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Asymmetric Trends of Daily Maximum and Minimum Temperature

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AN AMS CONTINUING SERIES

GLOBAL CHANGE

THIS ARTICLE IS THE SECOND IN A SERIES OF ARTICLES REPORTING ON THE U. S. GLOBAL CHANGE RESEARCH PROGRAM AND INTERNATIONAL GLOBAL CHANGE ACTIVITIES WITH PARTICULAR EMPHASIS ON THE WORLD CLIMATE RESEARCH PROGRAM, THE INTERNATIONAL GEOSPHERE–BIOSPHERE PROGRAM, AND THE HUMAN DIMENSIONS OF GLOBAL ENVIRONMENTAL CHANGE PROGRAM.

THE ARTICLES ARE SELECTED IN COOPERATION WITH THE BOARD ON GLOBAL CHANGE, BUT DO NOT NECESSARILY REFLECT THE OPINIONS OF THE NATIONAL ACADEMY OF SCIENCES, NATIONAL RESEARCH COUNCIL, OR THE AMERICAN METEOROLOGICAL SOCIETY.

A New Perspective on Recent Global Warming:

Asymmetric Trends of Daily Maximum and Minimum Temperature

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Abstract

Monthly mean maximum and minimum temperatures for over 50% (10%) of the Northern (Southern) Hemisphere landmass, accounting for 37% of the global landmass, indicate that the rise of the minimum temperature has occurred at a rate three times that of the maximum temperature during the period 1951–90 (0.84°C versus 0.28°C). The decrease of the diurnal temperature range is approximately equal to the increase of mean temperature. The asymmetry is detectable in all seasons and in most of the regions studied.

The decrease in the daily temperature range is partially related to increases in cloud cover. Furthermore, a large number of atmospheric and surface boundary conditions are shown to differentially affect the maximum and minimum temperature. Linkages of the observed changes in the diurnal temperature range to large-scale climate forcings, such as anthropogenic increases in sulfate aerosols, greenhouse gases, or biomass burning (smoke), remain tentative. Nonetheless, the observed decrease of the diurnal temperature range is clearly important, both scientifically and practically.

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1. Background

The mean monthly maximum and minimum temperatures are derived from an average of the daily maximum and minimum temperatures. The mean monthly diurnal temperature range (DTR) is defined as the difference between the mean monthly maximum and minimum temperatures. The dearth of appropriate databases that include information on the daily or mean monthly maximum and minimum temperature has previously impeded our ability to investigate changes in these quantities. The problem has historical roots. It arises because the climatological data that have been made accessible to the international community, by national meteorological or climate data centers throughout the world, do not normally include data with resolution higher than mean monthly temperatures. The data that are made available internationally are usually derived from the monthly climate summaries (CLIMAT messages) on the Global Telecommunications System (GTS), which do not include information on the maximum or minimum temperatures. The GTS is the means by which near-real-time in situ global climate data are exchanged. Moreover, the problem has been exacerbated because the World Meteorological Organization's retrospective data collection projects such as *World Weather Records* and *Monthly Climatic Data of the World* have always been limited to mean monthly temperatures. This has forced climatologists interested in maximum and minimum temperatures to either develop historical databases on a country-by-country basis (Karl et al. 1991) or try to work with the hourly GTS synoptic observations. The former is a painstakingly slow process, and the latter has been limited by poor data quality and metadata (information about the data) and records of short duration (Shea et al. 1992).

The first indication that there might be important large-scale characteristics related to changes of the mean daily maximum and minimum temperatures was reported by Karl et al. (1984). Their analysis indicated that the DTR was decreasing at a statistically significant rate at many rural stations across North America. Because of data accessibility problems, subsequent empirical analyses continued to focus on data from North America over the next several years (Karl et al. 1986a; Plantico et al. 1990). By 1990, however, a U.S./People's Republic of China (PRC) bilateral agreement organized by the U.S. Department of Energy and the PRC's Academy of Sciences provided the opportunity to analyze maximum and minimum temperatures from the People's Republic of China. Also about this time, the Intergovernmental Panel on Climate Change (IPCC) made arrangements with the Australian National Climate Centre to analyze maximum and minimum temperature data from southeastern Australia. The IPCC (1990) reported a significant decrease in the DTR from both of these regions. Meanwhile, work from another data exchange agreement, a bilateral agreement between the United States and the former USSR (Union of Soviet Socialist Republics), came to fruition as a dataset of mostly rural maximum and minimum temperatures was developed for the former USSR. Karl et al. (1991) reported on the widespread decrease of the DTR over the former USSR, PRC, and the contiguous United States that was reiterated by the IPCC (1992).

Additional data from other countries and updates to previous analyses have now been analyzed here and elsewhere. Additional data include the eastern half of Australia, Sudan, Japan, Denmark, northern Finland, some Pacific island stations, Pakistan, South Africa, and a few other long-term stations in Europe. Figure 1 shows the area of the globe that has now been analyzed for differential changes of the maximum and minimum temperature. The area now covers over 50% (10%) of the Northern (Southern) Hemisphere landmass, but still only about 37% of the global landmass.

2. Observed changes of mean maximum, minimum, and diurnal range

a. Spatial and season patterns of the contemporary trends

Daily maximum and minimum temperatures from more than 2000 stations were available for analysis in the countries shaded in Fig. 1 during the period 1951 to 1990 (except Sudan and the former USSR, which had data through 1987 and 1989, respectively). Selected subsets of these data were averaged within various regions of each country. Each region represents a compromise between climatic homogeneity and an adequate number of stations within its boundaries to reduce sampling error. The base period for calculating departures from the average included the years 1951–90 (or slightly fewer years in some countries, e.g., Sudan and the former USSR). The regions are delineated in Fig. 2 where, similar to other large-scale studies of the change of the mean annual temperature (Jones et al. 1986a,b; Jones 1988), the average of the trends of the mean annual maximum and minimum reveals a general rise of temperature. A decrease of the minimum temperature within any region is uncommon but is somewhat more frequent for the maximum temperature, as seen over the United States and the PRC. The differential rate of warming between the maximum and minimum temperatures is

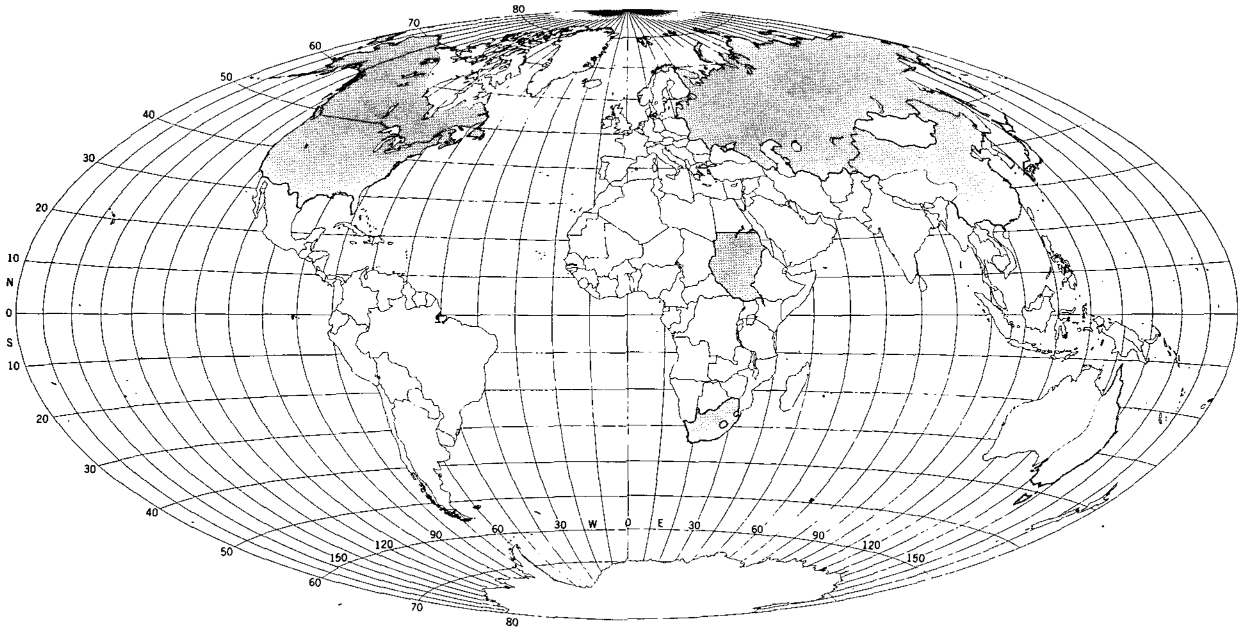


FIG. 1. Shaded areas represent areas of the world that have been analyzed for changes of mean maximum and minimum temperature.

apparent, with only a few regions reflecting an increase of the DTR. These weak exceptions occur in central Canada and southeasternmost Australia.

