impacts over the United States have been small (0.006C/decade and 0.015C/decade, respectively) and do not include the impact of other land-use changes due to agriculture and industrialization that can change the land properties over larger areas [*Lim et al.*, 2005]. Similar estimates for the global urban heat island impact are quoted in the *IPCC* [2001, p. 106] report, but both larger impacts [*Kukla et al.*, 1986; *Gallo et al.*, 1996] and smaller [*Peterson*, 2003] have been reported as well. Corrections due to nonclimatic effects such as changes in the type of thermometer, times of observation, and station location [*Karl et al.*, 1986; *Karl and Williams*, 1987; *Quayle et al.*, 1991; *Hansen et al.*, 2001; *Vose et al.*, 2003] have been found to be substantial and comparable in magnitude to that of the greenhouse warming over the United States (see also section 4).

[4] *Kalnay and Cai* [2003, hereinafter referred to as KC] proposed to estimate the impact of all changes in land use (including urbanization and agricultural practices such as

[1]Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland, USA.
[2]Department of Meteorology, Florida State University, Tallahassee, Florida, USA.

0148-0227/06/2005JD006555$09.00

irrigation) by comparing trends from surface observations with those of the NCEP/NCAR reanalysis (NNR) [*Kalnay et al.*, 1996; *Kistler et al.*, 2001]. They took advantage of the fact that the NNR is insensitive to surface observations over land because, except for surface pressure, they are not used over land, although they are used over ocean. In addition, the model used in the NNR has a coarse resolution (T62 or about 200-km grid size). The NNR does reflect the trends present in the atmospheric observations that were assimilated, such as rawinsondes and satellite soundings. A recent study [*Cai and Kalnay*, 2005] suggests that even if a model used in reanalysis does not include the forcing due to the increase in greenhouse gases, the trend from this forcing should be present in the reanalysis at essentially the full strength of the observations (see section 5).

[5] The essence of the "observation minus reanalysis" (OMR) method proposed by KC to at least partially identify the impact of land-use changes and other near-surface forcings is to compute the difference between the trends of the surface observations (which reflect all the sources of climate forcing, including surface effects) and the NNR (which only contains the forcings influencing the assimilated atmospheric temperature trends). This difference includes not only urbanization effects but also changes in agricultural practices, such as irrigation and deforestation, and also those of near-surface aerosols and precipitation associated not only with urbanization but also with industrialization. In addition, this approach allows canceling the trends due to natural climate variability (temporary changes in circulation), since those are present in both the observations and the NNR.

[6] The OMR method has recently been applied by *Zhou et al.* [2004] to estimate the impact of urbanization over southeastern China during the last 2 decades, when rapid growth took place. The winter trend difference between surface observations and the NNR was compared with trends obtained from census data and from the satellite index of greenness. They concluded that the geographical distribution of the estimated impact of urbanization warming trend (0.05°C/decade) was consistent with the estimates of urbanization from changes in the urban population and in satellite-measured greenness. *Lim et al.* [2005] showed that there is a strong dependence of the OMR trend on the type of land (determined using MODIS) and found the results using NNR or the European Centre for Medium-Range Weather Forecasts 40-year Reanalysis (ERA-40) very similar.

[7] In this paper we extend and slightly correct the OMR computations performed by KC. In section 2 we review the approach and the data, and in section 3 we extend and modify the computations of KC to include a seasonal analysis and provide separate trends for the 1959–1978 decades (presatellite) and the 1979–1998 decades (postsatellite) using the unadjusted observations. Section 4 contains an estimation of the impact of nonclimatic adjustments of the trends based on the adjustments obtained using U.S. Historical Climatological Network (USHCN) observations. Section 5 gives a discussion of other critical issues related to the proposed method, and section 6 summarizes the conclusions.

2. Data and Method

[8] The surface data that we have used are the daily surface observed maximum and minimum temperatures (Tmax and Tmin) from NCDC "Cooperative Summary of the Day" data set over the 48 conterminous United States (CONUS) for 1950–1999. These are "raw" observations that have not been adjusted for several nonclimatic changes such as station location and time of observation. We also used the NNR daily surface air Tmax and Tmin computed "on-the-fly," available on a Gaussian grid (with about 2.5° resolution) for the same period. The same analysis but using the subset of adjusted USHCN monthly averaged observations for the same periods is also presented in section 3, and in section 4 it is shown that these corrections can be applied a posteriori when using the raw observations (see also comments on KC by *Vose et al.* [2004] and the response by *Cai and Kalnay* [2004]).

[9] The analysis method is to interpolate the gridded reanalysis data to the observational sites and obtain monthly means by averaging daily data. We only consider observational sites that have at least 480 whole months of observations. We remove from both observations and NNR data the annual cycle at each site and only consider anomalies. This has the advantage of effectively eliminating NNR systematic errors even if they are significant, as long as they are not flow-dependent and do not contain significant trends [*Cai and Kalnay*, 2005]. The model topography and the real topography are quite different, requiring vertical extrapolations. The NNR surface temperature reflects the nonlinear physics of the model surface interacting with the atmosphere, and if the model surface topography is very different from the real topography, these nonlinear physical processes have flow dependent biases, and the correlation between observations and NNR estimates necessarily decreases. As a result, the correlation between the NNR and surface observations is much lower over the Rockies than east of the Rockies (Figure 1). Thus we did not include in our analysis stations with elevations above 500 m. Over the West Coast, even where the station elevation is low, the model elevation still varies due to interpolations and Gibbs phenomena so that the results in this area are also unreliable, as reflected in the relatively low time correlation in Figure 1. As a result, and in contrast to KC, we are now including only data east of the Rockies. Because the less reliable results in the West Coast were anomalous (KC) this change has a significant impact on the area average.

[10] It is well known that the NNR (and other reanalyses) are affected by changes in the observing systems. We did not include the 1950s decade in our analysis because there were important changes in the density and time of observation of the rawinsondes, making it much less reliable [*Kistler et al.*, 2001]. After 1958, the most important change was the introduction of satellite observing systems in December 1978. Because this major change could result in a spurious jump in the climatology, and hence in artificial trends, we decided to separate the trend calculations into two essentially homogeneous periods: the 2 decades of 1959–1978, with an observing system based on rawinsondes, and the 2 decades 1979–1998, with an observing system based on both satellite and rawinsondes. This is a correction to KC, where 1979 was included within the no-satellite period, but this correction has a negligible impact on the results.

[11] The trends in the 20 year no-satellite period 1959–1978 are computed as the decadal mean for 1969/1978

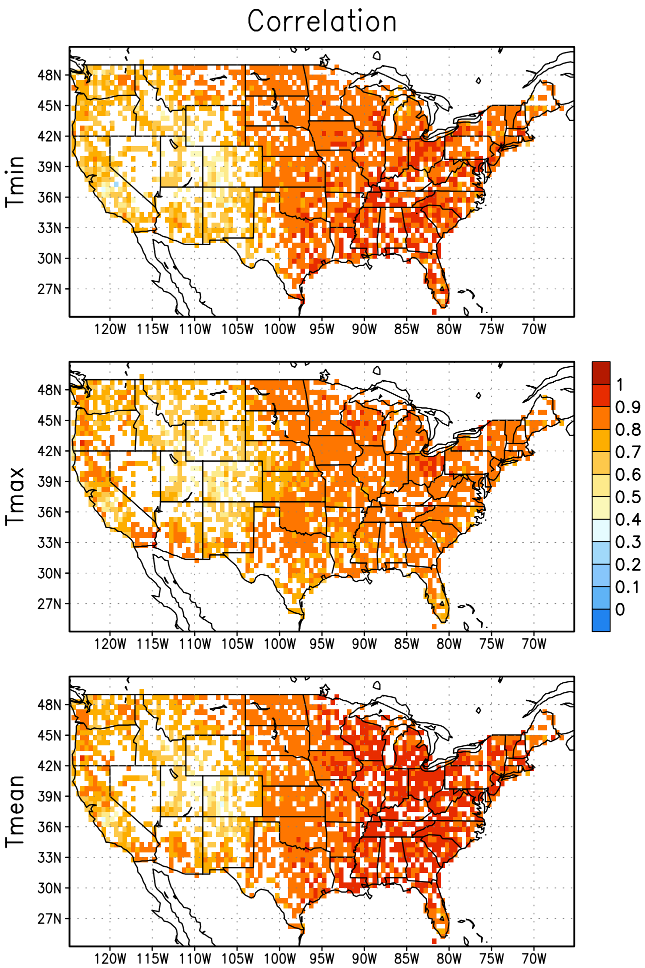

Figure 1. Correlation between the surface temperature anomalies with respect to the 50-year annual cycle for stations and for the NNR. (top) Minimum temperature, (middle) maximum temperature, (bottom) mean temperature.

minus the decadal mean for 1959/1968. (The 20-year trend obtained as the difference between two successive 10-year means is essentially identical to a linear 20-year trend.) Similarly, the postsatellite trends for 1979–1998 are computed as the decadal mean for 1989/1998 minus the decadal mean for 1979/1988. The 40-year trend is computed as the average of the trend in the first 2 decades and in the second 2 decades. This avoids computing trends across 1979, when satellite observations were introduced in the NNR resulting in climatological jumps and hence unreliable trends. The trends and adjustments with the USHCN data subset presented in section 4 are computed in the same fashion.

