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NOTES AND CORRESPONDENCE

Trends in Precipitation Amounts and the Number of Rainy Days and Heavy Rainfall Events during Summer in China from 1961 to 2000

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Abstract

Long-term trends in summer precipitation totals, the number of rainy days, and precipitation intensity were investigated with daily rainfall datasets for China from 1961 to 2000. Total precipitation significantly increased in summer in the Yangtze River basin and northwestern China, while total precipitation decreased in other regions. The number of rainy days increased in the Yangtze River basin, and over northwestern China. In contrast, the number of rainy days decreased over Tibet and over northern and northeastern China. Seasonal mean precipitation intensity became large at most of the stations in China.

To investigate trends in heavy rainfall, daily rainfall totals during the whole investigation period were grouped into ten classes, with class width equal to 10% of total number of rainy days from 1961 to 2000, and the number of rainy days, and summer mean rainfall amount for each class, were obtained for each summer. A simple linear fit was made to determine the linear trends in the 10-class precipitation time series. The upper 20 percentile of daily precipitation totals showed a statistically significant increase over the Yangtze River basin, and over northwestern China during the study period. Class average precipitation decreased in almost 10 classes over Tibet and north and northeastern China.

1. Introduction

During the East Asian summer monsoon season, summer precipitation produces greater than 40% of the annual precipitation in China, except over south China (Yatagai and Yasunari 1995). Heavy rainfall events frequently occurred, and brought about massive flood disasters during the summer monsoon season. Total precipitation is extensively used in climatic analysis. The contribution of different amounts of daily rainfall to total precipitation amounts, is a worthy topic for study. Takahashi

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(1993) studied regional differences in the contribution of daily rainfall to total precipitation in Eastern Asia during the Baiu/Meiyu season, using frequency distributions of daily precipitation and the dominant precipitation intensity class. Matsumoto and Takahashi (1999) showed that contribution to total summer (May–August) precipitation from heavy precipitation (daily totals exceeding 50 mm), is larger over the middle parts of the Yangtze and Huaihe River basins, and along the south coast of China. They also examined seasonal changes in heavy precipitation events. The northward migration of heavy precipitation events was linked to the northward movement of the Baiu/Meiyu rains.

Secular changes in precipitation have recently attracted the attention of many researchers in the context of climate change. IPCC (2001) notes that global precipitation trends were positive throughout the last century. However, trends vary with region and season. Chen et al. (1991) found that precipitation has decreased over most of China, especially northern and northwestern China. Zhai et al. (1999a) reported no significant trend in annual precipitation over China between 1951 and 1995. Yatagai and Yasunari (1994) showed no increase in annual precipitation over most of China. They also investigated trends in summer precipitation, and found a clear increase in summer precipitation over the middle and lower reaches of the Yangtze River. On the contrary, summer precipitation decreased over the middle reach of the Yellow River.

Temporal changes of precipitation totals are caused by both changes in precipitation frequency, and precipitation intensity during each event. Iwashima and Yamamoto (1993) investigated long-term changes of extreme daily precipitation in Japan, and found a remarkable increase between the 1890s and 1980s. Karl and Knight (1998) examined the century-long daily precipitation records over the United States, and showed an increase in heavy precipitation events exceeding 50.8 mm. Long-term variations in heavy precipitation were also examined over the UK (Osborn et al. 2000), Italy (Brunetti et al. 2001a; Brunetti et al. 2001b), and Australia (Suppiah and Hennessy 1998). Takahashi (2003) studied long-term variations in heavy precipitation over metropolitan Tokyo. Groisman et al. (1999) applied a statistical model to summer daily rainfall data from 1951 to 1994 over the USA, former USSR, China, Canada, Norway, Mexico, Poland, and Australia. Mean summer precipitation, and the frequency of summer precipitation events, increased in the USA, Norway, and Australia. No significant trends were detected in the rainfall data for China.

Zhai et al. (1999b) investigated trends in annual precipitation, and annual extreme precipitation in China for 1951–1995, and found no significant trends in annual precipitation or 1-day or 3-day maximum rainfalls. They also showed that the number of rainy days per year decreased, so an increase in precipitation intensity (precipitation divided by the number of rainy days) was obvious. They further showed that annual precipitation increased over northwestern China, and decreased over northern China. Recently Wang et al. (2004) analyzed the climate change in China from 1951 to 2000. They found that the annual total amount of rainfall has a slight decreasing trend. They also showed that summer total rainfall increased in the south of the Yangtze River, and the decrease of summer total rainfall in North China was observed. Nevertheless, regional characteristics of the temporal changes of heavy precipitation, and their relation to the temporal changes in total precipitation in China during summer have not been intensively studied. The present study focuses on regional characteristics in trends of summer precipitation, using daily precipitation data from 1961 to 2000 for more than 500 stations in China. Parameters considered include summer precipitation totals (hereafter PRJJA), precipitation intensity (INTENS), numbers of rainy days (PRDAYS), and the frequency and amount of heavy precipitation events. Section 2 describes the data and methods. Section 3 presents characteristic features of summer precipitation at individual stations, and six regions in China. Conclusions are presented in Section 4.