There are some seasonal variations of the rates of decreasing DTR, but they vary from country to country (Table 1). In Japan the decrease is not evident during summer, and it is not as strong during this season over the PRC. In the United States the decrease is weak during spring but quite strong during autumn. Alaska has strong decreases throughout the year, but Canada has only moderate decreases during summer and autumn. Over the former USSR the decrease in the DTR is significant throughout the year but somewhat weaker during the winter. Over Sudan, the rate of the DTR decrease is strong in all seasons except during the summer rainy season, where rains have been very sparse over the past few decades. Over South Africa, the DTR strongly decreases in the Southern Hemisphere spring, but actually increases slightly during autumn. In the eastern half of Australia the decrease of the DTR is apparent throughout the year but weakest during the Southern Hemisphere summer.

When collectively considered, 60% of the trends in Table 1 reflect statistically significant decreases of the DTR. A test for a change point in the trend (Solow 1987) indicates that for most seasons and areas there is insufficient evidence to suggest a statistically significant change point in the rate of the decrease.

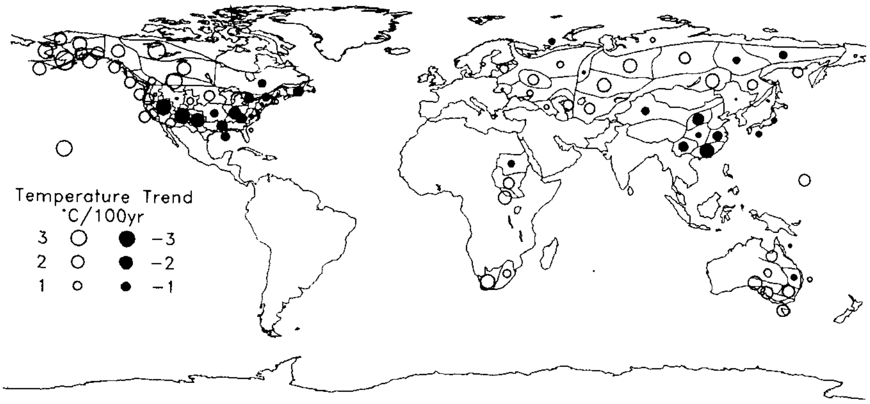
The trends can be area weighted to reflect the overall rate of DTR decrease. Table 2 shows the decrease both north and south of the equator, but without any pronounced seasonal cycle in the Northern Hemisphere. The area of available data in the Southern Hemisphere is too small to make any general statements about trends in that portion of the globe, but the decrease in the Northern Hemisphere is quite apparent. The rate of the decrease in the DTR (−1.4°C/100 years) is comparable to the increase of the mean temperature (1.3°C/100 years).

For all areas combined (Fig. 3), a noticeable differential rate of warming of the minimum relative to the maximum temperature began in the 1960s. The minimum temperature has continued to warm relative to the maximum through the 1980s. The time series ends in 1989, the year after the major North American drought, as data from the former USSR were not available past 1989. The variance of the time series is significantly impacted when such large regions drop out of the analysis, which is why the series ends prematurely. The end of the time series is significantly impacted by the major drought in North America during 1988, which leads to an enhanced DTR. Nonetheless, Fig. 3 reflects a gradual decrease of the DTR through much of the past several decades.

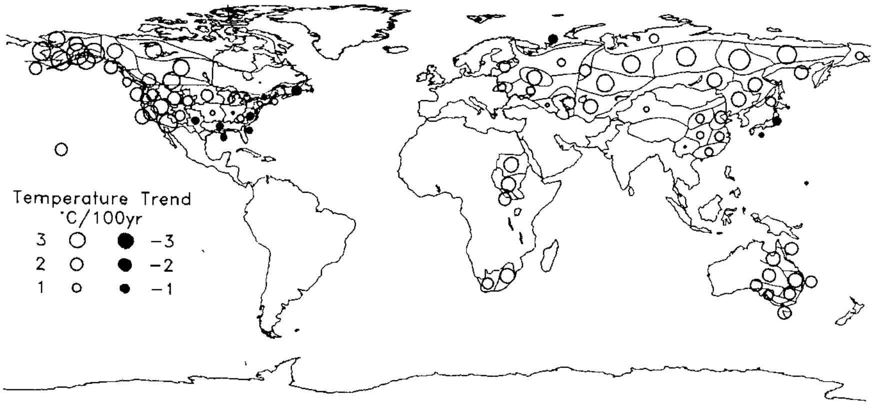
b. Longer-term variations

Unfortunately, the coverage of the globe with maximum and minimum temperature data is currently limited prior to 1951. In the United States, a network of approximately 500 high-quality stations has remained intact back to the turn of the century, and in the former USSR a fixed network of 224 (165 stations if only rural

MAX ANNUAL



MIN ANNUAL



RANGE ANNUAL

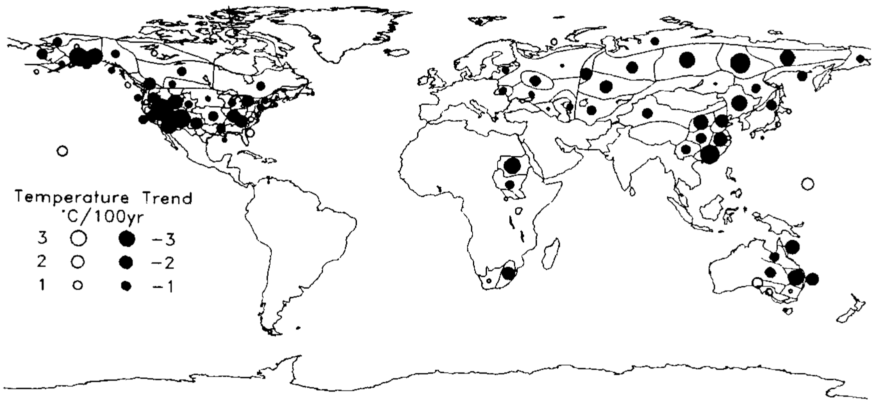


FIG. 2. Spatial patterns of annual trends of mean maximum, minimum, and diurnal temperature range (mostly 1951–90) in degrees Celsius per one hundred years. Diameter of circles is proportional to the trend and solid (open) circles represent negative (positive) trends. Circles pertain to regions within each country except for island stations, e.g., in the South Pacific and Hawaii.

stations are used) stations is available back to the 1930s. Time series from these countries reflect significant (Fig. 4) decadal variations in the DTR, as evident during the dry 1930s and early 1950s in the United States. The general decrease of the DTR did not begin in the United States until the late 1950s, and the DTR decreased rather dramatically in the mid- to late 1970s over the former USSR as part of substantial increases in the minimum temperature. The decrease of the DTR in these two countries is a phenomenon of recent decades. Data are also available farther back in time for smaller areas and countries, notably Japan, eastern Australia, and South Africa. Figure 5 indicates that the decrease in the DTR in eastern Australia occurs rather gradually since the steep decline in the late 1940s. In South Africa the decrease is predominately due to the sharp decline in the early 1950s.

A very long record of maximum and minimum temperatures was available from the Klementinum-Observatory in Prague, Czech Republic, as well as a benchmark station from northern Finland. Figure 6 portrays a remarkable *increase* of the DTR at the Klementinum-Observatory from the early to the mid–twentieth century, with a substantial decrease since about 1950. The increase coincides with the increase of mean temperature since the turn of the century, and the decrease occurs when the mean temperature reflects little overall change. In the first half of the nineteenth century, the DTR averages about 0.5°C lower compared with the latter part of the century. The DTR at Sodankylä, Finland, also displays a gradual decrease since 1950, but contrary to the Klementinum-Observatory, the decrease is evident back to the turn of the century. The mean temperature at Sodankylä reflects little or no change. The high-frequency variability of the DTR at

TABLE 1. Trends of temperature (°C/100 yr) for annual and three-month mean maximum (MAX), minimum (MIN), and diurnal temperature range (DTR) based on a weighted average of the regions (by country) in Fig. 1. Additionally, trends significant at the 0.01 level (two-tailed *t* test) are double underlined and those significant at the 0.05 level are single underlined. Trends with significant change points are denoted with an asterisk. The number of stations used to calculate the trends (in parentheses) and the time period relative to the trends is given for each country. PRC is the People's Republic of China, USA the contiguous United States of America, E. Australia the eastern half of Australia, USSR the former Union of Soviet Socialist Republics, and S. Africa the Republic of South Africa.

