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Observed changes in the diurnal temperature and dewpoint cycles across the United States

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Abstract. We analyzed hourly coterminous U.S. airport data, beginning in 1948, for changes in daily temperature and dewpoint regimes. We found an ubiquitous phase shift in the daytime cycle of warming, towards later in the day. Overall day and night temperature changes were very consistent with the results of *Karl et al.* [1993] even though this is an entirely different source of data, and one that is not specifically deurbanized, although we attempted to use stations that were not from downtown airports. We divided our results into eastern and western subsets as a first approximation for high and low sulfate aerosol conditions, and found evidence that was consistent with a sulfate effect on overall temperature, but inconsistent with modeled estimates of the effect of sulfates on the intradiurnal regime. It is difficult to establish the causes of the observed intradiurnal phase shift of warming time although urbanization and anthropogenic emissions are likely to be involved. The nature of our finding is subtle, and is consistent with other results that show very modest (and nonobvious) responses to greenhouse changes. Further research will ultimately clarify its causes and effects.

Introduction

Most temperature studies that have been designed to look for long-term climate change use data that are based on two observations made each day—maximum temperature and minimum temperature. From these observations, changes in seasonal and annual mean temperatures have been examined [e.g. *Jones et al.*, 1986; *Jones and Wigley*, 1990], as have changes in the diurnal temperature range [e.g. *Karl et al*, 1993]. However, studies based on this type of data cannot reveal how the structure of temperature within the day has been altered to produce the observed changes. Such intradaily temperature changes are important in evaluating the environmental response to climate change and, as such, need to be better understood in order to assess the overall impact of anthropogenic climate forcing. To answer these questions, temperature observations on a finer temporal scale must be employed.

Hourly weather data exist for many stations in the U.S. since the late 1940s. However, since hourly data are cumbersome to use (due to the large number of observations), few studies have employed them to look for changes in the diurnal pattern of daily temperatures. Rather, a modeling approach has been taken. *Stenchikov and Robock* [1995], for example, employed a sophisticated radiative-convective model to investigate how the diurnal temperature structure might be affected by changes in atmospheric CO_2 and aerosols concentrations. Clearly, however, an analysis of observations is needed to examine the validity of the modeled results.

In this work, we undertake such an investigation. We study temporal changes in the diurnal temperature cycles of 15 stations across the United States using hourly data collected at the stations, and we hypothesize possible causes for the observed changes.

Data and Analyses

Hourly surface climatological data were obtained from the National Climatic Data Center (NCDC) for over 70 stations across the United States. Stations which record hourly data are typically located at major airports, where current data are needed for proper flight operations. Typically, urban centers grow around communication hubs so many of the hourly weather stations can be used as prime examples of urbanization effects on weather observations. In an effort to minimize the urban heat island influence on our analysis, we tried to choose stations which were not in highly urbanized locations, although some of our stations (Denver, for example) clearly evolved in an increasingly urban direction and may have begun to suffer from this effect.

In all, 15 stations were selected from this NCDC data set in an effort to provide the best combination of geographic coverage, lack of urban heat influences, availability of hourly data, and duration of available record. Hourly data in this data set generally began in 1948 and ended in 1991. During the late 1960s though the mid-1970s, many U.S. stations changed reporting frequencies from hourly to three-hourly. Therefore, most stations contain a period of years in the middle of their record for which data were not suitable for our analyses. However, since we are primarily interested in the ends of the records, this data gap did not severely limit our station selection. Selected stations contained at least 30 years of usable data (Table 1).

The data were analyzed in 13-hour periods centered on the local times of sunrise and sunset. The time of local sunrise/set was calculated and assigned to the whole hour to which it was closest. This assignment introduced an error of no more than 30 minutes between the actual time of sunrise/sunset and the reported data. By using this floating reference frame, we were better able to characterize the diurnal cycle over extended periods (seasonally), since the actual times of sunrise/sunset (and thus the hourly traces of temperature) vary by many hours over the course of a year. Through this technique, we were able to extract a clearer signal from the data. The results from each analysis (i.e., sunrise-centered and sunset-centered) were then combined to approximate a complete 24-hour diurnal cycle.