3. Trends Computed With Unadjusted Observations

[12] We first show in Figure 2 examples of the 50-year monthly means of temperature anomaly series for two stations (Baltimore, Md. and Owings Ferry Landing, Md.), together with the same time series for the NNR. For clarity, we added a constant to make equal the average temperature for the 1950s for the stations and NNR, without affecting the trend. It can be seen that the NNR captures quite well the intraseasonal, interannual, and interdecadal variability (see also Figure 1), but there is a growing gap (OMR) between the station observations and the NNR, especially for the urban station.

[13] Figure 3 shows the 40-year trend for the minimum and maximum temperatures for all the 1728 stations included in the study. The top panels show the station observations trend, the second row panels show the NNR trend, and the third row panels show the OMR difference, attributed at least partially to land-use change and other surface forcings. The trends in each 0.5° by 0.5° box have been averaged, and the number is the average trend (C/decade) of the boxes with stations located below 500 m in the eastern United States, area-weighted by the cosine latitude. The bottom panels (discussed also in section 4) are also an OMR calculation but based on the trends using USHCN monthly mean observations that have been adjusted for nonclimatic effects.

[14] The results indicate that east of the Rockies the maximum temperature in the unadjusted observations shows a decrease of about −0.10C/decade, whereas the reanalysis shows a decrease of only −0.01C/decade. The OMR (third panel), which we would attribute to surface effects, is generally negative, with an average of −0.09C/decade, but with concentrated areas of warming of up to 0.5C/decade. The bottom panel shows the same OMR but based on the adjusted USHCN stations, where the adjustment has increased the maximum temperature trend by about 0.15C/decade. As a result of the adjustment, the estimated trend due to surface effects is increased to 0.07C/decade, but the areas of estimated warming or cooling remain very similar (compare the bottom two left panels). The minimum temperature increased in the raw observations over these 40 years by 0.21C/decade, and the reanalysis captures about 60% of this increase, so that the OMR portion attributed to land-surface effects is 0.08C/decade. Note that for the minimum temperatures these effects are also nonuniform, with strong warming concentrated in the midwest but cooling in the south. The USHCN adjustments increase the minimum temperature by over 0.03C/decade, but, as with the maximum temperature, they do not change the geographical distribution of regions with stronger warming or cooling (compare the patterns in the bottom right two panels).

[15] Figure 4 shows the 40-year trend of the mean temperature, indicating essentially the same trend (~0.06C/decade) for both the raw observations and the NNR, and hence little average OMR difference of the land changes on the mean trend. However, there is a contrast between the central plains and the east coast, which show OMR warming, and the south and Great Lakes, which show cooling. The diurnal temperature range (DTR) has a strong negative trend of about −0.31C/decade in the raw observations, and the OMR approach would estimate that land changes and greenhouse warming contribute almost equally [*Stone and Weaver*, 2002]. However, the USHCN nonclimatic adjustments increase the maximum temperature and thus substantially reduce the DTR of the raw observations (bottom panels of Figure 4) so that they also reduce the average OMR estimate of the land-use impact on the DTR (cf. section 4). Nevertheless, the USHCN adjustments

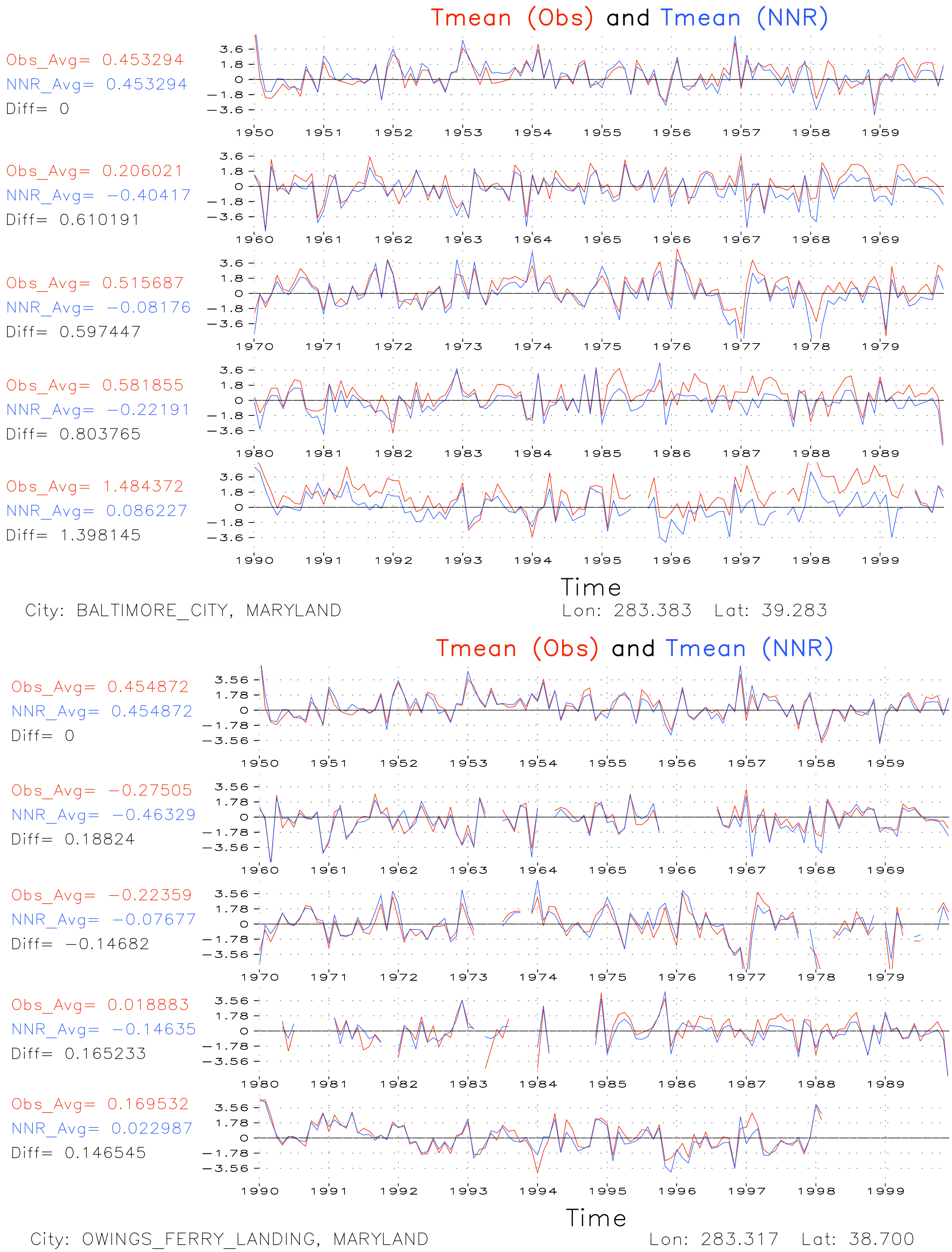

Figure 2. Comparison of the monthly averaged temperature anomalies for the NNR (blue) and stations (red), shifted so that they have the same zero average during the 1950s. The stations are Baltimore and Owings Ferry Landing, both in Maryland.

