# Estimation of the Impact of Land-Surface Forcing on Temperature Trends in Eastern United States

By

Hong Li

Advisors: Profs. Eugenia Kalnay and Ming Cai

A scholarly paper for the degree of Master of Science

Department of Meteorology, University of Maryland

College Park, Maryland

April 2005

## Acknowledgements

I am very grateful to my advisors Profs. Eugenia Kalnay and Ming Cai for their kind and valuable advice, and many useful suggestions. Thanks to all the Professors and students in the Department of Meteorology, University of Maryland, who gave me lots of advice and assistance both on my course study and on my research.

# Summary

The conventional method for estimating the urbanization effect is to compare observations in cities with those in rural areas, in which the difficulty is how to classify meteorological stations into urban and rural. Some estimates have been made based on population data and satellite night-light data used to distinguish urban and rural. However, the results differ from each other significantly (0.006 and 0.015ºC per decade, respectively) .

A new, much easier way to estimate the impact of urbanization and land-surface forcing on climate was proposed recently by Kalnay and Cai (2003, KC hereafter). In this approach they took advantage of the property that the NCEP/NCAR Reanalysis is sensitive to atmospheric climate changes other than surface observations because surface observations except surface pressure are not used in NNR. Therefore the differences between the observation and reanalysis surface temperature trends are at least partly attributable to the impact of land-surface forcing, including urbanization, agriculture and aerosol effects.

In this paper we extend and slightly correct the computations performed by KC. It was found that the correlation between the NNR and surface observations is much lower over the Rockies than east of the Rockies (Fig.1). 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 Fig. 1. As a result, and in contrast to KC, I am including only data east of the Rockies and all the trends in this paper are calculated over east American domain.

It is well known that the reanalyses are affected by changes in the observing systems. The introduction of satellite observing systems in December 1978 could result in a spurious jump in the climatology, and hence in artificial trends. Instead of putting 1979 in the non-satellite period, which is done by KC, here I separated the trend calculations into two essentially homogeneous periods: the two decades of 1959-1978, with an observing system based on rawinsondes, and the two decades 1979-1998, with an observing system based on both satellite and rawinsondes.

It is also important to know if there is a seasonal signal of the land-surface impact on temperature trend. In this paper besides the trend of annual average (shown in Fig3 and Fig 4) I calculated and plotted the trend of NNR, the observations and their difference in each season. Figs. 6 and 7 show the trends for summer and winter respectively (spring and fall are not shown), indicating that the greenhouse warming dominates in winter, both in the observations and the NNR. The estimated land-surface impact in winter over the US is relatively small, whereas it is strongest in the summer season when sunshine is greater. Table 1 is a summary of the 4-decade trend for all seasons and the annual average. For the trend of the annual average, the land-surface effect is to increase the minimum temperature, slightly decrease the maximum temperature and therefore decrease the diurnal temperature range (DTR). For the seasonal trend, 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. In summer the greenhouse warming is smaller and the estimated land-use impact is larger. Spring and fall show intermediate impacts.

In order to see the land-surface impact for more details, Table 2 provides a summary of the trends for the 1959-1978s decades and for 1979-1998s decades separately. The NNR mean annual warming trend is much larger in the last two decades (0.1258 C/decade) than in the first two decades (~0.00C/decade), indicating the global warming phenomenon is much obvious in the current two decades. The estimated impact of land-surface impact on the DTR is also stronger in the latter two decades (-0.2799C/decade) mainly because the land-use impact on the minimum temperature is bigger in the last two decades (0.1189C/decade) than in the first two decades (0.0408C/decade).

# Estimation of the Impact of Land-Surface Forcings on Temperature Trends in Eastern United States

Eugenia Kalnay[1]*, Ming Cai[2], Hong Li[1] , Jayakar Tobin[1]
[1]University of Maryland
College Park, MD, 20742-2425
and
[2]Florida State University

Revised March 2005

*ekalnay@atmos.umd.edu

**ABSTRACT**

We are using a method to at least partially identify 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 estimated surface temperatures (with trends only influenced by the assimilated atmospheric temperature trends). This difference would include 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. In this work we slightly correct previous results by including the year 1979 within the satellite decades, and by excluding all stations in the West Coast of the US, which were not well correlated with observations. The estimated land-use changes impact on the raw data increases the minimum temperature and decreases the maximum temperature. The impact on the mean temperature has a similar geographical distribution and amplitude to that obtained by Hansen et al (2001) using satellite observations of night-light to discriminate between rural and urban stations. The seasonal cycle results suggest that the impact of the greenhouse gases dominates in the winter, whereas it appears that the impact of surface forcings is more important in the summer. The impact of the adjustment for non-climatic trends in the observations is to increase the trend of the maximum temperature and, to a lesser extent, the minimum temperature, but without affecting the geographical distribution of the trends. Other considerations such as 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 non-climatic jumps in the observations are also discussed.

## 1. INTRODUCTION

Trends of surface temperature on the time scale of decades are due to either natural climate variability or to anthropogenic factors, so that their attribution is quite difficult (e.g., 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 et al, 2002, Kalnay and Cai, 2003, Zhou et al, 2004, Marshall et al, 2004) suggest that the impact of widespread land-use changes could be larger and should not be ignored.

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 US have been small (0.006C/decade and 0.015C/decade respectively), and do not include the impact of other land-use changes such coming from agriculture and industrialization that can change the land properties over larger areas. Similar estimates for the global urban heat island impact are quoted in the IPCC Report, Vol 2, p.106, but both larger impacts

(Kukla et al, 1986, Gallo et al, 1996) and smaller (Peterson, 2003) have been reported as well. Corrections due to non-climatic 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 US (see also section 4).

Kalnay and Cai (2003, KC from now on) proposed to estimate the impact of all changes in land use (including urbanization and agricultural practices such as irrigation) by comparing trends from surface observations with those of the NCEP/NCAR Reanalysis (NNR, Kalnay et al, 1996, Kistler et al, 2000). 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 200km 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).

The essence of the 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 aerosols and precipitation associated not only with urbanization but also with industrialization. In addition, this approach allows cancelling the trends due to natural climate variability (temporary changes in circulation), since those are present in both the observations and the NNR.

