

Taking China's Temperature: Daily Range, Warming Trends, and Regional Variations, 1955–2000

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ABSTRACT

In analyzing daily climate data from 305 weather stations in China for the period from 1955 to 2000, the authors found that surface air temperatures are increasing with an accelerating trend after 1990. They also found that the daily maximum (T_{\max}) and minimum (T_{\min}) air temperature increased at a rate of 1.27° and 3.23°C (100 yr^{-1}) between 1955 and 2000. Both temperature trends were faster than those reported for the Northern Hemisphere, where T_{\max} and T_{\min} increased by 0.87° and 1.84°C (100 yr^{-1}) between 1950 and 1993. The daily temperature range (DTR) decreased rapidly by -2.5°C (100 yr^{-1}) from 1960 to 1990; during that time, minimum temperature increased while maximum temperature decreased slightly. Since 1990, the decline in DTR has halted because T_{\max} and T_{\min} increased at a similar pace during the 1990s. Increased minimum and maximum temperatures were most pronounced in northeast China and were lowest in the southwest. Cloud cover and precipitation correlated poorly with the decreasing temperature range. It is argued that a decline in solar irradiance better explains the decreasing range of daily temperatures through its influence on maximum temperature. With declining solar irradiance even on clear days, and with decreases in cloud cover, it is posited that atmospheric aerosols may be contributing to the changing solar irradiance and trends of daily temperatures observed in China.

1. Introduction

Worldwide, the daily or diurnal temperature range (DTR) has decreased since the mid-twentieth century (Karl et al. 1991, 1993; Kukla and Karl 1993; Easterling et al. 1997), with exceptions reported in only a few regions (Weber et al. 1994). The decrease in DTR has regional and seasonal characteristics (Karl et al. 1991, 1993; Easterling et al. 1997). For most parts of the world, daily minimum temperatures T_{\min} have risen at a rate outpacing that of daily maximum temperatures

T_{\max} , producing a smaller range. In some places, T_{\max} has in fact decreased while T_{\min} increased (Plantico et al. 1990; Karl et al. 1993; Kukla and Karl 1993). The widely reported increase in mean daily temperatures T_{mean} can be attributed mostly to increases in T_{\min} in the regions where T_{\max} decreased or only slightly increased, and thus the decrease in DTR in these regions may be a stronger signal that is approximately equal to the increase in T_{mean} .

Many researchers have proposed that increases in cloud cover and precipitation lead to decreasing DTR (Plantico et al. 1990; Karl et al. 1993; Dai et al. 1997, 1999), but it is obvious that other factors may also contribute, including irrigation, greenhouse gases, and atmospheric aerosols (Kukla and Karl 1993). Clouds are

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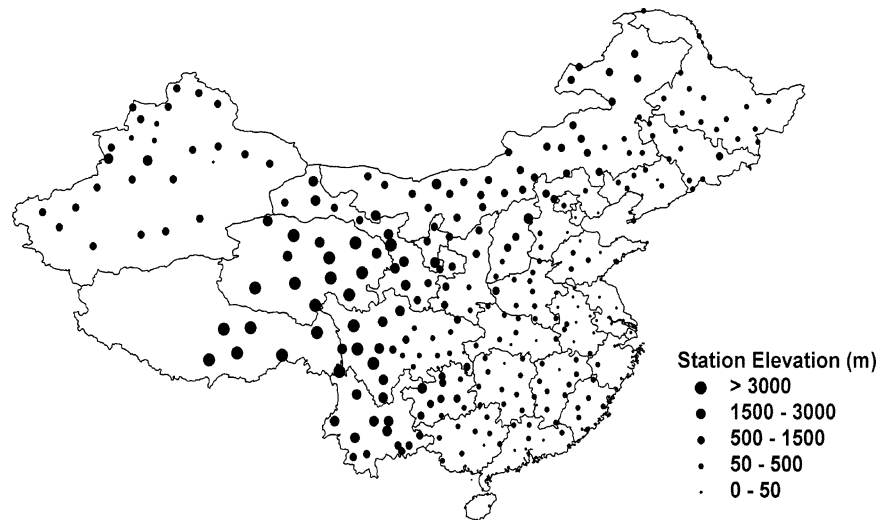


FIG. 1. Geographical distribution of the 305 weather stations used in this study.

expected to play a key role in DTR change because of their unbalanced effects on T_{\max} and T_{\min} : clouds can decrease T_{\max} by reducing incident shortwave solar radiation to the earth's surface during the day and can increase T_{\min} by intercepting outgoing longwave radiation at night (Campbell and Vander Haar 1997). Most studies suggest that aerosols should have a cooling effect on T_{\max} through their influence on the characteristics of cloud cover (Hansen et al. 1995; Dai et al. 1997). Previous studies also suggested that increasing atmospheric water vapor, resulting from the increasing surface T_{mean} , should increase both daytime and nighttime temperatures and thus should have a small effect on DTR (Dai et al. 1999).

Several previous studies have considered the regional and seasonal changes in T_{\min} , T_{\max} , and DTR in China. Three of these studies used data from a relatively limited number of weather stations: one analyzed data from 57 stations for the period 1951–89 (Karl et al. 1991), another used 58 stations for 1951–90 (Kukla and Karl 1993), and a third used 44 nonurban stations for 1951–88 (Karl et al. 1993). A fourth study analyzed data from 400 stations with data from the 1950s to the 1990s but aggregated the data into eight climatic regions (Shen and Varis 2001). Aggregating data at such a large regional scale is likely to obscure the spatial distributions of different temperature trends, as stations reporting opposite trends may be averaged out.

Understanding the mechanisms causing the reduction in global DTR is critical to the prediction of future climate change. In contrast to most other parts of the world, China's different rates of change between day- and nighttime temperatures can not be attributed to changes in cloud cover, since cloud cover decreased in China in the past decades (Baker et al. 1995; Kaiser 2000). In this study we report on trends in DTR calculated from weather stations managed by the China

Meteorological Administration. We analyzed data from 305 weather stations covering the period 1955 to 2000, including the decade of rapid climate change from 1990 to 2000, to examine the spatial and temporal trends of DTR and its relationships with other climate variables. With a half century of records from stations distributed across China, this dataset allows us to revisit previous analyses that relied on more limited data and to contribute to the ongoing debate on regional and global climate dynamics.

