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Where have all the showers gone? Regional declines in light precipitation events in China, 1960–2000

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ABSTRACT: China has seen a decline in recorded precipitation events over 1960–2000. We find that this decline is mainly accounted for by the decrease of light precipitation events, those with intensities of 0.1–0.3 mm/day. The annual number of light precipitation events drops off remarkably around 1978 and decreases rapidly until 1985. Trace precipitation events (precipitation noted but measuring <0.1 mm/day) decrease abruptly from 1982 through the end of the period. Meanwhile, the annual frequency of precipitation events with intensities above 0.3 mm/day shows almost no change for the same period. The analysis uses daily data from 272 stations distributed across China. We note regional and seasonal differences in the rates of change of different intensities of precipitation events. With almost no change in the frequency of precipitation events of 0.4–0.6 and 0.7–0.9 mm/day during the same period, it is difficult to attribute the abrupt decreases to inhomogeneities of the precipitation data. The temporal pattern of light precipitation events is similar to those observed for solar irradiance and total cloud cover, suggesting that there may be some connections between these climatic variables. Declines in solar irradiance and total cloud cover along with increased aerosol loading may have contributed to the abrupt decrease of these light precipitation events. However, light and trace precipitation events display different spatial and temporal patterns of change, complicating this explanation. Copyright © 2010 Royal Meteorological Society

KEY WORDS light precipitation; trace precipitation; climate change; China

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1. Introduction

Precipitation in China has increased slightly over the latter half of the past century, with strong regional and seasonal differences in the pattern of change (Endo *et al*., 2005; Li *et al*., 2005; Liu *et al*., 2005; Qian and Lin, 2005; Wang and Zhou, 2005; Zhai *et al*., 2005). Seasonally, precipitation increased in winter and summer but decreased in spring and fall; regionally, precipitation decreased in the north China plain and north central China, and increased in northwest China (Liu *et al*., 2005). Most regions show a strong decrease in the number of days of rain, snow or hail, with northwest China being an exception (Zhai *et al*., 1999, 2005; Gong *et al*., 2004; Liu *et al*., 2005; Wang *et al*., 2006; Qian *et al*., 2007a); details are shown in Table I. Zhai *et al*. (1999) showed that the frequency of precipitation events in China decreased by −3.9% per decade during 1951–1995, equivalent to −3.7 days per decade, given the average of 95 precipitation events (≥0.1 mm/day) annually at stations in China. Reports for this period also show that days of trace precipitation (less than measurable amounts) have declined over most parts of China (Fu *et al*., 2008). Although large-scale spatial and temporal features of precipitation frequency have been confirmed to be more stable than those of total precipitation (Englehart and Douglas, 1985), we can see that precipitation frequency has changed at a faster rate than total precipitation during the past several decades in China (Liu *et al*., 2005). Consequently, the amount of precipitation per rainy day has increased over nearly the entire country – in short, becoming less frequent but more intense (Zhai *et al*., 2005). By comparison, reports from other countries including the United States, Norway and Australia find no obvious changes in the frequency of summer precipitation events for the same period (Groisman *et al*., 1999). However, such comparisons should be made with caution, as different methods of defining precipitation events may influence the results. For example, to avoid inhomogeneities among data, some countries only consider days with precipitation ≥1.0 mm as the lower threshold of the precipitation events, whereas others use 0.3, 0.2 or 0.1 mm.

The characteristics of precipitation are just as vital as the total amount, and the characteristics of precipitation, including frequency and intensity, are more apt

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Table I. Trends in precipitation events reported in studies of China.

Regions	Time period	Season	Threshold of precipitation event (mm/day)	Trend slopes (days per decade)
			Zhai *et al.* (1999)	
China	1951–1995	Annual	≥0.1	−3.7
			Gong *et al.* (2004)	
North China	1956–2000	May to September	≥0.1	−1.56
			Liu *et al.* (2005)	
China	1960–2000	Annual	≥0.1	−2.3
China	1960–2000	October to March	≥0.1	−1.0
China	1960–2000	April to May	≥0.1	−0.2
China	1960–2000	June to August	≥0.1	−0.5
China	1960–2000	September	≥0.1	−0.6
			Wang *et al.* (2006)	
China	1954–2000	Annual	>0 (including trace)	−3.8
China	1954–2000	March to April	>0 (including trace)	−0.9
China	1954–2000	June to August	>0 (including trace)	−0.9
China	1954–2000	September to November	>0 (including trace)	−1.1
China	1954–2000	December to February	>0 (including trace)	−1.0
			Qian *et al.* (2007)	
China	1961–2005	June to August	≥0.1	−0.85

to change as climate changes (Trenberth *et al*., 2003). Given the concern about changes in precipitation frequencies for different intensities, prior research on precipitation frequency in China has concentrated mainly on changes in the number and intensity of the most extreme heavy precipitation events (Zhai *et al*., 1999, 2005; Endo *et al*., 2005; Wang and Zhou, 2005). Changes in such events can greatly influence the rate of change in annual precipitation as they account for a disproportionately high percentage of the annual total (Michaels *et al*., 2004). But the characteristic distribution of daily rainfall at a given station is dominated by light events (Groisman *et al*., 1999; Michaels *et al*., 2004), whereas heavy precipitation events are only small part of annual total precipitation frequency. The spatial patterns of change in extreme daily precipitation events are similar to the patterns in annual mean precipitation (Wang and Zhou, 2005), but differ from the spatial pattern of change for annual precipitation events. An analysis of changes in the frequencies of precipitation events of different intensities is important to understand the effects of a warming climate on the characteristics of precipitation.

A common method for categorizing precipitation intensities is to apportion precipitation events (days with measurable rain, snow or hail) into bins by precipitation amount (millimetres). One such analysis of China found a decrease in the frequency of light rain events of ≤1.0 mm/day, accounting for 85% of the decreasing trend of total rain events in the summer (Qian *et al*., 2007a). An alternative method apportions events at each station into fixed-percentile bins, such as deciles. In another analysis of China using the fixed-percentile method, the reduction in the category of lightest precipitation events (the bottom decile of all events over the study period) accounted for 66% of the total reduction in precipitation frequency between 1960 and 2000 (Liu *et al*., 2005).

Qian *et al*. (2007a) defined light precipitation days as ≤1.0 mm/day; these represented nearly 31% of the total number of summer precipitation days over the entire study period. By contrast, Liu *et al*. (2005) applied equal frequency deciles based on precipitation intensities at each station over the study period, so the category of lightest precipitation events was set to the lowest 10%. In practice, the bottom two deciles, which accounted for most of the decrease in annual precipitation frequency, comprised events of ≤0.6 mm/day for most stations. Thus, despite the different methods used, both studies agree that decreases in precipitation frequency are concentrated among light precipitation events of somewhat <1 mm/day.

In this article, we document the spatial and temporal trends of light precipitation events, focusing primarily on events of ≤1.0 mm/day. These account for about 40% of the total number of precipitation events for China from 1960 to 2000. We examine the frequency of events in ten categories of precipitation intensity, as well as trace precipitation events, to determine the contribution of each category to the overall decline in light precipitation events, and compare these temporal trends with those of other climatic variables to investigate the relationship between precipitation frequencies and climate change in China. Recognizing substantial differences among the regions of China in the frequency and annual total amount of precipitation, we conduct the analysis at regional and national scales as well as at the level of individual stations in this article.

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2. Data and methods

Data for this study consist of daily records provided by the China Meteorological Administration (CMA) through a bilateral agreement of joint research on global and regional climate change with the United States Department of Energy (Riches *et al*., 2000). The data set includes daily precipitation measurements from 305 stations from 1951 through 2000.

Precipitation is measured twice a day over China, at 0000 and 1200 UTC (0800 and 2000 Beijing time). The Chinese standard precipitation gauge (CSPG) has been the standard instrument for measuring both solid and liquid precipitation in China climatological and hydrological station networks since the late 1950s (Chinese Meteorological Administration, 1979). The gauge is a cylinder of galvanized iron, 65 cm long and 20 cm in diameter. A precipitation event of <0.10 mm is beyond the resolution of the CSPG and is recorded as trace amount of precipitation (Ye *et al*., 2004).