This method has recently been applied by Zhou et al (2004) to estimate the impact of urbanization over Southeastern China during the last two 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$^{o}$C/decade) was consistent with the estimates of urbanization from changes in the urban population and in satellite-measured greenness.

In this paper we extend and slightly correct the 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 (pre-satellite) and the 1979-1998 decades (post-satellite) using the unadjusted observations. Section 4 contains an estimation of the impact of non-climatic 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

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" dataset over the 48 conterminous United States (CONUS) for 1950-1999. These are "raw" observations that have *not* been adjusted for several non-climatic 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 $2.5^o$ resolution) for the same period. An *a posteriori* estimate of the impact on the trends that would be obtained using *adjusted* USHCN observations for the same periods is presented in Section 4 (see also comments on KC by Vose et al., 2004, and the response by Cai and Kalnay, 2004).

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 (Fig. 1). Thus, we did not include in our analysis stations with elevations above 500m. 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 Fig. 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.

It is well known that the NNR (and other reanalyses) are affected by changes in the observing systems. We did not include the 1950's 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, 2000). 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 two decades of 1959-1978, with an observing system based on rawinsondes, and the two 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.

The trends in the 20 year no-satellite period 1959-1978 are computed as the decadal mean for 1969/1978 minus the decadal mean for 1959/1968[1]. Similarly, the post-satellite 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 two decades and in the second two 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

We first show in Fig. 2 examples of the 50-year monthly means of temperature anomaly series for two stations (Baltimore, MD and Owing 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 Fig. 1), but there is a growing gap between the station observations and the NNR, especially  the urban station.

[1] The 20-year trend obtained as the difference between two successive 10-year means is essentially identical to a linear 20-year trend.

Fig. 3 shows the 40-year trend for the minimum and maximum temperatures for all the 1728 stations included in the study. The top panel shows the station observations trend, the middle panel shows the NNR trend, and the bottom panel shows their difference, attributed at least partially to land-use change and other surface forcings. The trends in each 0.5$^o$ by 0.5$^o$ box have been averaged, and the number is the average trend (C/decade) of the boxes with stations located below 500m in the Eastern US, area-weighted by the cosine latitude. Our results suggest that east of the Rockies, the minimum temperature increased over these 40 years by 0.21C/decade, and of this increase about 40% could be due to land-surface effects. The maximum temperature in the observations shows a decrease of about -0.10C/decade, and most of it could be attributed to land changes. The adjustments for non-climatic effects (Section 4, Fig. 8) increase the observational trends for the maximum temperature, and to a lesser extent the minimum temperature, but do not change significantly their geographical distribution.

Fig. 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 difference of the land changes on the mean trend. However, there is a contrast between the Central Plains and the East Coast, which show 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 our approach would estimate that land changes and greenhouse warming contribute almost equally (Stone and Weaver, 2002). However, the USHCN non-climatic adjustments substantially reduce the

DTR of the raw observations, so that they reduce the estimated land use impact on the DTR (see Section 4).

Figure 5 compares the land-surface change impact on the mean temperature trend that we obtained (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 Fig. 5 left are reversed compared to those of Fig. 4 (left, bottom) or Fig. 9 (left).  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 US.

Figs. 6 and 7 show the trends for summer and winter respectively, indicating that the greenhouse warming dominates in winter, both in the observations and the NNR. The estimated land-use change impact in winter over the US is relatively small. In summer the greenhouse warming is smaller and the estimated land-use impact is larger.

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.

Table 2 provides a summary of the trends for the 1959-1978s decades and for 1979-1998s decades separately. The observed mean annual warming trend is much larger in the last two decades (0.10 C/decade) than in the first two decades (~0.00C/decade). The estimated impact of land-use changes on the mean temperature, on the other hand, is slightly positive in the first two decades (0.01C/decade) and slightly negative (-0.02C/decade) in the latter two decades. The estimate of the land-use changes 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 1980's (Quayle et al, 1991, see next section).

## 4. IMPACT OF USHCN NON-CLIMATIC ADJUSTMENTS

So far we have used raw (unadjusted) TD3200 surface observations, whereas the USHCN data has been adjusted for a number of non-climatic 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, 2004a, 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 reduced artificially the real observational trend, especially in the maximum temperature. In addition, in the late 1980's 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 -0.7Cin the DTR. The net effect of the USHCN adjustment between 1958 and 1992 is an approximately linear trend of about 0.08C/decade. Before 1958 and after 1992 the net effect of the non-climatic corrections on the trend is small. See (www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html) for more details.

Since the adjustment changes can be added *a posteriori*, we have computed the non-climatic trends using the USHCN monthly data available at the NCDC website. 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). The trends were computed as described in section 2 for all 636 USHCN stations in the eastern US that are located below 500m. Fig. 8 shows the trends in the raw observations (top), the trends in the observations adjusted for all non-climatic factors except for the urban correction (center), and their difference, which represents the trend due to non-urban adjustments (bottom).

The trends of the raw observations obtained using all the 1728 stations in eastern US (Fig. 3, top) are very similar to those obtained with the USHCN subset (Fig. 8, top), both in magnitude and in geographical distribution, suggesting that the USHCN is an unbiased sub-sample of the raw data. This justifies our making an *a posteriori* adjustment as shown in Table 3. Since these non-climatic adjustments are substantial (about 0.09C/decade in Tmean), the question has been raised whether the results of KC and those presented here could be simply due to the fact we used raw data without including these adjustments. We feel that the answer to this question is negative based on the following evidence:

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 (Fig. 5). They both show similar areas of “urban warming” and “urban cooling”.
2) Our estimated trend bears no resemblance to the non-climatic, non-urban adjustment trends obtained using the same periods and method of calculation with USHCN. Fig. 9 shows that these adjustments produce a net increase of about 0.09C/decade, but they are rather uniformly distributed.

Adding the uniform non-climatic, non-urban adjustments to our estimates results increases our estimate of the average land-use impact to ~0.09C/decade (Table 3), an 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. The impact on the DTR is substantially reduced to –0.05C/decade, but it is still negative. We note that the USHCN urban correction (based on population density estimates, Easterling et al, 1997), is much smaller in magnitude, less than 0.01C/decade (not shown) and also rather uniform.

