Vol. 91: 1–19, 2023
https://doi.org/10.3354/cr01716

CLIMATE RESEARCH
Clim Res

Published August 17

*Contribution to CR Special 36 'Observed changes in climate over Asia'*

# Change in mean and extreme precipitation in eastern China since 1901

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ABSTRACT: Extreme precipitation in the monsoon region of China can cause a variety of weather and climate disasters, and its long-term change has a significant impact on human life and social production. However, due to the lack of high-resolution precipitation data for the early 20th century, the variation characteristics and causes or mechanisms of extreme precipitation change in eastern China in the last 100 yr or more are still unclear. Based on the 'daily precipitation dataset of 60 city stations in mainland China from 1901 to 2020' developed by the National Meteorological Information Center, China Meteorological Administration, the main characteristics of extreme precipitation changes at 38 stations in eastern China during a recent 120 yr period (1901–2020) are analyzed in this paper. The results show that: (1) From 1901 to 2020, there was no significant trend in precipitation amount and precipitation days in the region, but a quasi-period of about 15 to 20 yr or longer existed during the period. (2) The average daily precipitation intensity and most of the extreme precipitation indices first decreased and then increased over the whole time period. In the period 1901–1950, which has rarely been studied in the past, most of the extreme precipitation indices, including intense rainfall, rainstorms, and the maximum precipitation within 1 day, 3 consecutive days, and 5 consecutive days, showed a significant decreasing trend. Since 1951, however, various indices have tended to increase. (3) From 1901 to 2020, the precipitation and extreme precipitation indices to the north of 35° N generally decreased, while they consistently increased in the south. The spatial pattern of extreme precipitation changes for the first half of 20th century was also quite different from that of the last 70 yr. Overall, the mean and extreme precipitation change trends in eastern China were not consistent in different sub-periods during the past century.

KEY WORDS: Observational data · Extreme precipitation · Time series · Climate change · Mainland China

## 1. INTRODUCTION

Most areas in eastern China are characterized by a monsoon climate. The rainfall concentrates in the hot season, which is conducive to agricultural production. However, there is usually a high flow of energy in the summer monsoon season, producing a large amount of extreme precipitation that can easily cause flood disasters. On the other hand, precipitation in the dry season is scarce and drought disasters are also frequent. These meteorological disasters can cause major losses (Xiao et al. 2007). Global warming theoretically increases the convection energy, which is likely to increase the precipitation extremes (Allen & Ingram 2002, Trenberth et al. 2003, Sun et al. 2021). A number of studies have shown that extreme precipitation in most regions around the world has significantly increased in recent decades (Donat et al. 2013, 2016, Westra et al. 2013, O'Gorman 2015, IPCC 2021, Sun et al. 2021). It has also increased over

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the eastern part of China since the 1950s or 1960s (e.g. Zhai et al. 2005, 2007, Ding 2008, Min & Qian 2008, Huang & Du 2010, Tu et al. 2010, Ren et al. 2011, 2015, Han et al. 2019).

The increase in temperature has caused this increase and enhancement of extreme precipitation, but there are other factors in the climate system that cause periodic fluctuations in extreme precipitation (Li et al. 2012, Ning et al. 2017, Xiao et al. 2017, Xu et al. 2022). Some studies have found that extreme precipitation has not tended to increase in most parts of northern China in recent decades, especially since 2000 (Li et al. 2012, Zhan et al. 2013, Song et al. 2015, Ren et al. 2015, Xiao et al. 2017, Wang et al. 2017, Mei et al. 2018, Li et al. 2019, Yuan et al. 2019, Zhao et al. 2019, Yu et al. 2020). The question remains as to whether the above discovery shows that the changes in extreme precipitation in the second half of the 20th century can be attributed to natural climate variability on a multi-decadal scale. Wang et al. (2008) and Zhang & Ma (2011) respectively reported that most of the extreme precipitation indices in the middle and lower Yangtze River Basin and Sichuan region had periodic oscillations of 12–16 and 25 yr when they showed increasing trends over long time scales. However, as the datasets used previously did not include daily precipitation data before 1951 (Ren et al. 2012, Jaffrés 2019), research on extreme precipitation changes in eastern China focuses mainly on recent decades. In Europe and North America, which have relatively complete daily observation data, precipitation intensity in the early 20th century was greater, so extreme precipitation did not increase significantly in the first half of the 20th century (Westra et al. 2013, Donat et al. 2013), implying that the long-term changes in extreme precipitation may not have been completely driven by temperature changes.

In short, the characteristics of long-term changes and variability in regional extreme precipitation are not clear at present, and there are key questions about the regional response of extreme precipitation to global climate warming. With the multiple needs of monitoring, detection, attribution, projection, and adaptation of climate change, and also meteorological disaster prevention and mitigation, it is essential to fully understand the characteristics of extreme precipitation change in the eastern China monsoon region over more than 100 yr, by applying high-quality daily observational data.

This study analyzes the temporal and spatial patterns of extreme precipitation changes and variability in eastern China since 1901 by using the newly developed daily precipitation dataset of the 60 cities in mainland China from the National Meteorological Information Center, China Meteorological Administration (CMA) (Zhan et al. 2022).

## 2. DATA AND METHODS

The data used in this paper is the 'daily precipitation dataset of 60 city stations in mainland China from 1901 to 2020' developed by the National Meteorological Information Center, CMA. The daily precipitation data for between 1901 and 1950 are digitized data sourced from a variety of historical meteorological archives. The stations in eastern China are much denser than in the other regions of the country. The integrity and quality of the station data have been evaluated, and they are generally good, though the missing data in early years is not negligible (Zhan et al. 2022).

In this dataset, data were not homogenized, but those with obviously inconsistent observational locations were categorized as quality control code number 3, based on the metadata. We excluded all these data in this research to avoid potential inhomogeneity. Years with no less than 243 valid precipitation records in the whole year and 122 valid records in the flood season (May to September) were marked as valid years and included in the dataset. Using the standard of a sequence length of no less than 80 valid years, a total of 38 stations in eastern China were selected for use in this study (Fig. 1, Table 1).

In order to reduce the biases in the regional average series caused by the spatial unevenness of these stations, the latitude and longitude grid area-weighted average method was employed (Jones & Hulme 1996, Zhan et al. 2013, 2021, Ren et al. 2015) to calculate the regional average values by dividing the study region into 5.0° × 5.0° latitude and longitude grids. Grid values are the averages of all non-missing station data in the grid. A total of 19 grids with a data length of more than 80 yr were obtained (Fig. 1). Applying the climate reference period 1981–2010, the station and regional average Normalized Anomaly (NA) series of all the precipitation indices were constructed, and the characteristics of the long-term change and variability in the indices series from 1901 to 2020 were analyzed. NA is defined as the ratio of the precipitation index anomaly to the standard deviation (SD).

This study defines wet days or precipitation frequency as the number of days in a year with a daily

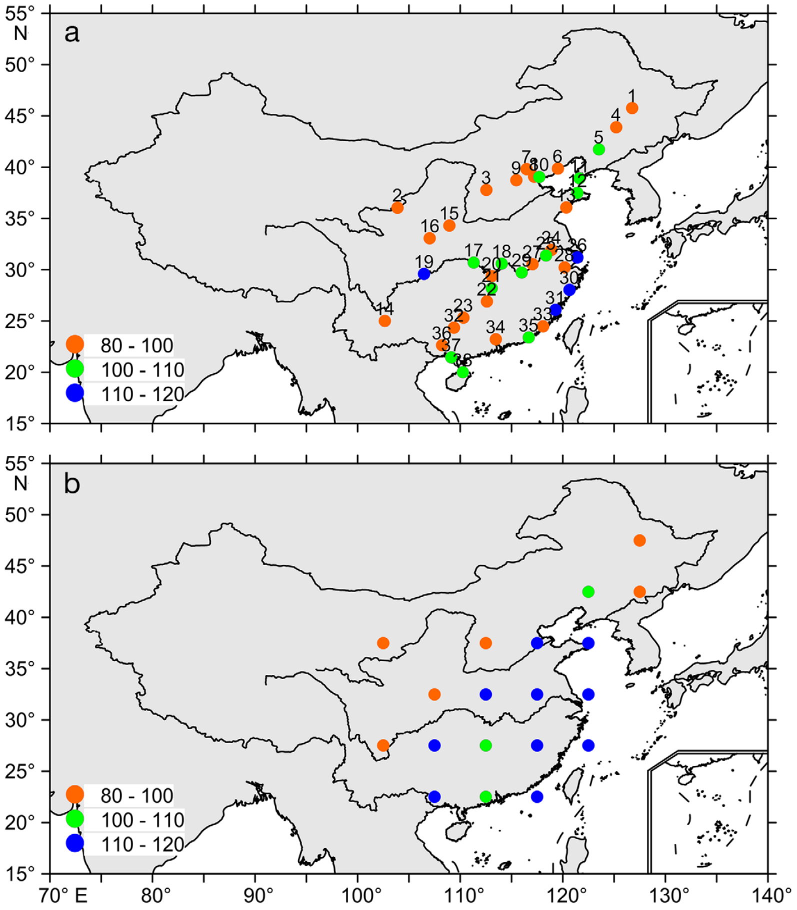

Fig. 1. Spatial distribution of precipitation data series with varied lengths (units are years) during the period 1901–2020 for (a) stations and (b) grids in eastern China. In (a), the numbers correspond to the stations in Table 1