We considered all precipitation events, defined as days with precipitation totals of ≥ 0.1 mm (Zhai *et al*., 1999; Liu *et al*., 2005). The CMA data also record days with trace precipitation (<0.1 mm) and we considered these events separately from the measurable precipitation events.

The consistency and completeness of measurements are of particular importance to a study of precipitation frequency. CMA protocols specify that measurements at all weather stations are made using the same standards and instrumentation. We have also taken additional measures to assess the homogeneity of the data used in this analysis (Liu *et al*., 2004a, 2004b, 2005). We have excluded records prior to 1960 due to inconsistent or missing measurements in some stations. For subsequent years, another 33 stations are also excluded because data for three or more consecutive days were missing. Records from the remaining 272 stations have been assessed to assure consistency and quality, with only 40 missing observations from 31 stations (a minimum of 99.97% data availability for each station). No single station accounted for more than four missing observations or two consecutive missing observations. Therefore, the missing data should have minimal impact on our results.

The 272 stations are well distributed across China including the Tibetan Plateau. There are large differences among the regions of China in the frequency and annual total amount of precipitation. In general, relative humidity increases across China from northwest to southeast. Precipitation is greatest over southern China and decreases gradually from the southeastern coast to the northwestern inland in China (Qian and Leung, 2007). The annual total rainfall is over 1500 mm in Southeast Coast, Pearl River and the lower Yangtze River Basin, but <100 mm in the northwestern region (Qian *et al*., 2009). Northwest China experiences both the fewest precipitation events and the lowest total amount, whereas southwest China has the highest frequency of events, and southeast China receives the greatest total amount. In fact, the average annual total precipitation in southeast China is about 15 times that in northwest China, and the average annual number of precipitation events in southwest China is about three times that in northwest China. Thus, it is important to consider regional as well as national trends.

In our analysis, we first calculated the anomaly based on the 1960–2000 period average for each station. Following the methods documented in Liu *et al*. (2005), station data were aggregated for national analyses using an area-weighted approach. A 5×5 grid was superimposed on the map of China and each weather station was assigned to a grid cell; precipitation values for each cell were calculated as the arithmetic average of all stations in the cell. These grid cells were then weighted by land area within China's borders to calculate changes of precipitation at the national level. We then divided China into 11 climatic regions of spatially coherent precipitation patterns, following the approach of Qin and Qian (2006), who applied a hierarchical cluster method to daily precipitation data from 1960 to 2000. The distribution of the 272 stations used in this analysis and the division of China into 11 climatic regions, as defined by Qin and Qian (2006), are shown in Figure 1. As spatial variability of change may exist on scales below the regions defined here, we also analysed the change in precipitation frequency using time series from individual stations. This analysis of station trends can reveal information about important local drivers of precipitation change, including land use change which may be manifested at a range of spatial scales (Pielke *et al*., 2007).

We calculated trends in the frequency of precipitation events on an annual and seasonal basis. Regression analysis was used to establish linear trends of precipitation events, and we used the t-test to determine whether the linear trends were significantly different from zero at the 5% probability level. Autocorrelation is not a problem in this study because the regression was performed on an annual basis; we confirmed this by using the Durbin–Watson statistic to test the time series for first-order autocorrelation. Seasons were defined as whole months, with winter comprising December through February, spring comprising March through May, etc. Changes were characterized in both absolute and percentage terms. For the purpose of analysing temporal variation in the change in precipitation days, we applied a nine-point binomial filter, a method to smooth out the year-to-year variations in a time series and show the longer term trend.

The data set of the 305 stations also includes daily measurements of mean temperature, water vapour pressure (surface specific humidity), relative humidity and total cloud cover from 1960 to 2000. Of the 305 weather stations, 85 stations also reported daily solar irradiance. Liu *et al*. (2004a, 2004b) provide a detailed introduction to the data. In order to compare the changes in precipitation frequency with other climatic variables, the overall trends and temporal variation of daily mean temperature,

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Figure 1. Geographical distribution of the 272 weather stations and the 11 climatic regions of China. I, northeast China; II, north China; III, mid and lower Yangtze River; IV, south of Yangtze River; V, south China; VI, middle and east parts of northwest China; VII, Han-wei River; VIII, Sichuan Region; IX, southwest China; X, Xinjiang Region; XI, Tibetan Plateau.

water vapour pressure, total cloud cover, relative humidity and solar irradiance were also calculated following the same method as for precipitation frequency.

An objective of this analysis was to identify more closely the range of precipitation intensities most responsible for the overall decrease in precipitation events. We then compared the temporal pattern of this target range of intensities with the patterns of other climatic variables to seek possible reasons for the decline.

3. Results and analysis

3.1. Overall trends

We first analysed the change in precipitation over time at individual stations. Figure 2(a) and (b) shows the spatial pattern of trends for annual precipitation amount and frequency, respectively. From 1960 to 2000, much of southeast China has exhibited an increase in annual total precipitation, while decreases were seen in parts of the north and northeast. This pattern of change has been described as 'Wet in the South, Drought in the North' (Hu *et al.*, 2003).

In eastern parts of China, although annual total precipitation exhibits a trend of 'Wet in the South, Drought in the North', the annual precipitation frequency presents a spatially consistent decreasing trend. Western parts of China (including the Xinjiang Region and the Tibetan Plateau) generally exhibit an increase in annual total precipitation. Unlike in the east, western regions generally exhibit increasing trends in annual precipitation frequency. Thus, the spatial pattern of change for annual total precipitation differs from the spatial pattern of change for number of rain days, especially for eastern China.

Based on the results of Liu *et al.* (2005) and Qian *et al.* (2007a), the decreases in precipitation frequency are accounted for by the changes in light precipitation events of somewhat <1 mm/day. We analysed the spatial pattern of trends of light precipitation events, focusing primarily on events of <1.0 mm/day. We found spatially consistent changes in light precipitation frequency with daily precipitation amounts between 0.1 and 0.3 mm. Figure 3(a) and (b) shows the spatial pattern of trends for annual precipitation frequency with daily precipitation amounts of 0.1–0.3 mm and $\geq$0.4 mm, respectively. The frequency of precipitation between 0.1 and 0.3 mm/day reveals widespread and significant decreasing trends across China. Only four widely dispersed stations show increasing trend and none of them reach the 95% statistical significance level. The frequency of daily precipitation amounts $\geq$0.4 mm shows regional differences in the direction of the trend. Most stations with increasing trends are distributed in western and southeastern China, while most stations with a decreasing trend are distributed in the eastern part of north central China. This is similar to the spatial trend of annual total precipitation.

Figure 4 shows the spatial pattern of trends for the annual total number of trace precipitation events. As with days with between 0.1 and 0.3 mm of precipitation, trace precipitation also reveals a decreasing trend for most parts of China. Only 24 stations show increasing trends and most of them are scattered in the southeast and southwest parts of China.

Finding spatially consistent changes in the frequency of light precipitation events, we analysed the trends for each daily precipitation intensity level in more detail, from the lowest measurable amount up to 0.9 mm/day, and show the results at the regional and national levels. We also