2. Data and methods

2.1 Data

This study used daily observations of precipitation and temperature over China compiled by the China Meteorological Administration. The dataset, hereafter referred to as PRCMA, consists of precipitation and temperature data at 726 stations. Many stations are located to the east of 100°E, but stations are also well distributed in northwestern China and in the eastern Tibetan Plateau. Since data record lengths are different at each station, only those stations with data in June, July, and August from 1961 to 2000 were selected. The Chinese monthly precipitation data NDP039 from the Carbon Dioxide Information Analysis Center (CDIAC) of the U.S. Department of Energy was used as a reference dataset. NDP039 includes monthly precipitation records at 267 stations over China.

PRCMA data were subjected to simple quality checks. Monthly precipitation data were compiled for all stations from the PRCMA daily rainfall data. Next, we selected stations that were present in both datasets. The PRCMA precipitation time series were compared to NDP039 time series at each selected station. As NDP039 data have been quality checked by CDIAC, NDP039 was used as a reference. The two monthly precipitation time series are identical, or have small difference less than 10 mm if there is a difference between two monthly precipitation data at each selected station. These results suggest that daily rainfall data from PRCMA is of good quality. These stations were therefore treated as reference stations for the rest of the quality control steps.

In the next step, we compared monthly precipitation time series between a station in PRCMA and a reference station. Correlation coefficients between the monthly records of the inspecting station, and those of all reference stations were calculated. The reference station with the highest correlation coefficient was chosen for the inspecting station. Although higher correlation coefficient occasionally appeared between a long distant two stations, the selected reference station was located near the inspecting station. Correlation coefficients between daily rainfall records at both stations were calculated for each summer. Average, and standard deviation of the correlation coefficient were calculated, and the correlation coefficient which lay beyond two standard deviations was listed. Daily rainfall data at the inspecting station were compared with the daily rainfall data at surrounding stations if the correlation coefficient of a summer was listed. Severe rainfall record, with no rainfall record at the surrounding stations in the listed summer, was discarded. Although severe rainfall in very small area might occur, rainfall was typically observed at the surrounding stations when severe rainfall was recorded at the inspecting stations in the eastern part of China, where station density is high. This procedure can be considered as effective to avoid outliers in the daily rainfall records. Although Karl and Knight (1998) used proxy data for voided stations produced by a gamma distribution with a random number generator to fill precipitation on any missing day, discarded data were not replaced in the present study. Daily rainfall records at 554 stations passed this quality check, and were used in the following analysis, station locations are shown in Fig. 1.

2.2 Method

PRJJA was obtained by summing daily rainfall data on days when rainfall was equal to or greater than 0.1 mm. 'Trace precipitation', rainfall events totaling less than 0.1 mm day^{-1}, were not summed. Rainy day is defined as a day exceeding rainfall more than 0.1 mm. In this study, INTENS is the seasonal precipitation amount divided by the number of rainy days. The number of trace precipitation days was separately counted, since trace precipitation information is included in the PRCMA dataset.

Changes in PRJJA can be caused by a change in the frequency of rainfall events, a change in the precipitation intensity per event, or by a combination of both. All daily rainfall data in 40 years (1961–2000) were sorted into ascending order and grouped into 10 classes for each station, in order to investigate how the frequencies and amounts of precipitation varied. Each of the 10 classes had an interval width equal to 10% of the total number of rainy days from 1961 to 2000. In contrast, Karl and Knight (1998) used 20 class intervals with class width equal to 5% of the total number of rainy days. In this study, the lightest precipitation class was PR_C1, followed by PR_C2, PR_C3, and so on up to PR_C10, the heaviest precipitation class. The number of rainy days and the summer mean rainfall amount for each class were obtained for each summer. Description of changes in the 10 precipitation classes can elu-