2. Methods

a. Data sources

As compared with previous analyses, in this paper we present data extending through the 1990s, a period of increasingly rapid change in temperatures, and consider several climate measures that may contribute to the observed changes in the spatial and seasonal patterns of DTR. The China Meteorological Administration dataset, from 305 stations distributed across the country (Fig. 1), includes daily measurements of precipitation, T_{mean} , T_{\min} , T_{\max} , water vapor pressure (surface specific humidity), relative humidity, total cloud cover, and surface wind speed from 1951 to 2000. Of the 305 weather stations, 85 stations also reported daily solar irradiance.

b. Data analysis

Most weather stations in China began operation in the early 1950s. Because of instrument malfunctions, data from the earliest years contain more gaps (missing values for more than 10 consecutive days), and so in this analysis we exclude the data from 1951 to 1954 and rely only on data reported from 1955 to 2000. For that period, we are confident in the quality and consis-

tency of the data. According to the China Meteorological Administration (formerly the State Meteorological Administration of China), identical standards and instrumentation were used at all 305 stations. We recognize that it is difficult to eliminate the influence of urban growth (specifically the urban heat island effect) on daily temperature measures. China has seen a rapid expansion of urban areas, especially in the post-Mao reform period beginning in 1978. On a large scale this influence is limited, however (Wang et al. 1990; Easterling et al. 1997).

Missing data are inevitable for long-term monitoring at most stations. Where data were missing for up to 7 consecutive days for T_{mean} , T_{min} , and T_{max} and up to 3 days for other variables examined, we used a simple linear interpolation algorithm to fill the data gaps. We used a stepwise regression to fill the gaps when the data were missing for more than 7 consecutive days for T_{mean} , T_{min} , and T_{max} , and more than 3 days for other variables. The stepwise regression was performed every 5 yr, with the missing station as the dependent variable and all of the other stations that had no missing values for the variable, considered after the simple linear interpolation, as independent variables. The stepwise regression gave a minimum coefficient of determination R^2 of 0.992, 0.998, and 0.996 for T_{mean} , T_{min} , and T_{max} , respectively. The longest time periods with missing data were 20, 15, and 18 consecutive days for T_{mean} , T_{min} , and T_{max} , respectively; most data gaps were only 1–2 days.

The methods we used to fill the missing data do not substantially affect our results in analyzing China's climate dynamics. Missing data accounted for less than 0.38% of the total records from 1955 to 2000 for all of the variables examined. We compared the gap-filled dataset with the original dataset (with missing values) and found that the differences in means and trends between the datasets were not statistically significant ($p = 0.05$). We used the gap-filled dataset in this study considering the fact that the missing data were not randomly distributed along the time series but rather had more data missing in the early years.

Solar irradiance is an important variable for analyzing climate change, and in this dataset solar irradiance data were reported for 85 of the 305 stations. The 85 stations were well distributed across China. To examine if the 85 stations were representative of the country we computed monthly and annual averages of the climate variables for all 305 stations and the solar irradiance for the 85 stations, respectively. The monthly and annual averages were very close, with correlation coefficients greater than 0.98 between the two sets of stations. In addition, the trends of the two groups of stations were also very close. We concluded that it is reasonable to examine the relationships between solar radiation and other climate variables though solar irradiance is only reported for a subset of the 305 stations.

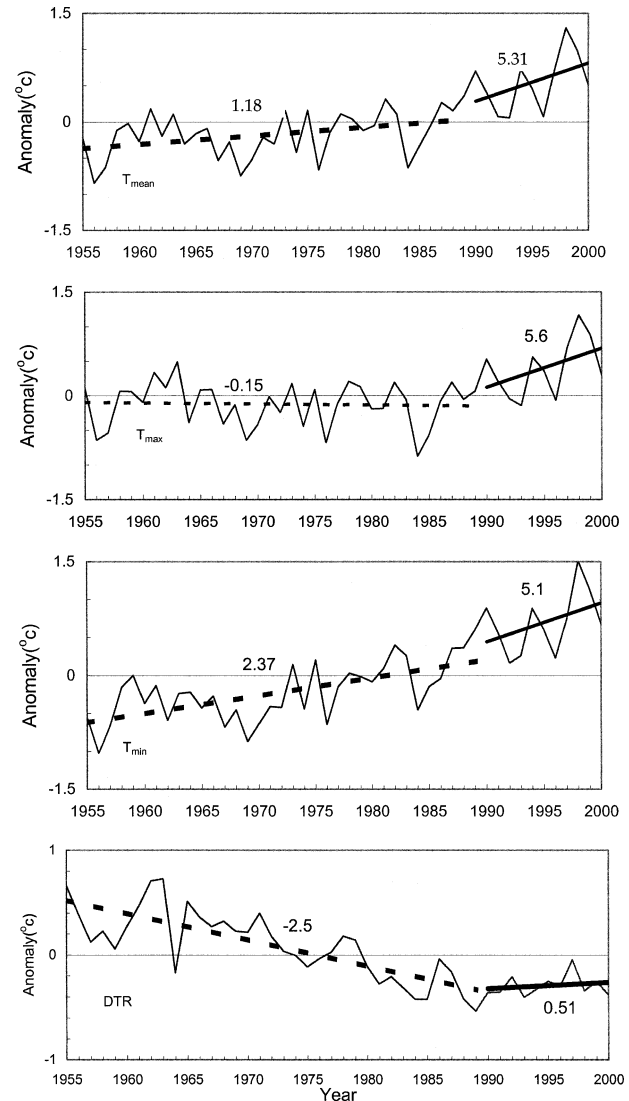


FIG. 2. Linear trends and anomalies from annual means of daily T_{mean} , T_{max} , T_{min} , and DTR for China. Linear trends: 1955–89 (dashed lines) and 1990–2000 (solid lines). Values along the trend lines are the rate of change [$^{\circ}\text{C} (100 \text{ yr})^{-1}$].

3. Results and discussion

a. Annual trends

Taking China as a whole, we calculated the trends in T_{max} , T_{min} , T_{mean} , and DTR for the entire study period. As shown in Fig. 2, we separately calculated trends for the periods before and after 1990 in order to allow for comparison with the results of earlier studies. We found that T_{max} increased at a rate of $1.27^{\circ}\text{C} (100 \text{ yr})^{-1}$ between 1955 and 2000. This trend was faster than that reported for the Northern Hemisphere— $0.87^{\circ}\text{C} (100 \text{ yr})^{-1}$ between 1950 and 1993 (Easterling et al. 1997)—and much higher than the earlier analyses of China (Karl et al. 1991, 1993). Whereas T_{max} declined modestly up to

TABLE 1. Seasonal trends [$^{\circ}\text{C}$ (100 yr) $^{-1}$]. Trends are calculated from data reported by 305 stations across China, comparing the periods 1955–89, 1990–2000, and 1955–2000.