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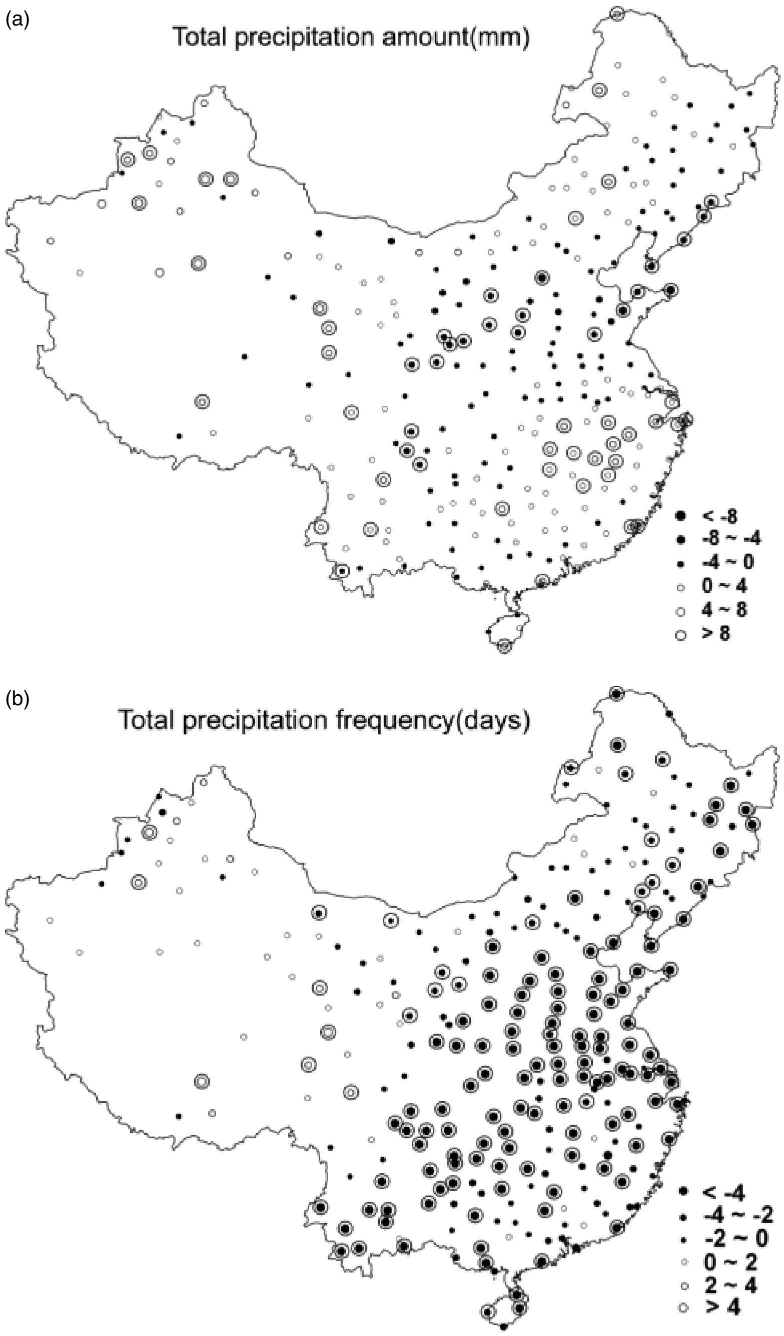

Figure 2. Trends of the annual total precipitation (a) amount and (b) frequency (events ≥0.1 mm/day). Station trend indicators with circle around them are statistically significant at the 0.05 level.

computed the corresponding changes for trace precipitation events. National and regional trends of the frequency of trace (<0.1 mm/day) and light (0.1–0.9 mm/day) precipitation events in China for 1960–2000 are shown in Table II. Trends are given both in absolute terms (days per decade) and in percentage terms. These results show statistically significant decreasing trends in the category of the lightest measurable precipitation events – those measuring 0.1 mm/day – nationally and in all climatic regions except Xinjiang and the Tibetan Plateau (for these two regions the decreasing trend do not reach statistical significance). Significant decreasing trends are also found for intensities of 0.2 and 0.3 mm/day for most of the climatic regions and for China as a whole. In general, the decreases are greatest in southwest China, followed by the middle and lower Yangtze River regions, both in absolute and percentage terms. Trends for trace precipitation events are statistically significant with declines nationally and in all climatic regions; the Tibetan Plateau shows the largest declines both in absolute and percentage terms, followed by northeast China.

For light precipitation events, the lower precipitation intensities generally see greater rates of decreasing precipitation frequency, and indeed the category of the lightest measurable precipitation events (0.1 mm/day)

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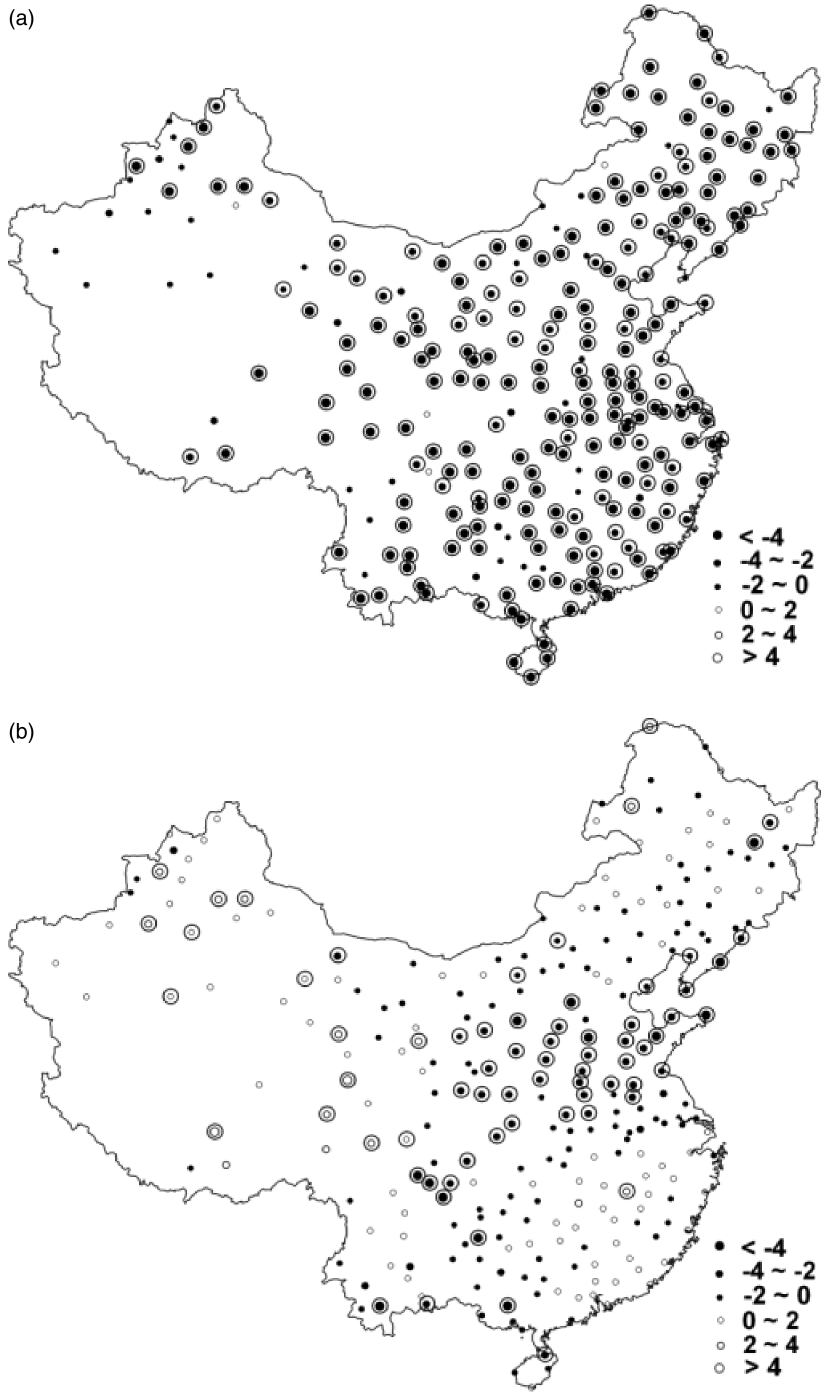

Figure 3. Trends of the annual total number of precipitation events with daily precipitation amount (a) between 0.1 and 0.3 mm and (b) ≥0.4 mm. Station trend indicators with circle around them are statistically significant at the 0.05 level.

has the greatest decline. Nationally, the magnitude of the decrease in frequency of precipitation events of 0.1–0.3 mm/day is 2.2 days per decade, accounting for 96% of the total decrease of 2.3 days per decade (Liu *et al.*, 2005). Within that range, events of 0.1 mm/day contribute 69%, events of 0.2 mm/day contribute 22% and events of 0.3 mm/day contribute 5% of the change in annual number of precipitation events.