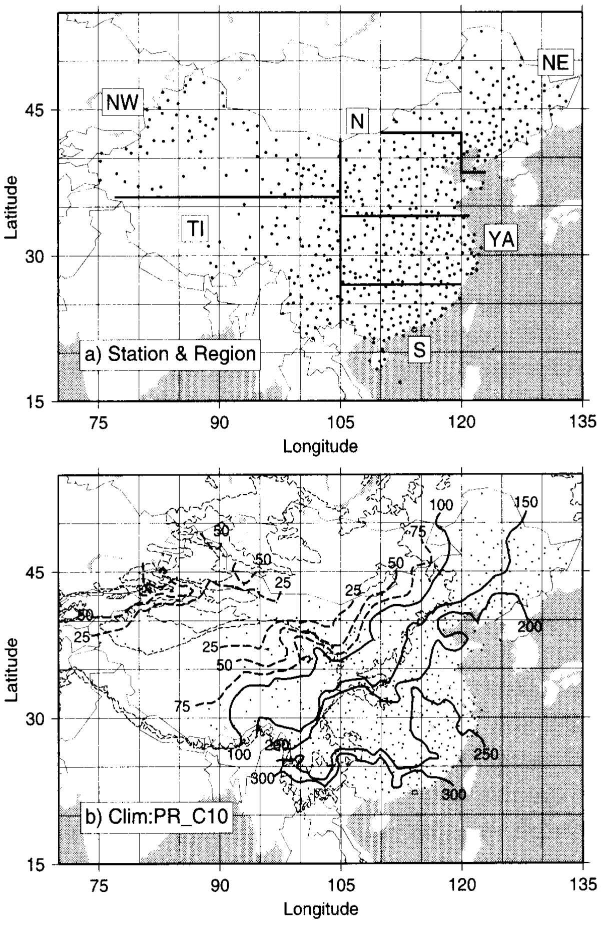

Fig. 1. a) Observation stations (554 stations) and geographic divisions used for the regional time series. 'N', 'TI', 'NE', 'S', 'NW' and 'YA' means northern China, Tibet, northeastern China, southern China, northwestern China, and Yangtze River basin, respectively. b) Spatial distribution of climatological rainfall amount of Class-10 (PR_C10), which was derived from the 90th to the highest percentiles. Contour interval of rainfall amount is 50 mm above 100 mm, and is 25 mm below 100 mm, respectively.

cidate that changes in PRJJA could be derived from changes in PRDAYS, with equal probability of precipitation event over all precipitation classes, or could be caused by changes in the amount of precipitation for a limited number of precipitation classes without PRDAYS change.

We defined six regions to describe the regional characteristics of the precipitation trends. According to the spatial pattern of the first component of EOF analysis for summer rainfall total obtained by Nitta and Hu (1996), we divided the area east of 105°E into north China (34°N–42°N, 105°E–120°E, including the Shandong Peninsula; 98 stations), the Yangtze River basin (27°N–34°N, east of 105°E; 116 stations), south China (21°N–27°N, east of 105°E; 73 stations), and northeastern China (north of 42°N; 98 stations) (Fig. 1a). The area west of 105°E was divided into northwestern China (north of 36°N; 81 stations), and Tibet (south of 36°N; 80 stations). Stations that are located in the south of 21°N were not included in the regional time series analysis. Regional average of PRJJA, PRDAYS, INTENS, and class average rainfall amount were obtained simply from the arithmetic mean.

The geographic distributions of precipitation trends, for the period 1961–2000, were estimated by a least square linear fit at each station. Regional time series of precipitation were also subjected to a simple linear regression, in order to facilitate a comparison between regional precipitation characteristics, and regional precipitation trends. The non-parametric Mann-Kendall test, evaluated the significance of the trends. A significance level of 0.05 was used throughout this analysis.

3. Regional characteristics of precipitation trends

Climatological PRJJA exceeded 700 mm in South China and Yunnan (Zhao 1994). PRJJA gradually decreased northward from South China to around 31°N, and decreased northwestward (inland) in the north of 31°N. Stations in the Yangtze River valley received about 500–600 mm during JJA. North of the Yangtze River, PRJJA was larger near the Bohai Sea and the East China Sea. PRJJA in Xinjiang, Nei-Mongol, and the western half of Gansu was less than 200 mm. PRJJA over the eastern Tibetan Plateau was about 200–400 mm.

Climatology of the amounts in the heaviest rainfall class (PR_C10) is shown in Fig. 1b. Over southernmost China, PR_C10 exceeded 300 mm day^{-1}. PR_C10 amounts exceeding 250 mm day^{-1} extended into the middle and lower parts of the Yangtze River basin. PR_C10 abruptly decreased from southernmost China to the middle parts of the Yangtze River basin, and the Sichuan basin. PR_C10 amounts

Table 1. Regional averages of number of rainy days (PRDAYS), total precipitation (PRJJA), precipitation intensity (INTENS), and class average precipitation for the ten classes (PR_Cx). Standard deviation is in parenthesis. Unit is mm/3-month for PRJJA, INTENS, and PR_Cx.