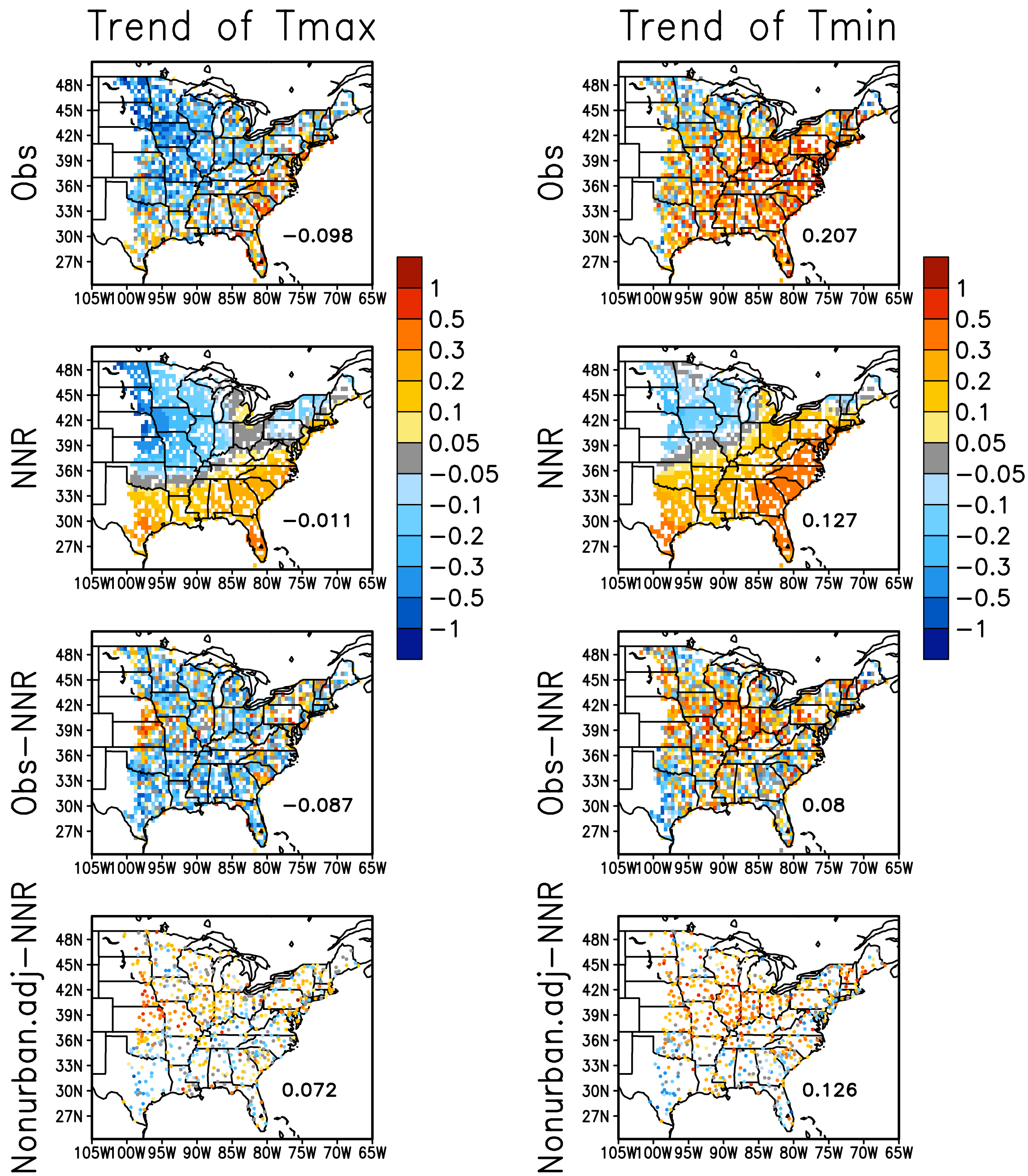

Figure 3. The 40-year temperature trends for the United States over stations located below 500 m. (top) Trends from stations (1728 raw observations); (second row) from the NNR; (third row) OMR raw observations minus NNR trend; (bottom) USHCN OMR observations with nonurban corrections minus NNR. (left) Trend of maximum temperature; (right) trend of minimum temperature. The top three panels are averaged over 0.5° latitude by 0.5° longitude, and the number represents the average trend east of the Rockies, area-weighted by cosine of the latitude. For the USHCN subset of 636 stations (bottom panels), the number is the cosine weighted station average. Note the similarity in the patterns of the two OMR results (bottom two panels).

do not change the regional distributions of warming and cooling or DTR patterns (compare the bottom right two panels).

[16] Figure 5 compares the land-surface change impact on the mean temperature trend obtained with OMR (left) with the urban correction (equal and opposite to the estimated trend) of the mean temperature based on satellite night lights obtained by *Hansen et al.* [2001] using adjusted observations. In order to facilitate the comparison, the colors in Figure 5 left are reversed compared to those of Figure 4 (left, third panel). Both figures show a generally similar geographical distribution, with anomalous "urban cooling" areas especially near the Great Lakes and in east Texas and other Gulf states, in addition to the expected "urban warming" which dominates the rest of the eastern United States. A possible explanation for the existence of

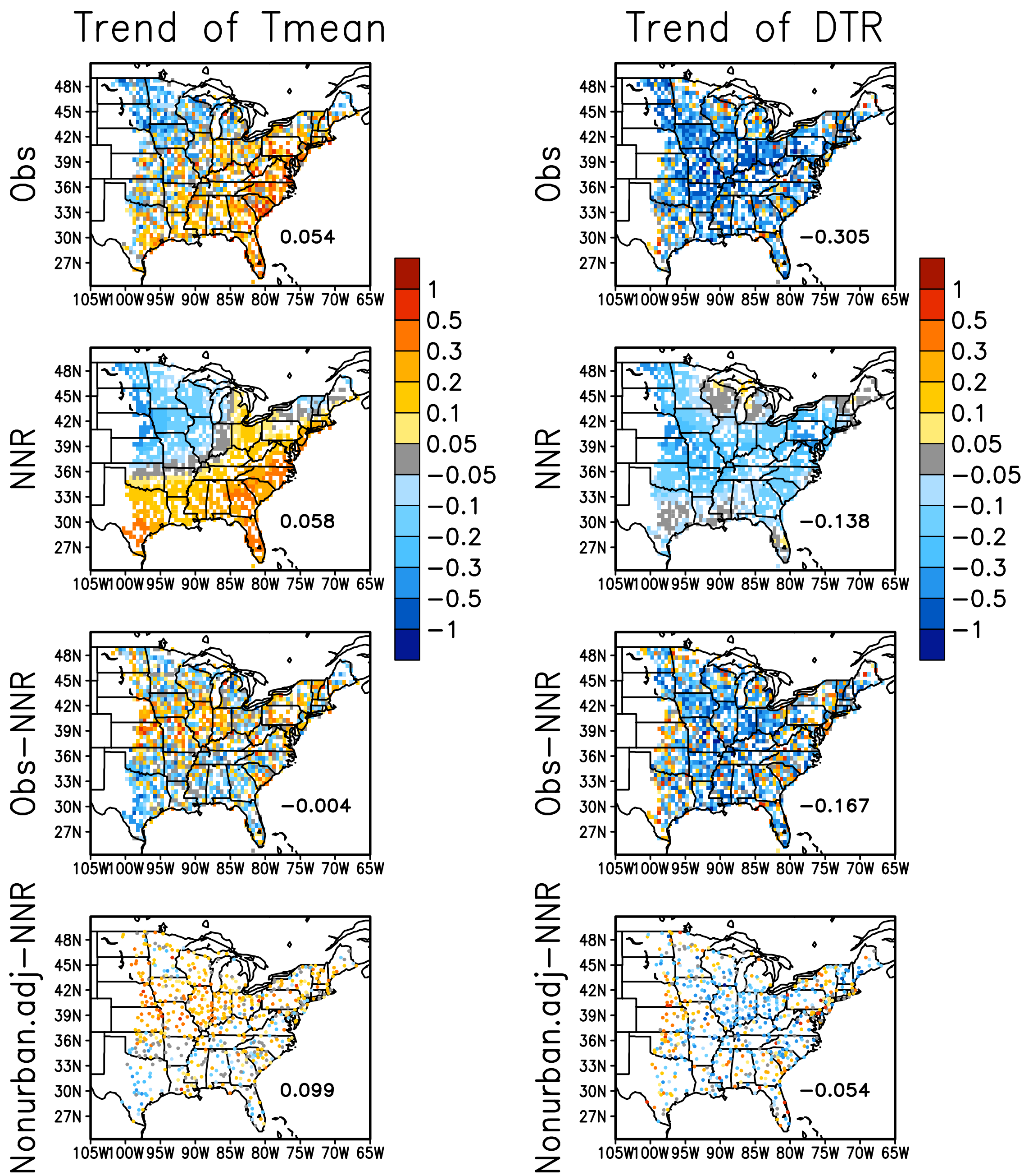

Figure 4. As Figure 3 but for the mean temperature (left) and the diurnal temperature range (right).

these abnormal regions of "urban cooling" may lie in the finding by *Lim et al.* [2005] that regions classified as cropland or grassland tend to have an OMR warming trend larger than average, whereas wooded savannas are variable but on the average (possibly because of reforestation) show negative OMR trend. In these cases urbanization (as estimated by night lights) may be a minor effect compared to other land-use changes. By contrast, urban corrections based on population density [*Easterling et al.*, 1997] indicate a uniformly positive "urban warming" that is an order of magnitude smaller than the regional trends shown in Figure 5.