For regions with decreasing trends of precipitation frequency, the decrease in the frequency of events of 0.1–0.3 mm/day contributed to most of the change. As noted, the characteristic distribution of daily rainfall is dominated by light events (Groisman *et al.*, 1999; Michaels *et al.*, 2004), and in China, precipitation events with intensities of 0.1–0.3 mm/day make up 22.56% of the total number of measurable precipitation events (≥0.1 mm/day) in this study period, even though they produce only 0.68% of total precipitation (Table III). Trends calculated on a percentage basis are needed to evaluate whether the changes in precipitation frequencies at these intensities are disproportionally high. Viewed on this basis, the category of the lightest precipitation events

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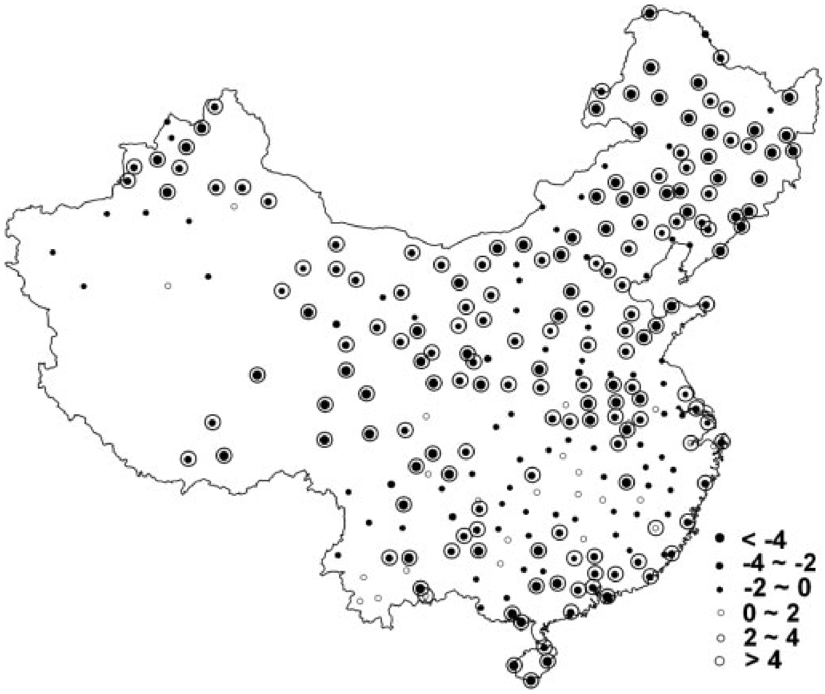

Figure 4. Trends of the annual total number of trace precipitation events. Station trend indicators with circle around them are statistically significant at the 0.05 level.

again has the highest rate of decline among categories of measurable events. This finding supports the conjecture that decreases in precipitation frequency are mainly concentrated in events of ≤0.3 mm/day, further refining earlier reports that attributed declines in precipitation frequency mainly to trends in events of ≤1.0 mm/day (Liu *et al.*, 2005; Qian *et al.*, 2007a). Because the changes in the frequency of precipitation events have concentrated in 0.1–0.3 mm/day, the changes do not have much effect on annual total precipitation. This can explain the earlier finding that the secular changes of precipitation days do not completely accord with changes in precipitation amounts over the past decades in China (Wang *et al.*, 2006).

Trace precipitation events show even greater declines in absolute terms than the lightest measurable light precipitation events in all regions except along the middle and lower Yangtze River, south of Yangtze River and in southwest China. However, on a percentage basis, the decline in trace precipitation events is not as great as that for the lightest measurable precipitation events (0.1 mm/day), both nationally and for most of the climatic regions. Comparing trace precipitation events with measurable light precipitation events of 0.1–0.3 mm/day, the percentage of trace events generally had a higher rate of change in northern regions, whereas the percentage of light events generally had a higher rate of change in southern regions.

Breaking these annual trends into their seasonal components (Table IV), we find that light precipitation events generally show decreases in all seasons over 1960–2000. Exceptions by region are the middle and eastern parts of northwest China and the Sichuan Region in spring, and the Xinjiang Region and Tibetan Plateau in winter and spring. Northern regions generally show a higher rate of change in summer and autumn, whereas southern regions have higher rate of change in autumn and winter. The seasonal patterns for trace precipitation events differ from those for light precipitation events. For example, northeast China has the greatest declines in light precipitation events during the summer, but for trace precipitation events that region's greatest declines (both in absolute and percentage terms) appear in the winter.

3.2. Time series analysis

Light precipitation events drive the abrupt decline in overall events starting in 1978. In Figure 5, we show the national average time series and trends for all measurable precipitation events (≥0.1 mm/day) followed by separate time series for light (0.1–0.3 mm/day) and heavier (≥0.4 mm/day) events. The temporal change of the number of light precipitation events (0.1–0.3 mm/day) is similar to the number of all measurable precipitation events (≥0.1 mm/day). We observe three distinct regimes. During the early part of the period (prior to about 1978), precipitation frequency was higher than the 1960–2000 period average by about 3 days. During the period 1978–1985, the precipitation frequency decreased by about 6 days. After 1985, the precipitation frequency was around 3 days below the long-term average with slightly decreasing trend. The number of all annual precipitation events declined at a statistically significant rate and decreased abruptly around 1978, a pattern also seen for light events. By contrast, the frequency of heavier events shows no significant change across the period; the frequency of heavier precipitation days fluctuates around

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Table II. National and regional trends of precipitation frequency with intensities of 0.1–0.9 mm, China 1960–2000.

Trends (days per decade)	Precipitation intensity (mm/day)									
	Trace	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Northeast China										
Change rate, days per decade	**−4.38**	**−1.41**	**−0.52**	**−0.20**	**−0.08**	−0.01	**−0.07**	−0.03	−0.04	−0.04
Change percentage, % per decade	**−9.04**	**−13.09**	**−7.22**	**−3.96**	**−2.00**	−0.11	**−2.26**	−1.25	−1.46	−1.72
North China										
Change rate, days per decade	**−2.80**	**−2.21**	**−0.83**	**−0.29**	**−0.12**	**−0.10**	−0.07	**−0.07**	**−0.07**	**−0.07**
Change percentage, % per decade	**−7.20**	**−25.84**	**−15.39**	**−7.92**	**−3.95**	**−3.94**	−2.90	**−3.30**	**−3.50**	**−3.61**
Mid and lower Yangtze River										
Change rate, days per decade	**−2.11**	**−4.39**	**−1.72**	**−0.27**	**−0.18**	−0.08	−0.05	−0.03	−0.07	0.05
Change percentage, % per decade	**−4.54**	**−28.11**	**−18.95**	**−4.68**	**−4.17**	−2.14	−1.63	−1.03	−2.48	2.01
South of Yangtze River										
Change rate, days per decade	**−1.38**	**−3.62**	**−1.51**	**−0.39**	−0.07	**−0.14**	−0.08	0.02	−0.01	−0.03
Change percentage, % per decade	**−2.71**	**−23.13**	**−16.19**	**−6.43**	−1.60	**−3.53**	−2.12	0.67	−0.38	−1.04
South China										
Change rate, days per decade	**−3.80**	**−2.86**	**−0.90**	**−0.26**	−0.04	**−0.16**	−0.01	−0.01	−0.07	0.01
Change percentage, % per decade	**−7.28**	**−20.63**	**−11.71**	**−5.03**	−1.00	**−4.57**	−0.39	−0.35	−2.48	0.06
Middle and east parts of Northwest China										
Change rate, days per decade	**−3.76**	**−0.61**	**−0.16**	−0.08	−0.05	0.07	0.01	−0.02	0.04	0.01
Change percentage, %per decade	**−8.77**	**−8.76**	**−3.33**	−2.25	−1.76	2.53	0.01	−0.93	1.64	0.44
Han-wei River										
Change rate, days per decade	**−2.70**	**−1.97**	−0.05	−0.12	−0.11	−0.10	0.01	0.12	−0.01	−0.04
Change percentage, % per decade	**−5.10**	**−17.98**	−0.74	−2.46	−2.81	−3.22	0.41	4.31	−0.44	−1.68
Sichuan Region										
Change rate, days per decade	**−3.71**	**−1.79**	**−0.75**	−0.21	−0.15	0.08	−0.10	0.01	0.03	−0.05
Change percentage, % per decade	**−6.25**	**−11.50**	**−7.70**	−2.90	−2.77	1.56	−2.27	0.17	0.68	−1.37
Southwest China										
Change rate, days per decade	**−1.24**	**−4.98**	**−2.24**	**−0.96**	**−0.42**	−0.14	−0.06	−0.08	0.07	−0.06
Change percentage, % per decade	**−2.40**	**−28.80**	**−20.95**	**−13.60**	**−7.96**	−3.32	−1.49	−2.34	2.11	−1.94
Xinjiang Region										
Change rate, days per decade	**−2.39**	−0.12	0.10	0.06	0.12	0.02	0.05	0.04	0.03	−0.02
Change percentage, % per decade	**−4.50**	−0.92	1.42	1.23	3.27	0.67	1.83	1.41	1.42	−0.85
Tibetan Plateau										
Change rate, days per decade	**−5.77**	−0.15	0.10	0.05	**0.28**	**0.23**	0.16	0.05	**0.16**	**0.17**
Change percentage, % per decade	**−9.52**	−1.35	1.92	1.05	**5.89**	**5.72**	4.49	1.67	**5.54**	**6.22**
National										
Change rate, days per decade	**−3.26**	**−1.59**	**−0.51**	**−0.12**	−0.03	0.02	0.001	0.001	0.03	0.03
Change percentage, % per decade	**−6.54**	**−14.66**	**−7.21**	**−2.51**	−0.80	0.67	0.05	0.004	1.22	1.26