precipitation of no less than 1 mm, and the unit is days (d). The annual precipitation (amount) is the sum of precipitation on wet days in the year, and the unit is millimeters (mm). The annual average daily precipitation intensity (precipitation intensity for short) is the ratio of annual precipitation to precipitation frequency (d), and the unit is millimeters per day (mm $d^{-1}$).

There are large regional differences in climate background in China, so the relative threshold method, in addition to the absolute method, is used to define intense precipitation. Referring to the method of Karl & Knight (1998), daily precipitation record of wet days in the climate reference period (1981–2010) of each station is sorted from small to large, and the value of the 95th percentile record is defined as the intense precipitation threshold of the station. The sum of all daily precipitation greater than this threshold is defined as the annual intense precipitation. The frequency and intensity of the intense precipitation are defined and calculated in a similar manner.

The amount and frequency of intense precipitation are compared with those of rainstorms, which are defined based on the absolute threshold of daily precipitation no less than 50 mm.

Referring to the method of Zhang et al. (2011), other absolute threshold-based extreme precipitation indices are defined, which include the annual maximum precipitation on 1 day, 3 consecutive days, and 5 consecutive days (RX1day, RX3day, RX5day), and the number of consecutive wet days in a year (CWD). All the definitions and units are listed in Table 2. According to the procedure of Zhan et al. (2018), we calculate the average value and SD of all precipitation indices for each station in the climate reference period, and the annual NA, by dividing the yearly anomalies by the SD.

All of the precipitation indices are used to obtain the regional average series, and the linear trends are calculated by the least square method. Multi-scale sliding linear trends are also calculated by changing the beginning year and ending year in order to reveal the variation characteristics in different periods. The correlation coefficient (r) is used to test the significance of linear trends. Unless stated otherwise, a confidence level of $p < 0.05$ is adopted.

## 3. RESULTS

### 3.1. Change in precipitation, wet days and precipitation intensity

From 1901 to 2020, the regional average NA of annual total precipitation in the study region did not have a significant trend, and the change rate was only 0.007 per decade ($decade^{-1}$). In terms of decadal variability, the annual precipitation in the early 20th century (1900s to 1910s) was high, forming an obvious peak. In the 1920s, precipitation significantly decreased, reaching a trough during the early to mid-1940s, with negative anomalies during most of the 1920s to the mid-1940s. From the mid-1940s to the 1950s, annual precipitation increased rapidly, reaching a peak in the mid-20th century. In the

Table 1. Observations at the 38 stations in eastern China

| No. | Station code | Station name | Starting year | Record length (mo) | Missing months | Percentage of missed months |
|---|---|---|---|---|---|---|
| 1 | 50953 | Harbin | 1910 | 984 | 348 | 35.37 |
| 2 | 52889 | Lanzhou | 1932 | 1048 | 20 | 1.91 |
| 3 | 53772 | Taiyuan | 1919 | 1034 | 190 | 18.38 |
| 4 | 54161 | Changchun | 1909 | 1137 | 207 | 18.21 |
| 5 | 54342 | Shenyang | 1907 | 1203 | 165 | 13.72 |
| 6 | 54449 | Qinhuangdao | 1908 | 1177 | 179 | 15.21 |
| 7 | 54511 | Beijing | 1915 | 1146 | 126 | 10.99 |
| 8 | 54517 | Tianjin | 1904 | 1185 | 219 | 18.48 |
| 9 | 54602 | Baoding | 1919 | 971 | 253 | 26.06 |
| 10 | 54623 | Tanggu | 1909 | 1241 | 103 | 8.30 |
| 11 | 54662 | Dalian | 1904 | 1220 | 184 | 15.08 |
| 12 | 54765 | Yantai | 1901 | 1237 | 203 | 16.41 |
| 13 | 54857 | Qingdao | 1902 | 1083 | 345 | 31.86 |
| 14 | 56778 | Kunming | 1929 | 1001 | 103 | 10.29 |
| 15 | 57036 | Xian | 1931 | 985 | 95 | 9.64 |
| 16 | 57127 | Hanzhong | 1934 | 983 | 61 | 6.21 |
| 17 | 57461 | Yichang | 1901 | 1274 | 166 | 13.03 |
| 18 | 57494 | Wuhan | 1901 | 1287 | 153 | 11.89 |
| 19 | 57516 | Chongqing | 1901 | 1430 | 10 | 0.70 |
| 20 | 57584 | Yueyang | 1909 | 1156 | 188 | 16.26 |
| 21 | 57679 | Changsha | 1909 | 1263 | 81 | 6.41 |
| 22 | 57872 | Hengyang | 1932 | 986 | 82 | 8.32 |
| 23 | 57957 | Guilin | 1935 | 961 | 71 | 7.39 |
| 24 | 58238 | Nanjing | 1907 | 1134 | 234 | 20.63 |
| 25 | 58334 | Wuhu | 1901 | 1244 | 196 | 15.76 |
| 26 | 58367 | Shanghai | 1901 | 1343 | 97 | 7.22 |
| 27 | 58424 | Anqing | 1931 | 963 | 117 | 12.15 |
| 28 | 58457 | Hangzhou | 1907 | 1068 | 300 | 28.09 |
| 29 | 58502 | Jiujiang | 1901 | 1330 | 110 | 8.27 |
| 30 | 58659 | Wenzhou | 1901 | 1366 | 74 | 5.42 |
| 31 | 58847 | Fuzhou | 1902 | 1357 | 71 | 5.23 |
| 32 | 59046 | Liuzhou | 1935 | 1003 | 29 | 2.89 |
| 33 | 59134 | Xiamen | 1913 | 1029 | 267 | 25.95 |
| 34 | 59287 | Guangzhou | 1920 | 1093 | 119 | 10.89 |
| 35 | 59316 | Shantou | 1901 | 1264 | 176 | 13.92 |
| 36 | 59431 | Nanning | 1932 | 979 | 89 | 9.09 |
| 37 | 59644 | Beihai | 1901 | 1290 | 150 | 11.63 |
| 38 | 59758 | Haikou | 1912 | 1226 | 82 | 6.69 |

1960s, annual precipitation reduced significantly to negative anomalies. In the 1970s and 1980s, precipitation fluctuated with alternating positive and negative values. Precipitation increased in the late 1990s, decreased in the 2000s, and then rose rapidly in the 2010s. After 2012, all of the annual NA values were positive (Fig. 2, Table 3). The highest annual precipitation occurred in 1911, followed by that in 2016, and the lowest precipitation was in 1925, followed by that in 1936.

From 1901 to 2020, the regional average NA series for precipitation frequency decreased, and the change rate was –0.009 decade$^{-1}$, which was not significant. Three rainy periods were obvious, and they lasted from 1905 to 1920, 1947 to 1961, and 2012 to 2020, respectively (Fig. 3a). Although the linear trends for the periods 1901–1950 and 1951–2020 were almost the same, only the decrease in the last 70 yr was significant at the confidence level of 0.05 (Fig. 3a, Table 3).