Season	T_{\min}			T_{\max}			DTR		
	1955–89	1990–2000	1955–2000	1955–89	1990–2000	1955–2000	1955–89	1990–2000	1955–2000
Winter (DJF)	4.15	0.86*	5.57	0.63*	5.70*	2.65	–3.50	4.84	–2.90
Spring (MAM)	1.59	8.50	2.96	–0.50*	13.10	0.94*	–2.10	4.59	–2.00
Summer (JJA)	0.63*	7.90	1.90	–0.87*	5.50*	0.54*	–1.51	–2.40*	–1.30
Autumn (SON)	2.21	5.40*	2.75	–0.76*	0.25*	0.95*	–2.96	–5.17	–1.79

* Trends not significant at the 0.05 level (two-tailed t test).

1990, it increased rapidly in the last decade of our study period (Fig. 2).

For T_{\min} , we calculated a rate of change of 3.23°C (100 yr) $^{-1}$ between 1955 and 2000 in China. This was again higher than the 1950–93 rate reported for the Northern Hemisphere, 1.84°C (100 yr) $^{-1}$ (Easterling et al. 1997), and previous studies for China. As with T_{\max} , T_{\min} rose faster in the 1990s than in the previous three and one-half decades. Those two measures kept pace with each other over the last 11 yr of the twentieth century, with T_{\max} increasing by 0.56°C and T_{\min} rising 0.51°C .

The 1990s saw a slight and nonsignificant increase in DTR—contrary to the rapid decrease noted from 1960 to 1990. For the whole study period, we calculated a rate of change in DTR of -2.02°C (100 yr) $^{-1}$. This is comparable to the -2.0°C reported in two of the previous studies of China that relied on smaller numbers of stations and ended with 1988 or 1989 (Karl et al. 1991, 1993). Excluding the new data for the 1990s, we found that the trend in DTR across our 305 weather stations became -2.5°C (100 yr) $^{-1}$ —a faster decline for the same period than reported in those two studies. Our results were more comparable to Shen and Varis's (2001) figure of -2.4°C (100 yr) $^{-1}$ calculated from 400 Chinese weather stations for the period from 1950 to the 1990s.

Our use of data for the 1990s, not available in the earlier studies, explained much of the difference in reported trends. We also saw that the number of stations and their geographical distribution had a great influence on the resulting temperature trends. These differences were most pronounced for T_{\min} and T_{\max} , less so for DTR. In particular, the previous studies did not include data from the Tibetan Plateau, a region of 2.5 million km^2 that encompasses 26% of China's total land area (Karl et al. 1991, 1993; Kukla and Karl 1993). The spatial distribution of weather stations is especially important in a study of China, which occupies the third largest land area of any country. Few if any countries can match China's range of latitudes, below 18°N in the South China Sea to above 53°N at the Siberian border, and altitudes, -154 m in the Tarim basin to 8850 m at the peak of Qomolangma (Mount Everest).

We discount the possible influence of the urban heat island effect, since this should be minor over large areas

(Karl et al. 1991; Easterling et al. 1997) and would not explain the large differences between our results and those of most of the previous studies that also included data from urban stations (Karl et al. 1991; Weber et al. 1994). In a preliminary study we removed 45 urban weather stations, located in cities with a population larger than one million, from the 305 stations to evaluate the urbanization effect on China's climate change in the past decades. As might be expected, temperatures in the urban stations increased slightly faster than those in the nonurban stations [a difference of 0.07° and 0.02°C (100 yr) $^{-1}$ for T_{\max} and T_{\min} , respectively], while DTR decreased faster for the nonurban stations [a difference of -0.05°C (100 yr) $^{-1}$]. These values are smaller than the estimates for the Northern Hemisphere (Easterling et al. 1997). Further studies are needed to isolate the effect of urbanization on climate change.

b. Seasonal trends

Changes in T_{\min} , T_{\max} , and DTR in China were greatest in winter and lowest in summer, with the exception of T_{\min} from 1990 to 2000 (Table 1). This finding differs somewhat from reports for the globe and the Northern Hemisphere, where changes were also greatest in winter but were lowest in autumn (Easterling et al. 1997). We attribute this difference to China's monsoon-driven climate, which concentrates precipitation in the summer months. Relative humidity was highest in summer, effectively slowing down changes in temperature. The seasonal changes seen in our calculations are similar to those in previous studies of China (Karl et al. 1991, 1993)—highest in winter and lowest in summer—though our data, including the decade of rapid change in the 1990s, shows greater seasonal changes in T_{\min} and T_{\max} . The previous studies showed either no change or decreases in T_{\max} for spring, summer, and autumn, and slight decreases in T_{\min} in summer. We calculated similar trends for the period of 1955–89, but the change of T_{\min} in summer was different from the previous analyses that reported an increasing trend (Karl et al. 1991, 1993).

Between 1990 and 2000, T_{\max} increased in all seasons, with greatest increases in spring; T_{\min} also increased in all seasons, with greatest increases in spring and summer. DTR in this period showed an increasing trend in winter and spring but a decreasing trend in summer and