Boldface indicates statistical significance at the 0.05 level.

the period average during entire period. Further disaggregating those heavier events, Figure 6 shows no significant change in the number of events of 0.4–0.6 or 0.7–0.9 mm/day.

The close correspondence between the temporal patterns for all precipitation events and light precipitation events supports the finding that declines in light precipitation events are most responsible for the overall decline in days of precipitation. Furthermore, it is the abrupt decline from 1978 to 1985 that accounts for most of the change during this period; after 1985, the annual frequency of these events fluctuates around 3 days below the period average with only a slight continuing decreasing trend.

Figure 7 shows the time series of national average values of the annual number of trace precipitation events. Here we observe two distinct regimes. During the early part of the period (up to about 1982), precipitation frequency was higher than the 1960–2000 period average by about 3 days. After 1982, the trace precipitation frequency decreased by about 12 days. As with light precipitation events, trace precipitation events also go into a steep decline around the middle of the study period. Up to 1978, the time series for trace precipitation frequency parallels that of light precipitation. However, the initial decline in trace precipitation events lags behind, starting around 1982, and does not level off, instead continuing through the end of the study period.

Figure 8 shows the time series of national average values of seasonal number of light (0.1–0.3 mm/day) and trace precipitation events. Generally, the seasonal change in the frequency of these two categories of precipitation events is similar to the annual change with the exception of winter. In winter, the frequency of trace precipitation events decreased abruptly around 1978, which is similar

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Table III. Percent of precipitation amount and frequency attributable to light precipitation events (0.1–0.3 mm) by region, China 1960–2000.

	Precipitation intensity equals 0.1–0.3 mm/day	
	Percentage of annual amount	Percentage of annual frequency
Northeast China	0.56	18.29
North China	0.32	15.65
Mid and lower Yangtze River	0.32	16.64
South of Yangtze River	0.24	14.60
South China	0.19	14.58
Middle and East Part of Northwest China	1.09	19.83
Han-wei River	0.37	15.61
Sichuan Region	0.40	15.17
Southwest China	0.35	16.20
Xinjiang Region	2.28	25.96
Tibetan Plateau	0.77	16.63
National	0.68	22.56

to the frequency of light precipitation events. In the other three seasons, the frequency of trace precipitation events begins to decline later than the frequency of light precipitation events.

3.3. Effects of measurement thresholds

One may well question whether changes in measurement techniques or instrumentation might produce these results. In many countries, precipitation gauges have improved over time, which may lead to the reporting of higher numbers of low-intensity precipitation events (Groisman *et al*., 1999; Nicholls and Murray, 1999). Thus, the choice of a threshold to define a precipitation event is not a negligible problem in this kind of analysis (Nicholls and Murray, 1999; Brunetti *et al*., 2004). The 0.1-mm threshold in this study is much lower than those applied in most other countries (Groisman *et al*., 1999; Brunetti *et al*., 2004). Indeed, as we find that decrease in precipitation events is mainly concentrated in the lowest precipitation intensities of 0.1–0.3 mm/day, and because the trends decline abruptly midway through the study period, we must consider the possibility that our results stem from inhomogeneities in the precipitation data. As Figure 5(c) reminds us, if we were to choose 0.4 mm as the minimum threshold for precipitation events, the national trend of precipitation frequency would shrink to an insignificant −0.05 days per decade, with almost no change across the study period of 1960–2000.

As noted, however, technological improvements in precipitation gauges generally lead to more, not fewer, reportable cases of low-intensity precipitation events (Nicholls and Murray, 1999; Brunetti *et al*., 2004). If improved instrumentation had been introduced, this data set should underestimate any decrease in such events. The mostly parallel, significant decrease in trace precipitation events offers additional evidence that this is a real phenomenon, while the unchanged frequencies of light precipitation events of somewhat higher intensities further reduces the possibility that the trends reported here result from changes in measurement technologies over time.

As for the choice of the low 0.1 mm/day threshold, we follow many other studies using Chinese data in adopting this threshold (Zhai *et al*., 1999; Endo *et al*., 2005; Liu *et al*., 2005; Qian *et al*., 2007a). As noted earlier, the Chinese meteorological network follows uniform data collection procedures, and previous assessments of these precipitation data by Groisman *et al*. (1999) have indicated no problems with instrumental homogeneity in China. As the decline of light precipitation frequency did not occur in all regions, and within regions did not occur in all seasons, it is difficult to attribute this pattern to data inhomogeneities.

3.4. Comparisons with other climatic phenomena

The abrupt decline in light precipitation events is paralleled in China by changes reported in other climatic variables. These include solar radiation (Liang and Xia, 2005) and total cloud cover (Kaiser, 2000), which show abrupt decreasing trends beginning in 1978, and surface air pressure (Kaiser, 2000), which shows abrupt increasing trends from around the same year. Similarly, sunshine duration has decreased since about 1980 (Kaiser and Qian, 2002). For comparison, trends in mean air temperature from 1955 to 2000 can be divided into two stages: up to the mid-1980s, mean air temperature increased slightly with night-time temperatures contributing most of the change, whereas in later years both daytime and night-time temperature increased more rapidly and in tandem (Liu *et al*, 2004a).

Figure 9(a) shows the time series of the national average solar irradiance. We characterize this in terms of three distinct regimes. During the early part of the period (prior to about 1978), solar irradiance remained relatively constant. During the period of 1978–1983, solar irradiance on clear days in China shows an abrupt decline, close to the period of rapidly decreasing precipitation frequency. The decline in solar irradiance was also observed in most of other parts of the world and became known as 'global dimming' (Stanhill and Cohen, 2001; Liepert, 2002). That trend has reversed since the late 1980s and especially in the 1990s, with increasing solar irradiance in China and other parts of the world (Wild *et al*., 2005). This is unlike the trend of trace and light precipitation events, which stabilized or continued to decrease through the 1990s.

A rapid increase in aerosol loading has been suggested as the principal cause for the decrease in solar irradiance and sunshine duration (Kaiser and Qian, 2002; Liang and Xia, 2005; Qian *et al*., 2007b). Can increased aerosol loading also explain the decline in the light precipitation events in China? The effects of aerosol on precipitation may operate through complex processes. Some kinds of

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Table IV. Seasonal trends of trace and light precipitation frequency, China 1960–2000.

