More frequent cloud-free sky and less surface solar radiation in China from 1955 to 2000

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[1] Newly available data from extended weather stations and time period reveal that much of China has experienced significant decreases in cloud cover over the last half of the Twentieth century. This conclusion is supported by the analysis of the more reliably observed frequency of cloud-free sky and overcast sky. The total cloud cover and low cloud cover have decreased 0.88% and 0.33% per decade, respectively, and cloud-free days have increased 0.60% and overcast days decreased 0.78% per decade in China from 1954–2001. Meanwhile, both solar radiation and pan evaporation have decreased in China, with solar radiation decreasing 3.1 W/m^2 and pan evaporation decreasing 39 mm per decade. Combining these results with findings of previous studies, we speculated that increased air pollution may have produced a fog-like haze that reflected/absorbed radiation from the sun and resulted in less solar radiation reaching the surface, despite concurrent increasing trends in cloud-free sky over China.

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1. Introduction

[2] East Asia, especially China, has become one of the most populated and rapidly developing regions of the world over the last several decades. The ever-growing population and human activities have led to a rapid and continued increase in the emission of aerosols and their precursors [*Qian and Giorgi*, 2000; *Qian et al.*, 2001]. With a population increase of 2.5-fold, emissions of fossil fuel black carbon (BC) and sulfur dioxide (SO_2) have increased about 9-fold in China since the 1950s [*Qian et al.*, 2003; State Environmental Protection Administration of China (2003), Report on the state of the environment in China, available at http://www.zhb.gov.cn/english/SOE/soechina2003/air.htm]. According to the Report on the State of the Environment in China for 2003, anthropogenic emissions of SO_2 and BC from industrial and household sources were 21.6 and 10.5 million tons, respectively. Industrial dust emissions in China have reached 10.2 million tons in 2003.

[3] Such a dramatic increase in the emissions of pollutants can result in a significant increase in anthropogenic aerosol loading in the atmosphere and affect the climate and hydrological cycle, as observed in South Asia during the Indian Ocean Experiment. *Ramanathan et al.* [2005] found that aerosol radiative forcing can result in dimming, which cools the surface, stabilizes the atmosphere, and reduces evaporation, leading to changes in the regional climate and hydrological cycle. Recently, some analyses have been performed using various long-term meteorological data from China [e.g., *Li et al.*, 1995; *Qian and Giorgi*, 2000] which have shown that some regions of Central and Eastern China, most notably the Sichuan Basin, have experienced cooling trends mainly due to a decrease in the daily maximum temperature. Other studies have found a downward trend in sunshine duration, solar radiation and diurnal temperature range in China [*Kaiser and Qian*, 2002; *Xu*, 2001; *Qian et al.*, 2003; *Che et al.*, 2005].

[4] The aforementioned decreasing trends in diurnal temperature range, solar radiation, and sunshine duration in China would seemingly suggest an increasing trend in cloud cover that reduces sunlight and day time temperature. Interestingly, *Kaiser* [1998] computed the trends of total cloud amount over 196 stations in China and found a decreasing trend over most stations from 1954–1996. However, the quality of surface human-observed cloud fraction is often questioned [*Menon et al.*, 2002] because biases and inconsistencies may arise among different observers. In this paper, we used the most recently available data from an expanded weather station network in China and calculated the trends of total cloud cover (TCC) and low cloud cover (LCC). We also analyzed the trends in frequency of occurrence of cloud-free sky and overcast sky, both of which are more reliably observed than mean cloud cover fraction, and compared these trends with the variations in solar radiation and pan evaporation. By analyzing the temporal trends and spatial patterns of these variables, we hope to elucidate possible relationships between these changes and increased anthropogenic aerosol particles in China.

2. Data

[5] The daily total cloud cover and low cloud cover data used in this study were obtained from the China Meteorological Administration (CMA) through a bilateral agreement of joint research between CMA and the U.S. Department of Energy on global and regional climate change [*Riches et al.*, 2000]. Stations with over 5% missing data during a month or a year were not used. As a result, data covering the period 1954–2001 from a total of 537 stations were examined. Cloud-free sky is defined by assigning days with daily mean TCC less than 0.10. Overcast sky is defined by assigning days with daily mean TCC larger than 0.90. Daily pan evaporation and solar irradiance data were obtained from *Liu et al.* [2004]. Only stations with both evaporation and