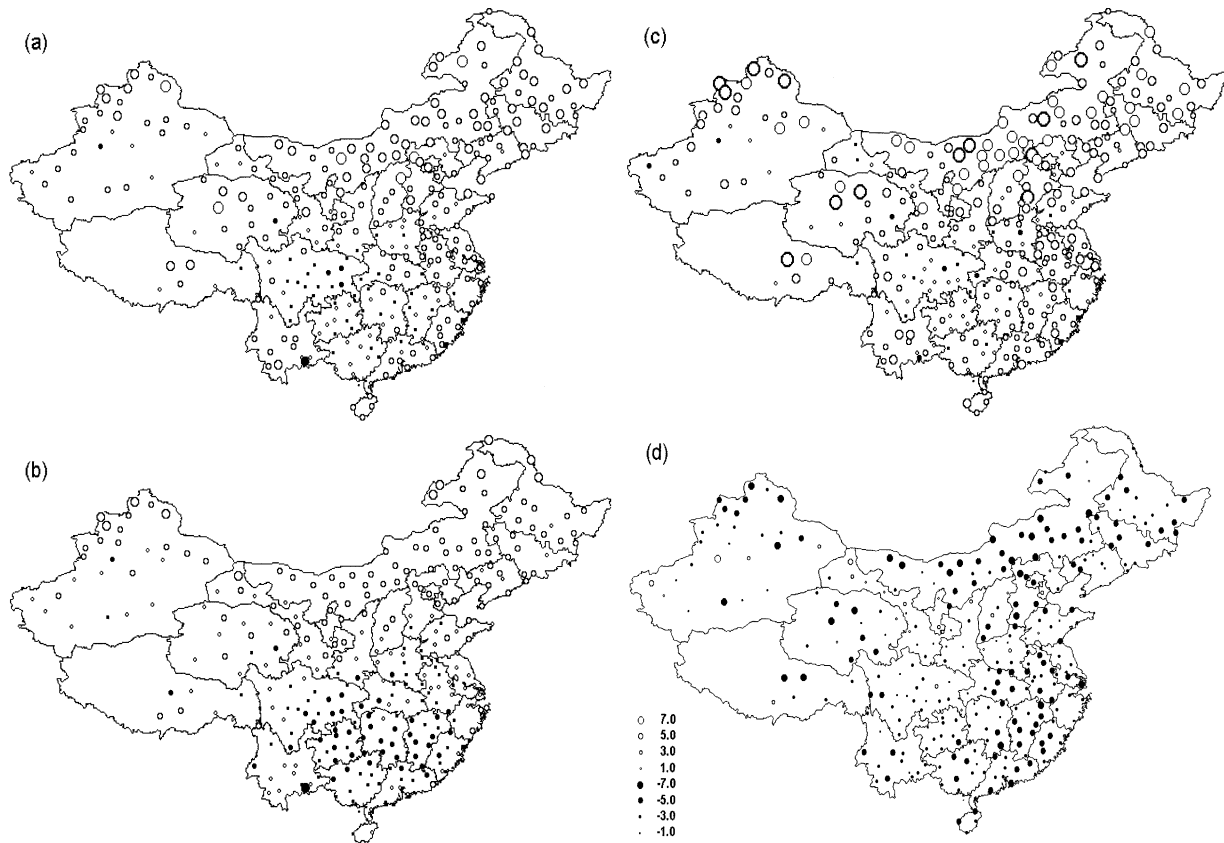


FIG. 3. Trends of (a) T_{mean} , (b) T_{max} , (c) T_{min} , and (d) DTR, 1955–2000 [$^{\circ}\text{C} (100 \text{ yr})^{-1}$].

autumn, though the summer decrease was not statistically significant (Table 1); T_{mean} increased in all seasons, fastest in spring and summer (data not shown). Thus when data from 1990 to 2000 were included, T_{max} and T_{min} were found to increase in all seasons.

c. Spatial patterns

Figure 3 shows the annual trends in T_{mean} , T_{min} , T_{max} , and DTR for each of the 305 stations calculated separately. Spatial patterns are clear. The warming trend apparent across most of China is highest in the northeast; only eastern Sichuan Province and Chongqing Municipality show a cooling trend. A transect running from northeast to southwest shows the warming trend change from high to low (as also reported by Shen and Varis 2001), excepting some high-altitude stations in mountainous Yunnan Province.

The greatest increase in T_{max} was found in north China and Inner Mongolia; the rate became slower as we moved from the north to central China. Across southern China, except in areas of high altitude, T_{max} decreased; T_{min} had the same spatial pattern, with nearly all stations showing an increase; again the rate was fastest in the north and slowest in the south. In general, T_{min} rose at

a faster pace than T_{max} , and thus DTR decreased at nearly every station, though this indicator showed less spatial coherence in other parts of the world (Easterling et al. 1997).

China's summers and winters are very different from each other because of the effects of the summer monsoon, which brings most of the year's precipitation. Accordingly, we analyzed these seasons separately (Figs. 4 and 5). In winter, T_{max} rose at most stations, but with a cluster of decreasing values in the Sichuan basin (eastern Sichuan Province and Chongqing Municipality). Daily maximum temperatures T_{max} rose faster in the north than in the south. Similarly, winter T_{min} and T_{mean} rose in almost all stations, again fastest in the north. These values produced a preponderance of decreasing winter DTR values across China, with no clear differences between north and south.

In contrast with the winter temperatures, T_{max} and T_{mean} in the rainy summer months decreased across large areas of central China. They increased in north China and along the southern coast. Daily minimum temperatures T_{min} increased most in the north, less in the south, and showed a modest decline at some stations of central China. Summer DTR, like winter, showed a general decline across China with no evident regional pattern.