Trends (days per decade)	Winter	Spring	Summer	Autumn
Northeast China				
Trace	**−1.59 (−13.59)**	**−1.20 (−8.91)**	**−0.77 (−5.89)**	**−0.76 (−7.47)**
0.1–0.3 mm/day	**−0.21 (−3.79)**	**−0.14 (−3.60)**	**−0.97 (−18.86)**	**−0.57 (−13.35)**
North China				
Trace	**−0.72 (−10.2)**	**−0.72 (−6.89)**	**−0.75 (−5.69)**	**−0.59 (−7.12)**
0.1–0.3 mm/day	**−0.51 (−17.10)**	**−0.50 (−15.15)**	**−0.64 (−14.01)**	**−1.20 (−28.78)**
Mid and lower Yangtze River				
Trace	**−0.54 (−4.92)**	**−0.59 (−4.88)**	**−0.41 (−3.25)**	**−0.57 (−5.22)**
0.1–0.3 mm/day	**−2.41 (−31.59)**	**−1.00 (−16.31)**	**−0.51 (−10.56)**	**−2.07 (−31.32)**
South of Yangtze River				
Trace	−0.39 (−3.22)	−0.08 (−0.63)	**−0.46 (−3.49)**	**−0.44 (−3.52)**
0.1–0.3 mm/day	**−2.11 (−27.51)**	**−0.92 (−14.63)**	**−0.38 (−7.58)**	**−1.64 (−26.35)**
South China				
Trace	**−1.08 (−7.94)**	**−1.04 (−6.94)**	**−0.73 (−6.13)**	**−0.95 (−8.10)**
0.1–0.3 mm/day	**−1.73 (−26.77)**	**−0.51 (−8.44)**	**−0.39 (−8.36)**	**−1.03 (−21.50)**
Middle and east parts of Northwest China				
Trace	**−0.91 (−11.67)**	**−0.76 (−7.09)**	**−1.20 (−7.33)**	**−0.87 (−10.68)**
0.1–0.3 mm/day	−0.06 (−1.88)	0.01 (0.28)	**−0.26 (−6.34)**	**−0.41 (−12.72)**
Han-wei River				
Trace	−0.67 (−5.15)	−0.42 (−2.99)	**−1.42 (−9.87)**	−0.19 (−1.62)
0.1–0.3 mm/day	−0.19 (−4.72)	−0.03 (−0.77)	−0.21 (−5.05)	**−1.43 (−26.17)**
Sichuan Region				
Trace	**−1.36 (−9.29)**	**−1.13 (−6.76)**	−0.28 (−1.97)	**−0.94 (−6.83)**
0.1–0.3 mm/day	**−0.82 (−11.91)**	0.01 (0.04)	**−0.54 (−9.48)**	**−1.21 (−18.00)**
Southwest China				
Trace	−0.22 (−2.13)	**−0.86 (−5.39)**	0.27 (2.16)	**−0.44 (−3.50)**
0.1–0.3 mm/day	**−3.65 (36.65)**	**−0.28 (−5.11)**	**−0.55 (−9.61)**	**−2.60 (−33.57)**
Xinjiang Region				
Trace	**−0.87 (−6.58)**	**−0.45 (−3.74)**	−0.29 (−1.54)	**−0.70 (−7.52)**
0.1–0.3 mm/day	**0.34 (5.51)**	0.04 (1.23)	**−0.18 (−4.01)**	−0.14 (−4.05)
Tibetan Plateau				
Trace	**−1.06 (−9.93)**	**−2.00 (−10.26)**	**−1.23 (−7.28)**	**−1.58 (−11.32)**
0.1–0.3 mm/day	**0.42 (10.85)**	0.20 (3.83)	**−0.27 (−4.64)**	**−0.32 (−6.66)**
National				
Trace	**−0.93 (−8.68)**	**−0.90 (−6.68)**	**−0.64 (−4.15)**	**−0.77 (−7.44)**
0.1–0.3 mm/day	**−0.60 (−11.7)**	**−0.17 (−3.63)**	**−0.54 (−10.7)**	**−0.86 (−19.1)**

Trends are given in days per decade (percentage of period average in parentheses). Boldface indicates statistical significance at the 0.05 level.

aerosol such as black carbon can absorb solar irradiance and change the atmospheric temperature structure, leading to the suppression of rainfall (the aerosol semi-direct effect) (Hansen *et al*., 1997; Ramanathan *et al*., 2001). Additionally, aerosols can serve as cloud condensation nuclei, such that an increase in aerosols can increase the number and concentration of cloud droplets while decreasing the droplet radius, resulting in a decrease in the precipitation efficiency (the aerosol second indirect effect) (Ramanathan *et al*., 2001). Albrecht (1989) suggested that drizzle would be inhibited from clouds with reduced droplet size. Rosenfeld (1999, 2000) gave evidence for a suppression of precipitation in clouds locally affected by high levels of pollution from biomass burning or industrial aerosols. Considering that the sulphur emissions in China have increased greatly since the 1960s (Ren *et al*., 1997), and that concentrations of sulphate aerosols in the atmosphere varies almost linearly with the sulphur emissions (Qian *et al*., 2001), increased aerosols may have contributed to the change in precipitation frequency in China.

Although several researchers have examined the effects of aerosols on precipitation in China, most of them have concentrated on aerosols' influence on changes in precipitation through its radiative forcing. Menon *et al*. (2002) suggest that the heat-absorbing properties of aerosols and their influence on large-scale circulation may be responsible for increasing rainfall in south China and droughts in north China. Zhao *et al*. (2006), studying the reduction of precipitation over eastern and central China, conclude that aerosols can affect radiative processes, which may strengthen atmospheric stability and weaken upward airflows and thus reduce precipitation. Huang *et al*. (2007) assess anthropogenic aerosols' impact on precipitation over East Asia using a coupled climate–chemistry/aerosol model; their results suggest that precipitation decreases are due to both direct and indirect effects of aerosols.

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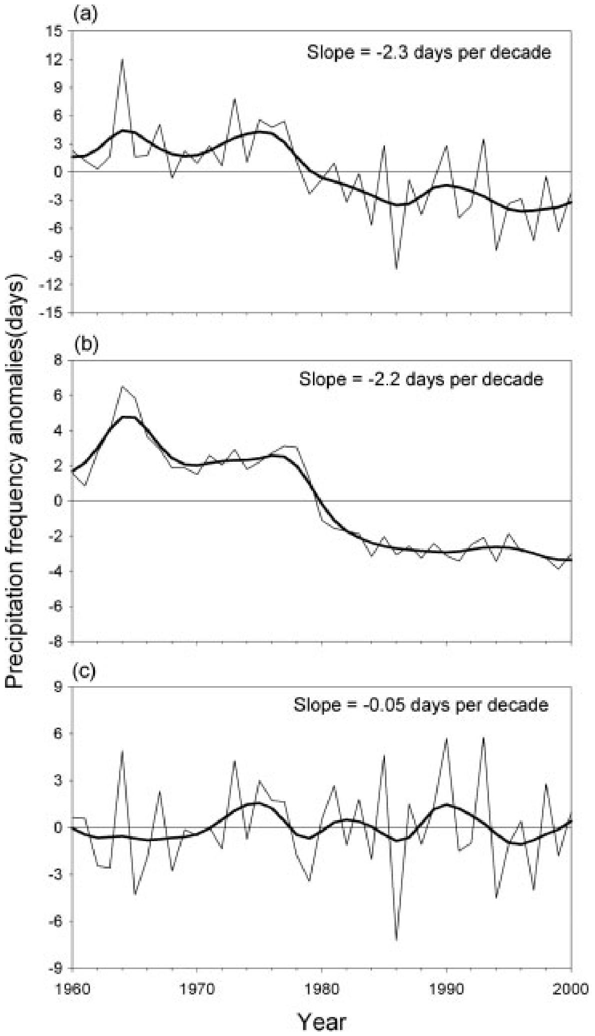

Figure 5. National time series of the annual number of precipitation frequency anomalies (from the 1960–2000 mean) for (a) all measurable events (≥0.1 mm/day), (b) events of 0.1–0.3 mm/day and (c) events of ≥0.4 mm/day. The heavy lines are the result of smoothing with a nine-point binomial filter with reflected ends. The trends for (a) and (b), but not (c), are statistically significant at the 0.05 level.