ALASKA (39) 1951–1990

Seasons	MAX	MIN	DTR
D–J–F	6.0	$\underline{\underline{8.8}}$	$-\underline{\underline{2.8}}$
M–A–M	3.1	$\underline{\underline{6.3}}$	$-\underline{\underline{3.2}}$
J–J–A	0.9	$\underline{\underline{2.4}}$*	$-\underline{1.5}$
S–O–N	–1.4	0.4	$-\underline{\underline{1.9}}$*
ANNUAL	$\underline{2.1}$	$\underline{\underline{4.5}}$	$-\underline{\underline{2.4}}$

USSR (FORMER) (165) 1951–1990

Seasons	MAX	MIN	DTR
D–J–F	2.8	4.2	$-\underline{\underline{1.3}}$
M–A–M	2.5	$\underline{\underline{3.8}}$	$-\underline{\underline{1.2}}$
J–J–A	–0.4*	$\underline{0.9}$*	$-\underline{\underline{1.3}}$
S–O–N	0.6	2.2	$-\underline{\underline{1.6}}$
ANNUAL	1.4	$\underline{\underline{2.8}}$	$-\underline{\underline{1.4}}$

CANADA (227) 1952–1990

Seasons	MAX	MIN	DTR
D–J–F	1.8	2.1	–0.2
M–A–M	$\underline{\underline{3.7}}$	$\underline{\underline{3.8}}$	–0.1
J–J–A	0.5	$\underline{\underline{1.4}}$	$-\underline{0.9}$
S–O–N	–2.2	–1.2	$-\underline{1.0}$
ANNUAL	0.9	1.5	$-\underline{0.6}$*

JAPAN (66) 1951–1990

Seasons	MAX	MIN	DTR
D–J–F	–0.5	–0.2	–0.2
M–A–M	–0.4	–0.7	0.3
J–J–A	0.5	0.0	0.4
S–O–N	–0.3	–0.5	0.2
ANNUAL	–0.2*	–0.4	0.2

USA (494) 1951–1990

Seasons	MAX	MIN	DTR
D–J–F	–2.3	–0.7	$-\underline{1.5}$
M–A–M	$\underline{\underline{2.3}}$	$\underline{\underline{2.5}}$	–0.2
J–J–A	–0.3*	$\underline{\underline{1.0}}$*	$-\underline{\underline{1.4}}$
S–O–N	–1.7	1.3	$-\underline{\underline{3.0}}$
ANNUAL	–0.6*	$\underline{1.0}$	$-\underline{\underline{1.5}}$

PRC (44) 1951–1988

Seasons	MAX	MIN	DTR
D–J–F	0.5	$\underline{\underline{3.5}}$	$-\underline{\underline{3.0}}$
M–A–M	–0.8	$\underline{1.4}$	$-\underline{\underline{2.2}}$
J–J–A	$-\underline{\underline{1.8}}$	–0.8*	$-\underline{\underline{1.0}}$
S–O–N	–0.6	1.0	$-\underline{\underline{1.6}}$
ANNUAL	–0.7*	$\underline{\underline{1.3}}$	$-\underline{\underline{2.0}}$*

SUDAN (15) 1951–1987

Seasons	MAX	MIN	DTR
D–J–F	–1.2	$\underline{\underline{2.7}}$	$-\underline{\underline{3.9}}$*
M–A–M	0.4	$\underline{\underline{3.3}}$	$-\underline{\underline{2.8}}$
J–J–A	$\underline{\underline{2.8}}$	$\underline{\underline{2.1}}$	0.7
S–O–N	1.4	$\underline{\underline{2.5}}$	$-\underline{\underline{1.1}}$
ANNUAL	0.9	$\underline{\underline{2.7}}$	$-\underline{\underline{1.7}}$

S. AFRICA (12) 1951–1991

Seasons	MAX	MIN	DTR
D–J–F	0.8	$\underline{\underline{2.0}}$	–1.2
M–A–M	$\underline{\underline{2.2}}$	$\underline{\underline{1.7}}$	0.5
J–J–A	1.3	1.3	0.0
S–O–N	–0.7	1.8	$-\underline{\underline{2.4}}$
ANNUAL	0.9	$\underline{\underline{1.7}}$*	–0.8*

E. AUSTRALIA (44) 1951–1991

Seasons	MAX	MIN	DTR
D–J–F	$\underline{1.8}$	$\underline{\underline{2.3}}$	–0.4
M–A–M	$\underline{\underline{1.6}}$	$\underline{\underline{2.8}}$	–1.2
J–J–A	0.8	1.4	–0.5
S–O–N	1.3	$\underline{\underline{2.2}}$	–0.9
ANNUAL	$\underline{\underline{1.4}}$	$\underline{\underline{2.2}}$	–0.7

both stations is less than that of their respective mean temperatures, but the converse is true for low-frequency variations.

If the data from the Klementinum-Observatory truly reflect the regional change of the DTR in central Europe, then the recent decrease of the DTR in this area is less persistent and less substantial than the increase prior to 1950. In light of the variations at the Klementinum-Observatory, what makes the results from Fig. 2 so remarkable is the fact that so many areas share an overall decrease of the DTR.

Recently, other investigators have also compiled information on the change of the DTR over other regions of the globe. Frich (1992) provides evidence to

TABLE 2. Trends of temperature (°C/100 yr) for annual and three-month mean maximum (MAX), minimum (MIN), and diurnal temperature range (DTR) for the areas denoted in Fig. 1 (less Pakistan, northern Finland, and Denmark). Percent of the land area covered for the Northern and Southern Hemisphere and the globe is denoted within parenthesis.

N. Hemisphere (50%) 1951–1990

Seasons	MAX	MIN	DTR
D-J-F	1.3	2.9	-1.5
M-A-M	2.0	3.2	-1.3
J-J-A	-0.3	0.8	-1.1
S-O-N	-0.4	1.3	-1.7
ANNUAL	0.5	2.0	-1.4

S. Hemisphere (10%) 1951–1990

Seasons	MAX	MIN	DTR
D-J-F	1.6	2.2	-0.6
M-A-M	1.7	2.5	-0.8
J-J-A	1.0	1.3	-0.4
S-O-N	0.8	2.1	-1.3
ANNUAL	1.3	2.0	-0.8

GLOBE (37%) 1951–1990

Seasons	MAX	MIN	DTR
D-J-F	1.3	2.9	-1.6
M-A-M	1.9	3.1	-1.2
J-J-A	-0.2	0.8	-1.1
S-O-N	-0.3	1.4	-1.7
ANNUAL	0.7	2.1	-1.4

indicate there has been a general decrease over Denmark since about 1950, based on an analysis of several long-term stations, most located in rural areas. Bücher and Dessens (1991) analyzed a long record of maximum and minimum temperatures from the Pic du Midi de Bigorre Observatory in the Pyrenees at a height of more than 2800 m. Their analysis revealed a significant decrease of DTR since the late nineteenth century, but an inhomogeneity in the record prevented a continuation of the analysis beyond 1970. Kruss et al. (1992) reported on changes of maximum and minimum temperature between the two 30-yr periods 1931–60 and 1961–90 over Pakistan. Despite considerable missing data, they managed to obtain at least 20 years of data from each of the two periods for 35 stations across Pakistan. Their analysis revealed a mix of decreasing and increasing changes of DTR. In our analysis of Pakistani data we could manage to identify only five stations with adequate data to analyze year-to-year changes; these were all located in the northern half of the country. These stations also depicted a decrease of the DTR.

c. Relation to variations of the seasonal and annual extremes

For a variety of practical considerations it is important to know whether the decrease in the mean DTR translates to a decrease in the extreme temperature range. Karl et al. (1991) provide evidence to suggest that indeed, over the United States and the former USSR (the only areas for which they had access to daily data), there was often a significant and substantial decrease in the seasonal and annual temperature extremes similar to the decrease in the seasonal and annual mean DTR. This similarity is also reflected in the time series of monthly extreme maximum and minimum temperature over Sudan (Jones 1992).

d. Data quality

A critical question arises related to the reliability of the data used to calculate the changes of the DTR. The data presented and discussed here have been subjected to various degrees of quality assurance. The degree to which precautionary measures have been taken to minimize data inhomogeneities varies considerably from country to country. In the United States,

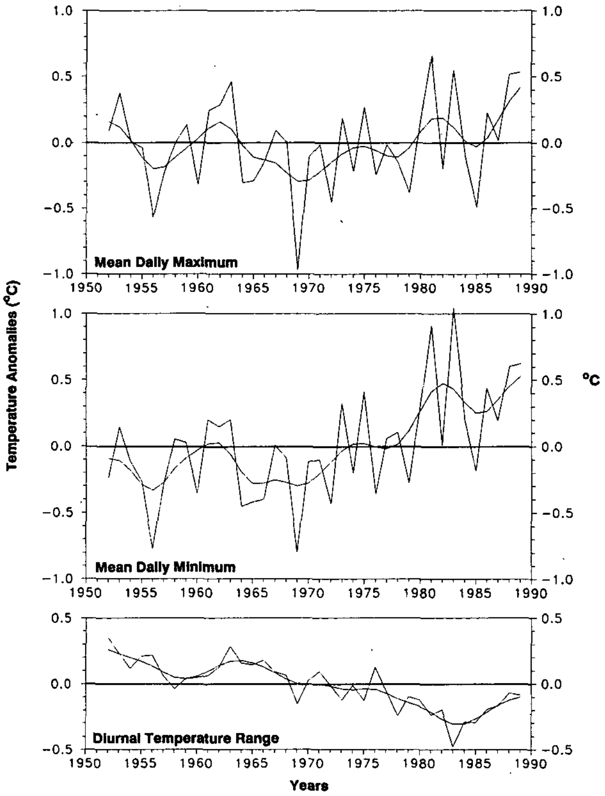


FIG. 3. Time series of the temperature anomalies of the annual mean maximum, minimum, and diurnal temperature range for 37% of the global landmass (areas shaded in Fig. 1). Smooth curve is a nine-point binomial filter with "padded" ends.