A simple regression analysis was performed on the seasonally averaged (DJF, MAM, JJA, SON) temperature and

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Table 1. Station used in this study

Station	Region	Available Years
Albany, NY	East	1945-64, 1968-74, 1982-91
Birmingham, AL	East	1948-65, 1978-79, 1981-91
Covington, KY	East	1948-65, 1973-91
Denver, CO	West	1948-64,1968,1973-91
Flint, MI	East	1948-63, 1970-76, 1982-91
Las Vegas, NV	West	1948-63, 1977-1991
Madison, WI	East	1948-64, 1973-91
Memphis, TN	East	1948-64, 1972-91
Point Mugu, CA	West	1948-70, 1981-87
Portland, OR	West	1948-64, 1973-91
Raleigh/Durham, NC	East	1948-64, 1972-91
Salt Lake City, UT	West	1948-91
Topeka, KS	West	1948-64, 1973-91
Wilmington, DE	East	1948-64, 1977-91
Youngstown, OH	East	1948-64, 1973-77, 1982-91

dewpoint temperature for each of the six hours preceding and following the time of sunset and sunrise as well as for the sunrise and sunset times themselves. The slopes of the best fit least-squares lines though the seasonal time series were then plotted against the hour of the day. These plots allow one to examine not only the trends in each successive hour of the day, but also the relationship of the hours to one another. The shapes of the hour-to-hour curves show the actual changes in the nature of the diurnal temperature and moisture cycles and provide information regarding changes in daytime warming rates and nighttime cooling rates.

Results and Discussion

Since the results from the 15 stations all were somewhat similar, we aggregated them in order to best assess their overall behavior (Figure 1). We present our results as one and one-half complete diurnal cycles in order to best illustrate the changes to the warming half and the cooling half of the daily temperature curve. During the winter and summer seasons, when day or night lengths are less than 12 hours, the diurnal curves are not complete; but this is of little consequence since the data are well-behaved and the missing hours are easily inferred.

It is clear from Figure 1 that nighttime temperatures are warming relative to daytime temperatures, producing a decrease in the daily temperature range. In three seasons of the year (spring, summer, and fall) nights are warming (positive slopes during all hours) and in two seasons (spring and summer) days are warming. Daytime temperatures are generally decreasing during the fall; and both daytime temperatures and nighttime temperatures are decreasing in the winter. These results are consistent with the findings of *Karl et al.* [1993], which showed a decrease in the daily temperature range across the U.S. occurring primarily as a result of night warming relative to daytime and which showed the same general seasonal signal in the mean temperature changes as our results. These similarities are encouraging, considering that the dataset used by *Karl et al.* [1993] was made up primarily of rural stations exhibiting no urban effect.

We also observed dewpoint temperatures across the country to be increasing during both day and night in all seasons except winter. There is additionally a slight tendency for daytime dewpoint temperatures to be increasing relative to the the night, most notably in the spring and summer seasons.

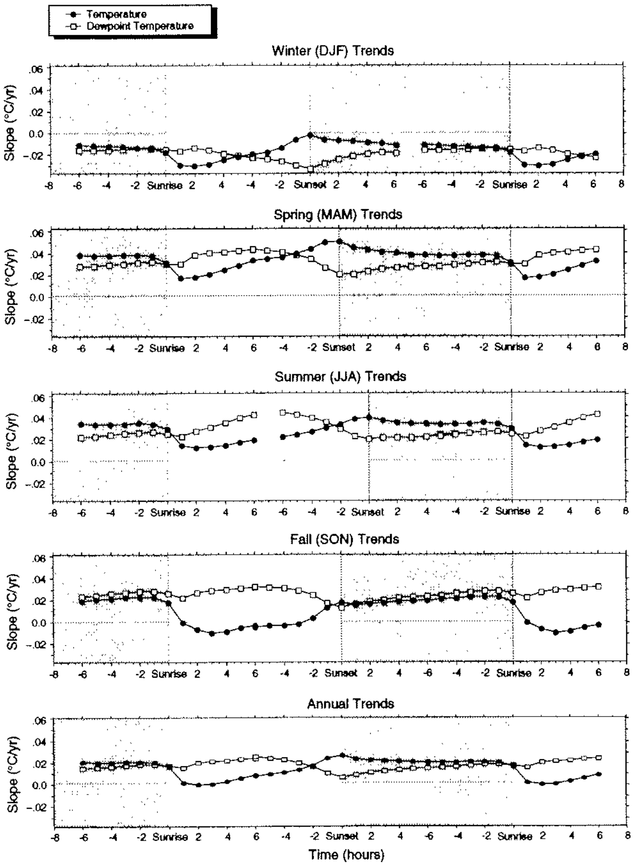

Figure 1. Trends in hourly temperatures for the 15-station aggregate representing the entire U.S. for each season and annually. The shaded portions of each graph represent nighttime.