Most previous studies have indicated that the average daily precipitation intensity in China has significantly increased in recent decades. In this study, the rate of change in precipitation intensity at the 38 stations in eastern China reached 0.071 decade$^{-1}$ from 1951 to 2020, which passed the 0.01 confidence level test. However, precipitation intensity showed a remarkable reduction from 1901 to 1950, which passed the 0.05 confidence level test. As a result, the change rate in the past 120 yr was fairly small (0.012 decade$^{-1}$) and not significant. Precipitation intensity was generally high at the beginning of the 20th century, decreased and was generally low from the 1920s to the 1980s, and increased quickly after the 1980s (Fig. 3b, Table 3).

On a time scale of about 15 to 20 yr, the sliding trend pattern shows that the changes in precipitation, precipitation frequency, and precipitation intensity from 1901 to 2020 all alternated between increase and decrease. During this period, precipitation and precipitation days experienced 5 cycles of drying and wetting, exhibiting the characteristics of significant cyclical changes. In the early 20th century, there were decreasing trends in precipitation and precipitation frequency in most periods, with the trends being significant when they started in 1905–1910 and ended in 1930–1945. The trends in precipitation and precipitation days around 1925–1955 reversed to increase significantly, and the time range of the significant increase in precipitation days was larger. The trends at 15 to 25 yr scales in precipitation and precipitation days starting around 1950 showed a significant decrease. However, the precipitation trends with scales of more than 50 yr did not change significantly, although the trends of precipitation days always showed a significant decrease. The precipitation trends ending in 2016–2020 almost all showed an increase, but the wet days mostly

Table 2. Definition and units of all precipitation indices used in this analysis

| Index | Definition | Unit |
|---|---|---|
| Precipitation (amount) | Sums of precipitation in wet days | mm |
| Wet days/precipitation frequency | Number of days with a daily precipitation no less than 1 mm | d |
| Precipitation intensity | Ratio of precipitation amount to wet days | mm $d^{-1}$ |
| Intense precipitation | Sums of precipitation greater than the 95th percentile record | mm |
| Intense precipitation days | Number of days with a daily precipitation greater than the 95th percentile record | d |
| Intense precipitation intensity | Ratio of intense precipitation to intense precipitation days | mm $d^{-1}$ |
| Rainstorm precipitation amount | Sum of precipitation no less than 50 mm | mm |
| Rainstorm precipitation days | Number of days with a daily precipitation no less than 50 mm | d |
| RX1day | Annual maximum precipitation on 1 day | mm |
| RX3day | Annual maximum precipitation on 3 consecutive days | mm |
| RX5day | Annual maximum precipitation on 5 consecutive days | mm |
| CWD | Number of consecutive wet days | d |

decreased, except for the past 40 yr when they began to increase (Fig. 4).

The sliding trend of precipitation intensity showed different characteristics from the amount and frequency of precipitation. The vast majority of the trends in the first half of the 20th century showed a decrease. Most of those beginning no later than 1915 and ending between 1936 and 1995 were significant. On the other hand, trends generally showed an increase after 1960. The upward trends beginning in 1920–1980 and ending after 2000 all passed the 0.05 confidence level test (Fig. 4). Therefore, the variations in precipitation amount and wet days were mainly characterized by the 15 to 20 yr or longer periodic cycles, but the variation in precipitation intensity exhibited a significant long-term trend.

In terms of the spatial variation over the past 120 yr, the annual precipitation at most stations in the Yangtze River Basin increased, and it decreased in Northeast China, North China, and Southwest China. However, the change rates were all less than 0.15 decade$^{-1}$, and significant changes were seen at only 5 stations (Fig. 5a). The changes in precipitation in 1901–1950 in most stations differed significantly from those in 1901–2020 (Fig. 5b). Precipitation at most stations in Northeast China, the Yangtze River Basin and the southeast coastal stations showed a decreasing trend, which was significant at a few stations. Precipitation at most stations in North China and the eastern part of Northwest China increased during 1901–1950, but the trends were not significant (Fig. 5b). Consistent with previous studies (Ren et al. 2011, 2015, Zhai et al. 2005), precipitation generally increased in the southern part of China and mostly decreased in the northern part during the period 1951–2020 (Fig. 5c). The spatial distribution pattern during the period 1901–2020 was close to that of the period 1951–2020, because the sequence lengths of most stations were evidently longer in the period 1951–2020 that in the period 1901–1950.

In the past century, precipitation frequency at stations in the southwestern and southern parts of China decreased significantly. It also decreased at all stations in the northeast and southeast coastal regions, although the downward trends were generally not significant (Fig. 5d). There was no obvious change in the Yangtze River Basin, North China, and the eastern part of Northwest China, and the absolute values

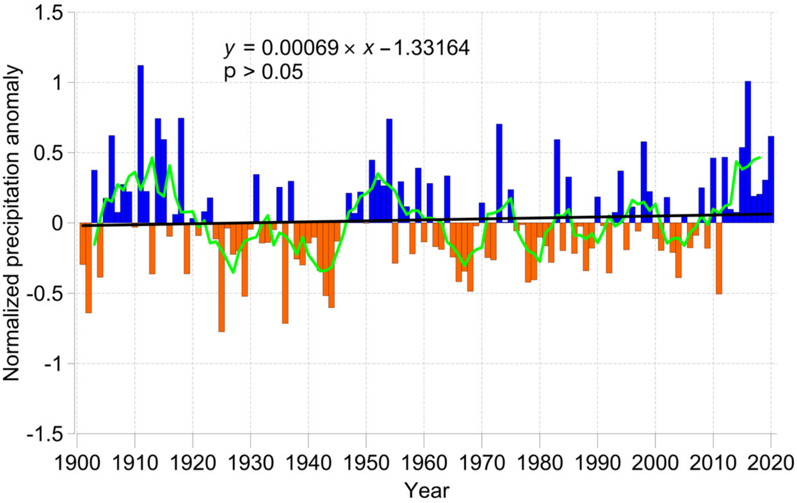

Fig. 2. The regional average normalized anomaly of annual precipitation over 38 stations in eastern China. Blue bars: positive values; orange bars: negative values; green curve: 5 yr moving average; black bold straight line: linear trend

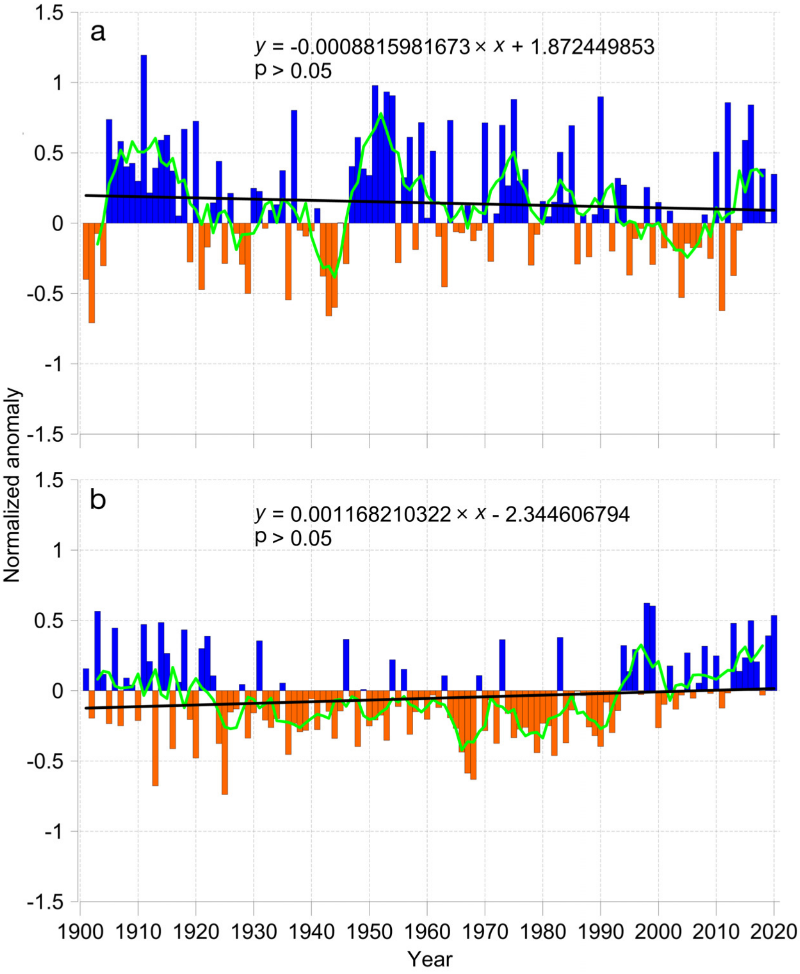

Fig. 3. Same as Fig. 2, but for (a) wet days and (b) precipitation intensity

of the change rates at these stations did not exceed 0.03 decade$^{-1}$. For the period 1901–1950, most stations in Northeast China, Southwest China, the lower reaches of the Yangtze River, and the southeast coastal areas had a decreasing precipitation frequency, but it usually increased in the middle of the Yangtze River Basin, North China, and the eastern part of Northwest China (Fig. 5e). There were significant decreasing trends in North China and Southwest China and weak trends in Northeast China, the lower reaches of the Yangtze River, and the southeastern coastal areas of China from 1951–2020 (Fig. 5f).