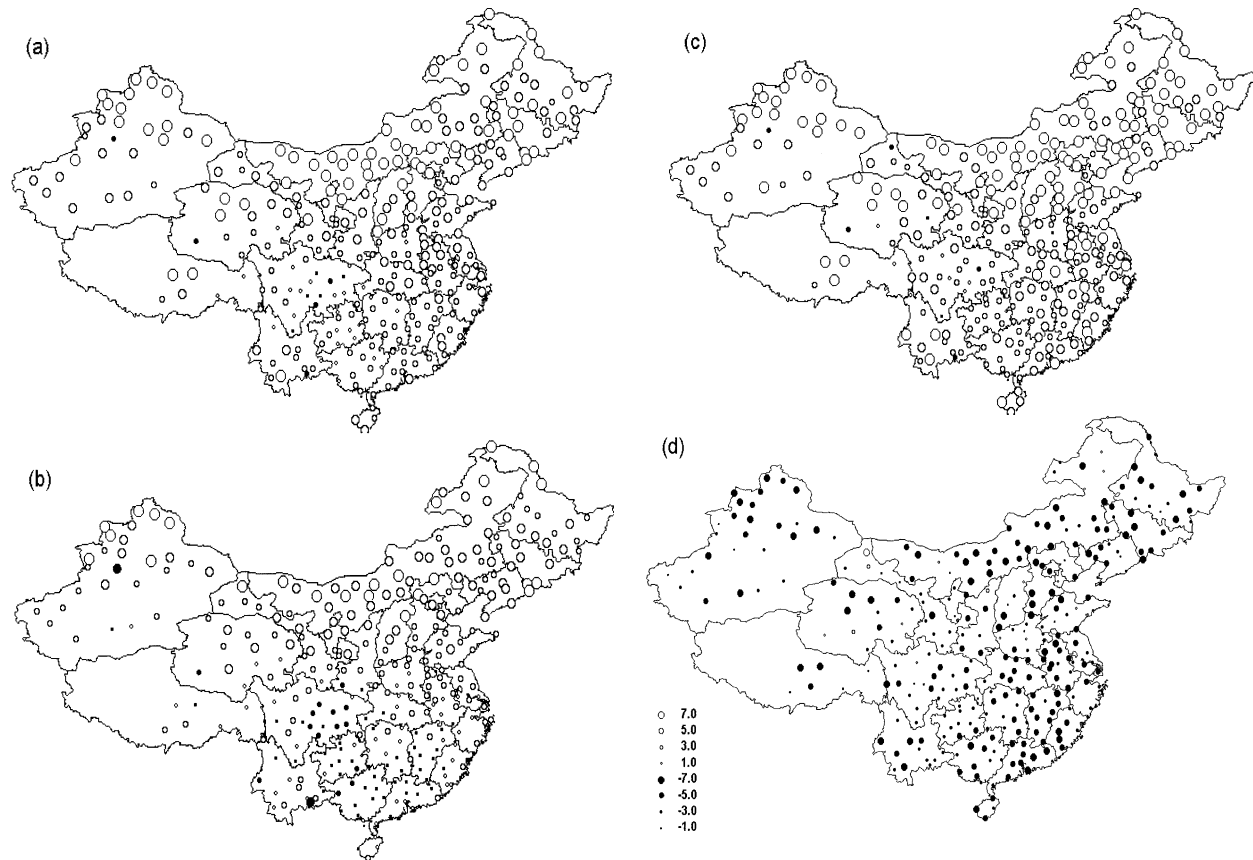


FIG. 4. Trends of (a) T_{mean} , (b) T_{max} , (c) T_{min} , and (d) DTR in winter (Dec–Feb), 1955–2000 [$^{\circ}\text{C} (100 \text{ yr})^{-1}$].

d. Possible factors contributing to DTR change

Looking at the trend of summer precipitation over the same time period (Fig. 6), we found that areas of increasing precipitation correspond to areas where summer T_{max} and T_{mean} have decreased. The same inverse relationship between precipitation and maximum or mean temperatures held for spring and autumn. This suggests that increased rainfall may have contributed to the observed temperature trends though the amount of precipitation change is small compared with the total annual precipitation. This spatial pattern of precipitation change might relate to the change of cloud cover, which could considerably affect the surface energy balance, and thus temperature.

Table 2 shows the correlation coefficients among indicators for each of the four seasons. [For convenience and consistency with other studies, the seasons here comprise whole months: winter is December, January, and February (DJF); spring is March, April, and May (MAM); summer is June, July, and August (JJA); and autumn is September, October, and November (SON).] DTR was strongly correlated with solar irradiance and relative humidity: energy and water conditions control DTR. Cloud cover had a strong negative correlation with DTR in winter and autumn, likewise with precipitation

in winter and summer and water vapor content in summer. For solar irradiance, the correlation with DTR was highest in winter. For relative humidity the negative correlation was greatest in summer.

In order to eliminate the effects on DTR of any interaction among variables, we calculated partial correlation coefficients of the variables with DTR (Fig. 7). The variables with the strongest correlation with DTR were total cloud cover, solar irradiance, and surface wind speed. Cloud cover had a negative effect on DTR. Contrary to the trend in the rest of the world, we found that China's cloud cover had decreased in all seasons over this study period, confirming earlier reports (Baker et al. 1995; Kaiser 2000). Were cloud cover the primary influence on change in DTR, we would expect DTR to increase over this time period, but this is not the case.

Surface wind speed should have an equal impact on T_{max} and T_{min} (Dai et al. 1999), and thus it too seemed not to explain the observed decrease in DTR. Wind speed correlated strongly with DTR in our analysis with the exception of the summer months.

It is in the summer months that surface specific humidity was strongly negatively correlated with DTR. Atmospheric water vapor, a greenhouse gas, was greatest in the summer monsoon season in China. We found

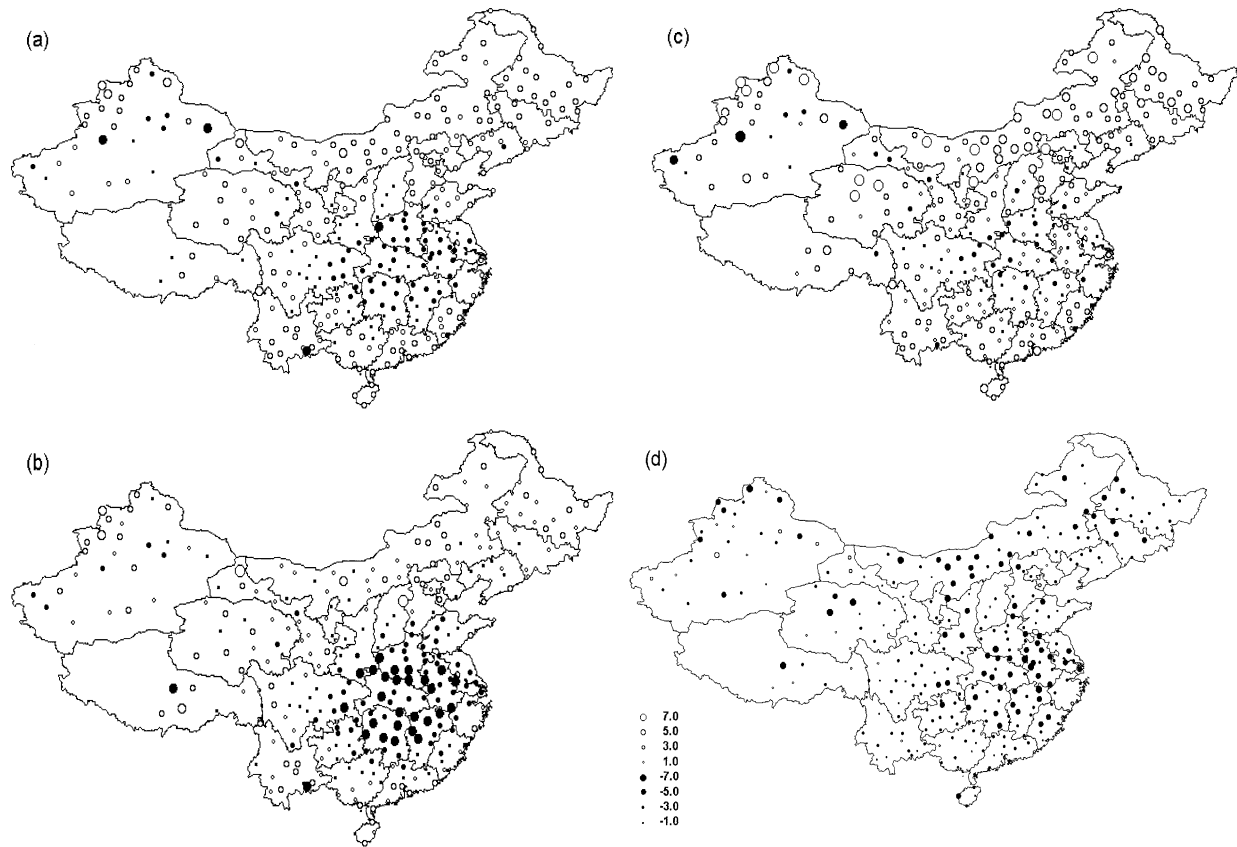


FIG. 5. Trends of (a) T_{mean} , (b) T_{max} , (c) T_{min} , and (d) DTR in summer (Jun–Aug), 1955–2000 [$^{\circ}\text{C} (100 \text{ yr})^{-1}$].