Given the large positive impact on the trend introduced by the non-climatic adjustments performed on the U. S. observations, but not on observations in many other areas, it may be worthwhile to try a simple alternative correction procedure. Given that the NNR (or any other reanalysis) provides an accurate proxy of the expected station values (as shown in Fig. 1), then 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 non-climatic adjustments.

## 5. OTHER CRITICAL ISSUES

It is notoriously difficult to perform climate trend studies without encountering sources of uncertainty, and this study is no exception. In the previous section we discussed the impact that the USHCN non-climatic corrections would have on our results. Here we discuss several additional issues that can be raised about our method and results:

a) The impact of the systematic errors and deficiencies of the NNR

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 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

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

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 time scale. 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 ECMWF reanalysis even though the model does not include volcanic aerosols.

b) The use of this method with reanalyses other than the NNR

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 improvement (Arkin et al, 2004). 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 (NDR, Kanamitsu et al, 2002). In the NDR the soil moisture estimation was improved by using observed weekly precipitation, in contrast to the NNR where the soil moisture was nudged towards 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 et al, 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 2m temperatures are combined in an offline Optimal Interpolation (OI) 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.

The 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 reanalysis, since this reanalysis uses weekly precipitation information. Similar caution should be used with the ERA-40, since this reanalysis uses surface temperature observations, albeit to modify the soil temperature and moisture.

c) Impact of other natural and anthropogenic effects like aerosols, clouds and contrails

A reduction of DTR has been observed in many areas of the world. Dai et al (1997) 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, Fig. 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 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 mid-West.

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

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, 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 differences between the observation and the NNR temperature trends solely to these near-surface forcings, but the results obtained are not incompatible 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 Table 1. 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. We note that we obtained trends with strong geographical variations, showing not only areas of estimated warming but also of cooling, and that these areas generally agree with those obtained by Hansen et al (2001) using satellite night-light observations to discriminate between rural and urban stations.

We used "raw" observations that have not been corrected for non-climatic factors (changes in the time of the observation, station location, and thermometers), but these effects can be added *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 US) and periods (two decades before the introduction of satellite data and two decades after). We found the non-climatic 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 non-urban 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 non-climatic adjustments are geographically relatively homogeneous (as would be expected), and very dissimilar to the distribution of warming and cooling found in our original trends. By contrast to Hansen (2001) night-light results, the estimation of the correction for urban impacts based on population density, also available for the USHCN data, is uniformly small, less than 0.01C/decade. Since non-climatic corrections are substantial, we suggest that reanalyses could be used to provide an alternative estimation 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.

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, and the impact of other human activities such as contrails and aerosols that can also reduce the diurnal temperature range.

## 7. ACKNOWLEDGEMENTS

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 three anonymous reviewers that helped to improve the paper.

## 8. REFERENCES


Andersen, U., E. Kaas, and P. Alpert, (2001), Using analysis increments to estimate atmospheric heating rates following volcanic eruptions, Geoph. Res. Lett., 28, 991-994.

Arnfield, A. J., (2003), Two Decades of Urban Climate Research: A Review of Turbulence, Exchanges of Energy and Water, and the Urban Heat Island. Int. J. Climatol. **23**: 1–26.

Cai, M. and E. Kalnay, (2004a) Reply, Climate (communication arising): Impact of land-use change on climate. *Nature, 427,* 214.

Cai, M, and E. Kalnay, (2004b), Can Reanalysis Have Anthropogenic Climate Trends Without Model Forcing? *J. Climate***.** (Accepted).

Dai, A., K. E. Trenberth and T. R. Karl. Effects of clouds, soil moisture, precipitation and water vapor on diurnal temperature range. *J. Climate*, *12*, 2451–2473. (1999).

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. $2^{nd}$ Intl. Conf. of Reanalyses, Reading, England, 23-27 Aug. 1999. World Meteorological Organization, Geneva, Switzerland.

Forster, P.M. de F. and S. Solomon, (2003), Observations of a “weekend effect” in diurnal temperature range. Proc. Nat. Acad. of Science, 100, 11225-11230.

Gallo, K. P., D. R. Easterling, 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, 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. *ECMWF Re-Analysis Project Report Series, 1.* ECMWF, Reading, UK, 77 pp.

Hansen, J. E. and co-authors (2001), A closer look at United States and global surface temperature change. J. Geophys. Res. 106, 23947–23963 (2001).

Kalnay, E. and coauthors, (1996), The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc., 77,*437-431.

Kalnay, E. and M. Cai, (2003), Impact of urbanization and land-use change on climate. *Nature, 423,* 528-531.

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., and C. N. Williams, Jr. 1987. An approach to adjusting climatological time series for discontinuous inhomogeneities. Journal of Climate and Applied Meteorology 26:1744-1763.

Karl, T.R., H.F. Diaz, and G. Kukla, (1988): Urbanization: Its detection and effect in the United States climate record, J. Clim., 1, 1099-1123.

Kistler, R., E. Kalnay, and co-authors, 2000: The NCEP/NCAR 50-year Reanalysis. *Bull. Am. Met. Soc. 82*, 247-267.

Kukla, G., J Gavin and TR Karl, 1986: Urban Warming. *J. of Climate and Applied Meteorology*, *25*, 1265-1270.

Landsberg H. E. (1981), The Urban Climate. *Academic Press*: New York.

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. Wea. Rev.*, *132*, 28-52. http://blue.atmos.colostate.edu/publications/pdf/R-272.pdf

Oke TR. 1982. The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society 108*: 1–24.

Pielke Sr., R.A., 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. A. Special Theme Issue, 360*, 1705-1719. http://blue.atmos.colostate.edu/publications/pdf/R-258.pdf

Pielke Sr., R.A., (2001) Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Rev. Geophys.*, *39*, 151-177. http://blue.atmos.colostate.edu/publications/pdf/R-231.pdf

Quayle, R.G., D.R. Easterling, T.R. Karl and P.Y. Hughes, Effects of recent thermometer changes in the cooperative station network, *Bull. Am. Meteorol. Soc.*, ***72***, 1718-1724, 1991.