	YANGTZE(YA)	NORTHWEST(NW)	SOUTH(S)	NORTHEAST(NE)	TIBET(TI)	NORTH(N)
PRDAYS	39.0(3.7)	22.8(2.2)	48.5(4.6)	40.6(4.1)	59.9(3.0)	33.0(3.9)
PRJJA	509.3(88.7)	77.7(10.6)	680.7(109.8)	351.5(53.0)	475.5(36.4)	313.1(52.6)
INTENS	12.8(1.3)	2.9(0.3)	13.8(1.4)	8.6(0.9)	7.8(0.4)	9.2(0.9)
PR_C10	248.0(59.5)	34.5(7.3)	324.1(73.5)	162.6(37.6)	197.9(22.2)	152.3(35.0)
PR_C9	108.5(17.3)	15.8(2.2)	140.9(24.8)	73.4(9.8)	99.2(9.5)	66.4(11.6)
PR_C8	64.2(9.2)	9.9(1.2)	86.0(11.1)	45.3(6.1)	64.6(5.0)	39.2(5.9)
PR_C7	39.1(4.8)	6.5(0.7)	54.5(6.9)	28.9(3.9)	43.5(3.6)	23.8(3.0)
PR_C6	23.5(2.8)	4.4(0.4)	34.3(3.8)	18.3(1.9)	29.3(2.3)	14.3(1.8)
PR_C5	13.4(1.4)	2.9(0.3)	20.7(2.1)	11.2(1.3)	19.2(1.3)	8.4(1.0)
PR_C4	7.2(0.7)	1.8(0.2)	11.6(1.1)	6.4(0.6)	11.6(0.7)	4.7(0.5)
PR_C3	3.4(0.3)	1.1(0.1)	5.6(0.5)	3.3(0.3)	6.4(0.4)	2.4(0.2)
PR_C2	1.4(0.1)	0.6(0.1)	2.3(0.2)	1.5(0.2)	2.8(0.2)	1.1(0.1)
PR_C1	0.5(0.1)	0.3(0.0)	0.7(0.1)	0.5(0.1)	0.9(0.1)	0.4(0.1)

decreased gradually northwestward north of 30°N. The 150 mm day^{-1} isohyet runs along the 1000-m above sea level (a.s.l.) contour. Table 1 summarizes the climatological values of PRJJA, INTENS, PRDAYS, and the rainfall amount of each class in each region. PRDAYS is about 60 days in Tibet, while it is about 23 days in Northwest China.

Figure 2a shows the geographic distribution of trends in PRJJA. In this paper, trends are expressed in figures as the percentage variations with respect to the mean value over the 1961–2000 period. The largest increases, with values exceeding 40% of its climatological value, occurred over the middle and lower parts of the Yangtze River basin. A decline in PRJJA occurred over northern China, especially over the Shangdong peninsula. PRJJA also decreased over the Liaodong peninsula, but increased over most of northeastern China. Over semi-arid and arid regions, such as Nei-Mongol and northwestern China, PRJJA increased. The PRJJA trend exceeded 30% in the Taklimakan Basin. In contrast, small trends dominated over South China, the eastern Tibetan Plateau, and Yunnan. Spatial distribution of the sign of trends is similar to the loading pattern of EOF-1, which indicates the trend of PRJJA, as obtained by Nitta and Hu (1996).

PRDAYS declined in north and northeastern China (Fig. 2b). The decrease was large, with a value of about 40% of climatological PRDAYS near the Bohai Sea. In contrast, PRDAYS clearly increased over northwestern China, and the lower reach of the Yangtze River basin. The largest trend, about 60%, was observed in the Taklimakan Basin. Decreases dominated over the Tibetan Plateau, Yunnan, and coastal southern China, but the trends were very small.

INTENS increased at most stations (Fig. 2c). Increase in INTENS was particularly large over the lower reaches of the Yangtze River and the Taklimakan Basin, regions where PRJJA and PRDAYS also increased. INTENS also increased over northern China, where PRJJA and PRDAYS decreased.

The heaviest class-interval, PR_C10, which designates daily rainfall greater than the 90th percentile, increased significantly over the Yangtze River basin (Fig. 2d). The largest trend exceeded 40% for the analysis period. In contrast, PR_C10 decreased over northern China, especially in Hebei, Shangdong, Shanxi and Shaanxi. PR_C10 also decreased over the Liaodong peninsula, while PR_C10 increased in most of northeastern China. The increase in PR_C10 exceeded 40% in Xinjiang. In the northeastern part of the Tibetan Plateau, PR_C10 also increased. Matsumoto (1989) found that heavy rainfall frequency is larger in the southern coast of China during JJA, on the contrary heavy rainfall frequency is relatively small in the Nanling mountains and the Wuyi