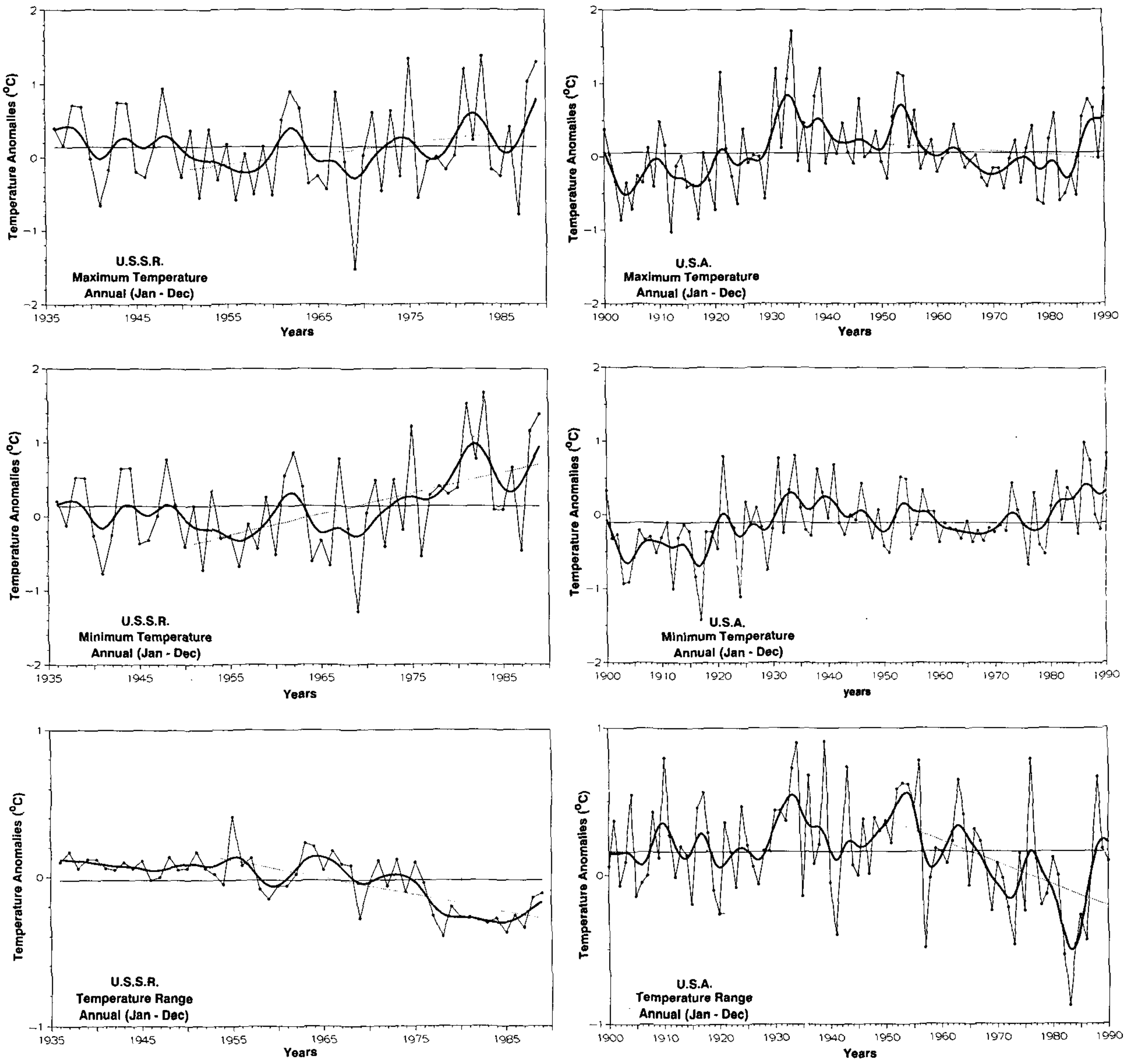


FIG. 4. Time series of the variations of the annual mean maximum, minimum, and diurnal temperature range for the contiguous United States and the former USSR. Smooth curve is the same as Fig. 3 and trends since 1951 are depicted by the dashed line.

a fixed network of stations in the Historical Climatology Network (HCN) is used (Karl et al. 1990), which largely consists of rural stations that have been adjusted when necessary for random station relocations, changes in instrument heights, systematic changes in observing times (Karl et al. 1986a; Karl et al. 1986b), the systematic change in instruments during the mid- and late 1980s (Quayle et al. 1991), and increases in urbanization (Karl et al. 1988). The potential warm bias of the maximum introduced by the HO83 series of thermometers (Gall et al. 1992) is not a factor in this network since the HO83 instrument is not used in the rural cooperative network that dominates the HCN (19 out of 20 stations).

In the former USSR the fixed network of 165 stations consists of rural stations (1990 populations less than 10 000 and local surroundings free of urban development). The former USSR data have not been adjusted for any random or systematic inhomogeneities. Station histories, however, indicate there have not been systematic changes in network operation over the course of the past 50 years.

In Canada, the results reported here are derived from a set of 227 rural stations (population less than 10 000). These data were selected from a network of 373 principal stations, but a large number of urban areas and stations, which relocated to airports, were eliminated from the analysis.

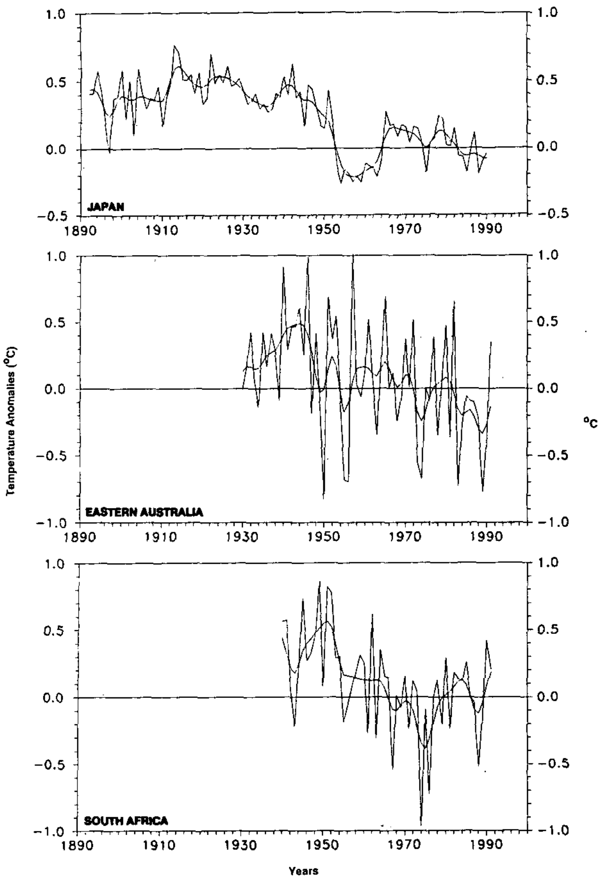


FIG. 5. Time series of the variations of the diurnal temperature range for Japan, eastern Australia, and South Africa. Smooth curve same as Fig. 3.

In Alaska, a network of 39 stations was used that included most stations operating in that state since the early 1950s with the exceptions of stations in the major cities of Juneau, Fairbanks, and Anchorage. Once again no attempt was made to adjust for station relocations, and the stations consist of a mix of instrument types with some changes at specific sites.

Station histories from the PRC do not reflect any changes in instrumentation, instrument heights, instrument shelters, or observing procedures relative to the maximum and minimum temperature. Our analysis is based on a subset of more than 150 stations available to us. No attempt was made to correct for random station relocations in the fixed network of 44 stations we finally selected from the larger network. The potential impact of urbanization precluded the use of many stations. We eliminated all stations that were in or near cities with populations of more than 160 000.

All stations in Australia are currently undergoing thorough homogeneity testing (Torok 1992, personal communication) but were unavailable for this analysis. Instead, stations were selected based on the length of record and distance from major areas of urbanization. All of the stations used in Australia are from small towns or rural areas, many from post office "backyards."

