Observed trends in extreme precipitation events in China during 1961–2001 and the associated changes in large-scale circulation

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[1] The observed trends in extreme precipitation events, and those in annual and seasonal mean precipitation in China during 1961–2001 are analyzed. The results show that the annual mean precipitation increases significantly in southwest, northwest, and east China, and decreases significantly in central, north and northeast China. The increasing trends in east China occurred mainly in summer, while the decreasing trends in central, north, and northeast China occurred in both spring and autumn. The increasing trends in most of northwest China occurred in all seasons. Patterns of the trends in extreme daily precipitation events are similar to those in the annual and seasonal mean precipitation except in the northwest China where most areas show increasing trends in extreme events only in summer. The extreme precipitation events in the Yangtze River basin increased dramatically by 10%–20% every 10 years in summer, consistent with the increasing trends in summer mean precipitation in the region. The circulation over East Asia shows a weakening trend in the summer monsoon over central-east China.
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1. Introduction

[2] One focus of study in recent years has been the investigation of the observed trends/changes in both the long-term climatic mean state and the intensity and frequency of climatic extremes, such as frequency of floods/droughts, heat waves, high winds, etc. [*Karl et al.*, 1999; *Easterling et al.*, 2000; *Manton et al.*, 2001]. An equally important area is the identification of the large-scale circulation trend associated with the trends in extreme events. Obviously these studies are important for understanding the projection of future climate change.

[3] China has experienced significant changes in both mean climatic state and extreme climatic events in the last century. In particular, one of the most destructive climate events in China is the extreme precipitation during the summer monsoon season [*Ding*, 1994]. Numerous studies have documented the trends in precipitation in China [e.g., *Zhai et al.*, 1999; *Gong and Wang*, 2000; *Manton et al.*, 2001; *Gemmer et al.*, 2004]. Most of these studies were concerned with the monthly-seasonal mean conditions. Changes in daily extreme events have received much less attention and such studies focused mostly on the summer season and did not examine carefully the associated large-scale circulation trend.

[4] *Zhai et al.* [1999] found no significant trends in annual precipitation but a significant increase in above normal mean intensity of precipitation in east China during 1951–1995. *Gemmer et al.* [2004] detected negative trends in monthly precipitation in spring and autumn but positive trends in summer in east China and negative trends in north and northeast China during 1951–2002. *Gong and Wang* [2000] and *Gong and Ho* [2002] found that mean precipitation exhibits a significant decreasing trend from the 1950s to mid-1970s, and a increasing trend since the late 1970s in east China, with the latter being attributed to enhanced global warming since the late 1970s.

[5] In this study, we extend the previous analyses of precipitation trends, especially the trends in extreme precipitation events, over China to four seasons and study the inter-relation between circulation trends and trends in both seasonal precipitation and extreme precipitation events in summer.

2. Data and Methodology

2.1. Data

[6] The observed daily precipitation data from 686 stations in China were obtained from the Chinese National Meteorological Centre for 1 January 1951–31 December 2001. (Note that the dataset available to us does not include data in Tibet.) The locations of the stations with the data used in annual trend analysis (see below) are given in Figure 1a. The density of stations is quite varied; it is particularly low in the sparsely populated high mountainous and desert/semi-desert areas of west and northwest China. To avoid bias in the trend analysis due to the missing data, we will restrict our analysis to the period from 1961 to 2001. For this period, 520, 521, 518 and 458 stations have a complete set of data for spring, summer, autumn, and annual analyses, respectively. To have enough data, the winter analysis includes stations in which less than 1% of the total winter data was missing – for a total 511 stations. The missing data were simply set to no-rain in the winter analysis. Figure 1a also shows the 41-year mean precipitation, which decreased from the southeast to the northwest. To facilitate our discussion, we divided China into seven regions: northwest, southwest, south, central, east, north, and northeast China (Figure 1a).