From 1901 to 2020, precipitation intensity at most stations to the south of the Yellow River increased (Fig. 5g). Among them, the middle and lower reaches of the Yangtze River and several stations in South China recorded a significant increase. Most of the stations to the north of the Yellow River had weak and insignificant trends for precipitation intensity. However, precipitation intensity at most stations showed a decreasing trend over the period 1901–1950 (Fig. 5h). Several stations in the middle and lower reaches of the Yangtze River had significantly decreasing trends, with the precipitation intensity trends at Wuhan, Jiujiang, Wuhu, and Nanjing generally exceeding −0.15 decade$^{-1}$ (Fig. 5h). During 1951–2020, precipitation intensity significantly increased in most stations in the southern part of China, while it did not experience any significant trends at most stations of the northern part (Fig. 5i).

The precipitation amount, frequency, and intensity series for 4 large cities (Beijing, Chongqing, Shanghai, and Guangzhou) are shown in Fig. 6. Beijing experienced peaks during the 1950s and troughs in the 2000s in all moving average series. There was another peak in the 1920s in the precipitation intensity series, while the NAs of the precipitation frequency were negative. As a result, there was a decreasing trend in the precipitation intensity series (Fig. 6).

There were no linear trends in any of the series for Chongqing, which is located in Southwest China. However,

Table 3. Linear trends of regional average time series of annual precipitation indices for various periods at 38 stations in eastern China (unit: decade$^{-1}$). Significance: $^{*}p < 0.05$; $^{**}p < 0.01$

| Index | Linear trend | | |
|---|---|---|---|
| | 1901–2020 | 1901–1950 | 1951–2020 |
| Precipitation | 0.007 | −0.065 | 0.022 |
| Wet days | −0.009 | −0.052 | −0.051* |
| Precipitation intensity | 0.012 | −0.063* | 0.071** |
| Intense precipitation | 0.010 | −0.076* | 0.043** |
| Intense precipitation days | 0.007 | −0.066 | 0.037* |
| Intense precipitation intensity | 0.018** | −0.044 | 0.032* |
| Rainstorm precipitation amount | 0.012 | −0.064* | 0.042* |
| Rainstorm precipitation day | 0.010 | −0.047 | 0.038* |
| RX1day | 0.015 | −0.083** | 0.043** |
| RX3day | 0.006 | −0.074** | 0.038** |
| RX5day | 0.001 | −0.066* | 0.030* |
| CWD | −0.015 | 0.007 | −0.019 |

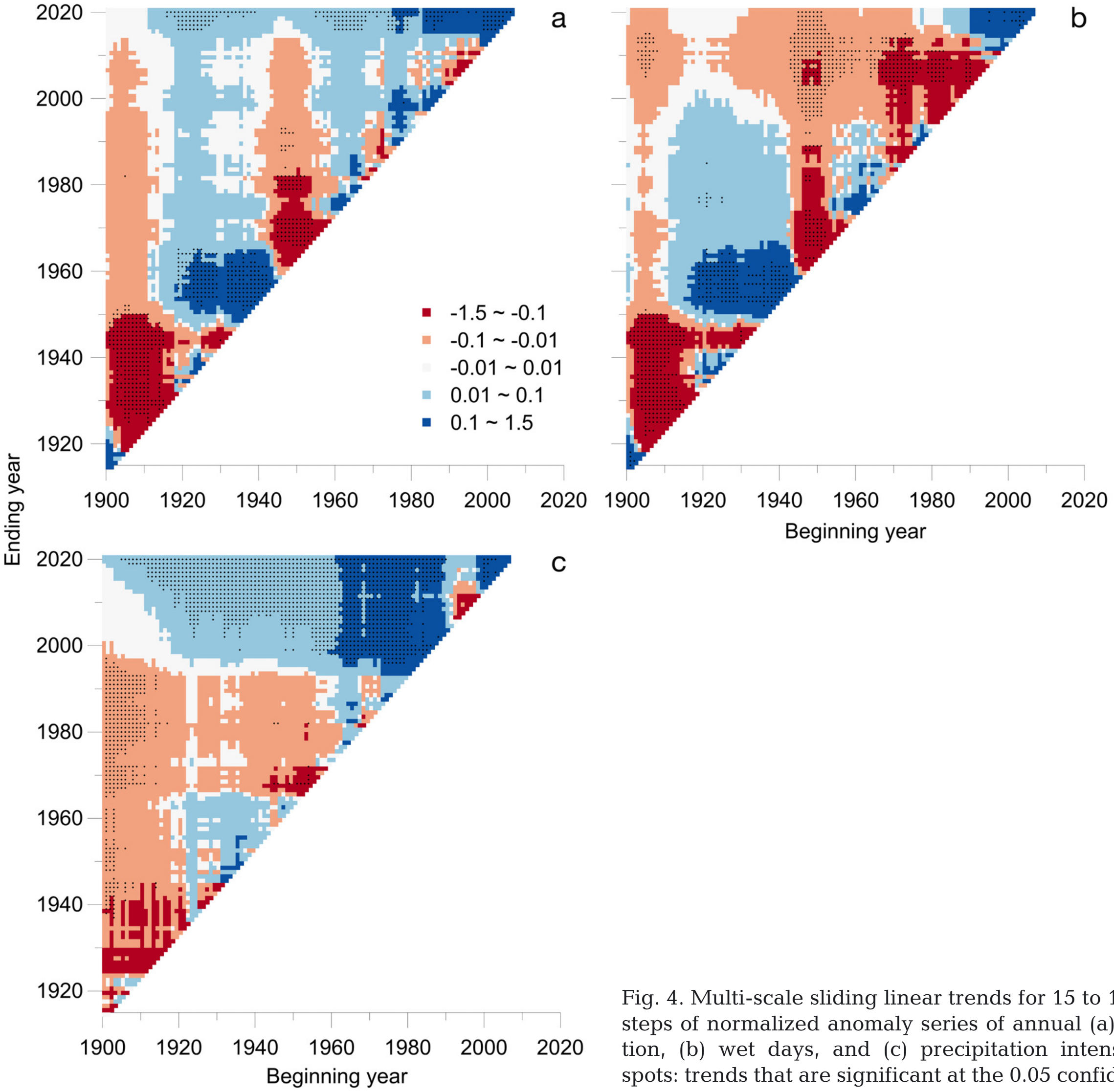

Fig. 4. Multi-scale sliding linear trends for 15 to 120 yr time steps of normalized anomaly series of annual (a) precipitation, (b) wet days, and (c) precipitation intensity. Black spots: trends that are significant at the 0.05 confidence level

the amount and intensity of annual precipitation both significantly increased in Shanghai and Guangzhou. As reported in previous studies (Ren et al. 2015, Liang & Ding 2017, Wang et al. 2017, Han et al. 2019), precipitation amount and intensity significantly increased in these cities during the period 1951–2020, while wet days showed no noticeable trends. The NAs of precipitation intensity were nearly all negative before 1951, but after that, increasing trends were clearly detectable. Precipitation frequencies in Guangzhou in the 1920s and 1930s were mostly positive anomalies, yielding a significant decreasing trend for the whole period. The NAs of precipitation frequencies in Shanghai before 1951 were not fully consistent, and the linear trend was small during the period 1901–2020 (Fig. 6).