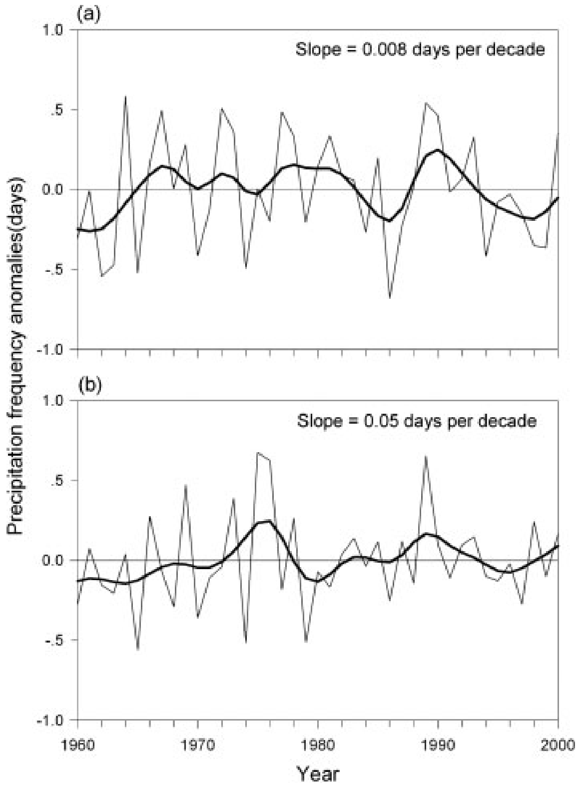

Figure 6. National time series of the annual number of precipitation frequency anomalies (from the 1960–2000 mean) for (a) events of 0.4–0.6 mm/day and (b) events of 0.7–0.9 mm/day. The heavy lines are the result of smoothing with a nine-point binomial filter with reflected ends. The trends are not statistically significant at the 0.05 level.

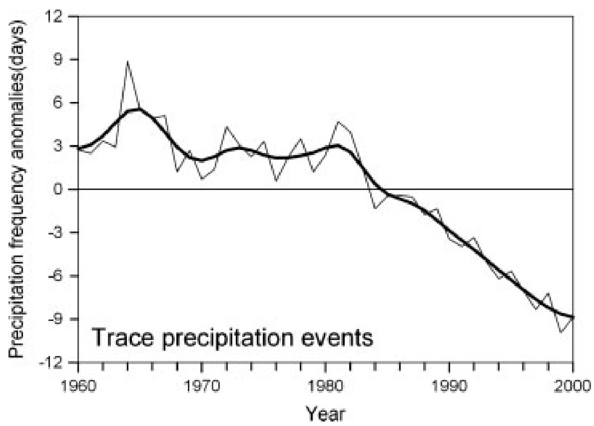

Figure 7. National time series of the annual number of precipitation frequency anomalies (from the 1960–2000 mean) for trace precipitation events. The heavy lines are the result of smoothing with a nine-point binomial filter with reflected ends.

Most of these studies have concentrated on the possible role played by aerosols in decreasing rainfall in north China and increasing rainfall in south China. These changes, as previously reported, are most evident in changing frequencies of heavy precipitation events (Liu *et al.*, 2005). Our current results indicate that declines in the frequency of light precipitation events reveal widespread decreasing trends across China. We note that the greatest declines are in two regions (southwest and mid and lower Yangtze River) with notably high levels of industrial pollution. Similarly, other studies have reported that the largest declines in global and direct solar irradiance appeared in eastern portions of China (east of about 100 °E and south of about 40°N), where aerosol loading is heavy and increasing significantly (Luo *et al.*, 2000; Liang and Xia, 2005).

As evidence of a possible influence of aerosols on precipitation frequency, Choi *et al.* (2008) revealed that on the timescale of a few days aerosol concentration is positively correlated with the frequency of moderate rainfall (10–20 mm/day) days but is negatively correlated with the frequency of light rainfall (<5 mm/day) days. Gong *et al.* (2006, 2007) find 'a weekly cycle of light rain frequency is evident' in east China during the summer, 'showing a maximum on Sunday and a minimum on Wednesday' (light rain here is defined as daily rain <5 mm, and includes trace rain events). They

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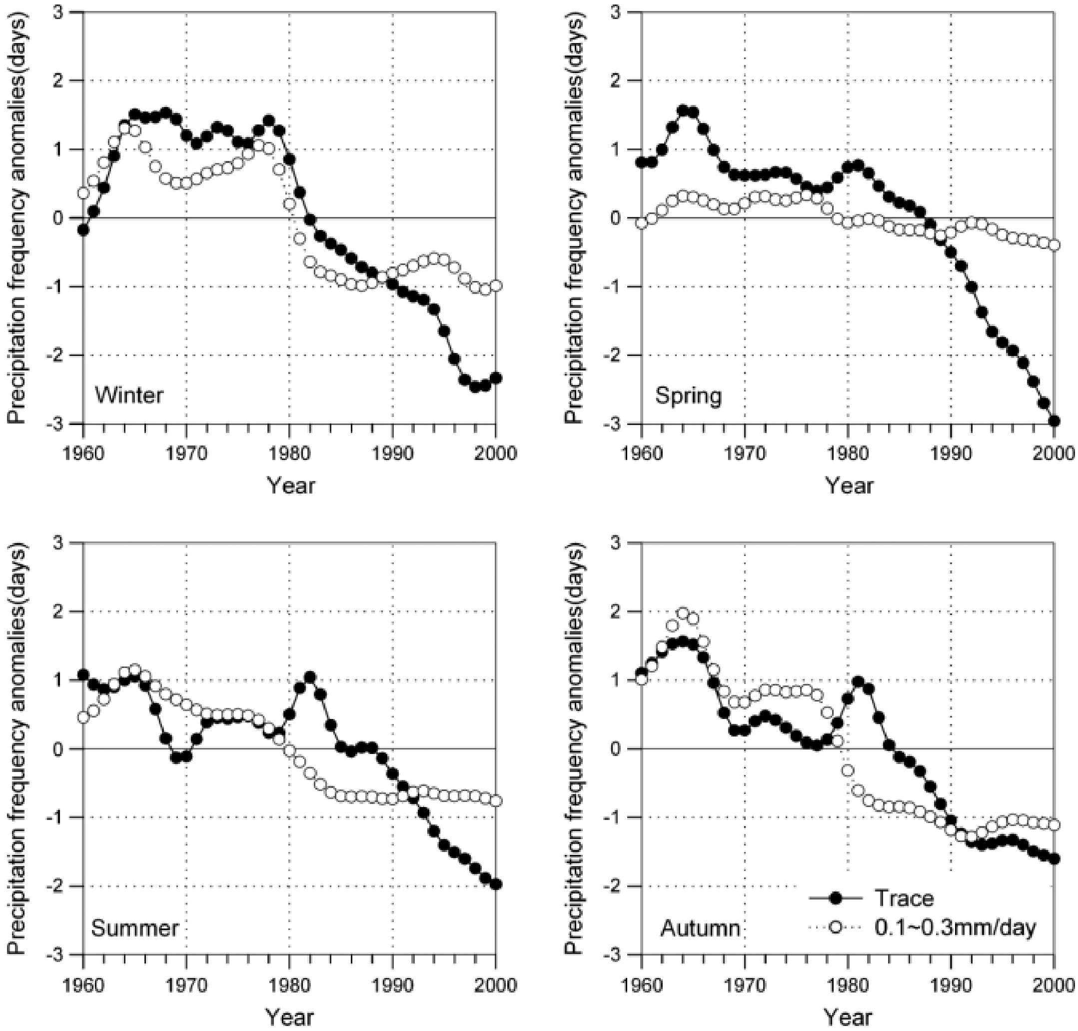

Figure 8. National time series of the seasonal number of precipitation frequency anomalies (from the 1960–2000 mean) for light (0.1–0.3 mm/day) and trace precipitation events. The values have been smoothed with a nine-point binomial filter with reflected ends.

suggest the existence of a weekly cycle in the production of anthropogenic aerosols, with the largest amounts emitted around midweek and smallest amounts on the weekend, which may be responsible for the suppressing precipitation frequency through indirect aerosol effects. In their analysis, they include both trace and measurable precipitation events in the annual number of precipitation events. However, similar research in the United States indicates that neither the occurrence nor the amount of precipitation significantly depends upon the day of the week (Schultz *et al*., 2007). Whether this weekly cycle of light precipitation events shares a common cause with the observed multidecadal decline in such events remains to be demonstrated. A recent study has demonstrated very weak relationships between large-scale moisture transport and light rain in east China, and suggests that the significantly increased aerosol concentrations produced by air pollution are at least partly responsible for the decreased light rain events observed in China over the past 50 years (Qian *et al*., 2009).