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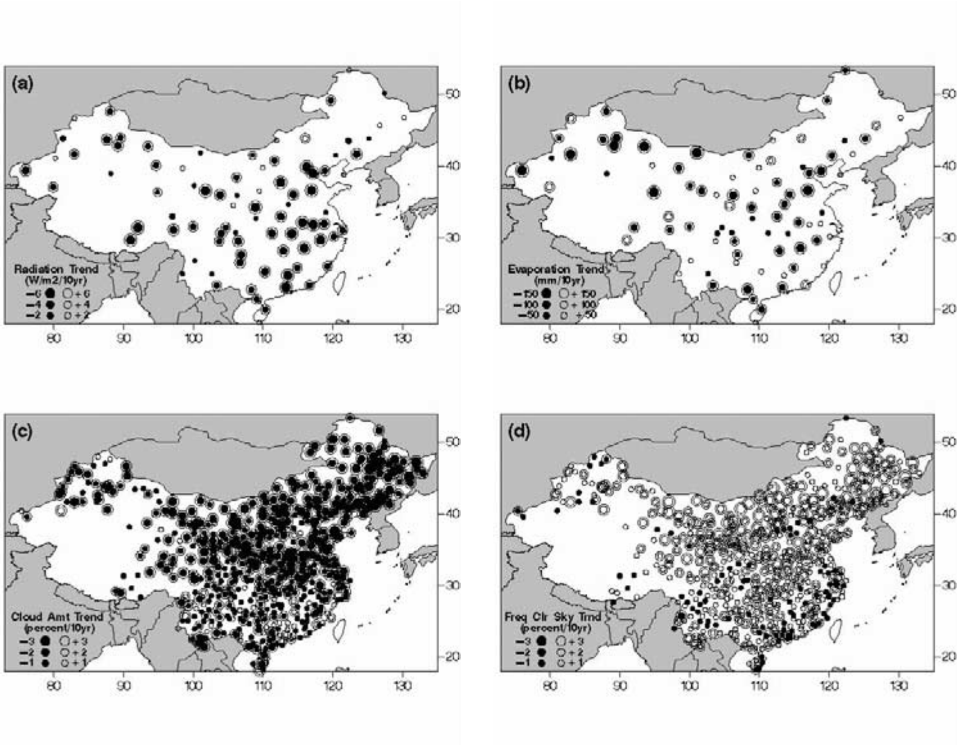

Figure 1. Trends in (a) annual mean solar irradiance (W/m^2 per 10yr) and (b) pan evaporation (mm per 10yr) for 1955–2000. Trends in (c) annual mean total cloud cover (percent per 10yr) and (d) frequency of occurrence of cloud-free sky (percent per 10yr) for 1954–2001. Station trend indicators with circle around them are significant at the 90% confidence level.

solar irradiance data were selected in order to investigate the relationship between these two variables. Finally 85 stations across China from 1955–2000 were used after excluding stations with too much missing data.

3. Results

3.1. Dimming

[6] Figure 1a shows the linear trends computed for the annual mean solar irradiance at individual stations during the period 1955–2000. The vast majority of stations show significant decreasing trends in annual mean solar irradiance (using a linear regression model at the 90% confidence level). More spatially coherent decreases are found over the central, eastern and southern China with trend values of approximately −4 to −6 W/m^2 per decade. Only a very few stations over northern China show increasing trends, but most of them are not statistically significant.

[7] The temporal trend of China was calculated by averaging the annual solar irradiance departures for all stations and is shown in Figure 2; a significant decreasing trend of −3.1 W/m^2 (−1.9%) per decade is found for all stations averaged. One can see from Figure 2 that the most dramatic decrease in solar radiation occurred from the 1960s to the 1980s. Consistent with the observations of *Wild et al.* [2005], a slight increasing trend is apparent from the variations since about 1990.

3.2. Decline in Pan Evaporation

[8] A significant decreasing trend of −39 mm (−2.2%) per decade is shown in Figure 2 for the annual mean pan evaporation averaged over China. The trend of pan evaporation is correlated with the trend of solar irradiance, with a correlation coefficient of 0.57 for the annual means after the linear trends are removed from the time series. This is consistent with the fact that about 50–85% of the radiative heating at the surface is balanced by evaporation [*Ramanathan et al.*, 2005]. Comparing the trends of solar radiation and pan evaporation at individual stations (see Figure 1b), we find that the trends are of the same sign for most stations. A minority of stations show trends of opposite signs, especially in the Yangtze-Delta region and southern China. This indicates that besides solar radiation, other factors such as surface temperature and relative humidity may also affect pan evaporation.