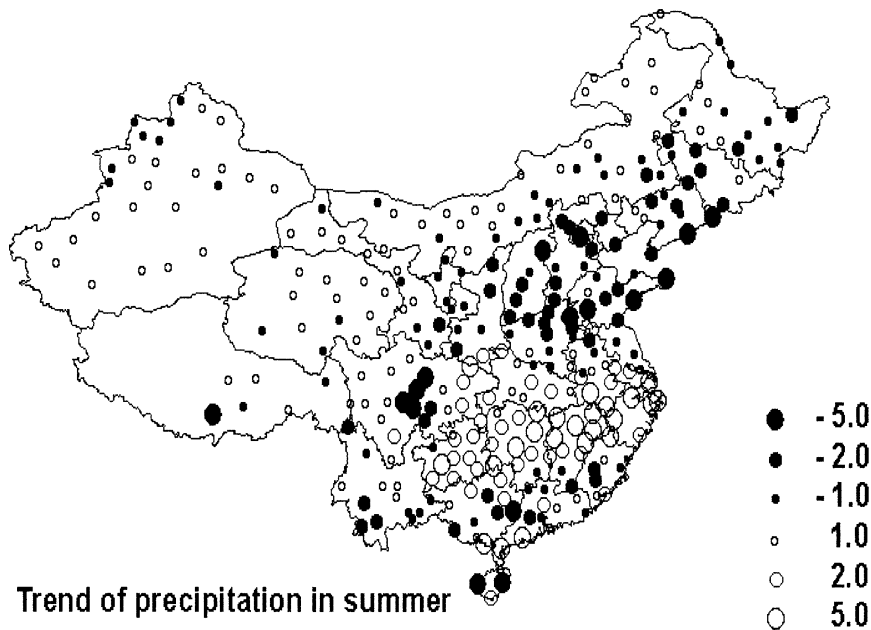


FIG. 6. Summer daily precipitation trends, 1955–2000 [$\text{mm} (100 \text{ yr})^{-1}$].

TABLE 2. The correlation coefficients among variables by season: DTR, total cloud cover (cc), T_{\max} , T_{mean} , T_{\min} , precipitation (p), surface wind speed (V), solar irradiance (Rs), relative humidity (Rh), and surface specific humidity (q). Values in boldface type statistically significant at the 0.01 level.

Variable	DTR	cc	T_{\max}	T_{mean}	T_{\min}	p	V	Rs	Rh	q
Winter (DJF)										
DTR	1.00	-0.34	0.30	0.10	-0.07	-0.35	0.47	0.71	-0.57	-0.19
cc	-0.34	1.00	-0.05	0.05	0.08	0.72	0.39	0.17	0.25	0.30
T_{\max}	0.30	-0.05	1.00	0.97	0.92	0.06	-0.08	0.33	-0.26	0.75
T_{mean}	0.10	0.05	0.97	1.00	0.98	0.16	-0.17	0.21	-0.15	0.83
T_{\min}	-0.07	0.08	0.92	0.98	1.00	0.20	-0.26	0.07	-0.05	0.86
p	-0.35	0.72	0.06	0.16	0.20	1.00	0.14	0.10	0.28	0.35
V	0.47	0.39	-0.08	-0.17	-0.26	0.14	1.00	0.57	-0.25	-0.14
Rs	0.71	0.17	0.33	0.21	0.07	0.10	0.57	1.00	-0.61	-0.10
Rh	-0.57	0.25	-0.26	-0.15	-0.05	0.28	-0.25	-0.61	1.00	0.26
q	-0.19	0.30	0.75	0.83	0.86	0.35	-0.14	-0.10	0.26	1.00
Spring (MAM)										
DTR	1.00	-0.11	0.45	0.36	0.27	0.12	0.49	0.57	-0.60	0.27
cc	-0.11	1.00	0.37	0.38	0.42	0.67	0.38	0.37	0.24	0.52
T_{\max}	0.45	0.37	1.00	0.99	0.97	0.82	0.10	0.94	-0.36	0.96
T_{mean}	0.36	0.38	0.99	1.00	0.99	0.84	0.04	0.92	-0.32	0.97
T_{\min}	0.27	0.42	0.97	0.99	1.00	0.86	0.00	0.89	-0.27	0.98
p	0.12	0.67	0.82	0.84	0.86	1.00	0.12	0.76	-0.10	0.88
V	0.49	0.38	0.10	0.04	0.00	0.12	1.00	0.24	-0.22	0.10
Rs	0.57	0.37	0.94	0.92	0.89	0.76	0.24	1.00	-0.42	0.89
Rh	-0.60	0.24	-0.36	-0.32	-0.27	-0.10	-0.22	-0.42	1.00	-0.17
q	0.27	0.52	0.96	0.97	0.98	0.88	0.10	0.89	-0.17	1.00
Summer (JJA)										
DTR	1.00	-0.08	-0.32	-0.48	-0.65	-0.43	0.47	0.57	-0.70	-0.65
cc	-0.08	1.00	-0.38	-0.30	-0.24	0.25	0.57	0.35	-0.31	-0.26
T_{\max}	-0.32	-0.38	1.00	0.98	0.92	0.14	-0.36	0.03	0.45	0.84
T_{mean}	-0.48	-0.30	0.98	1.00	0.97	0.22	-0.40	-0.05	0.52	0.90
T_{\min}	-0.65	-0.24	0.92	0.97	1.00	0.30	-0.47	-0.18	0.63	0.94
p	-0.43	0.25	0.14	0.22	0.30	1.00	-0.10	-0.06	0.31	0.36
V	0.47	0.57	-0.36	-0.40	-0.47	-0.10	1.00	0.62	-0.64	-0.51
Rs	0.57	0.35	0.03	-0.05	-0.18	-0.06	0.62	1.00	-0.58	-0.23
Rh	-0.70	-0.31	0.45	0.52	0.63	0.31	-0.64	-0.58	1.00	0.79
q	-0.65	-0.26	0.84	0.90	0.94	0.36	-0.51	-0.23	0.79	1.00
Autumn (SON)										
DTR	1.00	-0.42	0.25	0.13	0.03	-0.18	0.09	0.40	-0.55	-0.02
cc	-0.42	1.00	0.54	0.60	0.65	0.86	0.11	0.52	0.78	0.75
T_{\max}	0.25	0.54	1.00	0.99	0.97	0.79	-0.33	0.92	0.36	0.93
T_{mean}	0.13	0.60	0.99	1.00	0.99	0.83	-0.36	0.88	0.44	0.96
T_{\min}	0.03	0.65	0.97	0.99	1.00	0.86	-0.37	0.85	0.49	0.98
p	-0.18	0.86	0.79	0.83	0.86	1.00	-0.11	0.74	0.67	0.91
V	0.09	0.11	-0.33	-0.36	-0.37	-0.11	1.00	-0.12	-0.07	-0.27
Rs	0.40	0.52	0.92	0.88	0.85	0.74	-0.12	1.00	0.26	0.84
Rh	-0.55	0.78	0.36	0.44	0.49	0.67	-0.07	0.26	1.00	0.60
q	-0.02	0.75	0.93	0.96	0.98	0.91	-0.27	0.84	0.60	1.00