[17] Figure 6 shows the trends for minimum temperatures in the winter (left) and summer (right). They indicate that the greenhouse warming is largest in winter, both in the observations and the NNR. The estimated land-use change impact (OMR) in winter over the United States has a contrasting pattern of strong warming in the midwest and Gulf Coast and mostly cooling in the rest of the country. This pattern, which dominates the annual average, is very reminiscent of the regional contrast found by *Forster and Solomon* [2003] for the "weekend effect" in Tmin. In summer the greenhouse warming is smaller and the estimated land-use is a more uniform increase in the minimum temperature. For the maximum temperature (Figure 7), the results are similar with strong regional patterns of opposite sign. When the OMR trends are computed from the adjusted USHCN subset of stations the patterns for both maximum and minimum temperatures remain geographically the same, but there is rather uniform overall increase due to

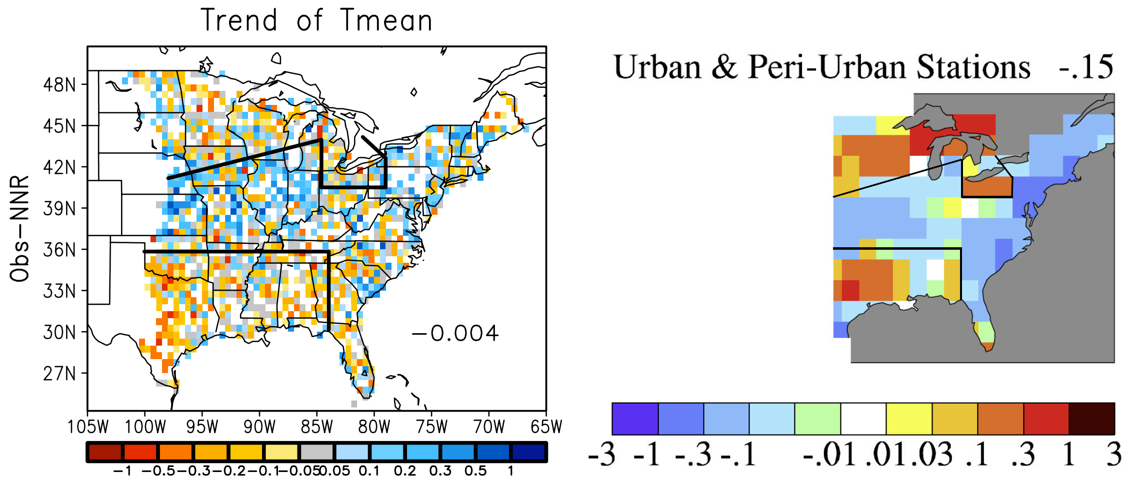

Figure 5. Comparison of two land-use impact trends. (left) Trend difference between the raw observations and the NNR where the scale of colors has been reversed so that warming appears as blue, in units of C/decade. (right) Urban correction (opposite of the trend) obtained by *Hansen et al.* [2001] using adjusted observations and nightlights to distinguish between rural and urban stations, in units of C/century. The lines have been drawn to separate major regions of cooling and warming in the map on the right.

the nonclimatic adjustments, especially for the maximum temperature (section 4).

[18] Table 1 is a summary of the 4-decade trend for all seasons and the annual average. Again, it suggests that the greenhouse warming is largest in winter for both maximum and minimum temperatures, and this trend is reflected in the NNR, whereas the estimated land-use impact is strongest in the summer season, when sunshine is greater. Spring and fall show intermediate impacts. However, positive and negative regional trends may be averaged out in these numbers since, as shown by *Lim et al.* [2005], the OMR trends depend strongly on the land type and their changes.

[19] Table 2 provides a summary of the trends for the 1959–1978 decades and for 1979–1998 decades separately. The observed mean annual warming trend is much larger in the last 2 decades (0.10 C/decade) than in the first 2 decades (∼0.00C/decade). The OMR of the mean temperature, on the other hand, is slightly positive in the first 2 decades (0.01C/decade) and slightly negative (−0.02C/decade) in the latter 2 decades. The OMR estimate is a reduction in the diurnal temperature range (DTR) in both periods, but the reduction is weaker in the earlier decades (−0.05C/decade) than in the latter decades (−0.28C/decade), possibly because of the effect of a change in thermometers in the late 1980s (*Quayle et al.* [1991]; see next section).

4. Impact of USHCN Nonclimatic Adjustments

[20] We have shown results from both 1728 unadjusted TD3200 daily surface observations, and from 636 USHCN monthly averaged station data that has been adjusted for a number of nonclimatic factors, the three most important being the change in the time of observations, changes in the location of the stations, and the change in thermometers [*Vose et al.*, 2003, 2004; *Cai and Kalnay*, 2004; *Quayle et al.*, 1991]. The effect of the change in time of observations is to warm-bias the maximum temperature observations made in the afternoon and to cool-bias the minimum temperature in the morning [*Vose et al.*, 2003]. Because the time of observations has been generally shifting from near sunset to morning observation times, over the past 50 years this has artificially reduced the real observational trend, especially in the maximum temperature. In addition, in the late 1980s the National Weather Service replaced the thermometers in about half the stations that constitute the TD3200 data set. This produced a change in these stations of about −0.4C in the maximum temperature and +0.3C in the minimum, with a corresponding +0.1C in the mean and −0.7C in the DTR. The net effect of all the USHCN adjustments between 1958 and 1992 is an approximately linear trend of about 0.08C/decade. Before 1958 and after 1992 the net effect of the nonclimatic corrections on the trend is small (www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html).

[21] We have computed the impact of the nonclimatic adjustments on the trends using the USHCN monthly data available at the NCDC Web site. We compare here the trends of the raw (unadjusted) data with those corrected for time of observation, thermometer changes, station history, and missing observations (but not for urban effects based on population density, which are much smaller). The trends were computed as described in section 2 for all 636 USHCN stations in the eastern United States that are located below 500 m. Figure 8 shows the trends in the observations adjusted for all nonclimatic factors except for the urban correction (top), the trends in the raw observations (center), and their difference, which represents the trend due to nonurban adjustments (bottom). The trends of the raw observations obtained using all the 1728 stations in eastern United States (Figure 3, top) are very similar to those obtained with the USHCN subset (Figure 8, center), both in magnitude and in geographical distribution, indicating that the USHCN is an unbiased subsample of the raw data, and that it is possible to add the nonclimatic adjustments to the trends a posteriori. We verified this in Table 3, which lists the USHCN nonurban corrections of the trend, the