Runnalls, K. E. & Oke, T. R. Dynamics and controls of the near-surface heat island of Vancouver, BC., (2000) *Phys. Geogr. 21*, 283–304.

Schubert, S, R Rood and J Pfaendtner, (1993): An assimilated data set for earth sciences applications. Bull. *Amer. Meteorol. Society, 74*, 2331-2342.

Seidel, D.J., Lanzante, J.R., 2004. An assessment of three alternatives to linear trends for characterizing global atmospheric temperature changes. *Journal of Geophysical Research*, *109*, D14108.

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. Wedi1, (2004): Comparison of trends and variability in CRU, ERA-40 and NCEP/NCAR analyses of monthly-mean surface air temperature. Submitted.

Stone, D A and AJ Weaver, (2002): Daily maximum and minimum temperature trends in a climate model. *Geoph. Research Letters, 29*, 1356.

Travis, D. J., Carleton, A. M. & Lauritsen, R. G., (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. *2nd Intl. Conf. of Reanalyses, Reading, England, 23-27 Aug. 1999. World Meteorological Organization*, Geneva, Switzerland.

Vose, RS, CN Williams Jr., TC Peterson, TR Karl, DR Easterling, (2003), An evaluation of the time of observation bias adjustment in the US Historical Climatology Network. *Geophys. Res. Lett., 30(20)*, 2046-2049, doi: 10.1029/2003GL018111.

Vose, R.S., T.R. Karl, D.R. Easterling, C.N. Williams, 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, RK Kaufman, C. J. Tucker, and R. B. Myneni, 2004: Evidence for a significant urbanization effect on climate in China. Proc. of the Nat. Academies of Sciences, 101, 9540-9544.

Average trends: 0.5*[ (1969/78-59/68)+(1989/98-79/88) ]

| | | 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 |

Table 1: Seasonal and annual 40-year trends of the observations, NNR and their difference, computed as an average of the trends from the decade 1959/1968 to the decade 1969/`978 (before satellites), and from the decade 1979/`988 to the decade 1989/1998 (after satellites). See section 2 for a discussion of the computation of the trends.

Trends computed from the mean during 1959/1968 to the mean during 1969/1978

| | | Year | Spring | Summer | Fall | Winter |
|---|---|---|---|---|---|---|
| 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

| | | Year | Spring | Summer | Fall | Winter |
|---|---|---|---|---|---|---|
| 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 |

Table 2: Same as Table 1 but showing separately the trends in the first two decades and in the last two decades.

Adjustment due to non-urban adjustments made to the USHCN observations

| Trends ($^{o}$C/decade)<br>(data used for the trend) | Tmax | Tmin | Tmean | DTR |
|---|---|---|---|---|
| (a) USHCN non-urban adjustments<br>(nonurban adj. – raw obs.) | *0.15* | *0.03* | *0.09* | *0.12* |
| (b) Original KC land-use estimate<br>(all raw obs.- NNR) | -0.09 | 0.08 | 0.00 | -0.17 |
| (b)+(a): Adjusted land-use estimate<br>(all raw obs.-NNR)+non-urban adj. | <u>0.06</u> | <u>0.11</u> | <u>0.09</u> | <u>-0.05</u> |

Table 3: Impact of the non-climatic, non-urban adjustments (estimated from the USHCN subset of stations, in italic) on our original estimated trends from the raw data. Our adjusted estimates are underlined.

**List of figures:**

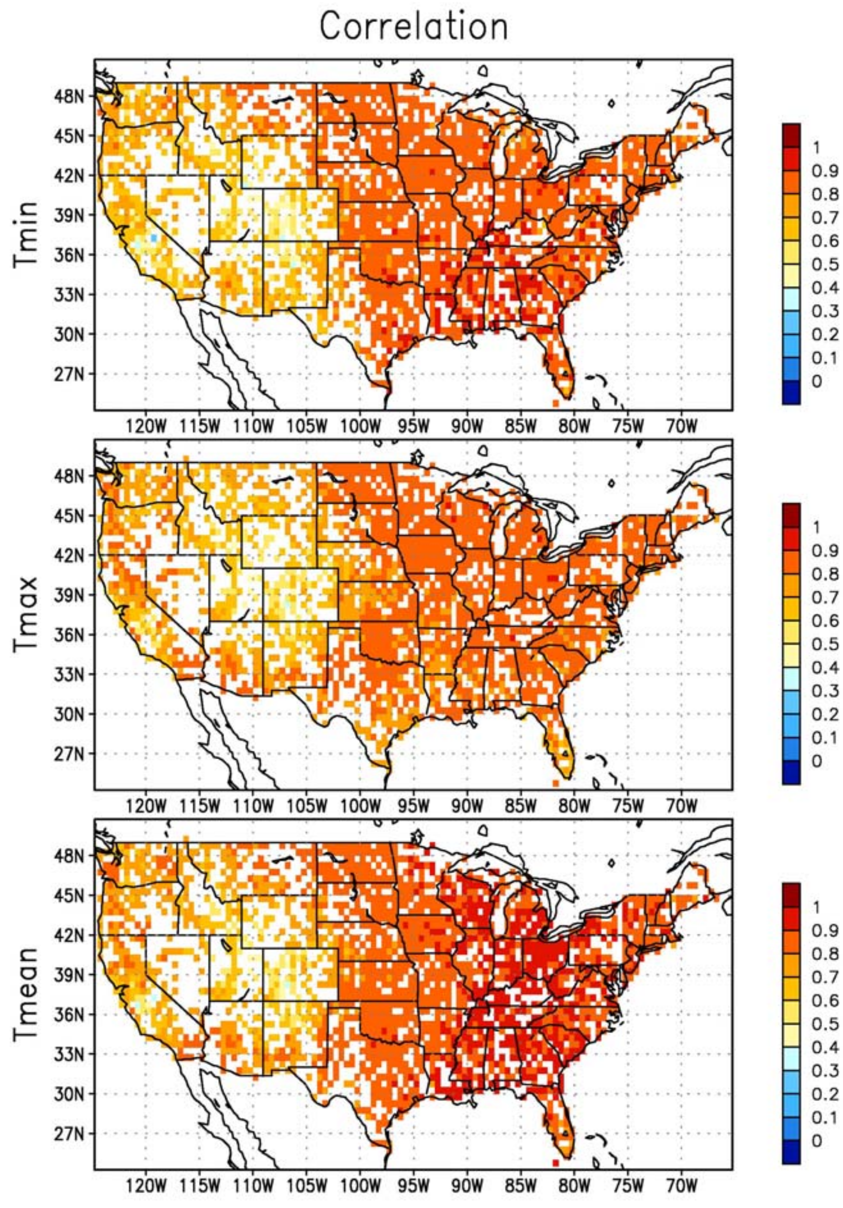
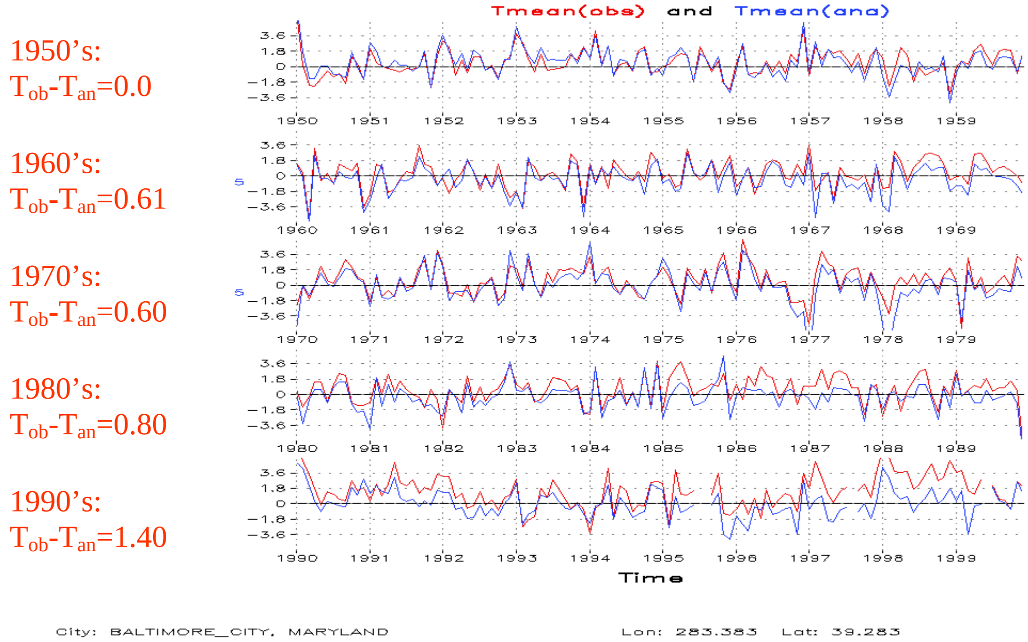