Fewer than half of the 154 stations available from Japan were used in this analysis. Similar to the PRC, many stations were eliminated because of their proximity to major urban areas. An inspection of the station histories reveals a number of network "improvements" related to the automation of the temperature measurements in recent years. A full assessment of the homogeneity of the data awaits a detailed analysis. The station networks from Sudan and South Africa include some stations from urban areas, but countrywide decreases of the DTR are not overwhelmed by these stations. Incomplete information was available regarding systematic changes in instrumentation at these locations during the past several decades, but the data were inspected and adjusted when necessary for station relocations based on temperature differences with neighboring stations. In total, four stations in South Africa were adjusted using the procedures outlined by Jones et al. (1986a).

3. Diurnal temperature range dependencies

a. Local effects

As more data become available from a variety of countries it becomes difficult to dismiss the general decrease of the DTR over the past several decades as an artifact due to data inhomogeneities. Observing networks are managed differently in each country. If local effects are significantly influencing the DTR, then at least three possibilities need to be explored. These include changes in urbanization, irrigation, and desertification. Evidence to support or refute the impact of these human-induced local and regional effects are discussed in subsequent subsections.

1) URBAN HEAT ISLAND

It is well known that the urban heat island often tends to manifest itself strongest during the nighttime hours (Landsberg 1981). In midlatitude North American cities the urban–rural temperature difference usually peaks shortly after sunset, then slowly decreases until shortly after sunrise, when it rapidly decreases, and for some cities actually vanishes by midday. In many cities, increases in urbanization would differentially warm the minimum relative to the maximum temperature.

A number of precautions have been taken to minimize the effect of increased urbanization in the climate records used in this analysis. In the contiguous United

States, the corrections for urban development recommended by Karl et al. (1988) have been applied to the data, so any residual heat island effect in this analysis should not be an issue. In Canada, only stations with population less than 10 000 were used in the analysis, and the average population of the cities in the proximity of the observing stations was slightly more than 1000. If the Canadian stations behave similarly to stations in the United States, the decrease of the DTR may be exaggerated by about 0.1°C due to urbanization. Similar values may also apply to Alaska. In the former USSR, the population limit for inclusion of any station into the network was 10 000, but in addition, no station could be within 1 km of any multistory urban development. If the impact of the effect of urbanization on the DTR in the former USSR is anything similar to that in the United States, the residual urban heat island effect on the DTR should be at least an order of magnitude smaller than the observed decrease of the DTR (nearly 1.5°C per 100 yr). In the PRC and Japan, a number of tests were conducted to identify the impact of urbanization on the DTR. Three networks of stations were categorized based on population. For the PRC, the categories included stations in proximity of cities with populations more than 1 000 000, less than 160 000, and those with populations between these two thresholds.

Categories in Japan were based on 500 000 and 50 000 threshold values. The PRC had 23, 42, and 44 stations, while Japan had 17, 71, and 66 stations, in each of the three population categories proceeding from high to low, respectively. Figure 7 shows that the decrease of the DTR actually becomes stronger in the PRC for the lowest population category compared with the moderate population category, while the trend of the average temperature continues to decrease. This suggests that urbanization effects in the PRC are dissimilar to those in the United States, as differential effects of the maximum and minimum temperature trends seem unaffected by urbanization in cities of 500 000 or less. In Japan, however, the impact of urbanization on the DTR is evident even in the lowest population category (less than 50 000); this is even more apparent for the average temperature. Based on these analyses it would seem that urbanization effects in the PRC are unlikely to significantly impact the trends reported in Tables 1 and 2.

A previous paper by Jones et al. (1990) investigated the impact of increasing urbanization in the land database used by the IPCC (1990, 1992) to calculate

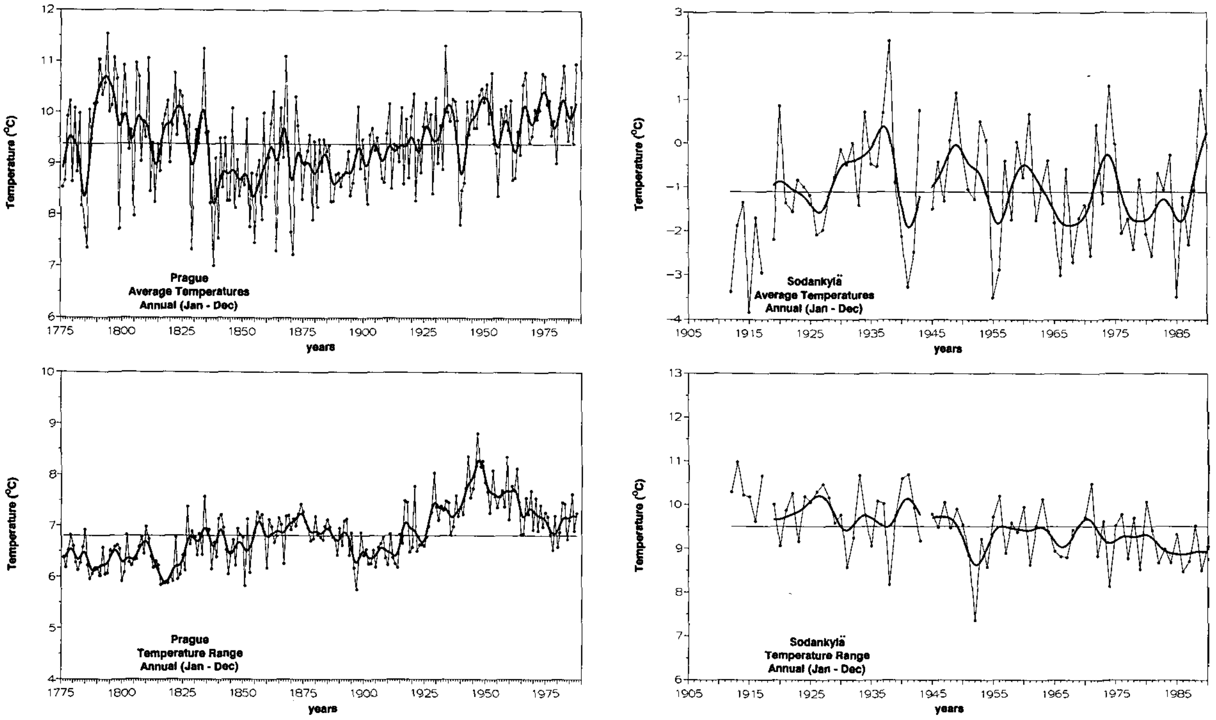


FIG. 6. Time series of the variations of the annual diurnal temperature range and the annual mean temperature from two long-term stations: Sodankylä, Finland, which has been designated as a climate reference station, and the Prague Klementinum-Observatory, Czechoslovakia. Smooth curve same as Fig. 3.

changes of global temperature. The conclusion from the work of Jones et al. (1990) was that any residual urban bias in the land-based average temperature records was about 0.05°C during the twentieth century. A comparison of the average temperature trends derived from the stations used in Tables 1 and 2 with the stations used by Jones (1988) revealed differences in trends from country to country, but virtually identical trends of temperature (within 0.02°C per 100 yr) were found when all areas depicted in Fig. 1 were considered. This suggests that the degree of urban-induced bias in these two datasets are of similar magnitude over the past 40 years, despite the use of substantially different station networks.

2) IRRIGATION

It can be argued that increases in irrigation may account for the decrease in the DTR. The evaporation associated with soil moisture would convert sensible to latent heat and thus significantly reduce daytime temperature. In order to test this hypothesis, the correlation coefficient (both Pearson product moment and the Spearman rank) was calculated using the values of the trends of the DTR and the change in land area under irrigation from 1950 to 1987 (U.S. Department of Commerce 1950, 1988) for each of the regions delineated in Fig. 2. No relationship was found between the change in the DTR and the increase of irrigated lands, and in fact many of the largest decreases of the DTR were associated with areas with the smallest increases of irrigation. Despite the significant decreases of the DTR over the past several decades and the relatively large increases of irrigation within the United States over the past 40 years compared to other countries, it seems unlikely that increases of irrigation can be regarded as a serious explanation for the widespread decreases of the DTR.

TABLE 3: Stations and years used to identify the sensitivity of the diurnal temperature range to various climatic variables.