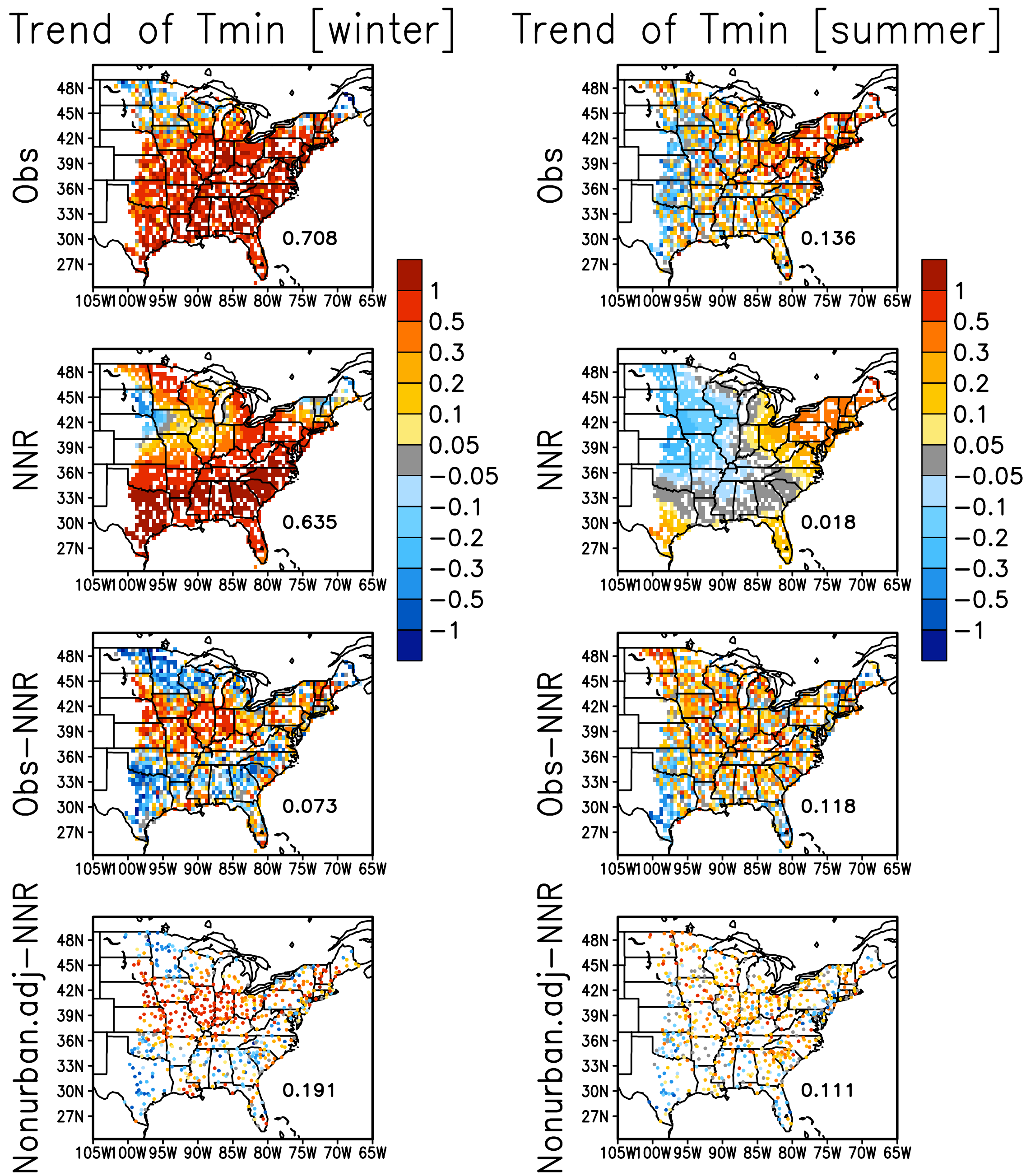

Figure 6. As in Figure 3, but for the winter (left) and summer (right) trends of minimum temperature.

original trend obtained using the OMR method with all the raw observations, the a posteriori adjusted correction and finally the OMR method applied only to the USHCN subset of stations. The results indicate that the corrections can be added a posteriori with an error of less than 0.01C/decade.

[22] Since these nonclimatic adjustments are substantial (about 0.09C/decade in Tmean), the question has been raised whether the OMR results of KC and those presented here could be simply due to the fact that we used raw data without including these adjustments. We believe that the answer to this question is negative based on the following evidence:

[23] 1. The comparison of our estimated trend agrees fairly well in geographical distribution and in magnitude with that obtained by *Hansen et al.* [2001] using adjusted observations and a completely independent method (satellite nightlights) to estimate urban impacts (Figure 5). They both show similar areas of relatively strong "urban warming" and anomalous "urban cooling," very different from the extremely weak but uniformly positive urban warming (smaller than 0.01C/decade) obtained by the population density method.

[24] 2. Our estimated trend bears no resemblance to the nonclimatic, nonurban adjustment trends obtained using the same periods and method of calculation with USHCN (Figure 8, bottom). Figure 9 shows that these adjustments produce a net increase of about 0.09C/decade but that the corrections are rather uniformly distributed.

[25] Adding the uniform nonclimatic, nonurban adjustments to our OMR results increases our estimate of the average land-use impact to ~0.09C/decade (Table 3), an

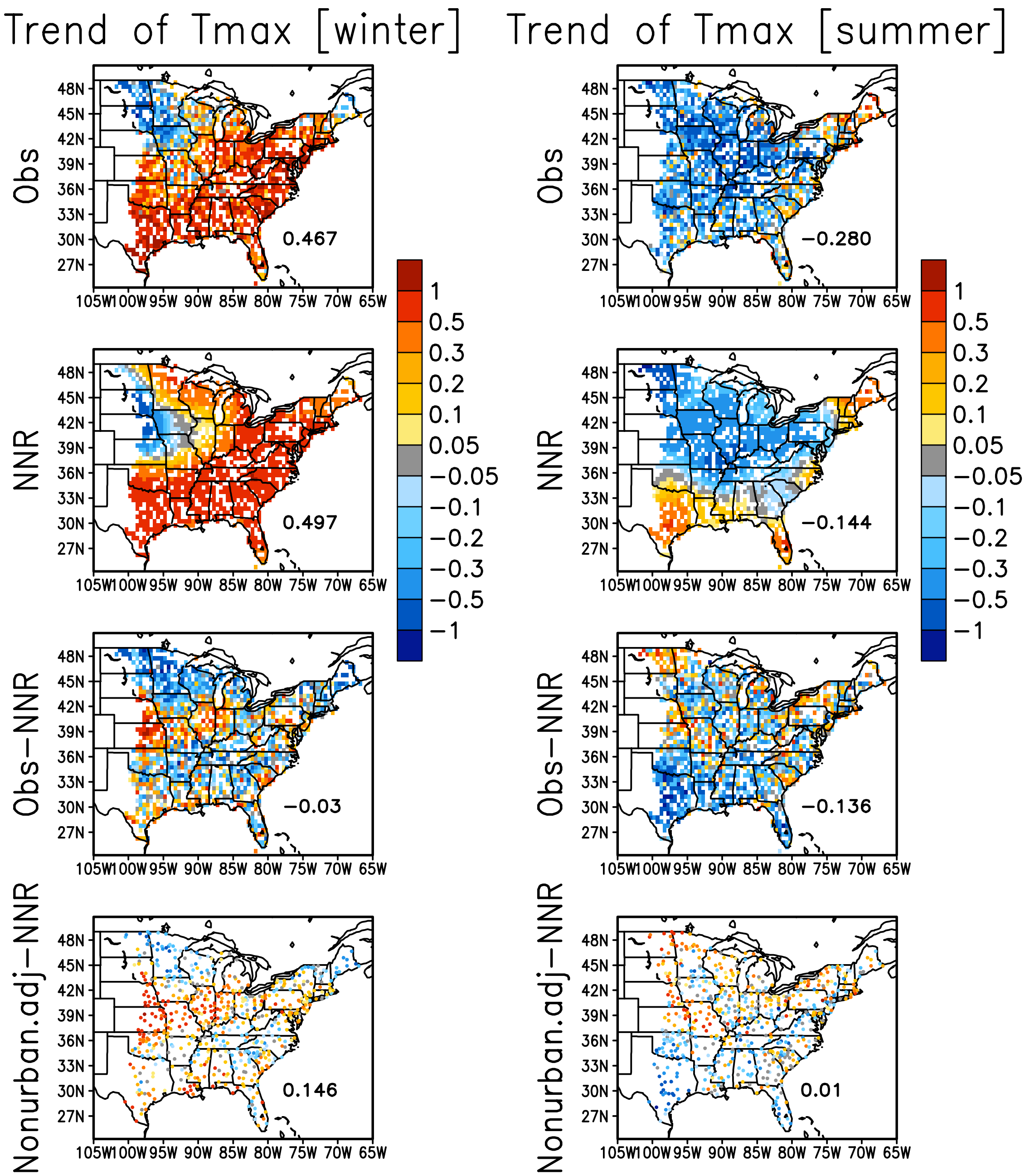

Figure 7. As in Figure 3, but winter (left) and summer (right) trends of maximum temperature.

impact which is of the same order as those found by *Gallo et al.* [1999] and *Kukla et al.* [1986], but which does not substantially change the geographical distribution that includes (like *Hansen et al.* [2001]) regions with large positive and negative trends. The impact on the DTR is substantially reduced to −0.05C/decade, but it is still negative. The USHCN urban correction (not included in the present computations) based on population density estimates [*Easterling et al.*, 1997], by contrast, is uniformly positive, and an order of magnitude smaller than the OMR estimates or the other nonclimatic USHCN adjustments.

[26] Given the large positive impact on the trend introduced by the nonclimatic adjustments performed on the U.S. observations but not on observations in many other areas, it may be worthwhile to try a simple alternative adjustment procedure. Since the NNR (or any other reanalysis) provides an accurate proxy of the expected station values (as shown in Figure 1), sudden changes between the expected and observed values in the daily-observed anomalies could be detected, compared with metadata information and their correction could be estimated. The approach could be tested by comparing it with the benchmark provided by the careful USHCN corrections. If the comparison is satisfactory, it could be used in other areas of the world that do not have the benefit of a long history of nonclimatic adjustments.