[7] To examine the linear trends in the large-scale circulation, the monthly mean geopotential height and horizontal winds at 850 and 500 hPa from the National

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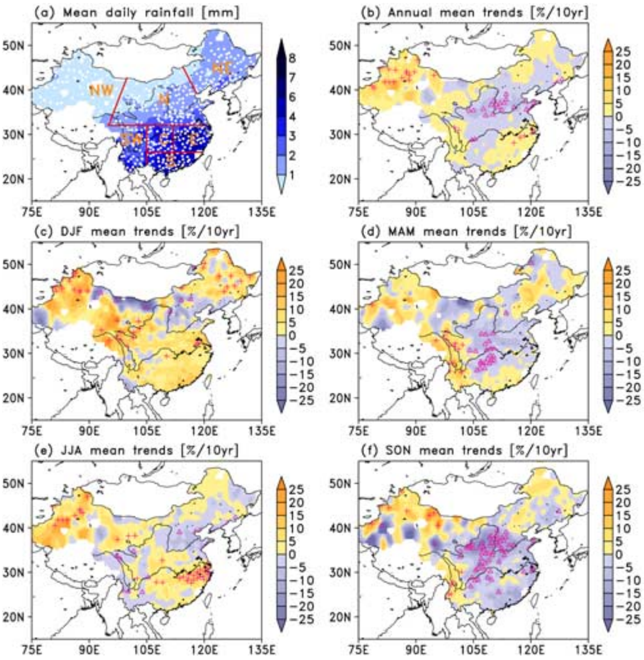

Figure 1. (a) The locations of the observing stations (in white dots) in China used in annual trend analysis and the mean precipitation during 1961–2001 together with the 7 regions defined in this study; (b) the linear annual trends (in percentage of annual mean precipitation every 10 years); and trends (in percentage of seasonal mean precipitation every 10 years) in (c) winter (DJF), (d) spring (MAM), (e) summer (JJA), and (f) autumn (SON). Plus/triangle shows positive/negative trends at those stations statistically significant at the 95% confidence level.

Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data were used.

2.2. Methodology

[8] We follow *Bell et al.* [2004] and defined extreme events as those that exceed a threshold percentile of daily precipitation. In our analysis, two threshold values – 97.5% (or top 2.5%) and 95% (or top 5%) – were used for annual extreme daily precipitation analysis and the seasonal extreme precipitation analysis, respectively. The linear trend was calculated based on the linear regression. Trend was defined as the linear regression coefficient. The significance of the trend is checked with the correlation coefficient method as used by *Niu et al.* [2004].

3. Trend Analyses

3.1. Trends in Annual, Seasonal Mean Precipitation

[9] The annual mean precipitation shows increasing and decreasing trends in different regions (Figure 1b). Statistically significant decreasing trends at the 95% confidence level occurred in central and north China, while statistically significant increasing trends occurred in southwest, northwest China, and east China. These are generally consistent with the results of *Gemmer et al.* [2004]. The increase in precipitation in some areas in northwest China is as large as 10–20% every 10 years, indicating that the dry conditions in some areas in the arid/semi-arid northwest China have been gradually alleviated over the last 40 years. On the other hand, the decrease in precipitation of approximately 10% every 10 years in central-north China together with the population increase and agricultural expansion has put considerable stress on the available water resource in these regions.

[10] The trends in the annual mean precipitation are not uniformly distributed over the four seasons (Figures 1c–1f). In winter (DJF), increasing trends occurred in most of the country except in north China between the latitude bands of 40–45°N, where significant decreasing trends occurred in some areas (Figure 1c). The increasing trends, however, are significant only in the regions of northwest and northeast China and some small areas in the Yangtze River basin (between 26–33°N). In spring (MAM), significant increasing trends occurred in southwest China, while significant decreasing trends occurred in central-north China (Figure 1d). In summer (JJA), coherent significant increasing trends occurred in the Yangtze River basin (central-east China) and northwest China. Some decreasing trends occurred in southwest and north-northeast China (Figure 1e). Summer rainfall in the lower reach of Yangtze River and northwest China increased by as much as 10–15% every 10 years. Since summer mean daily rainfall is already large, this large increase in the Yangtze River basin indicates a significant increase in summer monsoon rainfall in the region. In autumn (SON), on the other hand, statistically significant decreasing trends occurred in most of the country except in the far northwest and southwest China, and some areas in northeast China, where actually some significant increases are noted (Figure 1f).

[11] Comparing Figures 1b and 1c–1f, we can see that the significant increasing annual mean trends in northwest China result mainly from increasing precipitation during all four seasons. The increasing annual trends in the mid-lower reaches of the Yangtze River come largely from the increasing precipitation during summer. In contrast, the decreasing annual trends in central-north China are a result of decreasing precipitation during both spring and autumn, especially during autumn in north China between the latitude bands of 32–40°N. The coherent trends in summer and autumn mean precipitation indicate a seasonal shift in the main precipitation belt. In particular, in the lower-middle reaches of Yangtze River, the rainfall increased in summer and decreased in spring. These results are consistent with those of *Gemmer et al.* [2004]. We will show in section 3.3 that such a seasonal shift is related to the weakening of the East-Asian summer monsoon.