Fig. 1: Correlation between the surface temperatures anomalies with respect to the 50 year annual cycle for stations and for the NNR. Top: Minimum temperature, middle: maximum temperature, bottom: mean temperature.



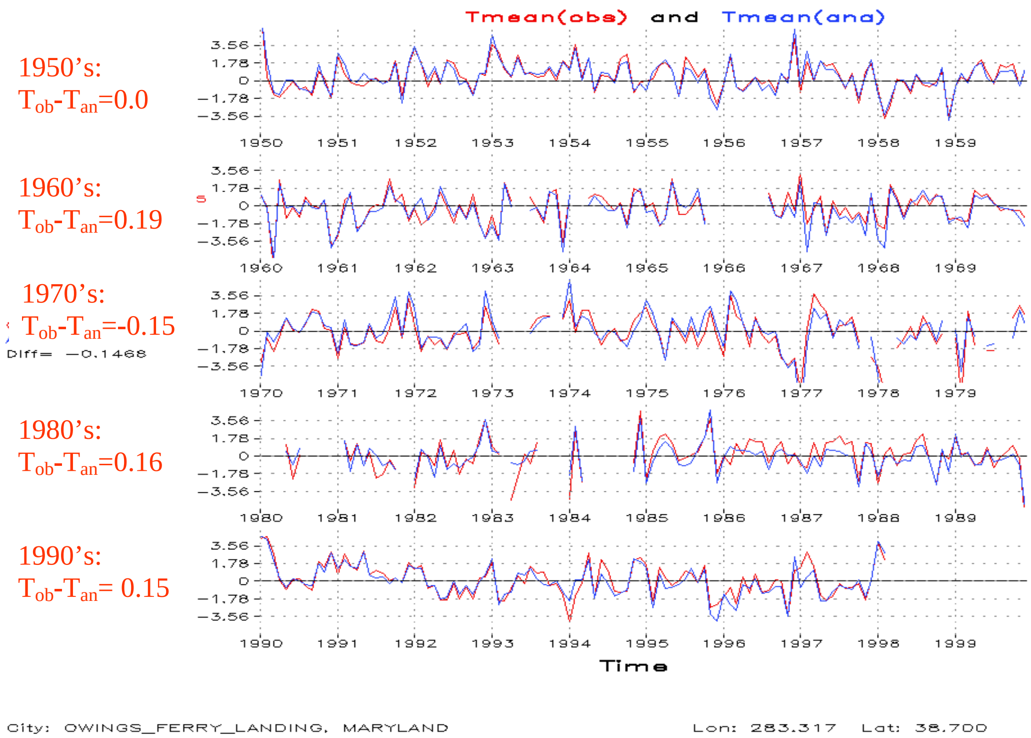




Fig. 2: Comparison of the monthly averaged temperature anomalies for the NNR (blue) and stations (red), shifted so that they have the same average during the 1950's. The stations are Baltimore and Owings Ferry Landing, both in Maryland.