5. Other Critical Issues

[27] It is notoriously difficult to perform climate trend studies without encountering sources of uncertainty, and this

Table 1. Seasonal and Annual 40-Year Trends of the Observations, NNR, and Their Difference (OMR), Computed as an Average of the Trends From the Decade 1959–1968 to the Decade 1969–1978 (Before Satellites) and From the Decade 1979–1988 to the Decade 1989–1998 (After Satellites) and Using Unadjusted Daily Station Observations[a]

		Year	Spring	Summer	Fall	Winter
Tmax	Obs	−0.0984	−0.2276	−0.2803	−0.3544	0.4675
	NNR	−0.0110	−0.1821	−0.1439	−0.2149	0.4968
	Obs-NNR	−0.0873	−0.0455	−0.1364	−0.1395	−0.0293
Tmin	Obs	0.2069	0.0270	0.1368	−0.0445	0.7078
	NNR	0.1270	−0.0224	0.0180	−0.1228	0.6353
	Obs-NNR	0.0799	0.0494	0.1189	0.0783	0.0725
Tmean	Obs	0.0542	−0.1003	−0.0717	−0.1995	0.5876
	NNR	0.0580	−0.1022	−0.0630	−0.1689	0.5660
	Obs-NNR	−0.0037	0.0019	−0.0088	−0.0306	0.0216
DTR	Obs	−0.3052	−0.2546	−0.4172	−0.3099	−0.2404
	NNR	−0.1380	−0.1597	−0.1619	−0.0921	−0.1385
	Obs-NNR	−0.1672	−0.0948	−0.2553	−0.2178	−0.1018

[a]See section 2 for a discussion of the computation of the trends. Average trends: 0.5*[(1969/78 − 59/68) + (1989/98 − 79/88)].

study is no exception. In the previous section we discussed the impact that the USHCN nonclimatic corrections would have on our results. Here we discuss several additional issues that can be raised about our method and results:

5.1. Impact of the Systematic Errors and Deficiencies of the NNR

[28] It is well known that the NNR has significant systematic errors. By working with the anomalies with respect to the annual cycle, we have essentially eliminated deficiencies that are not flow-dependent and have no trend in the NNR. Since the model used in the NNR has constant mixing ratio of greenhouse gases and no aerosols and has other known deficiencies such as imperfect cloud cover, it might be assumed that the NNR necessarily underestimates the greenhouse impact and that our procedure could be attributing this difference to surface effects [*Trenberth*, 2004]. However, *Cai and Kalnay* [2005] have recently shown analytically that a reanalysis essentially reproduces the full strength of trends present in the assimilated observations. This happens after a short transient, of the order of a few analysis steps, even if the forecasts used as a first guess are made with a model that does not contain the forcings responsible for the observational trends. The ratio of the trend per analysis time step N in the analysis T_A $(N\Delta t) - T_A$ $((N-1)\Delta t)$ divided by the observed trend (WΔt) is given by

$$\frac{T_A(N\Delta t) - T_A((N-1)\Delta t)}{W\Delta t} = \left[1 - \frac{a\frac{\Delta t}{\tau}}{1 - a\left(1 - \frac{\Delta t}{\tau}\right)}\right]$$

where a is the relative weight given to the forecast and $\Delta t/\tau$ is the ratio between analysis time steps (e.g., 6 hours in the NNR) and the radiative adjustment timescale. This ratio is estimated to be of the order of 10^{-2}. Even if observations are given a low weight compared to the model (for example, a = 0.2), after only 20 analysis steps the analysis trend is over 95% of the observed trend. Such an estimate is supported by *Andersen et al.* [2001] finding that they were able to detect the heating impact of volcanic eruptions in the ERA-40 reanalysis even though the model does not include volcanic aerosols.

5.2. Use of This Method With Reanalyses Other Than the NNR

[29] The global data assimilation community is developing plans to perform reanalyses with a fixed data assimilation and modeling system every few years, when the operational methods undergo a sufficiently major improve-

Table 2. Same as Table 1 but Showing Separately the Trends in the First 2 Decades and in the Last 2 Decades

		Year	Spring	Summer	Fall	Winter
		Trends Computed From the Mean During 1959–1968 to the Mean During 1969–1978				
Tmax	Obs	−0.0753	0.0579	0.0066	−0.4586	0.0332
	NNR	−0.0615	−0.0363	0.2238	−0.3826	−0.0511
	Obs-NNR	−0.0137	0.0942	−0.1578	−0.0760	0.0843
Tmin	Obs	0.0827	0.0912	0.0916	0.0374	0.1113
	NNR	0.0420	0.1723	0.1762	−0.1019	0.0723
	Obs-NNR	0.0408	−0.0811	0.0740	0.1394	0.0313
Tmean	Obs	0.0037	0.0745	0.0788	−0.2106	0.0723
	NNR	−0.0098	0.0680	0.1207	−0.2422	0.0144
	Obs-NNR	0.0135	0.0065	−0.0419	0.0317	0.0578
DTR	Obs	−0.1580	−0.0333	−0.0256	−0.4960	−0.0781
	NNR	−0.1035	−0.2086	0.2062	−0.2806	−0.1311
	Obs-NNR	−0.0545	0.1753	−0.2318	−0.2154	0.0530
		Trends Computed From the Mean During 1979–1988 to the Mean During 1989–1998				
Tmax	Obs	−0.1215	−0.5130	−0.6267	−0.2503	0.9017
	NNR	0.0394	−0.3278	−0.5117	−0.0473	1.0447
	Obs-NNR	−0.1609	−0.1851	−0.1550	−0.2030	−0.1430
Tmin	Obs	0.3310	−0.0372	0.1821	−0.1265	1.3043
	NNR	0.2121	−0.2170	0.0183	−0.1437	1.1907
	Obs-NNR	0.1189	0.1798	0.1638	0.0172	0.1137
Tmean	Obs	0.1048	−0.2751	−0.2223	−0.1884	1.1030
	NNR	0.1258	−0.2724	−0.2467	−0.0955	1.1177
	Obs-NNR	−0.0210	−0.0027	0.0244	−0.0930	−0.0147
DTR	Obs	−0.4525	−0.4758	−0.8088	−0.1238	−0.4027
	NNR	−0.1726	−0.1108	−0.5300	0.0964	−0.1460
	Obs-NNR	−0.2799	−0.3649	−0.2788	−0.2202	−0.2567

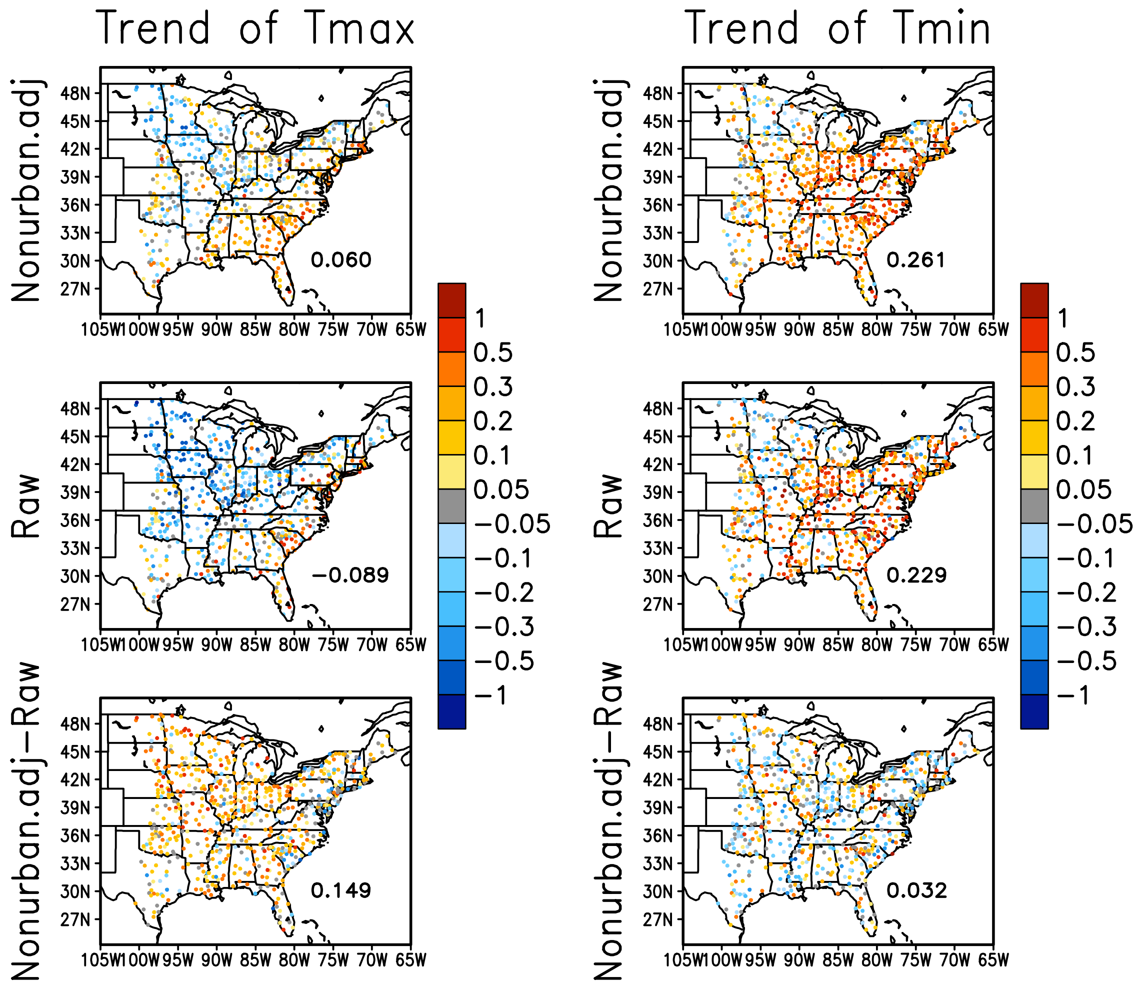

Figure 8. Impact of the nonclimatic adjustments in the USHCN data computed for the same areas and periods used in Figures 3–6. (top) Trend including all the non-climatic adjustments except for urban adjustment. (center) Trend of the raw data (comparable to the top of Figure 3 using all the data). (bottom) Trend due to the nonclimatic adjustment. (left) Tmax; (right) Tmin.