Stations	Years
Sacramento, CA	1961–69
Tallahassee, FL	1962–70
Indianapolis, IN	1966–74
Worcester, MA	1961–69
Bismarck, ND	1973–81
Scotts Bluff, NE	1971–79
Reno, NV	1961–69
Oklahoma City, OK	1975–83
Pittsburgh, PA	1961–69
Columbia, SC	1971–79
San Antonio, TX	1973–81
Seattle/Tacoma, WA	1971–79
Spokane, WA	1966–75
Green Bay, WI	1971–79

3) DESERTIFICATION

The converse of the theoretical effects of irrigation would result from increased desertification, i. e., an increase of the DTR. This might arise from poor land practices such as overgrazing or deforestation. Given the mid- and high-latitude bias of the results reported here, it seems unlikely that desertification would have a significant impact on the results reported in Tables 1 and 2. Moreover, this effect would tend to make the magnitude of the reported decreases too small, especially during the warm season, as desertification would increase the maximum and decrease the minimum.

b. Climatic effects

Since it seems unlikely that any of the human-induced local effects can provide a satisfactory answer to the widespread decrease of the DTR, a number of climatic variables that differentially affect the maximum and minimum temperature were analyzed to discern which climatic variables most strongly affect the DTR. More than 50 000 days of climatic observations were selected from the stations listed in Table 3 during periods of consistent measurement procedures for the variables defined in Table 4. The rationale for selection of variables to be studied was based on a priori information. For example, increases of the DTR over land have previously been related to snow cover ablation as simulated by the U. K. Meteorological Office's General Circulation Model (GCM) with doubled CO_2 (Cao et al. 1992). Our analysis included more than 4000 cases of snow cover. It is well known that the ability of the surface boundary layer to absorb, radiate, transform, and mix sensible heat differentially affects the maximum and minimum temperature. The relative humidity and cloudiness are two important climate variables that influence these surface-layer properties. In this analysis cloud-related information was contained in two climatic variables: the sky cover (in tenths) and an index of the ceiling height. The ceiling height (CIG) was categorized into seven categories. The cloud ceiling is defined as height above ground of the lowest cloud layer that covers 50% or more of the sky. The wind speed is an effective measure of the degree of mixing within the

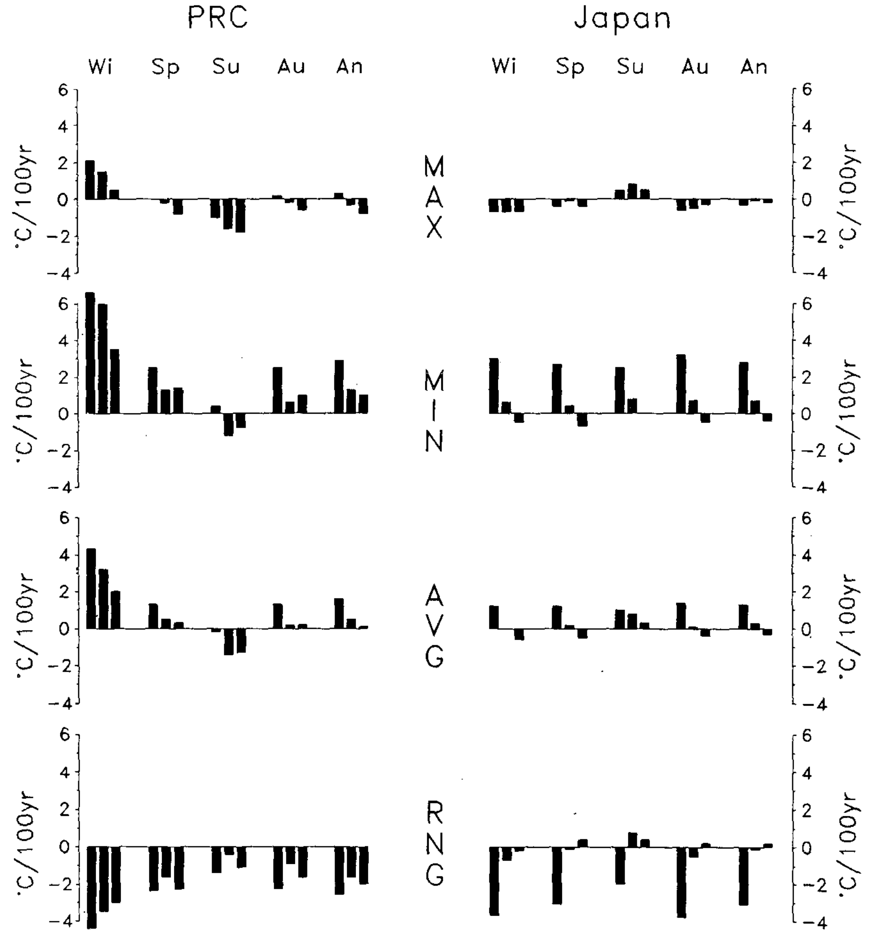


Fig. 7. Temperature trends using stations from various population categories (high, medium, low—left to right) as defined in text. Abbreviations; Wi—winter, Sp—spring, Su—summer, Au—autumn, MAX—maximum, MIN—minimum, AVG—average, and RNG—diurnal range.

surface boundary layer as it affects and interacts with the frequency or intensity of inversions and super-diabatic lapse rates. Additionally, the DTR is affected by the seasonal and latitudinal changes of incoming solar radiation as well as the magnitude of day-to-day temperature differences. The inclusion of TRAD can also be regarded as a surrogate for temperature especially when used in conjunction with the other variables listed in Table 4. Karl et al. (1986b) demonstrate the impact of the interdiurnal temperature difference on the maximum and minimum temperature. These day-to-day changes of temperature are largely controlled by the thermal advection associated with synoptic-scale cyclones and anticyclones.

All of the variables in Table 4 were used in a multiple regression analysis. Variables were regressed against the square root of the DTR, as opposed to the actual DTR, because the DTR is bounded by zero. Without the transformation, nonnormal residuals result in multiple linear regression analyses, making it more difficult to interpret the results. Figure 8a indicates that the partial correlation coefficients of each variable to the DTR are often significantly different from the simple linear correlation coefficients, making it difficult to speculate on the effect of changes in any one variable without knowing (or assuming constancy) the changes in the other variables. Given the huge sample size, very low correlations have high statistical significance (even considering the day-to-day persistence of the DTR). On a local basis, a generalized multiple linear regression model (one model for all stations and all days) based on the seven climatic variables in Fig. 8a explains about 55% (53% without the square-root transformation) of the daily variance of the DTR. Although the explained variance is substantial, it is apparent that other factors may also need to be considered with respect to explaining the variations of the DTR (e.g., better representations of the atmospheric stability, external forcing factors, more precise techniques to calculate the mean quantities used in the analysis), or that the relationships are not adequately expressed by a linear equation or both.

On a variable-by-variable basis the signs of all the partial correlations make qualitative physical sense. It is interesting to note the higher partial correlation of ΔTMP compared with the simple correlation coefficient (Fig. 8a) as the correlation between TRAD and ΔTMP mask the importance of ΔTMP in influencing DTR. The decrease of the partial correlation relative to the simple correlation for the variables RH, CIG, and SKY is to be expected because changes among each of these variables are related to each other. The decrease in the partial correlation of SNOW is particularly noteworthy, especially since Cao et al. (1992) attribute the ablation of snow cover in their model to an increase in the DTR. The empirical results in Fig. 8a suggest that SNOW is only weakly related to the DTR, especially compared to other variables.

In order to investigate the linearity, or lack thereof, of the relationships implicit in Fig. 8a, the data were

TABLE 4. Definitions and abbreviations of the climatic variables used to test the sensitivity of the diurnal temperature range.

Variables	Abbreviations
Diurnal temperature range (daily max–daily min)	DTR
Snow cover (binary, if snow depth 2.54 cm)	SNOW
Mean relative humidity (0600 LST and 1500 LST)	RH
Mean wind speed (0600 LST and 1500 LST)	WS
Mean sky cover (0600 LST and 1500 LST)	SKY
Mean ceiling (0600 LST and 1500 LST)	CIG
Total daily top of the atmosphere solar radiation	TRAD
Day-to-day temperature differences $(\lvert TMP_0 - TMP_{-1}\rvert + \lvert TMP_0 - TMP_{+1}\rvert)$	ΔTMP

partitioned by TRAD. Figure 8b provides strong evidence to suggest that the relationships change with the amount of TRAD. In particular, the partial correlation coefficients of RH, WS, and SKY become stronger as TRAD (and thus temperature) increases. This probably has more to do with a reduction of the maximum temperature than an increase of the minimum. During daylight hours high values of the RH, WS, and SKY are indicative of higher albedos, higher potential evapotranspiration, higher atmospheric water vapor absorption of incoming radiation, and larger than normal mechanical mixing. These factors act to retard the maximum temperature that would otherwise result from high intensity TRAD, which would be manifested as sensible heat within the surface boundary layer. The nonlinearity of RH as TRAD increases is substantially greater than WS (Fig. 8b). As the TRAD to the surface increases the temperature increases, and a greater portion of the TRAD can be used for evaporation compared with raising surface temperature, as would be anticipated by the Clausius–Clapeyron equation when integrated to obtain saturation vapor pressure as a function of temperature.