### 3.2. Change in extreme precipitation indices

During the period 1901–2020, the regional average intense precipitation at the 38 stations in eastern China showed a slight increase (Fig. 7a). The linear trend of intense precipitation from 1901–2020 was only 0.010 decade$^{-1}$, which was not significant. The change rate for the period 1901–1950 was –0.076 decade$^{-1}$, while it was 0.043 decade$^{-1}$ in 1951–2020. These 2 trends both passed the 0.05 confidence level test (Fig. 7, Table 3). Before 1925, intense precipitation in most years was higher than normal. From the mid-to-late 1920s to the 1940s, however, it reversed to be lower. The annual intense precipitation briefly increased in the mid and late 1950s, became lower again in the 1960s and continuing through to the early 1990s, and then quickly in-

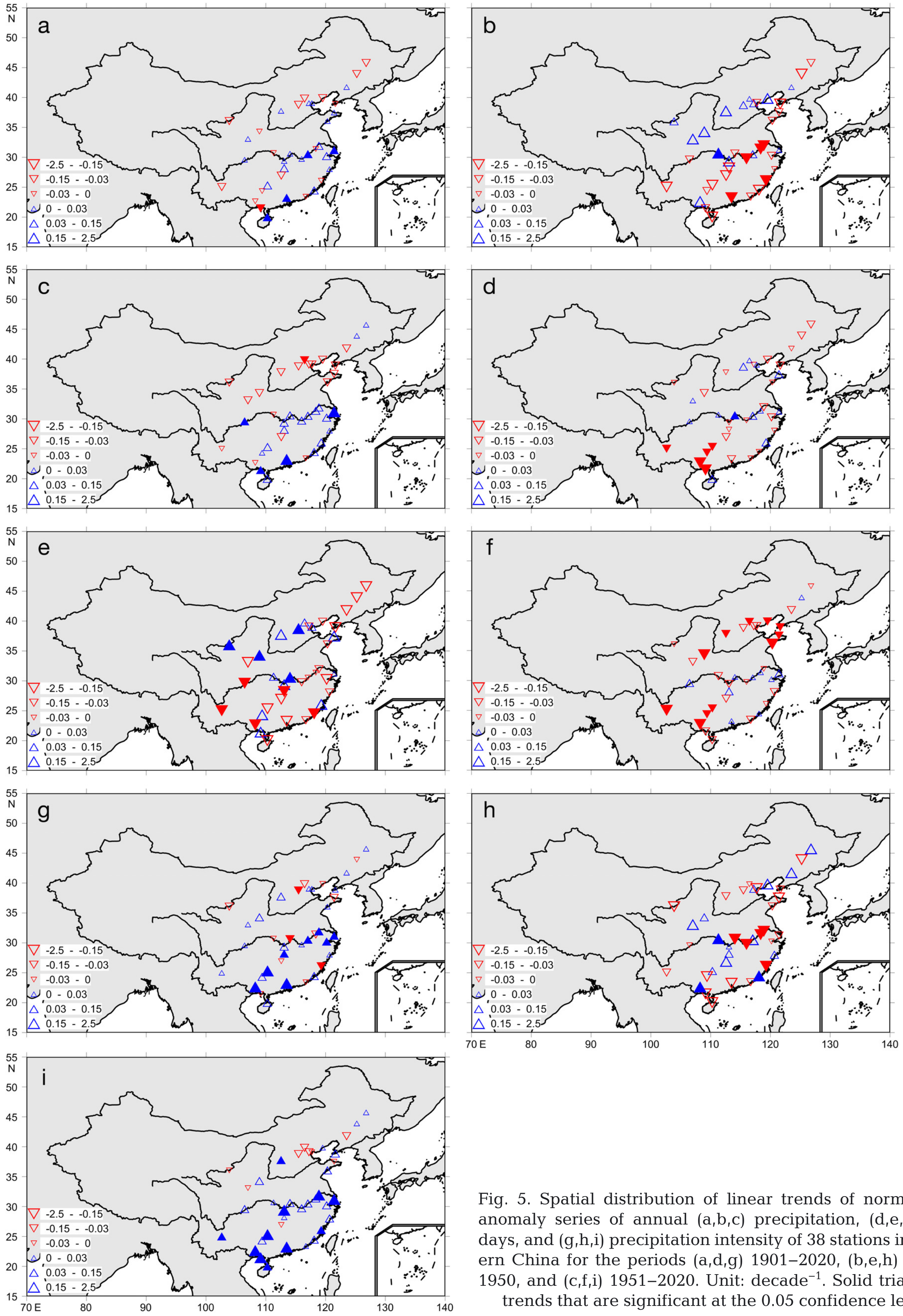

Fig. 5. Spatial distribution of linear trends of normalized anomaly series of annual (a,b,c) precipitation, (d,e,f) wet days, and (g,h,i) precipitation intensity of 38 stations in eastern China for the periods (a,d,g) 1901–2020, (b,e,h) 1901–1950, and (c,f,i) 1951–2020. Unit: decade$^{-1}$. Solid triangles: trends that are significant at the 0.05 confidence level

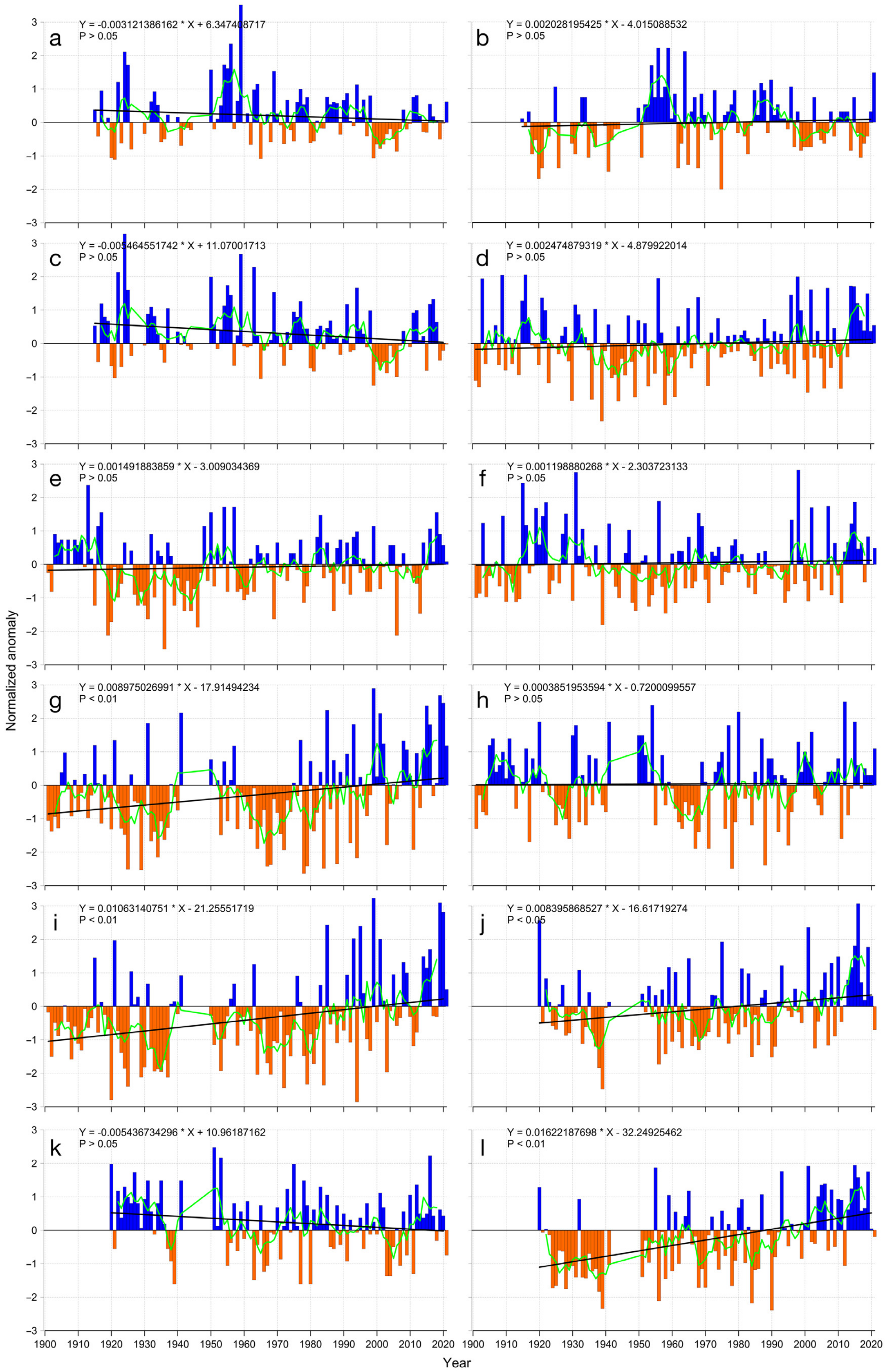

Fig. 6. The normalized anomaly of annual (a,d,g,j) precipitation, (b,e,h,k) wet days, and (c,f,i,l) precipitation intensity in 4 individual cities: (a,b,c) Beijing, (d,e,f) Chongqing, (g,h,i) Shanghai, and (j,k,l) Guangzhou. Blue bars: positive values; orange bars: negative values; green curve: 5 yr moving average; black bold straight line: linear trend