that specific humidity increased slightly over the study period, having a dampening effect on temperature change, with no diurnal difference (Dai et al. 1999). This helps explain why China's temperatures showed the least change in summer.

Of the variables tested, solar irradiance had the highest correlation with DTR in all seasons. Solar irradiance is, of course, unbalanced between day and night, with its greatest effect on daytime T_{\max} and a lesser effect on nighttime T_{\min} . Surface T_{\max} should increase with the increase of solar irradiance and decrease with the decrease of solar irradiance. In addition, greenhouse gases such as water vapor, carbon dioxide, and nitrous oxide also affect T_{\max} during the daytime as they affect T_{\min}

during the night. The effects of declining solar irradiance and increasing greenhouse gas concentration on T_{\max} may cancel each other out—a reasonable explanation for the relatively small change in T_{\max} from 1955 to 1990 in China. Meanwhile the greenhouse effect would account for the rapid increase in T_{\min} and thus the decline in DTR during the same period (Fig. 8). For the 1990s, increasing solar irradiance can explain the apparent increase of T_{\max} in China while T_{\min} continued to increase as in the previous decades. The effect on DTR was to reverse the decreasing trend, producing a slight increase during the 1990s. This supports the conclusion that the decrease in solar irradiance has played a key role in the decrease in DTR in China.

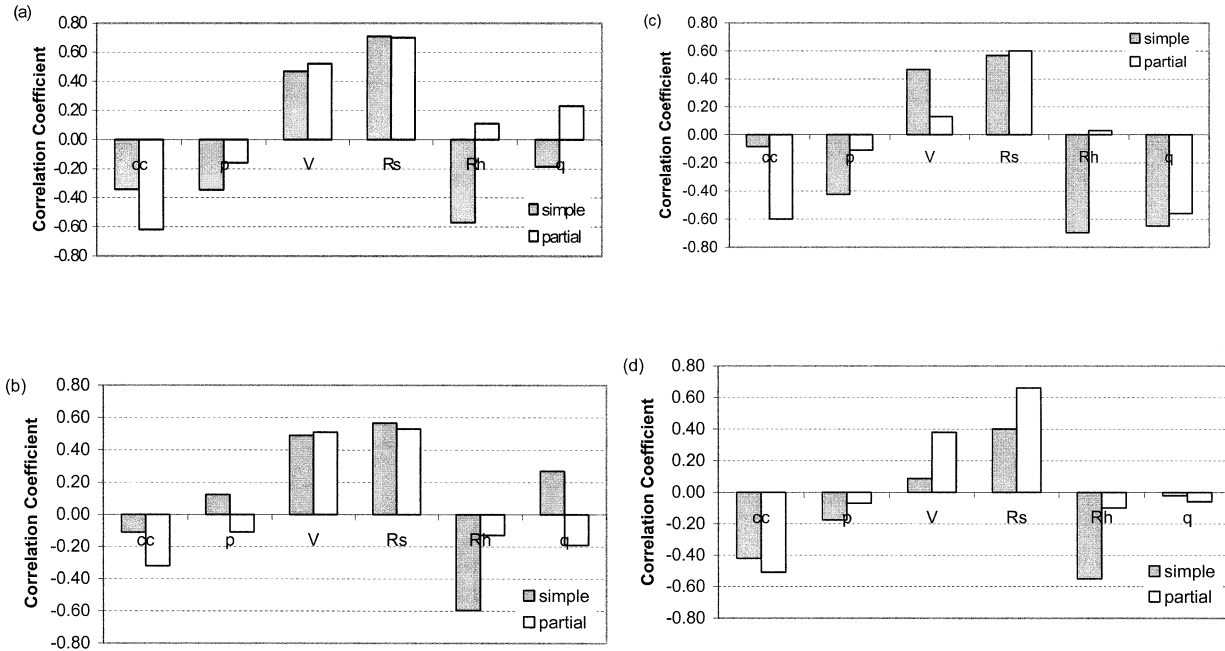


FIG. 7. Simple and partial correlation coefficients by season between DTR and total cloud cover (cc), precipitation (p), surface wind speed (V), solar irradiance (Rs), relative humidity (Rh), and surface specific humidity (q): (a) winter, (b) spring, (c) summer, and (d) autumn. Correlation coefficients of approximately 0.22 are statistically significant at the 0.01 level.

Several factors can reduce solar irradiance, most obviously cloud cover. Paradoxically, cloud cover has been decreasing in China along with solar irradiance. Our calculations showed that the downward trend in solar irradiance was evident even when only cloud-free days are considered (Fig. 9). Thus we considered other factors. Increased atmospheric aerosols resulting from industrial pollution are known to reduce solar irradiance, since they cut down on the amount of sunlight reaching the ground (Stanhill and Cohen 2001; Power 2003). The sulfur aerosol effect is largest in summer, coinciding with the largest decrease in solar irradiance and the smallest increase in T_{max} (Menon et al. 2002). This supports the hypothesis that sulfur aerosols are a plausible cause for the decrease of solar irradiance in China, but adequate data to test that hypothesis remain lacking.