In order to assess changes in the *pattern* of intradaily temperatures, we examined the trends in the hourly temperatures relative to each other. During the night, the hour-to-hour temperature trends exhibit a slight downward slope relative to each other from sunset to sunrise in all seasons except fall. This observation indicates that the rate of cooling during the night has been increasing, contrary to what one might intuitively expect from the general observation of warming nights. The increase is probably not caused by a general increase of outgoing radiation due to increased temperatures, however; since, during the winter, overall temperatures have declined, and the nighttime cooling rate increase is still present. It is also likely not caused by decreases in atmospheric water vapor, since the nighttime dewpoint temperatures have increased in most cases. The change in cooling rate is slight however; and in general, the observed change in nighttime temperatures has been such that the *mean* hourly temperatures have changed while their relationship to each other has remained relatively constant.

During the daytime, however, a definite change in the shape of the hourly warming curve has been observed. The change is such that the late afternoon hours have become warmer relative to the rest of the day, while the pre-noon hours have cooled when compared to the hours surrounding them. This pattern of change is found across all seasons and is occurring regardless of whether daytime temperatures are warming or cooling (slopes of the hourly temperatures are

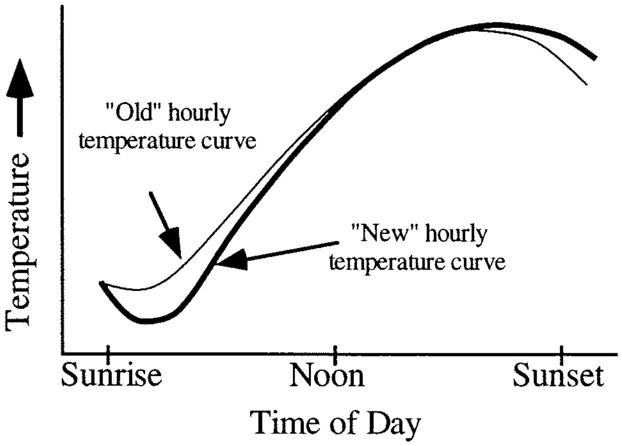

Figure 2. Schematic diagram of the daytime portion of the diurnal temperature cycle showing that the late afternoon hours have become relatively warmer, while the early morning hours have become relatively cooler. The two curves are matched at sunrise to most clearly illustrate the changes.

increasing or decreasing). This change represents a slight phase shift in the diurnal heating rate towards later in the day (Figure 2).

There are many influences on the local diurnal cycle of temperature, including CO_2 and aerosol forcing and associated water vapor and cloud feedbacks, land surface moisture and biosphere feedbacks, aerosol effects on cloud and cloud ice microphysics, vertical and horizontal advection, other greenhouse gases, etc. [*Stenchikov and Robock*, 1995]. In addition to atmospheric changes, urbanization or local site changes can also have an influence. It is therefore difficult to isolate any of these as the probable cause of the observed changes. We can, however, discuss some causes in light of the observations and of previous studies.

Since the observed patterns of change show up in aggregates of stations, local effects on each station are unlikely to be the cause, unless similar changes are occurring at most of the stations. One such uniform change might be urbanization. Even though we have attempted to select stations in which this effect would be minimized, it has been shown [*Karl et al.*, 1988] that even small changes in the local urban environment can be detected in the temperature record. *Landsberg* [1981] finds that buildings and pavement tend to store heat, so that the temperature does not fall off as rapidly after the afternoon high temperature has been reached. This elevates temperatures in late afternoon and throughout the night. This effect is very much like the one that we find in our data—temperatures increasing late in the afternoon and throughout the night relative to the early part of the day.

In a succeeding study of this interesting record, we will add several remote Canadian stations in order to provide a better parameterization of the urban component of our findings—resources were not available at the time of this work to perform that analysis. However, we currently hypothesize that, because the diurnal phase shift shows up in all of our individual records, it is not purely urban.