Another possible cause for the decreasing frequency of precipitation is the decline in total cloud cover. The significant decline in total cloud cover over China is unique among the trends deduced from various national cloud data sets made available in recent years (e.g. for the former USSR, United States and Australia), and the reasons for this decline remain unclear (Kaiser, 2000). Wang *et al.* (1993) found a strong relationship between cloud cover and rain days in China. Indeed, both phenomena show abrupt declines from 1978 onwards. Figure 9(b) shows the time series of the national average total cloud amount. As with solar irradiance, there are three distinct regimes. During the early part of the period (prior to about 1978), there is no obvious change in total cloud amount. From 1978 to 1985, there is an abrupt decline in total cloud amount across China paralleling the rapid decrease in light precipitation frequency. After 1985, total cloud amount remains relatively constant with a slight decreasing trend. The similarities in these temporal patterns suggest that the declines in cloud cover could be a cause for the drop in light precipitation events. However, we need to use caution as we try to connect the changes in cloud cover amount with the changes of frequency of light precipitation events, as not all types of clouds produce precipitation and our data set does not distinguish among cloud types.

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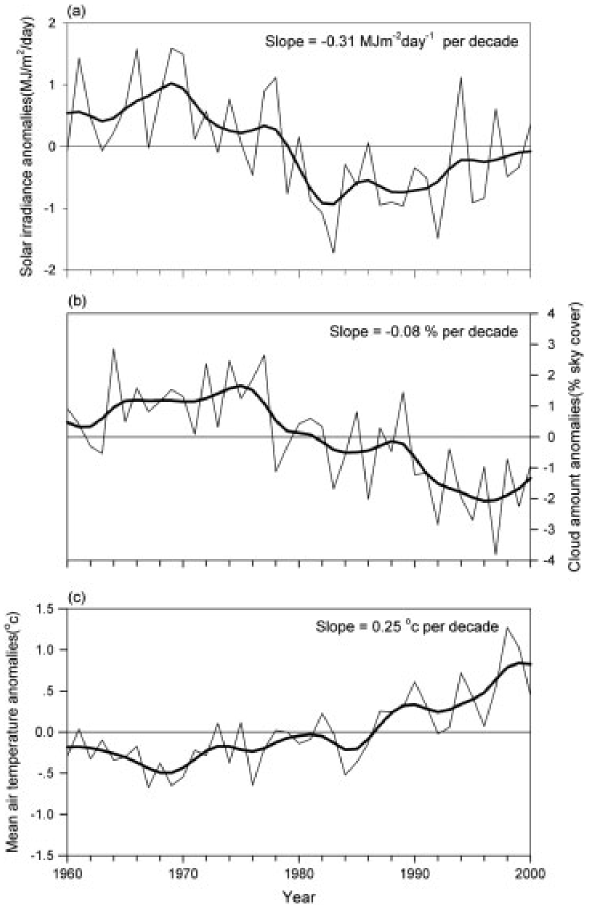

Figure 9. National time series of (a) solar irradiance in clear days, (b) cloud amount and (c) mean air temperature anomalies (from the 1960–2000 mean). The heavy lines are the result of smoothing with a nine-point binomial filter with reflected ends. The trends for (a), (b) and (c) are statistically significant at the 0.05 level.

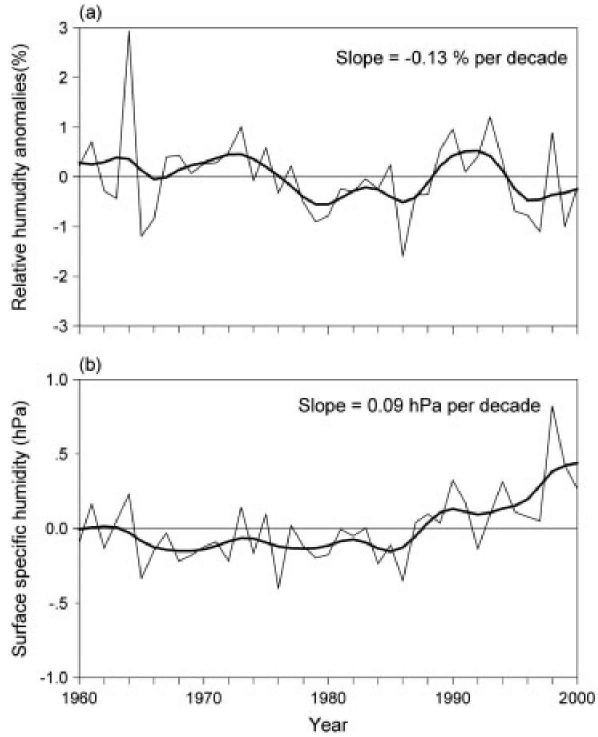

Figure 10. National time series of anomalies (from the 1960–2000 mean) in (a) relative humidity anomalies and (b) surface specific humidity. The heavy lines are the result of smoothing with a nine-point binomial filter with reflected ends. The trend for (b), but not (a), is statistically significant at the 0.05 level.

In comparison with light precipitation events, the trends for trace precipitation events show a later turning point – around 1982 (Figure 7) – and different spatial patterns, generally higher rates in northern regions (Table II), suggesting that these changes may have different causes. As pointed out by Fu *et al*. (2008), changes in various precipitation intensities may be caused by different processes and mechanisms. They find that the decreasing trend of trace precipitation days corresponds with the increasing trend of temperature in China. They suggest that higher temperatures could increase the condensation height of precipitable clouds and reduce cloud amount so that trace or slight precipitation days are in turn reduced. As shown in Figure 9(c), annual mean air temperatures increased rapidly from around 1984 and continued to increase through the end of the study period, consistent with an inverse relationship with trace precipitation. Higher rates of change in mean air temperatures are generally found at higher latitudes (Liu *et al*., 2004a), again consistent with the pattern observed for trace precipitation. More research will be needed to uncover the mechanisms linking these phenomena.

Choi *et al*. (2008) suggest that the reduction in relative humidity is the main reason for the decrease of summer rainfall frequency in China for the past few decades. We find that annual average relative humidity shows a slightly decreasing trend over the past several decades (Figure 10(a)), similar to the report by Ju *et al*. (2001). Average relative humidity in autumn shows a small but statistically significant decreasing trend at the rate of 0.44% per decade, but in the other three seasons, the average relative humidity shows almost no change. At the same time, surface specific humidity shows a statistically significant increasing trend over the past several decades (Figure 10(b)), with air temperatures significantly increasing over the same period (Figure 9(c)). As relative humidity is a function of water vapour and temperature (Lu and Zeng, 2005), we should not expect obvious changes in relative humidity where temperature and water vapour increase similarly. As such, it would be difficult to credit the changes in relative humidity as the main cause for the decrease of light precipitation events. Further investigation is needed to explore these physical processes in detail.

4. Conclusions

Precipitation events in China have declined significantly over the later part of the last century. The decreasing trend is mainly due to changes in light precipitation events with daily intensities of 0.1–0.3 mm/day. The annual number of light precipitation days shows a remarkable drop-off around 1978, with a rapid

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decreasing rate through 1985. Trace precipitation events begin their decline later, around 1982, and continue to decrease through the end of the century.

The precipitation declines reported in the Chinese meteorological record appear to be unique, but few other countries have analysed records of precipitation events including comparably low levels of intensity. We note regional and seasonal differences in the rates of change between trace and very light precipitation events, while finding almost no change in the frequency of precipitation events of intensity 0.4–0.6 and 0.7–0.9 mm/day. This discounts the possibility that the trends reported here may be an artefact of changes in instrumentation or other data inhomogeneities. Furthermore, similar declines have been noted in solar irradiance and total cloud cover. Changes in these phenomena, or the related effects of aerosol loading from sources within and outside of China, may be contributing to the observed change. The differences in spatial and temporal patterns between light and trace precipitation events suggest that there may be different causes for their change. Because light precipitation events make up the largest share of rain days, further research on this topic will be important to understand better the causes and effects of a changing climate.

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