3.2. Trends in Extreme Precipitation Events

[12] Figure 2a shows the trends in annual extreme precipitation events defined as the top 2.5% in daily precipitation from 1961 to 2001. It can be seen that the trends in extreme events show a similar spatial pattern to those in annual mean precipitation (Figure 1b). For example, the extreme events in east, southwest, and northwest China increase as annual mean precipitation increases, while the extreme events in central-north China decrease with decreasing annual mean precipitation. However, in the southern region of northwest China, the annual extreme events

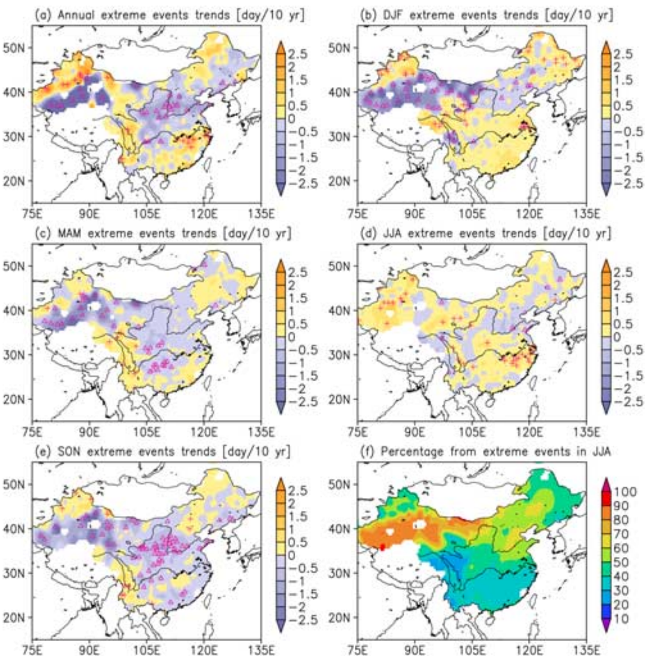

Figure 2. (a) Annual trend in extreme precipitation events defined as top 2.5% of the daily precipitation (in number of days every 10 years). Trends in extreme precipitation events defined as the top 5% in daily precipitation for four seasons: (b) winter, (c) spring, (d) summer, and (e) autumn (in number of days every 10 years). (f) Percentage of the top 5% extreme daily precipitation in the summer mean precipitation during 1961–2001.

decrease whereas the annual mean precipitation increases (Figure 1b), suggesting more frequent and less intense precipitation in the region.

[13] Figures 2b–2e show the trends in extreme precipitation events defined as the top 5% in individual seasons. Increasing trends in extreme events occurred in the far northwest China and some regions in southwest China during all four seasons, and in the mid-lower reaches of the Yangtze River during both winter and summer. Decreasing trends occurred in central-north China during both spring and autumn. In northwest China, extreme events significantly decreased during winter, spring and autumn, while the seasonal mean precipitation slightly increased during all seasons (Figure 1), again indicative of more frequent and less intense precipitation over most of the region.

[14] The increasing trends in extreme precipitation events in east China in summer could have a great societal impact since it is one of the most developed areas in China. The extreme precipitation events in summer increased by 0.5–1.0 events (about 10–20%) every 10 years. Although these extreme events are rare, the top 5% extreme events contributed to about 40–50% of total summer rainfall during 1961–2001 in east China and even higher in north and northwest China (Figure 2f).

3.3. Trends in Large-Scale Circulation

[15] We have shown above that both the seasonal mean precipitation and the extreme precipitation events in summer exhibit coherent increasing and decreasing trends in the lower reach of Yangtze River and central-north China, respectively. To see whether these coherent trends are related to large-scale circulation trends, a linear trend analysis was conducted for the geopotential height and horizontal wind fields using the NCEP/NCAR reanalysis for summers from 1961 to 2001. The results show a trend toward large-scale increasing geopotential height with an anticyclonic circulation over the Eurasian continent and a trend toward decreasing geopotential height with a cyclonic circulation over the western Pacific in the mid-lower troposphere (Figures 3a and 3b).