Atmospheric water vapor, as measured by the surface dewpoint, is generally increasing across all hours of the day and in every season except for winter. Since atmospheric water vapor plays a strong role in the radiation budget, changes in its concentration may be manifested in the diurnal cycle. The observations show, however, that the pattern of temperature diurnal change is consistent across all seasons, with winter being no exception. This indicates that the observed phase shift in daily temperatures is not caused by general dewpoint increases.

In order to assess the effect that aerosol (primarily sulfate) loading might have on the diurnal temperature cycle, we divided the country into two parts—stations west of the Mississippi River representing relatively "clean" air, and stations east of the Mississippi River representing conditions with a higher aerosol loading. This geographic definition roughly corresponds to the regions of sulfate loading outlined by *Charlson* [1991]. Figure 3 shows the results of these aggregations. While the patterns of change in both regions are similar to each other, the magnitude of the temperature change is greater in the western station aggregate than in the eastern station aggregate. Annually, the eastern part of the country shows a small nighttime warming and little change in daytime temperatures, taken as a whole, while in the west, both nighttime and daytime temperatures have increased. Dewpoint temperatures are up in the west and have changed little in the east. If sulfate-enhanced cloudiness were responsible for the night warming, one would expect it would be minimized, rather than accentuated, in our western subset. We therefore tender as a working hypothesis that sulfates are not the primary agent responsible for the night portion of our phase shift. However, they may be reducing the overall daily maximum temperature, as this effect is more pronounced in the eastern subset.

Many studies using climate models to investigate the climatic influences of anthropogenic emissions have found that the diurnal temperature range should decrease with increasing CO_2 concentrations [*Stenchikov and Robock*, 1995; *Hansen et al.*, 1995; *Hansen et al.*, 1993; *Cao et al.*, 1992, *Rind et al.*, 1989] and increasing sulfate concentrations [*Stenchikov and Robock*, 1995; *Hansen et

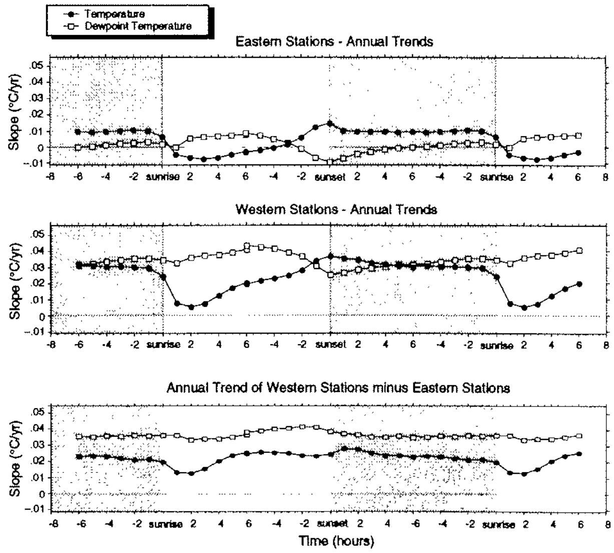

Figure 3. Annual trends in hourly temperatures for the 9-station aggregate representing the eastern (sulfate) region (top); 6-station aggregate representing the western (sulfate-free) region (middle); and the difference between the west and the east regions (bottom).

al., 1995; *Hansen et al.*, 1993]. Of these, *Stenchikov and Robock* [1995] describe how the intradaily temperatures should respond individually to these increases.

They found, through using a radiative-convective model of the land-atmosphere system, that increases in both CO_2 and aerosols, along with feedback processes, produce an equilibrium response to the diurnal cycle which lowers the daily temperature range. In addition, they found that the equilibrium CO_2 response alone also acts to raise the diurnal mean temperature more so than the equilibrium aerosol response, which can actually lower the diurnal mean temperature in some cases.

Results similar to these are found in the observations—the daily temperature range is reduced, and the aerosol laden region (east) shows less mean temperature change than does the relatively aerosol free region (west). However, the *shape* of the observed changes in the diurnal cycle is significantly different than the shape predicted by Stenchikov and Robock. The modeled decrease in the diurnal temperature range is caused primarily by decreased cooling rates at night accompanied by decreased warming rates during the day. This is not the pattern found in the observed data. Instead, nighttime cooling rates actually increase slightly while the daytime heating is shifted later into the day. The reduction in the diurnal temperature range occurs because heat of the late afternoon (after the time of high temperature) is stored longer and is not completely dissipated by the end of the night. The net change from this effect is that temperatures during the night are elevated at all hours while temperatures during the daytime, when taken as a whole, remain relatively unchanged.