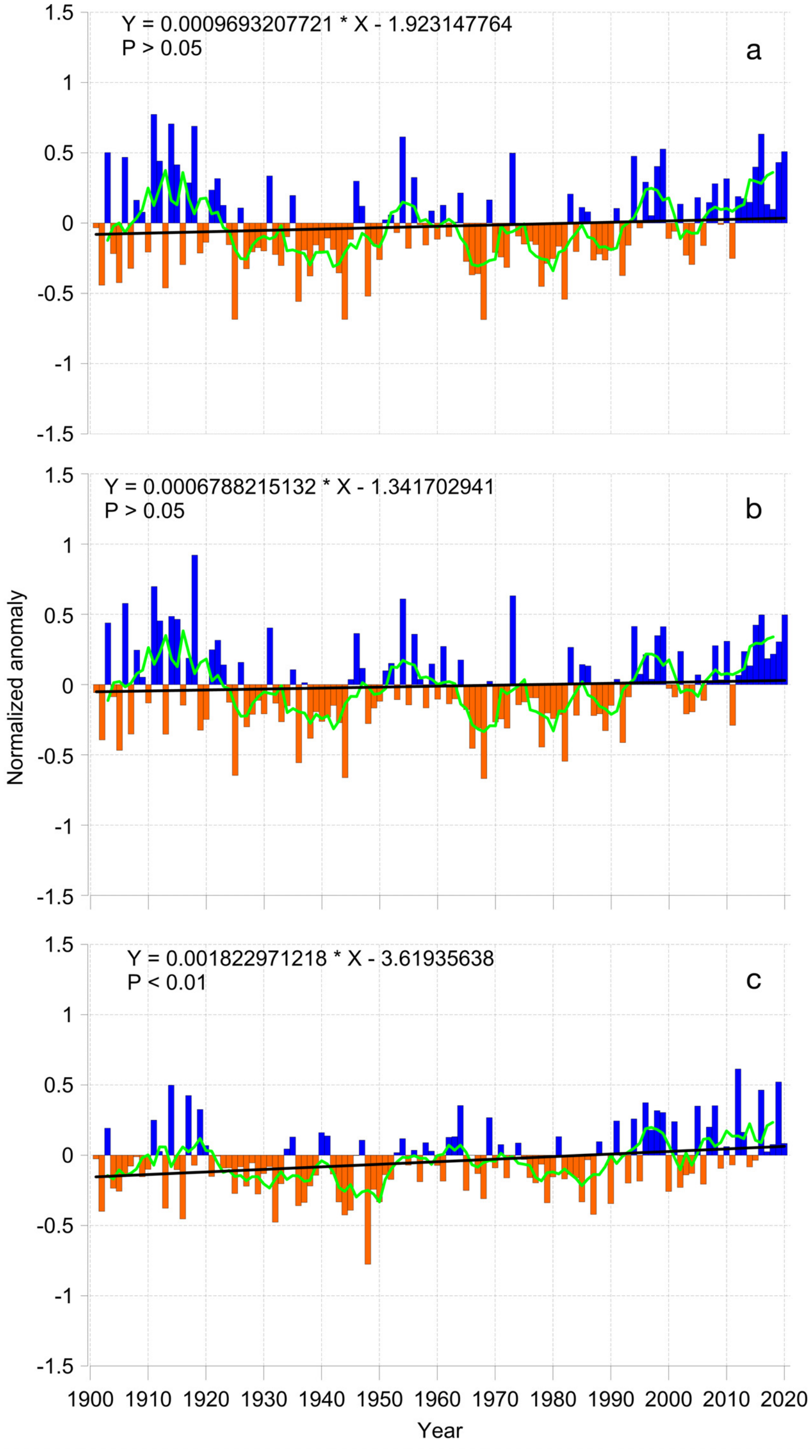

Fig. 7. Same as Fig. 2, but for (a) intense precipitation, (b) intense precipitation days, and (c) intense precipitation intensity

creased to become positive after 1994 (Fig. 7a). Although intense precipitation was lower in the early 21st century, there were obvious positive anomalies in most of the remaining years of the century.

From 1901 to 2020, the changing characteristics of intense precipitation frequency were very similar to those of the amount of intense precipitation. The absolute value of the change rate was slightly smaller than that of the amount of intense precipitation, and the overall trend was not significant. During the 2 periods of 1901–1950 and 1951–2020, the intense precipitation frequency also showed decreasing and increasing trends, with change rates of −0.066 and 0.037 decade$^{-1}$ respectively, which were weaker than those of the amount of intense precipitation (Fig. 7b, Table 3).

The temporal pattern of intense precipitation intensity was not very different from that of intense precipitation, but the fluctuation was obviously smaller. The positive anomalies in the early and mid-20th century were not significant, and the absolute value did not exceed 0.5 SD. Although intense precipitation intensity was basically negative in the mid-1970s to 1980s, the absolute value did not exceed 0.5. However, the linear trends increased significantly over the periods 1901–2020 and 1951–2020. This was likely caused by the slightly stronger increase in intense precipitation than in intense precipitation days (Fig. 7c, Table 3). In short, the time series of the amount, frequency, and intensity of intense precipitation were similar to those of precipitation intensity, and all experienced decreasing trends before 1950 and increasing trends after 1951.

From the perspective of spatial characteristics, the amount, frequency, and intensity of intense precipitation all showed increasing trends to the south of 35° N and decreasing trends to the north from 1901 to 2020. Most stations in Northeast China and the area around the Bohai Sea recorded a decrease, and those in the Yangtze River Basin and the southeast coastal areas generally recorded an increase. Regardless of the increasing or decreasing trends, the absolute values of the change rates were generally small, with most of them no more than 0.15 decade$^{-1}$ (Fig. 8).

The spatial pattern of intense precipitation during the period 1901–1950 was obviously different from that during 1901–2020. The amount, frequency, and intensity of the annual intense precipitation around the Bohai Sea increased. However, they all decreased in the middle and lower reaches of the Yangtze River Basin and the southeast coastal areas. Several stations, such as Nanjing, Wuhu, Jiujiang, Fuzhou, and Guangzhou, showed significant decreasing trends in the amount and frequency of intense precipitation. For the 1951–2020 period, the amount and frequency of annual intense precipitation nearly all increased in the south, and there were more stations with significant trends than during 1901–2020. The decreasing trends during 1951–2020 were also more significant than those in 1901–2020 at most stations in North China or around the Bohai Sea (Fig. 8).

From 1901 to 2020, the time series of the regional average amount and frequency of annual rainstorms were relatively consistent with each other. Both were higher in the early 20th century and the 21st century and lower in the 1920s to 1940s and the 1970s to 1980s. The change rates of the 2 series were not very different from the amount and frequency of intense precipitation. There was a significantly increasing trend for the period 1951–2020, but they both decreased from 1901 to 1950, and no significant trend was detectable over the period 1901–2020 (Fig. 9, Table 3).

From 1901 to 2020, the annual maximum precipitation in 1 day, 3 consecutive days, and 5 consecutive days all decreased at first and subsequently increased. All 3 indices showed an increase for the whole 120 yr, though the trends were not statistically significant (Fig. 10a,b,c, Table 3). The rate of increase became larger from 5 consecutive days to 1 day, indicating that short-duration intense precipitation tended to increase more obviously than long-duration intense precipitation in the study region. In the early 20th century, most of the indices were positive anomalies. In the mid-1920s, however, they all reduced to become negative anomalies. They remained negative until the early 1950s, and then rose briefly from the 1950s to mid-1960s. From the mid-1960s to the 1980s, most years had obvious negative anomalies, but they increased significantly in the 1990s to remain consistently positive until the present (Fig. 10, Table 3).