[16] Such circulation trends indicate a strengthening of the continental high over Eurasia and a weakening of the western Pacific subtropical high. A similar large-scale circulation trend over the East Asia has been found recently by *Weng et al.* [2004]. The northeasterly wind tendency in the lower troposphere over central-east China (100–122°E) is weakening the southwesterly summer monsoon flow (Figure 3a), limiting the northward extension of the summer monsoon to north China. As a result, Meiyu fronts (quasi-stationary fronts with heavy rainfall systems elongated mainly in the east-northeast to west-southwest orientation over East Asia from late spring to midsummer [*Ding*, 1994]) stay longer in the Yangtze River basin and shorter in north China. As a result, both the annual and summer mean precipitation and the extreme precipitation events consistently decreased in north China, and increased in the middle-lower reaches of Yangtze River. *Yu et al.* [2004] also identified the weakening in the East-Asian summer monsoon during the same period.

[17] The trend in circulation changes discussed above may also explain changes in the seasonal cycle of precipitation over central-east China. The monthly mean precipitation exhibits an increasing trend in summer and a decreasing trend in late spring (Figure 4). Over the last 40 years, the rainfall peaks in May and June have shifted

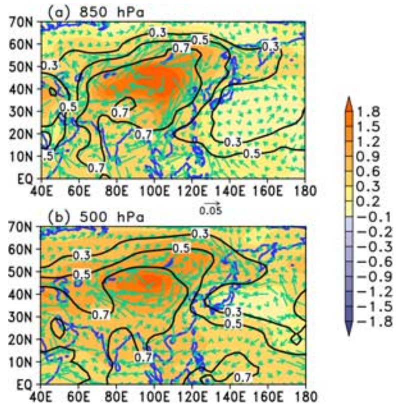

Figure 3. Trends in geopotential height (shaded with the unit of 1 gpm per 10 years) and the corresponding horizontal winds in summer during 1961–2001 at (a) 850 hPa and (b) 500 hPa (vectors in unit of 0.5 m s^{-1} per 10 years). The contours indicate the correlation coefficient between time and the geopotential height, for which values larger (smaller) than 0.3 (−0.3) are statistically significant at the 95% confidence level.

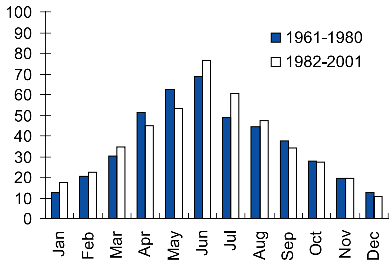

Figure 4. Seasonal cycles of monthly mean daily precipitation (mm) over the Yangtze River basin (26–32°N, 105–122°E) during 1961–1980 and 1982–2001.

to June and July, implying a trend of not only a weaker but also a later East-Asian summer monsoon.

4. Conclusions

[18] Based on high quality daily precipitation data from meteorological stations in China during 1961–2001, the trends in annual and seasonal mean precipitation, and the trends in extreme precipitation events were analyzed. The results show that the annual mean precipitation increases significantly in southwest, northwest, and east China and decreases significantly in central, north, and northeast China. The increasing trend in east China occurred mainly during the summer season, while the decreasing tends in central, north, and northeast China occurred during both spring and autumn. The increasing trend in northwest China was observed during all seasons.

[19] Consistent with the annual mean precipitation trends, the annual extreme precipitation events increased in east and northwest China and decreased in central, north, and northeast China. The increasing trends in east China occurred mainly in summer, while the decreasing trends in central-north China occurred in both spring and autumn. The extreme precipitation events in Yangtze River basin increased dramatically at a rate of 10%–20% every 10 years, consistent with the increasing trends of 10–20% in summer precipitation in the region. Significant increasing trends in extreme precipitation events in northwest China occurred only in summer, while the seasonal mean precipitation slightly increased in all seasons, implying more frequent and less intense precipitation over most of the region.

[20] The summer circulation over East Asia shows a strengthening trend of the continental high over Eurasia and a weakening trend of the western Pacific subtropical high. The northeasterly wind tendency over central-east China is weakening the southwesterly summer monsoon in the region, limiting the northward extension of the summer monsoon and causing a longer Meiyu season in the Yangtze River basin and a shorter rainy season in north China. As a result, the annual and summer mean precipitation and the extreme precipitation events in summer consistently decreased in north China and increased in the middle-lower reaches of Yangtze River. The trend in circulation changes also explains the change in the seasonal cycle of precipitation over central-east China, where the monthly mean precipitation increased in summer and decreased in late spring. The relationship between circulation and precipitation trends discussed in this study will help to understand the physical processes underlying the observed precipitation trends and can be used to study climate variability and climate change in coupled model simulations.

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