The reduction of the partial correlation of TRAD with the DTR after partitioning by TRAD (Fig. 8b) relates to the balance between long nights and short days. During the late autumn and early winter in the northern half of the United States (areas that include the lowest partition of TRAD), a moderate increase in the TRAD (by interseasonal and latitudinal variations) generally results in a higher DTR. Contrarily, in the warm half of the year, TRAD and its associated daylight are more than ample so that the relation between TRAD and DTR is near zero. In fact, a further partition of the TRAD into a very high category leads to negative partial correlations between TRAD and the DTR.

The reduction of the partial correlation of ΔTMP as TRAD increases is related to the decrease in intensity of the day-to-day changes of temperature during the warm season. Rossby waves and extratropical cyclones have reduced amplitude, speed, and intensity during the warm season.

A change in sign of the partial correlation coefficient of SNOW with the DTR (Fig. 8b) suggests that the length of night relative to the TRAD is a significant factor when considering the impact of changes in snow cover on the DTR. In the northern United States, around the winter solstice, TRAD is relatively low. Snow on the ground at this time of the year is important because of its excellent insulation (reduces heat flow from the soil) and high emissivity, which help lower the nighttime minimum. During the daytime the TRAD is already low, so the amount of solar radiation reflected by the snow cover is no longer as important. As a result, snow cover at this time of the year and these latitudes leads to an increase in the DTR. This is not the case as the season progresses or the latitude decreases, as reflected by the negative partial correlations (lower values of DTR with snow cover) associated with the highest category of TRAD; there were still nearly 1000 cases of snow cover. The data suggest that snow cover ablation will not necessarily lead to an increase of the DTR.

From the aforementioned analysis, it is apparent that there are many factors, often intricately related, that affect the DTR. Many of the variations in these variables are very much related to a greenhouse effect, some of which may be anthropogenically induced. Overall, the two variables related to changes in cloudiness, sky cover, and ceiling height explain the greatest portion of the variance of the DTR. Changes in cloudiness should be one of the first considerations in searching for an explanation of the observed decrease of the DTR (Fig. 2). Indeed, when large continental scales are considered, the relationship between cloud amount (or sky cover) and the DTR is quite impressive (Fig. 9). Plantico et al. (1990) have already demonstrated that the decrease in the DTR over the United States is strongly linked to an observed increase in daytime and nighttime cloud cover and a lowering of cloud ceilings.

Is there a general increase in cloud cover over much of the globe? Empirical evidence by Henderson-Sellers (1986, 1989, 1992) and Jones and Henderson-Sellers (1992) suggests this may be the case over Canada, the United States, Europe, the Indian subcontinent, and Australia. Analyses of cloud cover changes over the PRC from a network of 58 stations across the PRC are inconclusive, but there is evidence for a decrease in the sunshine (a 2% to 3% decrease in sunshine from the 1950s to the 1980s). The quality of the cloud data (and perhaps the sunshine data) is questionable because the correlation between monthly anomalies of sunshine and cloudiness at many sites is not high. Analyses of changes in cloudiness over the former USSR by Balling (1992, personal communication) reveal a general increase of cloud cover (3.5%) during the period 1965–86 with stratus and stratocumulus clouds (low ceilings) increasing in frequency by about 2%. He also found considerable interannual and interstation variability, so the quality of these data could also be called into question. Nonetheless, the trend over the former USSR is consistent with a decrease in the DTR. Frich (1992) and Bücher and Dessens (1991) also found that decreases in the DTR in Denmark and at the Pic du Midi de Bigorre Observatory occurred with an increase in cloudiness. An analysis of changes in cloud cover over Japan, using many of the same stations selected for the analysis of the maximum and minimum temperatures, indicates cloud cover may have increased on an annual basis by nearly 1% since 1951, but there is no apparent response in the DTR. Changes in sunshine in Japan are not altogether consistent with the increase in cloud cover, but a new sunshine instrument was introduced into the network in 1986.

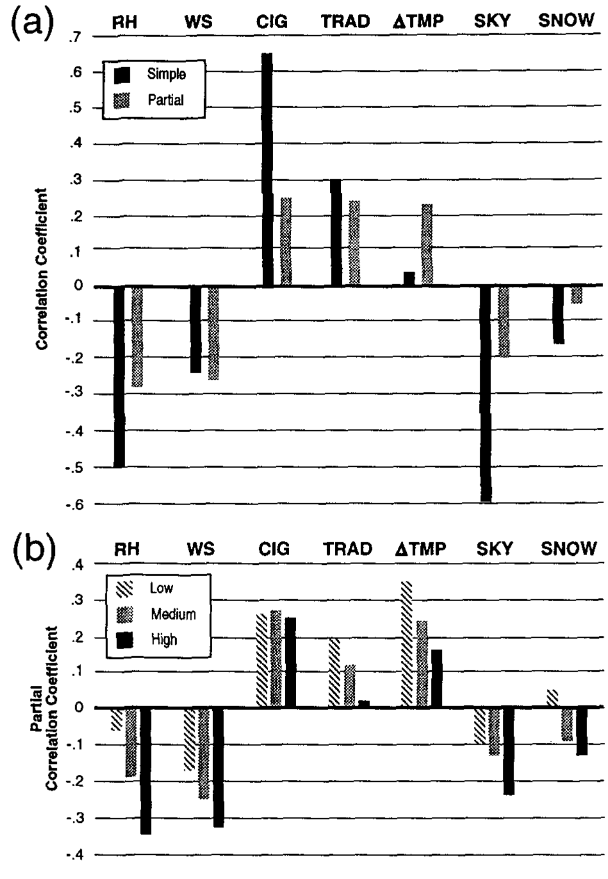


FIG. 8. Relationship between various climate variables and the diurnal temperature range. (a) Simple and partial correlation coefficients (removing the effects of all other variables) between each variable (defined in Table 4) and the diurnal temperature range. (b) Partial correlation coefficients of each variable for cases partitioned by the total daily solar radiation at the top of the atmosphere 170 Wm^{-2} (low); 271 Wm^{-2} (high); remainder (moderate)

4. Large-scale anthropogenic effects

a. Greenhouse gases

Interest in the potential change of the DTR with increasing anthropogenic greenhouse gases has prompted several modeling groups to publish information from their models regarding the projected change in the DTR from doubled CO_2 experiments. Table 5 summarizes the results of these models. For the GCM experiments, the magnitude of the decrease is small relative to overall warming of the mean global temperature. Moreover, these experiments reflect a level of CO_2 increase well in excess of present-day values, so even smaller changes should be expected in the observed temperature record.

Cao et al. (1992) also conducted a number of experiments with a one-dimensional radiative–convective model (RCM), which showed that the decrease in the diurnal temperature range with doubled CO_2 in that model is primarily due to a water vapor feedback. Only a 0.05°C reduction in the DTR was observed when the absolute humidity was held constant. Table 5 indicates that the increased sensible heat exchange and evaporation are also important factors leading to a reduction in the DTR in RCM simulations with enhanced CO_2.

Interestingly, the ratio of the DTR decrease relative to the increase of the mean temperature in the RCM compared with the GCM is closer to the observed ratio over the past several decades (Table 5). The RCM omits the positive feedbacks to the DTR from reductions in cloud and surface albedo as contained in the GCM simulations (Cao et al. 1992). This tends to increase the DTR because of reduced atmospheric (cloud cover) and surface (snow cover) albedo. Other GCM simulations have both increases and decreases in cloudiness with global warming: decreases in much of the troposphere, but increases in the high troposphere, low stratosphere, and near the surface in high latitudes (Schlesinger and Mitchell 1985). If the observational evidence is correct regarding the tendency for a general increase in cloud cover over the land (which now seems likely), then this could help explain the

TABLE 5. Summary of modeling results with respect to the relationship between doubled CO_2 concentrations and changes in the diurnal temperature range (DTR) and the maximum and minimum temperatures. Abbreviations are ΔT_{eq} is the equilibrium global temperature change (°C) for doubled CO_2 concentrations, ΔDTR is the equilibrium global change of the DTR (°C) for doubled CO_2 concentrations, CCC is the Canadian Climate Centre, GISS is the Goddard Institute for Space Studies, and UKMO is the U. K. Meteorological Office.

GCM Model	Author	Resolution		Ocean	T_{eq}	DTR_{eq}
		Horiz.	Vert.			
CCC	Boer 1989	T32	10	Mixed layer	3.5	−0.28
GISS	Rind et al. (1989)	8° x 10°	9	Mixed layer	4.2	−0.7 (sum, USA) −0.1 (ann, USA)
UKMO	IPCC (1990)	8° x 10°	11	Mixed layer	5.2	−0.17
UKMO	Cao et al. (1992)	5° x 7.5°	11	Mixed layer	6.3	−0.26

Radiative Convective Model (Cao et al. 1992)

Type	Maximum T_{eq}	Minimum T_{eq}	DTR
Fixed absolute humidity	X	X	−0.05
No surface turbulence	2.5	2.9	−0.4
No evaporation	2.3	2.9	−0.6
Full surface exchange	1.5	2.2	−0.7

large discrepancy between the observed data and the model projections of the ratios of the decrease in the DTR range relative to the *mean temperature increase*. This assumes, of course, that the recent warming is induced by increases in anthropogenic greenhouse gases. On the other hand, this raises questions regarding the cause of the apparent change in cloudiness and how it has impacted the mean temperature.