ment. A number of such reanalyses have already been carried out [e.g., *Schubert et al.*, 1993; *Kalnay et al.*, 1996; *Gibson et al.*, 1997; *Kistler et al.*, 2001; *Kanamitsu et al.*, 2002; *Simmons et al.*, 2004]. The NCEP-NCAR reanalysis (NNR) used here was performed with a system similar to that operational in 1995 and is continuing in real time, with a reanalysis available from 1948 to the present. The NNR contained several identified errors [*Kistler et al.*, 2001] that were corrected in the NCEP-DOE reanalysis (R2) [*Kanamitsu et al.*, 2002]. In the R2 the soil moisture estimation was improved by using observed weekly precipitation, in contrast to the NNR where the soil moisture was nudged toward a climatological field. ECMWF carried out a 15-year-long reanalysis (ERA-15) using radiances rather than the retrievals used in the NNR, but artificial trends in the tropical precipitation were introduced by the tuning of satellite data [*Uppala et al.*, 1999; *Fiorino*, 1999]. A more advanced system was recently used to perform 40+ years of reanalysis (ERA-40) [*Simmons et al.*, 2004], starting with 1958, after the new schedule for rawinsondes was established. Unlike the NNR, the ERA-40 does make use of surface observations, although in an indirect way: Surface observations and model forecasts of the 2-m temperatures are combined in an offline optimal interpolation (OI)

Table 3. Impact of the Nonclimatic, Nonurban Adjustments (Estimated From the USHCN Subset of Stations, in Italic) on Our Original Estimated Trends From the Raw Data[a]

Trends, °C/decade (Data Used for the Trend)	Tmax	Tmin	Tmean	DTR
(a) USHCN nonurban adjustments (nonurban adj. – raw obs.)	*0.15*	*0.03*	*0.09*	*0.12*
(b) Original KC land-use estimate (all raw obs.- NNR)	−0.09	0.08	0.00	−0.17
(b)+(a): Adjusted land-use estimate (all raw obs.-NNR)+nonurban adj.	0.06	0.11	0.09	−0.05
Adjusted land-use data using USHCN observations only	0.07	0.12	1.00	−0.05

[a]The adjusted estimates (corrected a posteriori, underlined) can be compared with the values obtained using USHCN observations directly (last row).

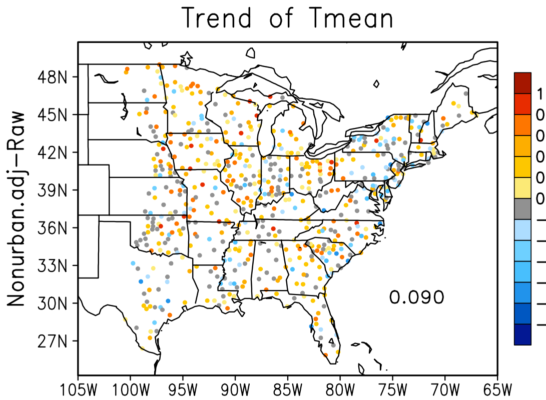

Figure 9. Impact on the trends of Tmean due to all nonurban adjustments using the USHCN stations.

analysis of the surface air temperature. This surface temperature analysis is then used to initialize the model soil temperature and moisture in the ERA-40.

[30] The OMR method proposed by KC is based on the assumption that surface observations are not being used in the reanalysis. Therefore it should be used with caution with the NCEP-DOE R2 reanalysis, which uses weekly precipitation information, and with the ERA-40, which uses surface air observations as indicated above. Nevertheless, *Lim et al.* [2005] found that the OMR trends for different types of land were very similar when computed using either NNR or ERA-40 reanalyses, but the latter were, as expected, slightly smaller. The results were also robust with respect to the use of GHCN or CRU surface temperatures.

5.3. Impact of Other Natural and Anthropogenic Effects Like Aerosols, Clouds, and Contrails

[31] A reduction of DTR has been observed in many areas of the world. *Dai et al.* [1999] have shown that there is a relationship between increased cloud cover and reduction of DTR. Anthropogenic aerosols may be related to the changes in clouds and DTR, and aerosols themselves may be implicated in a reduction of DTR [*Hansen et al.*, 1998]. Contrails have also been shown to decrease the DTR [*Travis et al.*, 2002], and an increase in precipitation, observed in many regions [*IPCC*, 2001, Figure 2.25] can also be related to such a decrease. Recent findings of a surprisingly strong "weekend effect" of about 0.5C [*Forster and Solomon*, 2003] indicate that there are short-lived anthropogenic effects, presumably associated with smog/aerosol/cloud variability that have a large impact. The minimum temperature is lower during the weekend (with a corresponding larger DTR) over the east and west coasts, but there is a weekend higher minimum temperature in the midwest.

[32] The fact that both station observations and the NNR exhibit a decrease in DTR suggests that this reflects the impact of an increase in low-level clouds [*Dai et al.*, 1999]. However, surface observations show an even larger decrease in DTR and we would attribute the difference largely to land use changes. This assertion agrees with previous studies showing that urban effects also have a substantial impact on the decrease of DTR [*Gallo et al.*, 1996]. Nevertheless, it is not clear how the effects of natural changes in precipitation can be separated from anthropogenic effects such as irrigation.

6. Summary and Discussion

[33] The NNR reanalysis is driven by the assimilation of atmospheric observations but lacks any information about changes concentrated at the surface, including land surface temperature, land-cover, soil moisture, albedo, roughness, aerosols, and consequent changes in precipitation. The human impact on climate change near the surface can be associated not only with urbanization but also with agricultural practices, deforestation, and reforestation, and more generally, industrialization. It is not possible to definitively attribute the OMR differences between the observation and the NNR temperature trends solely to these near-surface forcings, but the results obtained seem compatible with such an interpretation. To the extent that both urbanization and irrigated agriculture contribute to an increase in the effective heat capacity of the surface allowing faster conduction of heat into the surface, they would contribute to an increase in the minimum temperature, a decrease in the maximum temperature, and a reduction in the diurnal temperature range shown in our estimates east of the Rockies. These effects should be maximum in the summer, when the surface heating by the Sun is stronger, as observed in Figures 6 and 7. This suggests that the comparison of urban and rural stations, without including agricultural or industrialization effects, could underestimate the total impact of land use changes and that effects could vary regionally. More importantly, we obtained trends with strong geographical variations, showing not only areas of estimated warming but also of cooling, and these estimates generally agree in magnitude and geographical distribution with those obtained by *Hansen et al.* [2001] using satellite night light observations to discriminate between rural and urban stations. The regional pattern of positive and negative changes in OMR for the winter minimum temperature also agrees with the pattern in the "weekend effect" found on the minimum temperature by *Forster and Solomon* [2003], which indicates the presence of near surface processes affecting the surface temperature that are regionally dependent.

[34] We used both "raw" daily station observations that have not been corrected for nonclimatic factors (changes in the time of the observation, station location, and thermometers) and monthly averaged USHCN stations and found that the effects of the station corrections can be estimated fairly accurately by adding the corrections to the raw observations a posteriori. We estimated the changes these corrections would introduce by using the USHCN subset of observations, and computing trends with and without the adjustments, for the same area (eastern United States) and periods (2 decades before the introduction of satellite data and 2 decades after). We found the nonclimatic adjustments are substantial: an increase in the maximum and minimum temperature trends of 0.15C/decade and 0.03C/decade, respectively, a mean temperature increase of 0.09C/decade and an increase of DTR of 0.12C/decade. When these nonurban corrections are added, our technique would yield an adjusted trend in the mean temperature of about 0.09C/decade and a reduction of DTR of –0.05C/decade. These numbers are not unreasonable given that they include not

just urbanization effects but any other trend in surface forcing not included in the NNR. Moreover, we found that the nonclimatic USHCN adjustments are geographically relatively homogeneous (as would be expected), and very dissimilar to the distribution of warming and cooling found in our original trends so that the OMR results cannot be attributed to these adjustments. By contrast to *Hansen et al.* [2001] night light results, the estimation of the correction for urban impacts based on population density, also available for the USHCN data, is uniformly positive and very small, less than 0.01C/decade. Since nonclimatic corrections are substantial, we suggest that reanalyses could be used to provide an alternative estimation of the nonclimatic adjustments taking advantage of the fact that they provide an accurate estimate of the expected value of the surface observations (absent sudden changes). If this method compares well with that used in the USHCN data set, it can be extended to other areas of the world where such careful corrections are not available.