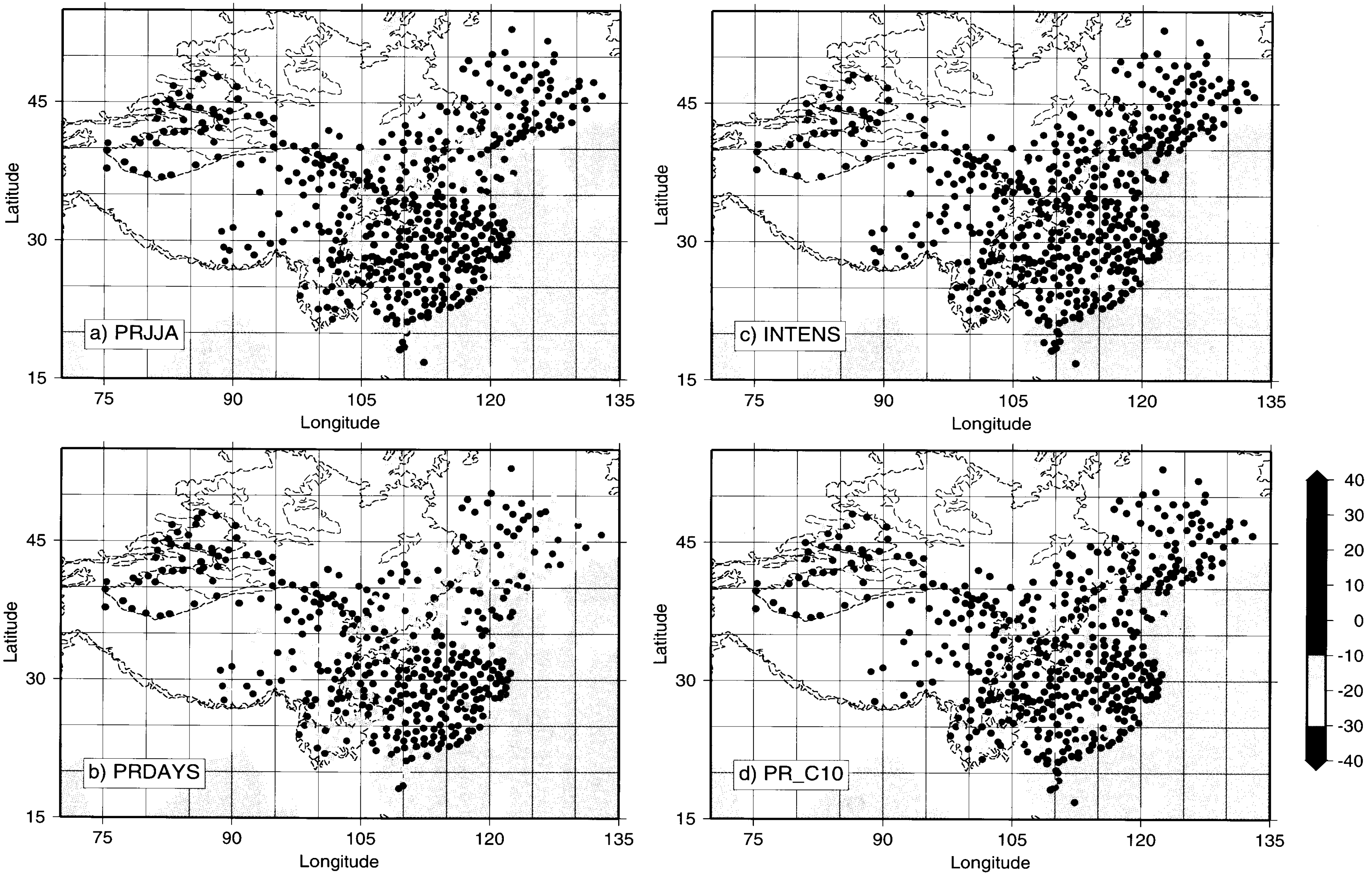

Fig. 2. Trends for 1961–2000 in a) summer total precipitation (PRJJA), b) number of rainy days (PRDAYS), c) precipitation intensity (INTENS), and d) rainfall amount of Class-10 (PR_C10). Trends are expressed as the percentage variations with respect to the mean value over the 1961–2000 period.