During the period of 1901 to 1950, the annual maximum precipitation in 1 day, 3 consecutive days, and 5 consecutive days all significantly decreased, and the absolute value of the linear trends of RX1day was the maximum (−0.083 decade$^{-1}$) while RX5day was the minimum (−0.066 decade$^{-1}$). From 1951 to 2020, however, they increased significantly, and the absolute values of the change rates decreased from RX1day to RX3day and RX5day, being 0.043, 0.038, and 0.030 decade$^{-1}$, respectively (Fig. 10, Table 3). Once again, short-duration intense precipitation generally exhibited a larger and more significant change during the different periods before and after 1950.

From 1901 to 2020, annual CWD at the 38 stations in eastern China showed a decreasing trend at a rate of −0.015 decade$^{-1}$, which was not significant. During 1901–1950, annual CWD was slightly higher, with more years with positive anomalies, but the overall trend was weak and not significant. There was a vast majority of years with positive anomalies from the 1950s to the mid-1960s, and the linear change in 1951–2020 was characterized by a decreasing trend, with the change rate being −0.019 decade$^{-1}$, which failed to pass the 0.05 confidence level test (Fig. 10, Table 3).

For the spatial pattern of change, most of the stations south of the Yangtze River had upward trends in RX1day during the period 1901–2020, but these were significant only at the Shanghai, Anqing, Xiamen, and Haikou stations. The Bohai Sea Rim region (North China) tended to decrease, though not significantly. A total of 24 stations (63 %) showed increasing trends, and 4 of them (10.5 %) showed statistically significant increasing trends. The proportion is approximately consistent with other studies using station data from the last decades to a century, such as Westra et al. (2013) and Sun et al. (2021). Most of the stations south of the Yangtze River had an increasing trend for RX3day, but only the changes at the Nanjing and Haikou stations were significant. Most of the stations north of the Yangtze River also recorded a decrease in RX3day. Among them, the decreasing rates at the Beijing, Baoding, and Lanzhou stations exceeded 0.03 decade$^{-1}$, and they passed the 0.05 confidence level test. The spatial pattern of RX5day change was similar to that of RX3day. The phenomenon of increasing in the south and decreasing in the north also existed for RX5day, but the Fuzhou and Beihai stations in the southern coastal region experienced a significant decrease (Fig. 11).

From 1901 to 1950, RX1day in Northeast China and the Bohai Sea Rim region generally decreased, but the changes were not significant. The Yangtze River Basin also saw a decrease, with the trends at the Nanjing and Jiujiang stations decreasing signifi-

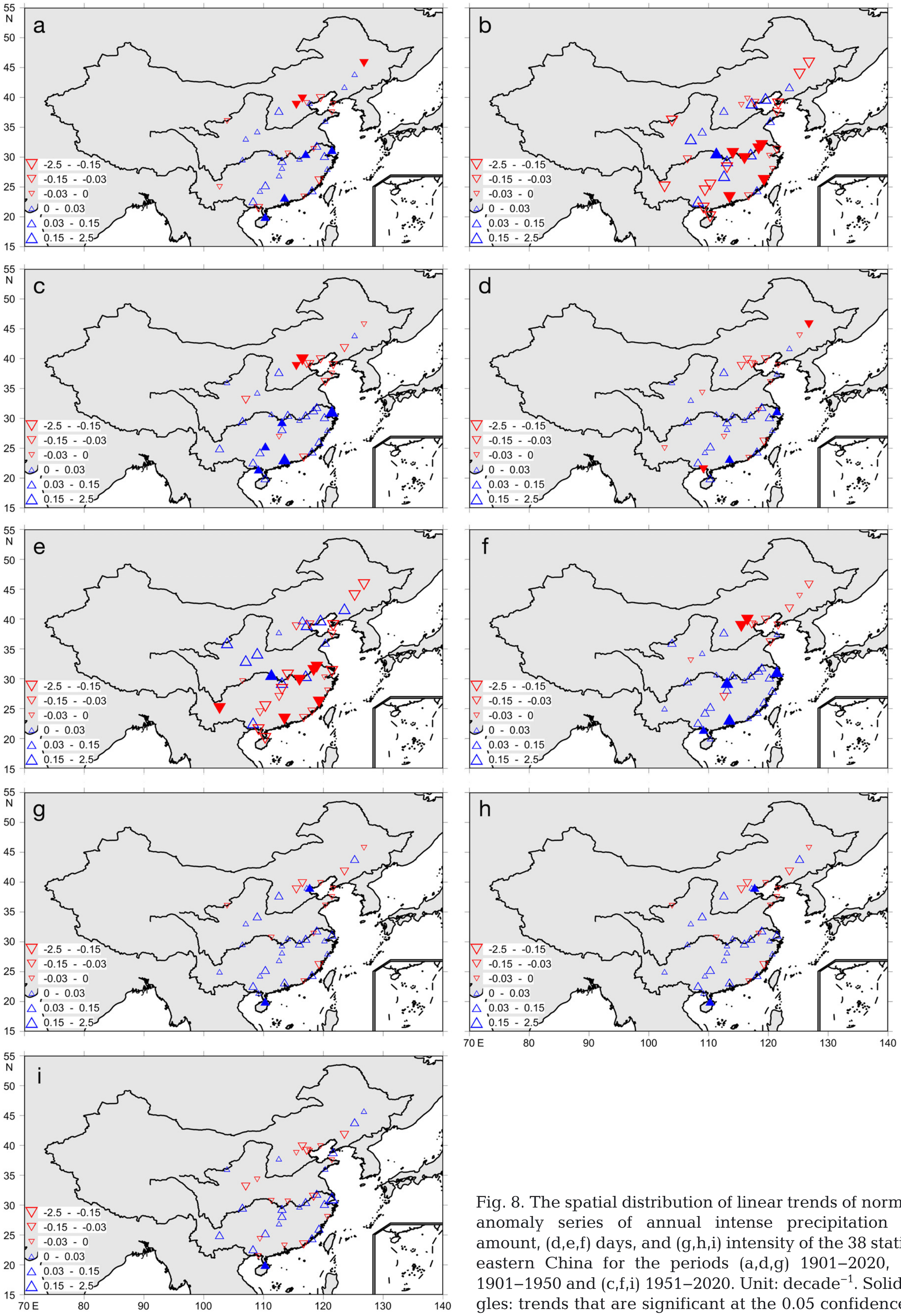

Fig. 8. The spatial distribution of linear trends of normalized anomaly series of annual intense precipitation (a,b,c) amount, (d,e,f) days, and (g,h,i) intensity of the 38 stations in eastern China for the periods (a,d,g) 1901–2020, (b,e,h) 1901–1950 and (c,f,i) 1951–2020. Unit: decade$^{-1}$. Solid triangles: trends that are significant at the 0.05 confidence level