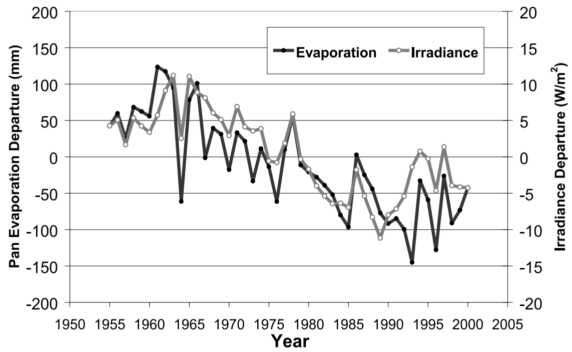

Figure 2. Time series of annual departures of pan evaporation and solar irradiance for 1955–2000, averaged over all stations in China.

3.3. Reduction of Total Cloud Cover and Low Cloud Cover

[9] *Kaiser* [1998, 2000] computed the trends of total cloud amount over 196 stations in China from 1954–1996. Here we update the analysis through 2001 and expand to 537 stations, based on the newly available daily data for both TCC and LCC. By using a more evenly distributed network of stations and annual means, the uncertainty of human-observed cloud fraction data is reduced.

[10] Figure 1c shows the spatial distribution of the trends in annual mean TCC. A decreasing trend over much of China (88% of stations) is observed. Most stations in northern, central and western China show statistically significant decreases of 1–3% sky cover per decade. Only a few stations in South China show an increasing trend. Seasonal trends of TCC (not shown) were found to be generally similar to that shown for the annual mean, except for South China, where more stations with increasing trends were found during winter and spring and less during summer and fall when compared with the yearly average.

[11] Averaging over the 537 stations, the annual mean TCC decreased by 0.88% per decade from 1954 to 2001 (see Figure 3). The seasonal TCC decreased by 0.72% per decade in fall to 1.00% per decade in spring (not shown). Compared with the −0.76% per decade annual mean TCC trend averaged over 196 stations from 1954–1996 [*Kaiser*, 2000], the decreasing trend of mean TCC has become more significant with more stations included in this study. Since no more obvious decreasing trends are found after 1996, we can conclude that the 340 newly-added stations also support the decreasing trend of total cloud cover in China.

[12] Although the spatial pattern of LCC trends (not shown) is more variable than TCC, an overall decreasing trend was still found for all seasons. The all-China averaged trends are −0.33%, −0.33%, −0.32% and −0.45% per decade, respectively, for spring, summer, fall and winter. The decreasing trend for LCC is less than that for TCC, but the sign is consistent. The correlation coefficient between TCC and LCC trends is 0.69.

3.4. Increase in Cloud-Free Sky Days and Decrease in Overcast Days

[13] It is accepted that cloud-free sky or overcast sky observations are much more reliable than the original cloud cover fraction data since cloud-free sky or overcast sky can be more objectively and consistently determined by individual observers. Figure 1d shows the spatial distribution of the trends of the frequency of occurrence of cloud-free sky (FCFS). The spatial pattern of trends is very similar to that of the total cloud cover (Figure 1c) but with opposite sign. Except for a few stations mostly in the southern region, much of China shows statistically significant increases of 1–3% FCFS per decade. Seasonal trends of FCFS (not shown) are similar to that shown for the annual mean.

[14] Figure 3 shows the time series of FCFS departure averaged over the 537 stations in China. FCFS has increased 0.60% per decade from 1954 to 2001. The anti-correlation between TCC and FCFS is obvious and the correlation coefficient is −0.90.

[15] Figure 3 also shows the time series of the average frequency of overcast sky (FOS) departure. The annual mean FOS decreased 0.78% per decade from 1954 to

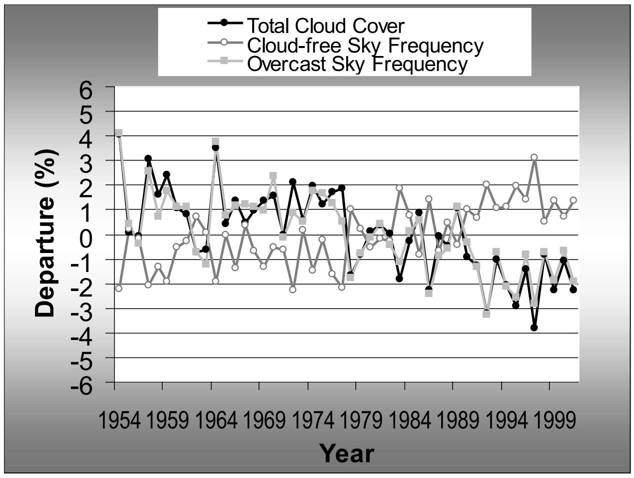

Figure 3. Time series of annual departures of total cloud cover (in percent of sky cover) and of frequency of occurrence of cloud-free sky and overcast sky (percent) for 1954–2001, averaged over all stations in China.