[35] More studies are necessary, including a comparison of geographical distribution of NNR trends with other upper air observations, such as rawinsondes and satellites, a more precise space and time definition of the urban and rural observing stations, the impact of other land-use changes such as agriculture and deforestation or reforestation, and of other anthropogenic effects such as contrails and aerosols that can also reduce the diurnal temperature range.

[36] **Acknowledgments.** This work was supported by NOAA grant NAO4OAR431029 and by NSF grants ATM-403211 and 403518. We are very grateful for the constructive comments of four anonymous reviewers that helped to improve the paper.

References

Andersen, U., E. Kaas, and P. Alpert (2001), Using analysis increments to estimate atmospheric heating rates following volcanic eruptions, *Geophys. Res. Lett.*, *28*, 991–994.
Cai, M., and E. Kalnay (2004), Reply, Climate (communication arising): Impact of land-use change on climate, *Nature*, *427*, 214.
Cai, M., and E. Kalnay (2005), Can reanalysis have anthropogenic climate trends without model forcing?, *J. Climate*, *18*, 1844–1849.
Dai, A., K. E. Trenberth, and T. R. Karl (1999), Effects of clouds, soil moisture, precipitation and water vapor on diurnal temperature range, *J. Climate*, *12*, 2451–2473.
Easterling, D. R., et al. (1997), Maximum and minimum temperature trends for the globe, *Science*, *277*, 364–367.
Fiorino, M. (1999), The impact of observing system changes on the climate-scale variability and temperature in the ECMWF and NCEP reanalyses, in *2nd Int. Conf. of Reanalyses, Reading, England, 23-27 Aug. 1999*, World Meteorol. Org., Geneva, Switzerland.
Forster, P. M. D., and S. Solomon (2003), Observations of a "weekend effect" in diurnal temperature range, *Proc. Nat. Acad. Sci.*, *100*, 11,225–11,230.
Gallo, K. P., D. R. Easterling, and T. C. Peterson (1996), The influence of land use/land cover on climatological values of the diurnal temperature range, *J. Climate*, *9*, 2941–2944.
Gallo, K. P., T. W. Owen, D. R. Easterling, and P. F. Jamason (1999), Temperature trends of the U.S. historical climatology network based on satellite-designated land use/land cover, *J. Climate*, *12*, 1344–1348.
Gibson, J. K., P. Kallberg, S. Uppala, A. Noumura, A. Hernandez, and E. Serrano (1997), ERA description, in *ECMWF Re-Analysis Project Rep.*, vol. 1, 77 pp., ECMWF, Reading, UK.
Hansen, J. E., M. Sato, A. Lacis, R. Ruedy, I. Tegen, and E. Matthews (1998), Climate forcings in the industrial era, *Proc. Natl. Acad. Sci. USA*, *95*, 12,753–12,758.
Hansen, J. E., et al. (2001), A closer look at United States and global surface temperature change, *J. Geophys. Res.*, *106*, 23,947–23,963.
Intergovernmental Panel on Climate Change (IPCC) (2001), *Climate Change 2001: The Scientific Basis*, edited by J. T. Houghton et al., Cambridge Univ. Press, New York.
Kalnay, E., and M. Cai (2003), Impact of urbanization and land-use change on climate, *Nature*, *423*, 528–531.
Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 431–437.
Kanamitsu, M., W. Ebisuzaki, J. Woollen, S.-K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter (2002), NCEP-DOE AMIP-II reanalysis (R-2), *Bull. Am. Meteorol. Soc.*, *83*, 1631–1643.
Karl, T. R., and C. N. Williams Jr. (1987), An approach to adjusting climatological time series for discontinuous inhomogeneities, *J. Clim. Appl. Meteorol.*, *26*, 1744–1763.
Karl, T. R., C. N. Williams, P. J. Young, and W. M. Wendland (1986), Model to estimate the time of observation bias associated with monthly mean maximum, minimum and mean temperatures for the United States, *J. Clim. Appl. Meteorol.*, *25*, 145–160.
Karl, T. R., H. F. Diaz, and G. Kukla (1988), Urbanization: Its detection and effect in the United States climate record, *J. Climate*, *1*, 1099–1123.
Kistler, R., et al. (2001), The NCEP/NCAR 50-year reanalysis, *Bull. Am. Meteorol. Soc.*, *82*, 247–267.
Kukla, G., J. Gavin, and T. R. Karl (1986), Urban warming, *J. Clim. Appl. Meteorol.*, *25*, 1265–1270.
Lim, Y.-K., M. Cai, E. Kalnay, and L. Zhou (2005), Observational evidence of sensitivity of surface climate changes to land types and urbanization, *Geophys. Res. Lett.*, *32*, L22712, doi:10.1029/2005GL024267.
Marshall, C. H., Jr., R. A. Pielke Sr., L. T. Steyaert, and D. A. Willard (2004), The impact of anthropogenic land-cover change on the Florida peninsula sea breezes and warm season sensible weather, *Mon. Weather Rev.*, *132*, 28–52.
Peterson, T. C. (2003), Assessment of urban versus rural in situ surface temperatures in the contiguous United States: No difference found, *J. Climate*, *16*, 2941–2959.
Pielke, R. A., Sr. (2001), Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall, *Rev. Geophys.*, *39*, 151–177.
Pielke, R. A., Sr., G. Marland, R. A. Betts, T. N. Chase, J. L. Eastman, J. O. Niles, D. Niyogi, and S. Running (2002), The influence of land-use change and landscape dynamics on the climate system- relevance to climate change policy beyond the radiative effect of greenhouse gases, *Phil. Trans. R. Soc. London, Ser. A*, *360*, 1705–1719.
Quayle, R. G., D. R. Easterling, T. R. Karl, and P. Y. Hughes (1991), Effects of recent thermometer changes in the cooperative station network, *Bull. Am. Meteorol. Soc.*, *72*, 1718–1724.
Schubert, S., R. Rood, and J. Pfaendtner (1993), An assimilated data set for earth sciences applications, *Bull. Am. Meteorol. Soc.*, *74*, 2331–2342.
Simmons, A. J., P. D. Jones, V. da Costa Bechtold, A. C. M. Beljaars, P. W. Kållberg, S. Saarinen, S. M. Uppala, P. Viterbo, and N. Wedi (2004), Comparison of trends and low-frequency variability in CRU, ERA-40 and NCEP/NCAR analyses of surface air temperature, *J. Geophys. Res.*, *109*, D24115, doi:10.1029/2004JD005306.
Stone, D. A., and A. J. Weaver (2002), Daily maximum and minimum temperature trends in a climate model, *Geophys. Res. Lett.*, *29*(9), 1356, doi:10.1029/2001GL014556.
Travis, D. J., A. M. Carleton, and R. G. Lauritsen (2002), Contrails reduce daily temperature range, *Nature*, *418*, 601.
Trenberth, K. E. (2004), Climate (communication arising): Impact of land-use change on climate, *Nature*, *427*, 213.
Uppala, S., J. K. Gibson, M. Fiorino, A. Hernandez, P. Kallberg, X. Li, K. Onogi, and S. Saarinen (1999), ECMWF second generation reanalysis: ERA40, in *2nd Int. Conf. of Reanalyses, Reading, England, 23–27 Aug. 1999*, World Meteorol, Org., Geneva, Switzerland.
Vose, R. S., C. N. Williams Jr., T. C. Peterson, T. R. Karl, and D. R. Easterling (2003), An evaluation of the time of observation bias adjustment in the US Historical Climatology Network, *Geophys. Res. Lett.*, *30*(20), 2046, doi:10.1029/2003GL018111.
Vose, R. S., T. R. Karl, D. R. Easterling, C. N. Williams, and M. J. Menne (2004), Climate (communication arising): Impact of land-use change on climate, *Nature*, *427*, 213–214.
Zhou, L., R. E. Dickinson, Y. Tian, J. Fang, Q. Li, R. K. Kaufman, C. J. Tucker, and R. B. Myneni (2004), Evidence for a significant urbanization effect on climate in China, *Proc. Natl. Acad. Sci.*, *101*, 9540–9544.

M. Cai, Department of Meteorology, Florida State University, Tallahassee, FL 32303, USA.
E. Kalnay, H. Li, and J. Tobin, Atmospheric and Ocean Sciences, University of Maryland, College Park, MD 20742-2425, USA. (ekalnay@atmos.umd.edu)