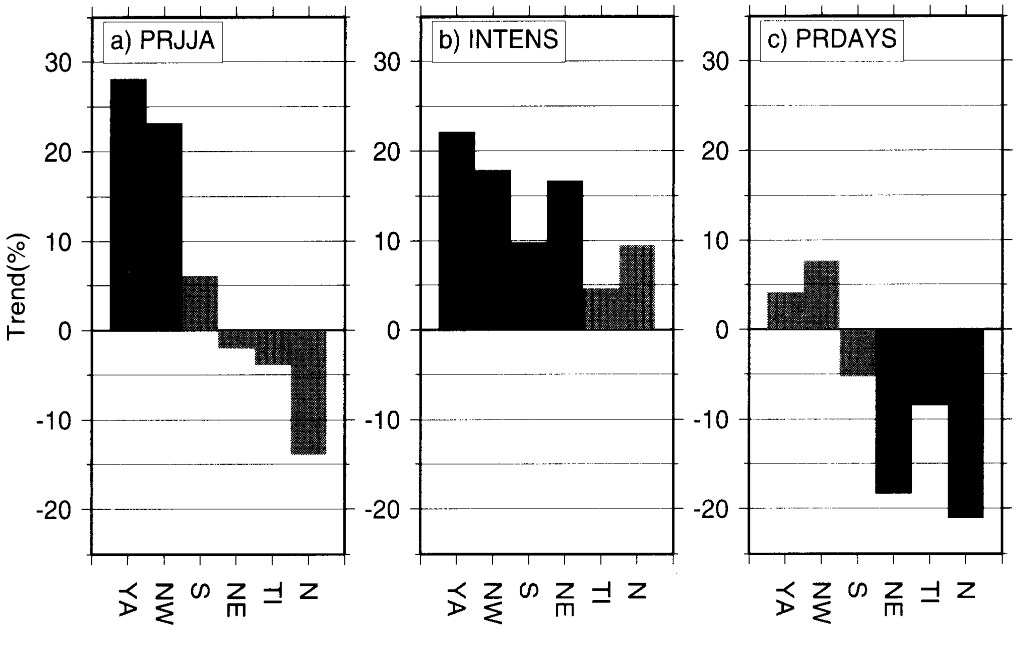

Fig. 3. Regional trends for 1961–2000 in a) summer precipitation total (PRJJA), b) precipitation intensity (INTENS), and c) number of rain days (PRJJA). Labels 'N', 'TI', 'NE', 'S', 'NW' and 'YA' are as in Fig. 1. Trends are expressed as the percentage variations with respect to the mean value over the 1961–2000 period. Black bar indicates statistical significance at the 0.05 confidence level.

mountains, which are located between the southern coast of China and the Yangtze River. PR_C10 showed an upward tendency in the southern coast of China, while PR_C10 showed a smaller change, or negative trends in the Nanling and Wuyi mountain ranges.

PRJJA increased over the Yangtze River basin, northwestern China, and southern China (Fig. 3a). The trend in PRJJA over the Yangtze River basin was more than 25% of the climatological mean of 509.3 mm (Table 1), that is, about 35 mm decade^{-1}, which was statistically significant at a 95% confidence level, for the period from 1961 to 2000. The increase in PRJJA over northwestern China (about 4.5 mm decade^{-1}) was smaller than that over the Yangtze River basin, but was still statistically significant (rate of increase). INTENS over both the Yangtze River and northwestern China increased significantly (Fig. 3b), and a slight increase in PRDAYS was concurrently observed (Fig. 3c). The regional trends for each of the ten rainfall classes are shown in Fig. 4. The two upper-most classes showed significant increases for 1961–2000 over the Yangtze River basin (Fig. 4a). Table 1 shows that the climatological values of the average daily rainfall were 248.0 mm for PR_C10, and 108.5 mm for PR_C9, over the Yangtze River basin. The frequency of heavy rainfall exceeding about 100 mm increased in the Yangtze River basin during the study period. Class-average daily rainfall for PR_C8 was 64.2 mm, which reflects an increase, albeit at statistically insignificant levels. Figure 5 shows time series of PR_C10 for the six regions. The increase of PR_C10 was evident after the late-1970s in the Yangtze River basin (Fig. 5a). As described earlier, PRJJA increased over northwestern China, where a significant increase occurred in PR_C10 and PR_C9 (Fig. 4b). The climatological values of PR_C10 and PR_C9 were 34.5 mm and 15.8 mm in northwestern China, respectively (Table 1). The increase in PRJJA over the Yangtze River basin and northwestern China are, therefore, largely attributable to an increase in the number of heavy precipitation events.

PRJJA decreased over northern and northeastern China and Tibet (Fig. 3a). In northern China, reduction of PRDAYS was statistically significant, while the trend of INTENS was positive (Figs. 3b and 3c). Although PR_C10 also showed negative trend from 1961 to 2000 in northern China (Fig. 4f), larger PR_C10 years appeared in the 1990s (Fig. 5f). As shown