2001. The FOS is closely correlated with TCC (r = 0.92). This indicates that the downward trend in overcast days is highly consistent with the decreasing trend of TCC. FOS is also anti-correlated with FCFS and the correlation coefficient is −0.69. The excellent correlation between TCC and FCFS or FOS, both of which are believed to be more reliably observed, support the conclusion of decreasing trends in cloud cover over China.

4. Summary and Discussion

[16] By analyzing a recently-available dataset, we find that total cloud cover and low cloud cover have decreased significantly in most parts of China since the mid-1950s, which is supported by the more reliably estimated frequency of occurrence of cloud-free sky (found to have increased) and overcast sky (found to have decreased). The correlation coefficients between the total cloud cover and cloud-free sky frequency or overcast sky frequency are over 0.90. The trends of TCC and LCC are both negative and they have decreased 0.88% and 0.33% per decade, respectively, when averaged over China from 1954–2001. This suggests that the variations of clouds at different vertical levels are rather consistent. Meanwhile, cloud-free days have increased 0.60% and overcast days decreased 0.78% per decade in China. *Kaiser* [1998] and *Sun et al.* [2000] also found that the trends in cloud amount are the same sign for daytime and nighttime. Less cloud cover and more cloud-free skies, regardless of their causes, should have resulted in more solar radiation reaching the surface. Surprisingly, the data show that both solar radiation and pan evaporation have decreased in most parts of China by 1.9% (3.1 W/m^2) and 2.2% (39 mm) per 10-year, respectively. Combined with other evidence revealed in previous studies [*Luo et al.*, 2001; *Qian and Giorgi*, 2000; *Cheng et al.*, 2005; *Che et al.*, 2005], such as decreased sunshine duration, reduced visibility or clearness, and elevated aerosol optical depth, we speculated that air pollution may have produced a fog-like haze that reflected/absorbed radiation from the sun and resulted in less solar radiation reaching the surface

(corroborated by the reduced pan evaporation), despite concurrent upward trends in cloud-free skies over China.

[17] Two interesting questions need to be investigated further. First, the decline in solar radiation for the period from 1960 to 1990 was also reported over other regions of the world [*Liepert*, 2002]. Furthermore, the small increasing trend in solar radiation at the surface during the 1990s found in this study is also consistent with some of the other regions. *Wild et al.* [2005] speculated this change from dimming to brightening might be caused by a decrease of aerosol burden due to more effective clean-air regulations and decline in the economy. However the total emissions of SO_2 and black carbon in China had been continuously increasing until the mid-1990s. So the trends in solar radiation and pollutant emissions in China do not match very well in the 1990s. This mismatch reminds us of the complexity of aerosol composition and mixing, and scattering/absorbing properties that could affect solar radiation in different ways. One cannot expect a simple correspondence between pollutant emissions and solar radiation on annual or even decadal time scales.

[18] Second, one may argue that increased aerosol particles could lead to increased cloud cover, hence contradicting the observed trends in the frequency of cloud-free sky. This argument is based on the *indirect* effect of aerosols, which refers to the aerosol-induced increase in droplet number and decrease in droplet size, increasing the reflectivity of clouds and/or producing clouds with a longer lifetime and potentially increasing the average cloud cover [*Intergovernmental Panel on Climate Change*, 2001]. Although evidence of this indirect effect has been found in ship tracks, *Ackerman et al.* [2004] noted that it occurs only when the overlying air is humid or droplet concentrations are very low; otherwise cloud water or cloud amount may decrease with the increases in aerosols. Based on measurements and modeling, *Lelieveld et al.* [2002] and *Koren et al.* [2004] found that pollution reduces and inhibits the formation of clouds and precipitation over the Mediterranean and Amazon, respectively. However, cloud formation depends not only on the number of aerosol particles and cloud droplets, but also on atmospheric stability and moisture availability that are, to a large degree, controlled by large scale circulation. It is difficult to quantitatively detect the change of cloud cover induced by increased aerosols solely based on observations. To interpret the observed trend in cloud cover is beyond the scope of this paper. Future studies using higher temporal resolution data combined with modeling experiments may provide more insights into the various aspects of cloud cover change that occurred in China and improve the detection and attribution of the change.

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