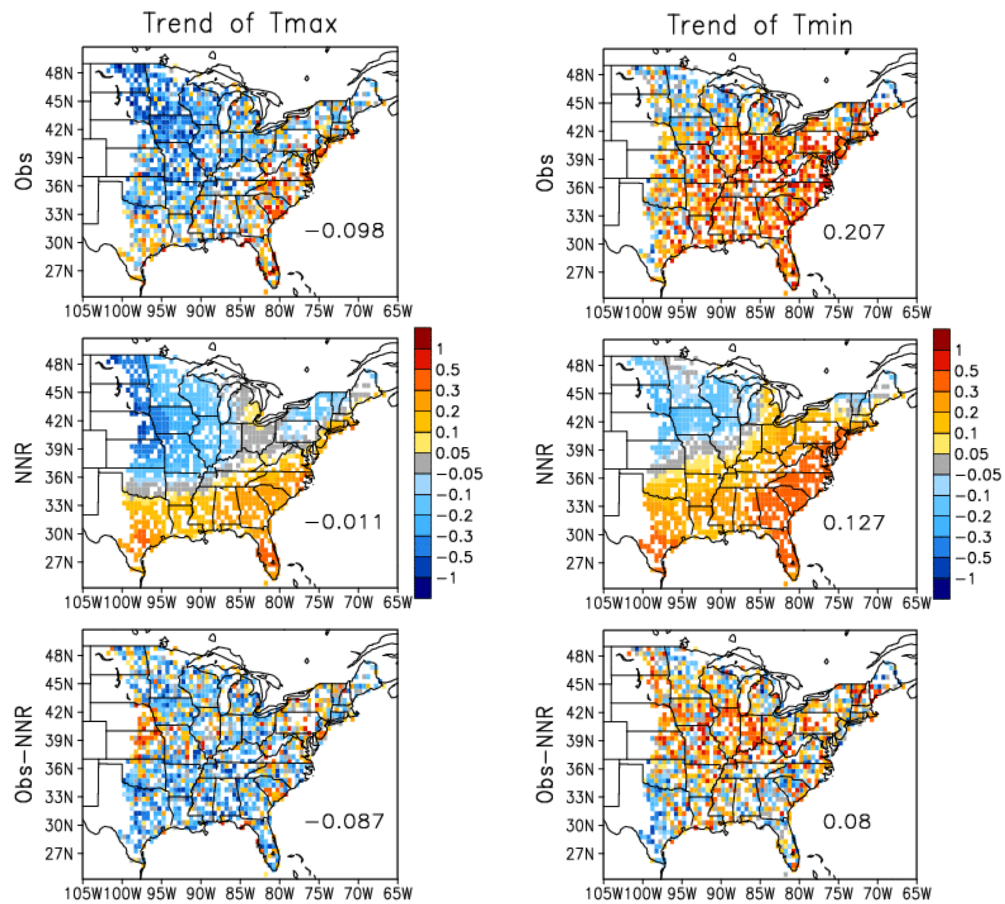



Fig. 3: 40-year temperature trends for the US over stations located below 500m, averaged over 0.5$^{o}$ latitude by 0.5$^{o}$ longitude. Top panel: trends from stations, middle panel: from the NNR, bottom panel: observations minus NNR trend. Left: trend of maximum temperature, right, trend of minimum temperature. The number represents the average trend east of the Rockies, area weighted by cosine of the latitude.

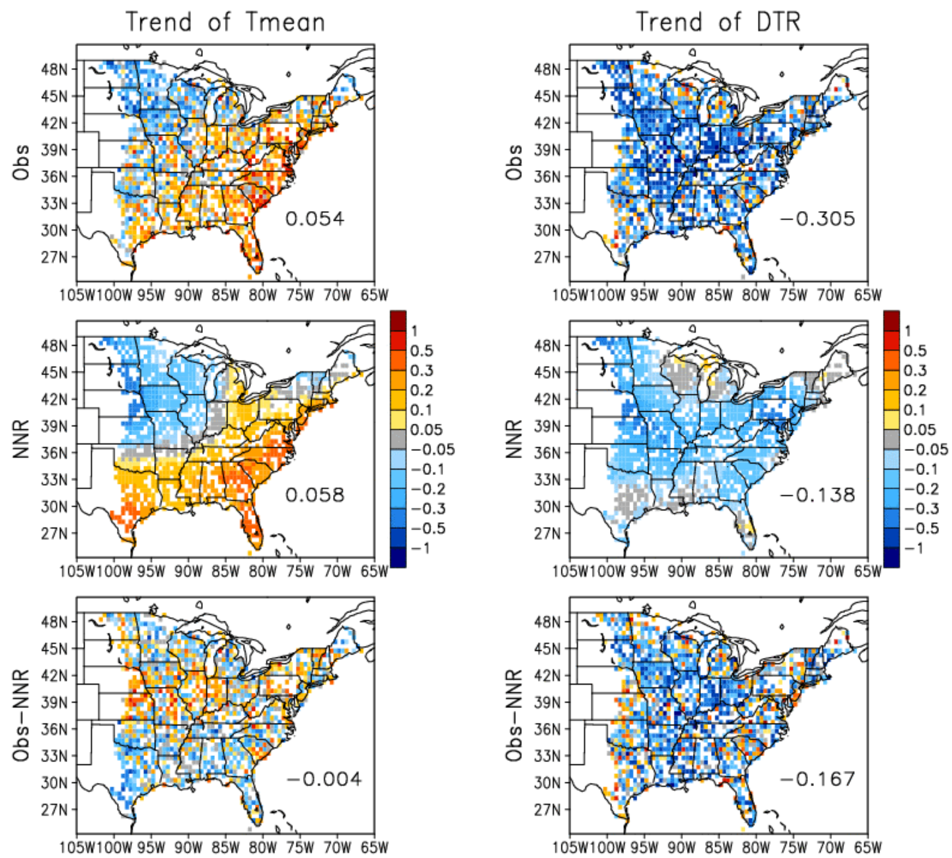



Fig. 4: As Fig. 3 but for the mean temperature (left) and the diurnal temperature range (right).