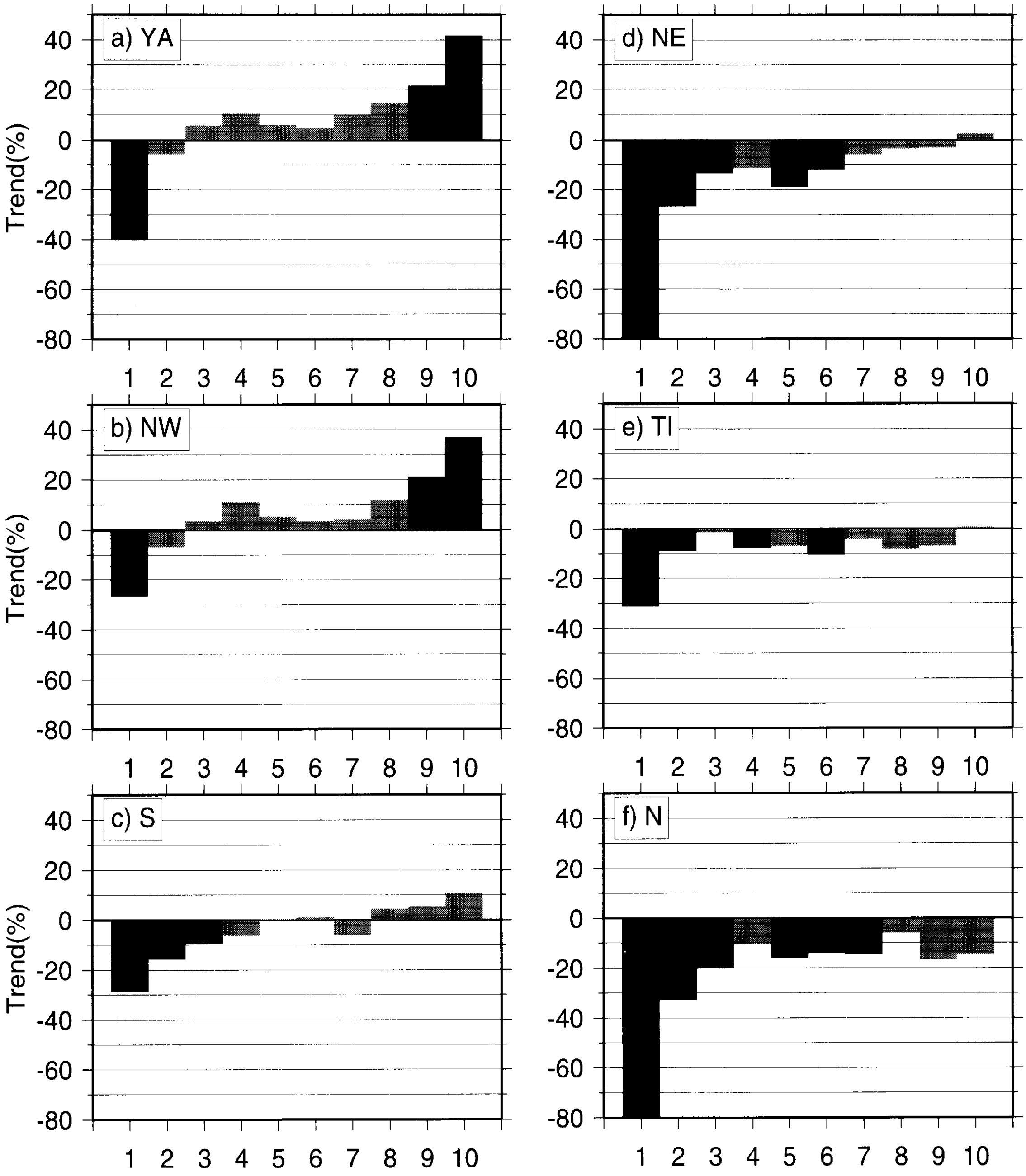

Fig. 4. Regional trends of summer precipitation for each classes of precipitation defined by ten percentile class intervals for a) Yangtze River basin, b) northwestern China, c) southern China, d) northeastern China, e) Tibet, and f) northern China. Trends are expressed as the percentage variations with respect to the mean value over the 1961–2000 period. Black bar indicates the trend is statistically significant at the 0.05 significance level.

in Fig. 2d, the negative trend of PR_C10 was observed in the Liaodong peninsula. However, there were statistically significant increases in INTENS and decreases in PRDAYS over northeastern China (Figs. 3b and 3c). Therefore, the INTENS increase is linked to the PRDAYS decrease, and the number of light precipitation events decreased as the number of heavy precipitation events increased in this region. PRDAYS significantly decreased in Tibet (Fig. 3c), while INTENS slightly increased (Fig. 3b). In addition, average precipitation in most of the precipitation classes declined in these regions (Figs. 4d, 4e, and 4f).

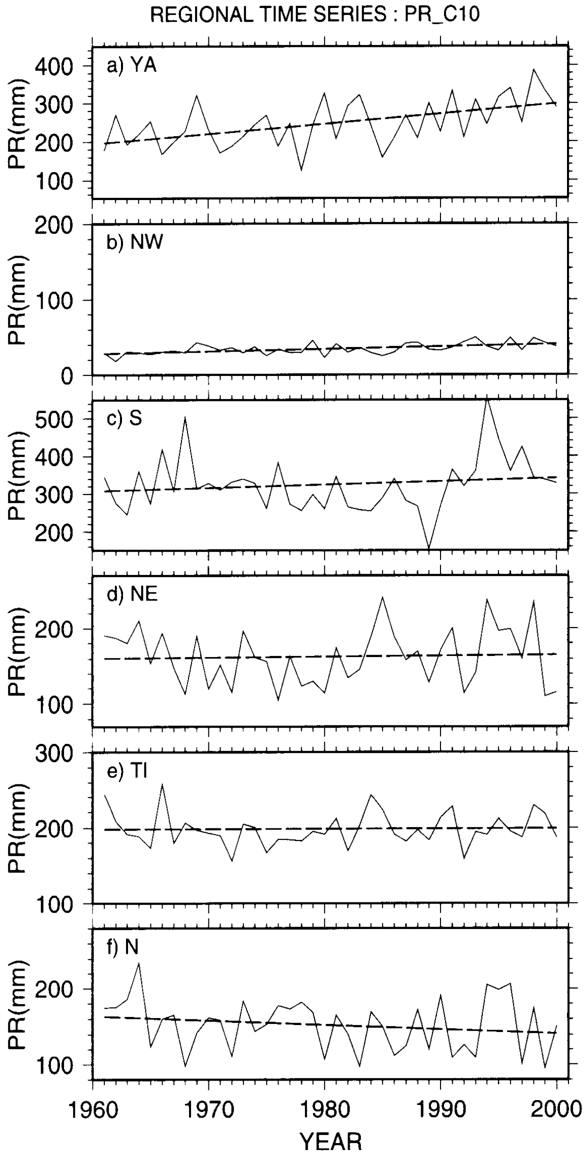

Fig. 5. Regional time series of PR_C10. Labels 'N', 'TI', 'NE', 'S', 'NW' and 'YA' are as in Fig. 1. Dashed line indicates linear trends of PR_C10.