The ability of present day GCMs to adequately simulate projected changes in the DTR with enhanced CO_2 is also affected by surface parameterizations of continental-scale evaporation. As Milly (1992) points out, present-day GCMs can overestimate the surface evaporation because of the failure to properly account for the cooling that occurs with the evaporation. Milly (1992) raises concerns about the veracity of the results from studies of soil moisture changes induced by an increase of greenhouse gases. Accurate projections of the change in the surface boundary-layer DTR with increases of anthropogenic greenhouse gases will be strongly dependent on adequate simulation of these processes.

Given the dependency of the DTR on surface-layer processes, interactions with the land surface, and cloudiness, all areas of significant uncertainties within present-day GCMs, it may not yet be possible to adequately project changes of the DTR with enhanced concentrations of greenhouse gases.

b. Tropospheric aerosols

It has recently been shown that increases in sulfate aerosols over and near industrial regions can significantly impact the earth's surface heat balance (Charlson et al. 1992). Charlson et al. (1991) and Charlson et al. (1992) provide evidence to indicate that the anthropogenic increase of sulfate (and carbonaceous) aerosol is of sufficient magnitude to compete regionally with present-day anthropogenic greenhouse forcings. This forcing is confined primarily to the Northern Hemisphere and is a combination of direct aerosol forcing (especially over the land) and indirect aerosol forcing leading to increases in cloud albedo (especially over the marine environment). At present, Charlson et al. (1992) conclude that it is too uncertain to estimate the effects of sulfate aerosols on the lifetime of clouds (smaller droplet sizes leading to a decrease in the fallout rate) which presumably could lead to an increase in cloud cover. Charlson et al. (1991) provide the geographic pattern where direct aerosol forcing should be greatest. It is difficult to identify a direct relation between the pattern and magnitude of the decrease in the DTR (Fig. 2) and the anthropogenic radiative forcing calculated by Charlson et al. (1991). Moreover, Karl et al. (1986a) and Karl et al. (1986b) provide evidence to suggest that there is little change of the maximum relative to the minimum temperature in the United States for cloudless skies even when the daily data are stratified by dewpoint and wind direction.

Recently, Penner et al. (1992) have argued that atmospheric aerosols from biomass burning also act to increase the planetary albedo both directly by clear-sky planetary albedo increases and indirectly through increases in cloud albedo. Since biomass burning is most extensive in subtropical and tropical areas, this effect may be directly relevant only to a small portion of the data analyzed here.

Two tropospheric aerosol forcing agents (aerosols from sulfur emissions and biomass burning) have been identified that tend to increase the clear-sky albedo. Neither forcing is believed to have dominant infrared forcing. The question arises whether either of these forcings has acted to reduce the maximum temperature and thereby the DTR. In the United States and northern (and perhaps eastern) Europe, however, where we detected a significant decrease in the DTR, there has actually been a net decrease in sulfur emissions over the past several decades that would qualitatively appear to eliminate sulfate aerosols as an influence on the DTR in these areas. There are reasons why such a conclusion may be premature. First, the climate forcing due to tropospheric aerosol loading is influenced both by the emission rate and the residence times of sulfate aerosol in the atmosphere. In the United States, at least, the effective heights, or stack heights, of the sulfur emissions have increased as a consequence of the U.S. Clean Air Act. This may have had an effect on the lifetime of the SO_2 and sulfate aerosols

5. Conclusions

Strong evidence exists for a widespread decrease in the DTR over the past several decades in many

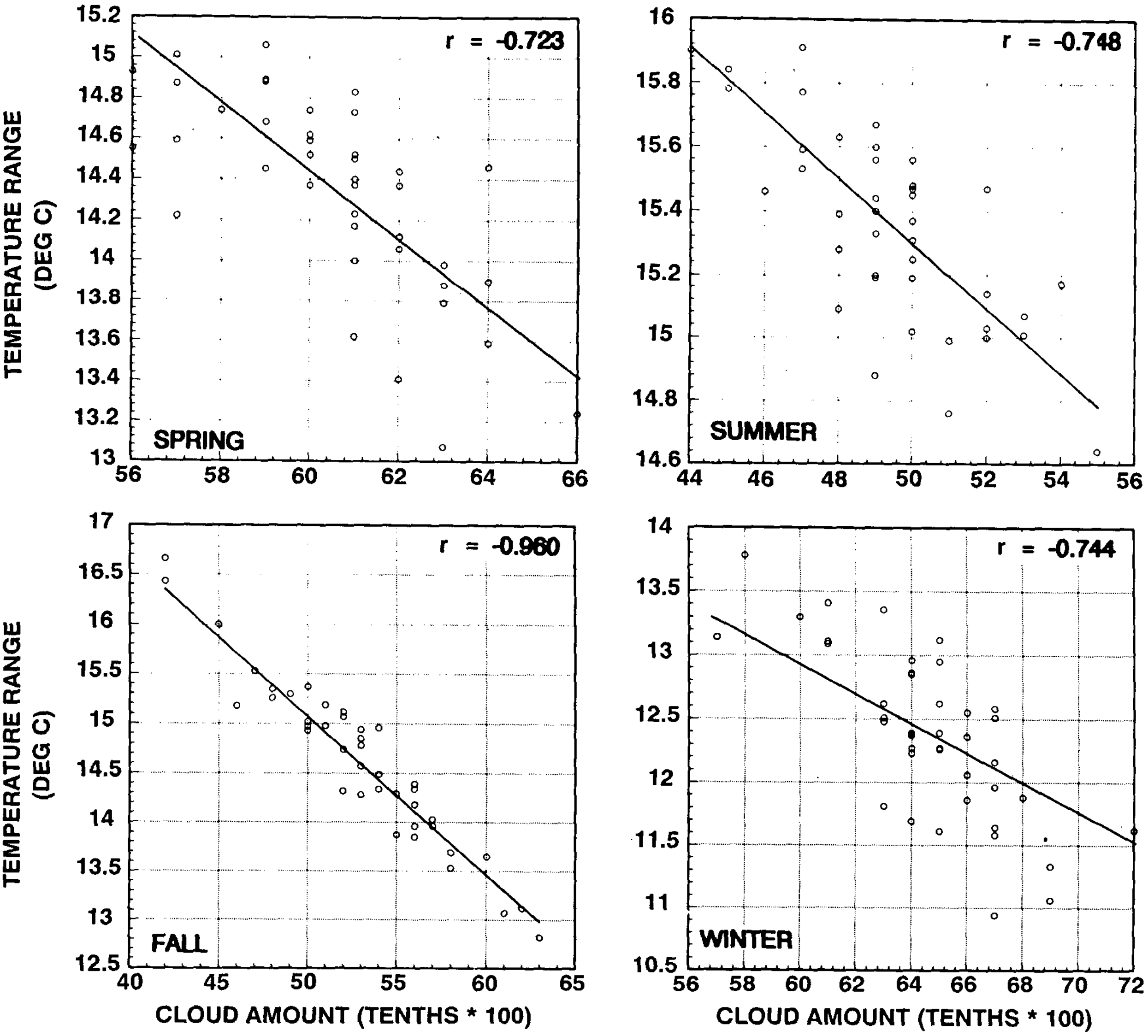


FIG. 9. Seasonal relationships between U.S. area-averaged cloud cover and the diurnal temperature range.

regions of the globe. There are many possible climatic factors that affect the DTR, but indications are that cloud cover, including low clouds, has increased in many areas that have a decrease in the DTR. The increases in cloud cover could be indirectly related to the observed global warming and increases of greenhouse gases, related to the indirect effects of increases in aerosols, simply a manifestation of natural climate variability, or a combination of all three.

A robust answer regarding the cause(s) of the decrease in the DTR will require efforts in several areas. First, an organized global effort is required to develop relevant and homogeneous time series of maximum and minimum temperature along with information on changes of climatic variables that influence the DTR such as cloudiness, stability, humidity, thermal advection, and snow cover. Second, improvements in the boundary-layer physics and treatment of clouds within existing GCMs are critically important. Third, the treatment of both anthropogenic tropospheric aerosols and greenhouse gases must be realistically incorporated into GCMs with a diurnal cycle. Fourth, measurements need to be made to help clarify the role of aerosols. Finally, imaginative climate change detection studies that link the observed climate variations to model projections will be required to convincingly support any relation between anthropogenic-induced changes and the DTR.

It will be difficult to satisfactorily explain the observed changes of the mean temperature until an adequate explanation for the observed decrease in the DTR can be determined. Moreover, the practical implications of projected temperature changes and whether they are likely to continue will be even more difficult to assess.

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