Previous analyses have concluded that cloud cover and precipitation are the primary causes of the decrease

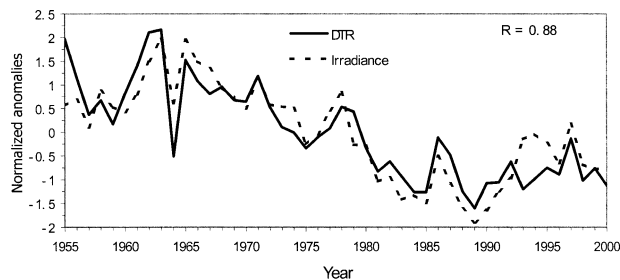


FIG. 8. Annual DTR and solar irradiance normalized (by std dev). The two lines correlate with a correlation coefficient R of 0.88.

in DTR in most parts of the world (Dai et al. 1999; Shen and Varis 2001) in this dataset for China, precipitation correlated poorly with DTR, and the trend of increasing precipitation was not statistically significant. Thus we conclude that these factors do not play the major roles in China that they do globally.

4. Conclusions

For China, it is clear that temperatures increased across the entire 1955–2000 study period, especially in the last decade of the twentieth century. The temperature trends differed between T_{max} and T_{min} —that is, between day and night. Warming was most pronounced in the northeast and least pronounced in the southwest. Win-

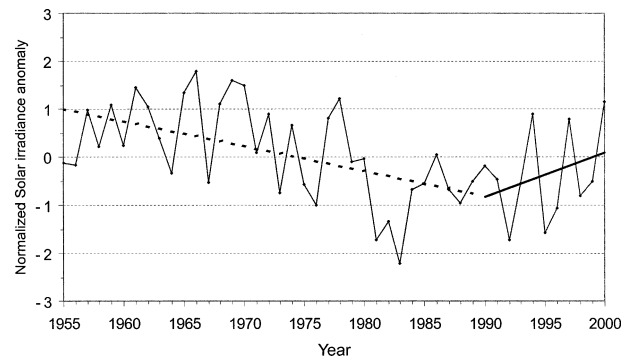


FIG. 9. Mean annual solar irradiance anomalies and linear trends in clear days. Linear trends: 1955–89 (dashed lines) and 1990–2000 (solid lines).

ters became distinctly warmer (in terms of both T_{\max} and T_{\min}); the trend for summer was less steep.

The relative difference between changes in T_{\min} and T_{\max} resulted in changes to DTR. DTR showed detectable changes in all seasons at most weather stations in China, with the fastest decrease in winter and the slowest in summer. Change in DTR during our study period can be divided into two stages. In the first stage, China's DTR decreased rapidly between 1960 and 1990. The decrease in this stage was caused by the increase in T_{\min} and a slight decrease in T_{\max} . In the second stage, from 1990 to 2000, DTR increased slightly, as both T_{\min} and T_{\max} showed rapid increases at almost equal paces. By extension, T_{mean} also increased rapidly in this stage.

Cloud cover and precipitation appeared not to be the main cause of the decrease in DTR in China over the study period. The change in DTR correlated strongly with changes in solar irradiance, prompting us to conclude that that indicator is a key contributor to DTR through its influence on T_{\max} . Atmospheric aerosols, particularly sulfur aerosols, represent a possible cause for the decrease in solar irradiance, but further research is needed to establish this relationship. Determining the root causes of changing solar irradiance and DTR, whether resulting from natural fluctuations or human activity, is an important task for understanding present and future climate dynamics.

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REFERENCES

- Baker, C. B., R. G. Quayle, and W. Wang, 1995: The influence of night time cloud cover on the observed minimum temperature in China. *Atmos. Res.*, **37**, 27–35.
- Campbell, G. G., and T. H. Vonder Haar, 1997: Comparison of surface temperature minimum and maximum and satellite measured cloudiness and radiation budget. *J. Geophys. Res.*, **102**, 16 639–16 645.
- Dai, A., A. D. Del Genio, and I. Y. Fung, 1997: Clouds, precipitation and temperature range. *Nature*, **386**, 665–666.
- , K. E. Trenberth, and T. R. Karl, 1999: Effects of clouds, soil moisture, precipitation, and water vapor on diurnal temperature range. *J. Climate*, **12**, 2451–2473.
- Easterling, D. R., and Coauthors, 1997: Maximum and minimum temperature trends for the globe. *Science*, **277**, 364–367.
- Hansen, J., M. Sato, and R. Ruedy, 1995: Long-term changes of the diurnal temperature cycle: Implications about mechanisms of global climate change. *Atmos. Res.*, **37**, 175–209.
- Kaiser, D. P., 2000: Decreasing cloudiness over China: An updated analysis examining additional variables. *Geophys. Res. Lett.*, **27**, 2193–2196.
- Karl, T. R., G. Kukla, V. N. Razuvayev, M. J. Changery, R. G. Quayle, R. R. Heim Jr., D. R. Easterling, and C. Fu, 1991: Global warming: Evidence for asymmetric diurnal temperature change. *Geophys. Res. Lett.*, **18**, 2253–2256.
- , and Coauthors, 1993: Asymmetric trends of daily maximum and minimum temperature. *Bull. Amer. Meteor. Soc.*, **74**, 1009–1022.
- Kukla, G., and T. R. Karl, 1993: Nighttime warming and the greenhouse effect. *Environ. Sci. Technol.*, **27**, 1468–1474.
- Menon, S., J. Hansen, L. Nazarenko, and Y. Luo, 2002: Climate effects of black carbon aerosols in China and India. *Science*, **297**, 2250–2253.
- Plantico, M. S., T. R. Karl, G. Kukla, and J. Gavin, 1990: Is recent climate change across the United States related to rising levels of anthropogenic greenhouse gases? *J. Geophys. Res.*, **95**, 16 617–16 637.
- Power, H. C., 2003: Trends in solar radiation over Germany and an assessment of the role of aerosols and sunshine duration. *Theor. Appl. Climatol.*, **76**, 47–63.
- Shen, D., and O. Varis, 2001: Climate change in China. *Ambio*, **30**, 381–383.
- Stanhill, G., and S. Cohen, 2001: Global dimming: A review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. *Agric. For. Meteorol.*, **107**, 255–278.
- Wang, W., Z. M. Zeng, and T. R. Karl, 1990: Urban heat islands in China. *Geophys. Res. Lett.*, **17**, 2377–2380.
- Weber, R. O., P. Talkner, and G. Stefanicki, 1994: Asymmetric diurnal temperature change in the Alpine region. *Geophys. Res. Lett.*, **21**, 673–676.