Conclusions

In this paper we examined changes in the diurnal cycles of temperature and moisture by using a long history of hourly observations from 15 stations across the U.S. We found that the daily temperature range has been decreasing, primarily due to nights warming relative to days. We also found a change in the pattern of daytime warming. There has been more warming in the late-afternoon and less in the morning hours.

The decrease of the diurnal temperature range is similar in nature to the results of *Karl et al.* [1993]. They attribute the changes, in part, to increases in cloudiness across the U.S. Aerosol loading may also play a part in the observed mean temperature changes, in that stations away from regions of high aerosol loading (west) have exhibited greater temperature increases than have stations within regions of high aerosol loading (east), as predicted by the diurnal temperature model of *Stenchikov and Robock* [1995].

The changes in the pattern of the diurnal cycle are similar to those expected under conditions of increasing urbanization, although we found the pattern to be remarkably consistent across all stations. Given that we attempted to limit the urbanization signal through station selection, we cannot believe that the changes are caused by this factor entirely. The observed pattern of change did not match the pattern of diurnal temperature change predicted by *Stenchikov and Robock* [1995] to occur under conditions of increased CO_2 and sulfate aerosols. Surely this result does not rule out the effects of anthropogenic emissions, but neither does it validate them. Instead, further study is needed.

Our results indicate that an interesting climate change is occurring in the diurnal cycle of temperature and moisture. The change is subtle, inasmuch as it has, to date, escaped detection, and any effects it may have on the natural environment are likely to be equally subtle. This is consistent with other results [e.g. *Karl et al., 1995; Thompson, 1995*] that show very modest (and nonobvious) responses to greenhouse changes. However, it is unclear as to whether the observed changes are due to the anthropogenic influences of the greenhouse effect, urbanization, or both. Nonetheless, it is important to understand the causes and effects of this change in the way that heat is distributed throughout the day.

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References

Cao, H.X., J.F.B. Mitchell, and J.R. Lavery, Simulated diurnal range and variability of surface temperature in a global climate model for present and doubled CO_2 climates, *J. Climate*, 5, 920-943, 1992.

Charlson, R.J., J. Langner, H. Rodhe, C.B. Leovy and S.G. Warren, Perturbation of the Northern Hemisphere radiative balance by backscattering from anthropogenic sulfate aerosols, *Tellus*, 43A-B(4), 152-163, 1991.

Hansen, J., M. Sato, and R. Ruedy, Long-term changes of the diurnal temperature cycle: Implications about mechanisms of global change. *Atmos. Res.*, 37, 175-209, 1995.

Hansen, J., A. Lacis, R. Ruedy, M. Sato, and H. Wilson, How sensitive is the world's climate? *Natl. Geogr. Res. Explor.*, 9, 142-158, 1993.

Jones, P.D., S.C.B. Raper, R.S. Bradley, H.F. Diaz, P.M. Kelley, and T.M.L. Wigley, Northern Hemisphere surface air temperature variations: 1854-1984. *J. Clim. App. Met.*, 25, 161-79, 1986.

Jones, P.D., and T.M.L. Wigley, Global Warming Trends. *Sci. Amer.*, 263, 84-91, 1990.

Karl, T.R., P.D. Jones, R.W. Knight, G. Kukla, N. Plummer, V. Razuvayeu, K.P. Gallo, J. Lindesday, R.J. Charlson, and T.C. Peterson, Asymmetric trends of daily maximum and minimum temperature, *Bull. Am. Meteorol. Soc.*, 74, 1007-1023, 1993.

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

Karl, T.R., R.W. Knight, and N. Plummer, Trends in high-frequency climate variability in the twentieth century. *Nature*, 337, 217-220, 1995.

Landsberg, H.E., *The Urban Climate*, 285pp., Academic Press, New York, NY, 1981.

Rind, D., R. Goldberg, and R. Ruedy, Change in climate variability in the 21st Century. *Climate Change*, 14, 5-38, 1989.

Stenchikov, G.L., and A. Robock, Diurnal asymmetry of climatic response to increased CO_2 and aerosols: Forcings and feedbacks. *J. Geophys. Res.*, 100, 26211-26227, 1995.

Thomson, D.J. 1995, The seasons, global temperature, and precession, *Science*, 268, 59-68, 1995.

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