Average precipitation in the lightest precipitation class decreased in all regions, and the lowest class average daily rainfall was less than 1 mm (Table 1). However, the contribution of the trend in the lightest precipitation class, to the trend in PRJJA was very small. Trace precipitation also decreased over most of China (not shown).

5. Summary and discussion

A new daily rainfall dataset that includes more than 500 stations in China from 1961 to 2000 was used to investigate long-term trends in summer precipitation totals, the number of rainy days, and precipitation intensity, which is defined as the summer precipitation totals divided by the number of rainy days. Total precipitation in summer increased significantly over the Yangtze River basin and northwestern China. Total precipitation decreased in other regions. The number of rainy days increased over the Yangtze River basin and northwestern China, where summer total precipitation increased. In contrast, the number of rainy days decreased in Tibet and in northern and northeastern China, where total summer precipitation also decreased. Seasonal mean precipitation intensity became large at most of the stations in China.

Daily precipitation totals were grouped into 10 classes, with class width equal to 10% of the total number of rainy days from 1961 to 2000, and the number of rainy days and summer mean rainfall amount for each class were obtained for each summer. A simple linear fit was made to determine the linear trends in the 10-class precipitation time series. The upper 20 percentile of daily precipitation totals increased in a statistically significant manner over the Yangtze River basin, and northwestern China during the study period. Most of the ten-class precipitation totals decreased in Tibet, and in northern and northeastern China, over which locations summer precipitation totals also declined.

In this study, the increase of seasonal average precipitation intensity (INTENS) was observed over most of China. Similar results were observed in Japan (Iwashima and Yamamoto 1993), United States (Karl and Knight 1998), Australia (Suppiah and Hennessey 1998), United Kingdom (Osborn et al. 2000), and Italy (Brunetti 2001a). A similar increasing trend also appeared in model experiments (Noda and Tokioka 1989; Gordon et al. 1992; Fowler and Hennessy 1995; Frei et al. 1998). Trenberth (1998) found that the increase in the surface temperature leads to the increase of atmospheric water holding capacity, and the increased atmospheric moisture content in the coupled AOGCM climate change simulation. The increased moisture content may favor more intense precipitation. In fact, the precipitable water demonstrates an upward trend from 1973 to 1995 in eastern China (Ross and Elliott

2001). Hence, the increase of surface temperature could induce the enhancement of the hydrological cycle in eastern China. Meanwhile, the INTENS increase is linked to the PRDAYS decrease, with the decrease of weak precipitation in northeastern China. Further studies are needed to examine the physical reason for the decrease of weak precipitation in northeastern China.

Trends in summer total precipitation (PRJJA), and the heaviest class of daily rainfall amount (PR_C10), are clearly different between the Yangtze River basin and in northern China. Weng et al. (2004) analyzed spatiotemporal variation in PRJJA, and regional atmospheric circulation in China and Japan. Their Singular Value Decomposition (SVD)-1 showed that there is a blocking high over eastern Siberia, an elongated mid-latitude low from northern China and Japan, and a southwestward advanced, and intensified subtropical high in the western Pacific. The weakening of the Asian monsoon in most areas over East Asia, and the strengthening of the Asian monsoon in the south, produce a convergence zone along the southwestern edge of the elongated mid-latitude low over the Yangtze River basin. SVD1 represents the increase of PRJJA in the Yangtze River basin, and the decrease of PRJJA in northern China. The enhanced convergence zone prefers to form rain bands in the Yangtze River basin, and may be partly responsible for the increase of PR_C10. Besides, the increase in atmospheric water content over eastern China (Ross and Elliott, 2001) may be related to the increase of PR_C10. Meanwhile, the weakening of the summer monsoon in most areas over East Asia is also related with the decreasing trends of PRDAYS and PR_C10 in northern China. Inoue and Matsumoto (2004) recently noted that NCEP reanalysis data over Mongolia have spurious interannual/interdecadal variations. Thus, the SVD analysis made by Weng et al. (2004) may partly be affected by these spurious variations. Further investigation for changes in synoptic pattern for heavy rainfall over the Yangtze River basin is necessary in order to investigate the relationship between climatic variations, and heavy rainfall occurrences.

The present study shows an increase in PRJJA over northwestern China. Further research is necessary to investigate long-term changes in water vapor transport, and atmospheric circulations, related to trends in PRJJA over northwestern China.

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