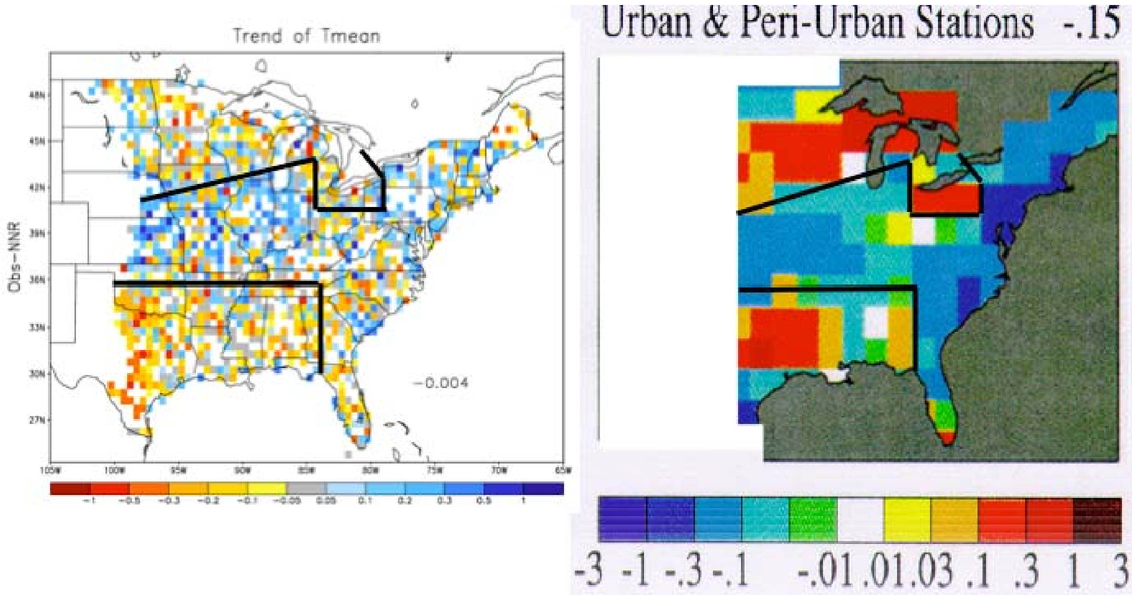



Fig. 5: Comparison of two land-use impact trends. Left: trend difference between the raw observations and the NNR where the scale of colors has been reversed so that warming appears as blue, in units of C/decade. Right: urban *correction* (opposite of the trend) obtained by Hansen et al. (2001) using 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.

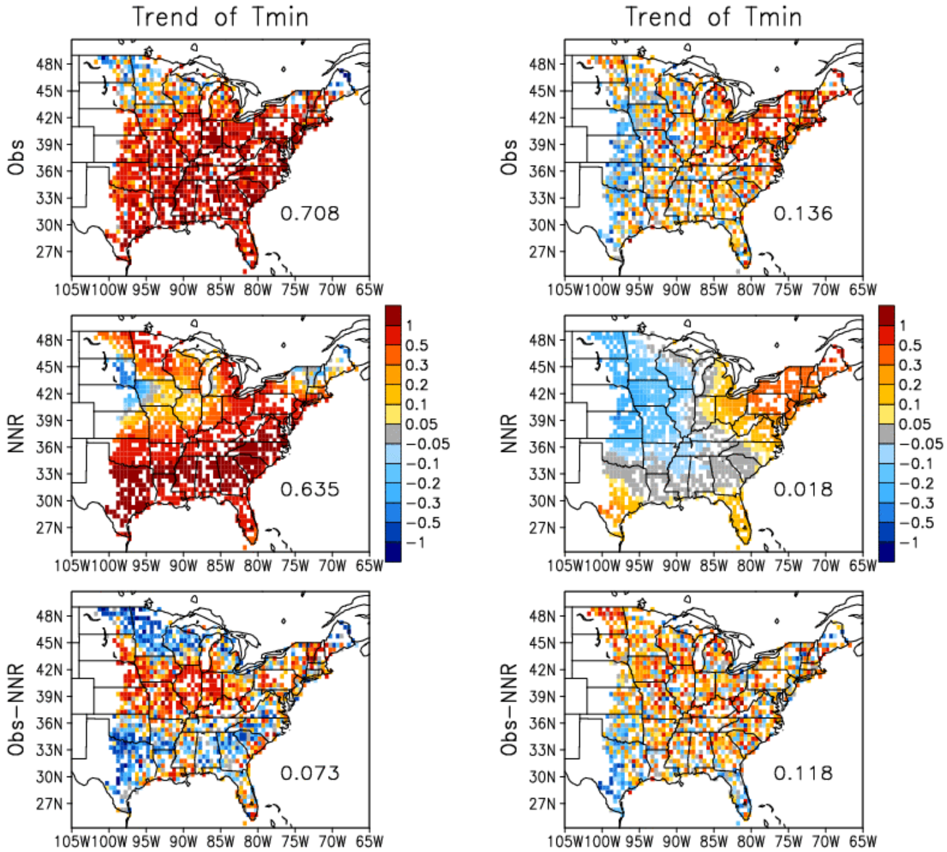



Fig. 6: As in Fig. 3, but for the winter (left) and summer (right) trends of minimum temperature.

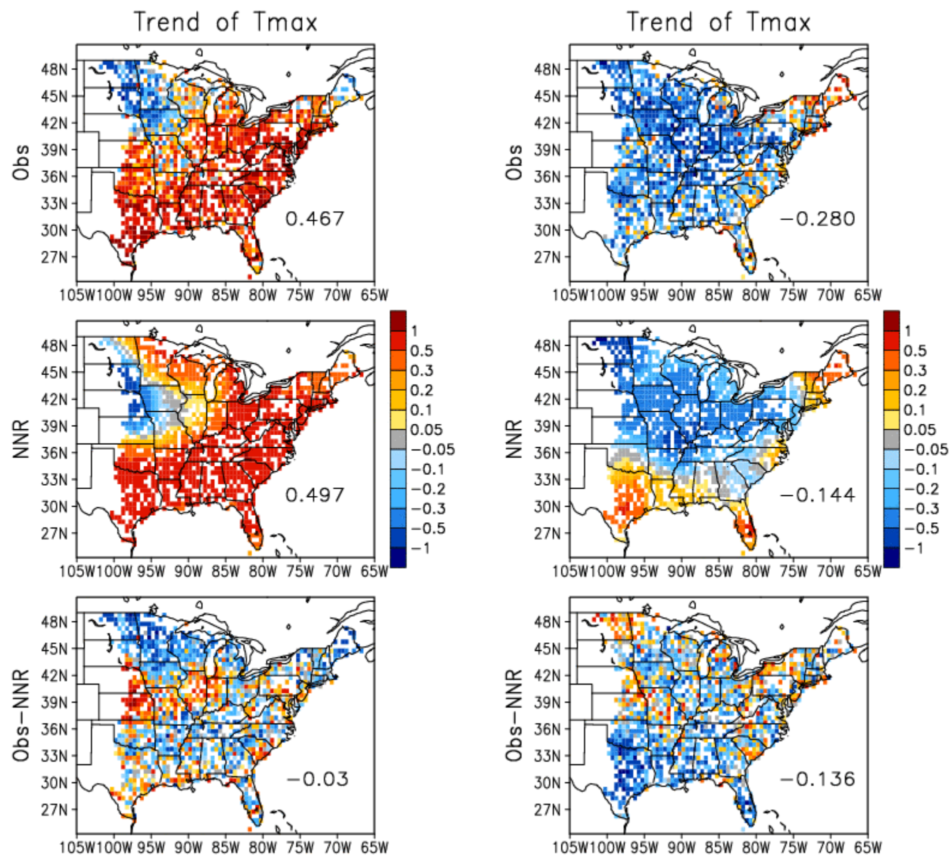



Fig. 7: As in Fig. 3 but winter (left) and summer (right) trends of maximum temperature.

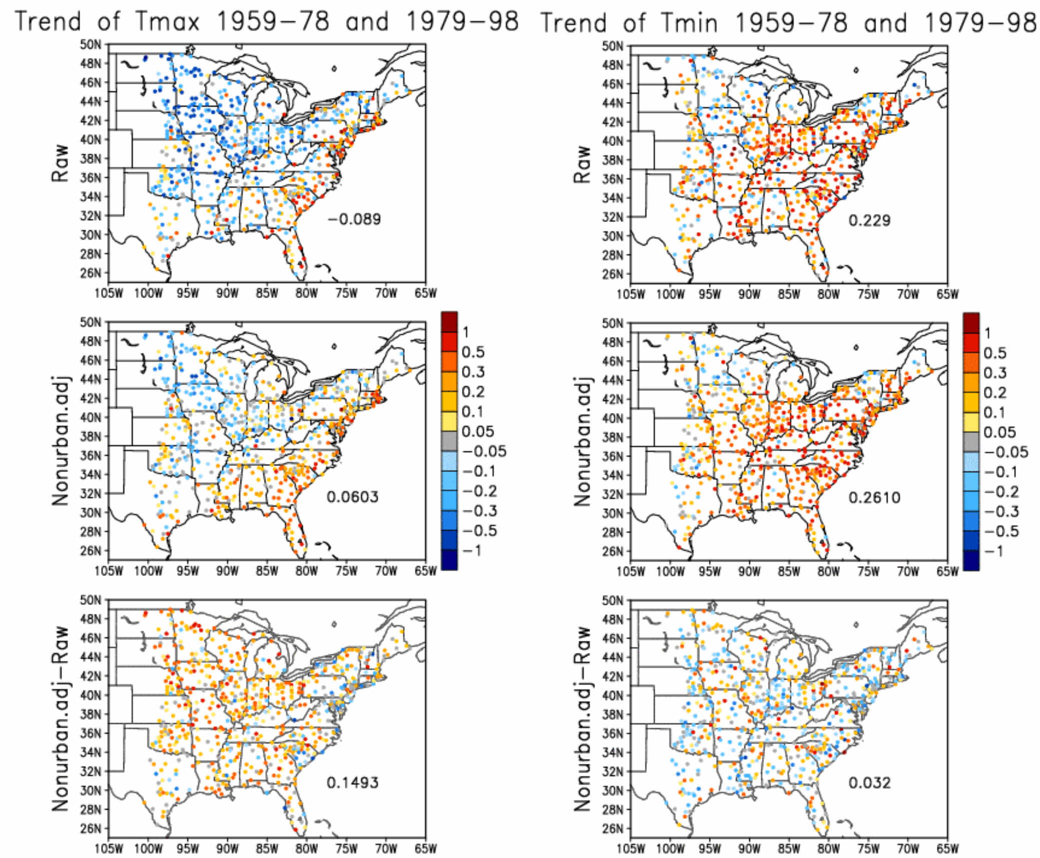



Figure 8: Trends computed for the same areas and periods used in Figures 3-6 but using the USHCN data subset. Top: trend of the raw data (comparable to the top of Figure 3 using all the data). Center: trend including all the non-climatic adjustments except for the urban adjustment. Bottom: Impact of the non-urban adjustments on the trend. Left: Tmax; Right: Tmin.

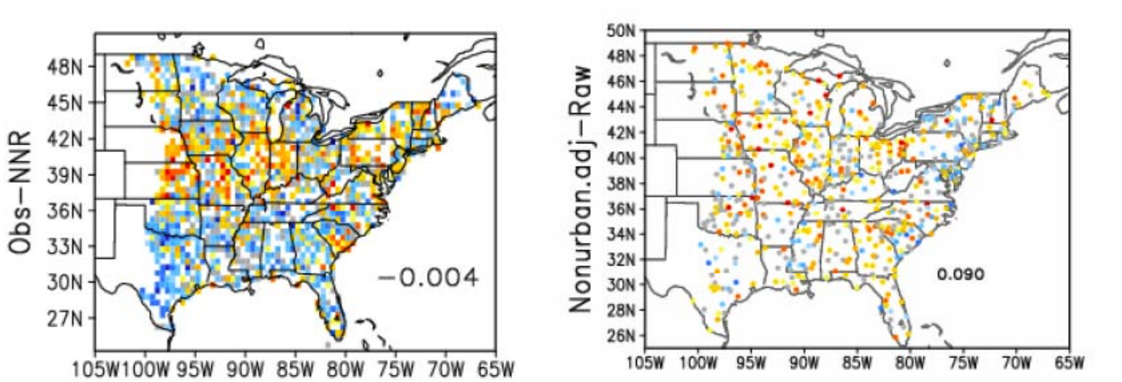



Fig. 9: Comparison of the land-surface estimated Tmean trends obtained in the present study (left) and the trends on Tmean due to all non-urban adjustments using the USHCN stations. The color scheme is the same for both figures, and is reversed with respect to Fig. 5.