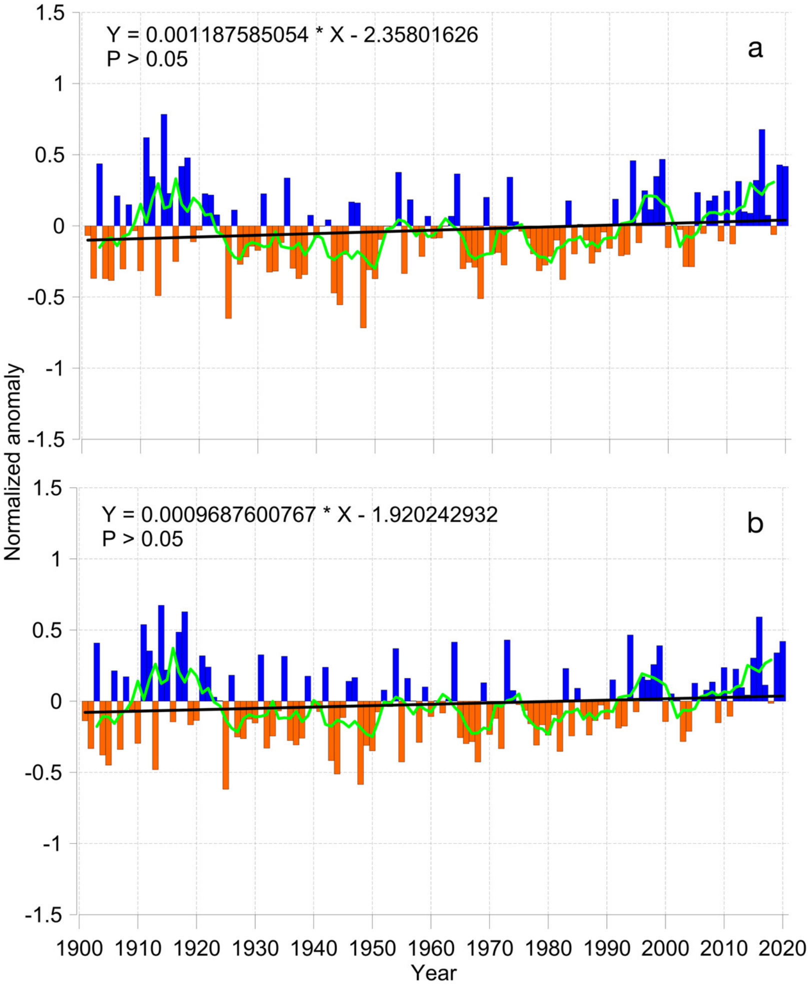

Fig. 9. Same as Fig. 2, but for annual (a) amount and (b) days of rainstorms

cantly. Most stations in the southeast coast and the southwestern region also decreased, but their trends were not significant. In total, only about one-third (13) of the stations showed increasing trends. During this period, the spatial patterns of the changes in RX3day and RX5day approximated that of RX1day (Fig. 11).

From 1901 to 2020, annual CWD at 6 stations in the southeast coastal region of China, as well as the Wuhan and Baoding stations, increased non-significantly, and it decreased rapidly and significantly at the stations around the Bohai Sea. The change rates at most stations in the other regions were generally less than 0.03 decade$^{-1}$ and not significant. From 1901 to 1950, the stations in the southeast coastal region and the middle and lower reaches of the Yangtze River did not have obvious increasing or decreasing changes. Most stations in the southwest region recorded a slight decrease. Stations in the eastern part of Northwest China and western North China recorded an increase, while CWD in Northeast China and the Bohai Sea Rim was generally reduced, but these trends were not significant (Fig. 11).

## 4. DISCUSSION

This paper examines the change in mean and extreme precipitation indices during the past 120 yr, and shows that they all tended to increase except for wet days and CWD. These findings are mostly consistent with previous research of global changes (Westra et al. 2013, O'Gorman 2015, Donat et al. 2016, IPCC 2021, Sun et al. 2021). However, one of the important findings of this study is that the precipitation and extreme precipitation indices were all significantly higher in the early 20th century, and the phenomenon of precipitation extremity (more extreme intense precipitation events) did not occur in the first half of the 20th century, but did occur in the later half of the 20th century and the first 2 decades of the 21st. Donat et al. (2013) also found that precipitation amount and intensity was larger in Europe, North America, and other regions in the early than in the mid-20th century using 100 yr daily precipitation data. However, this phenomenon was not observed in India, which is located in the South Asian monsoon region (Sen Roy & Balling 2009).

These findings may indicate that the changes in extreme precipitation are inconsistent throughout space and time. The spatial and temporal consistency of extreme precipitation is weaker than that of temperature, which has consistently increased over the whole of Asia and most regions of China during the past century (e.g. Sun et al. 2019). Compared to the large-scale temperature changes, it is noticeable that the change trends of temperature and extreme precipitation were asynchronous, despite the fact that both have experienced increasing trends since the early 1930s. The big regional differences and the overall weak trends in precipitation indices shown in this study imply that the observed changes in precipitation extremes over the past more than 100 yr may not have been completely driven by global tempera-

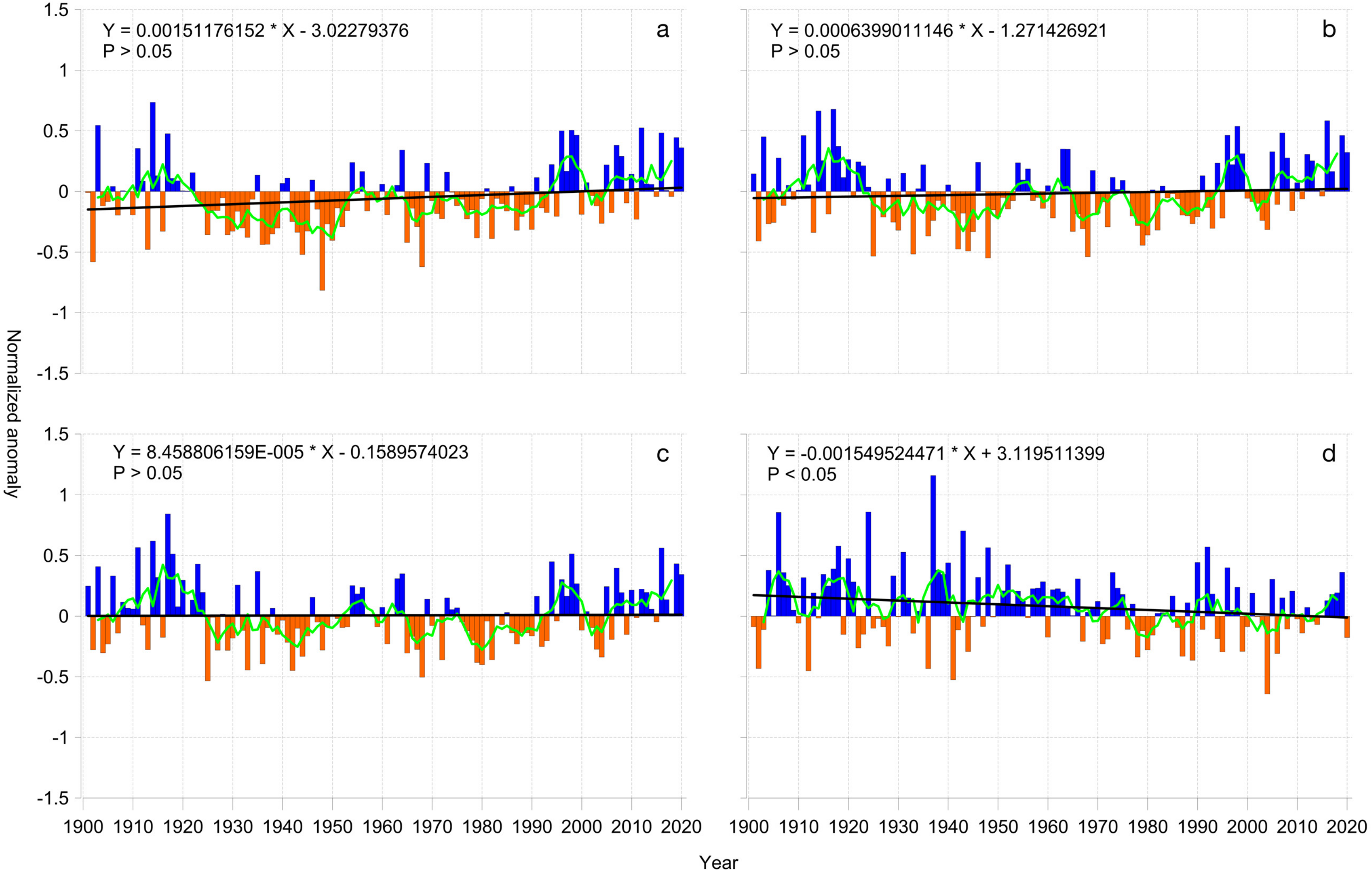

Fig. 10. Same as Fig. 2, but for annual maximum precipitation in (a) 1 day (RX1day), (b) 3 consecutive days (RX3day), (c) 5 consecutive days (RX5day), and (d) consecutive wet days (CWD)

ture change, although the anthropogenic signal may be stronger if the aerosol influence is excluded (IPCC 2021, Sun et al. 2022).

An interesting phenomenon of extreme precipitation change at the 38 stations in eastern China is that all the extreme precipitation indices showed a downward trend before 1951, and a significant upward trend afterwards. These opposing trends are the main reason why the 120 yr upward trends in extreme indices are not so evident. For a long time, studies did not find any significant change in total and extreme precipitation since the 1950s in mainland China and

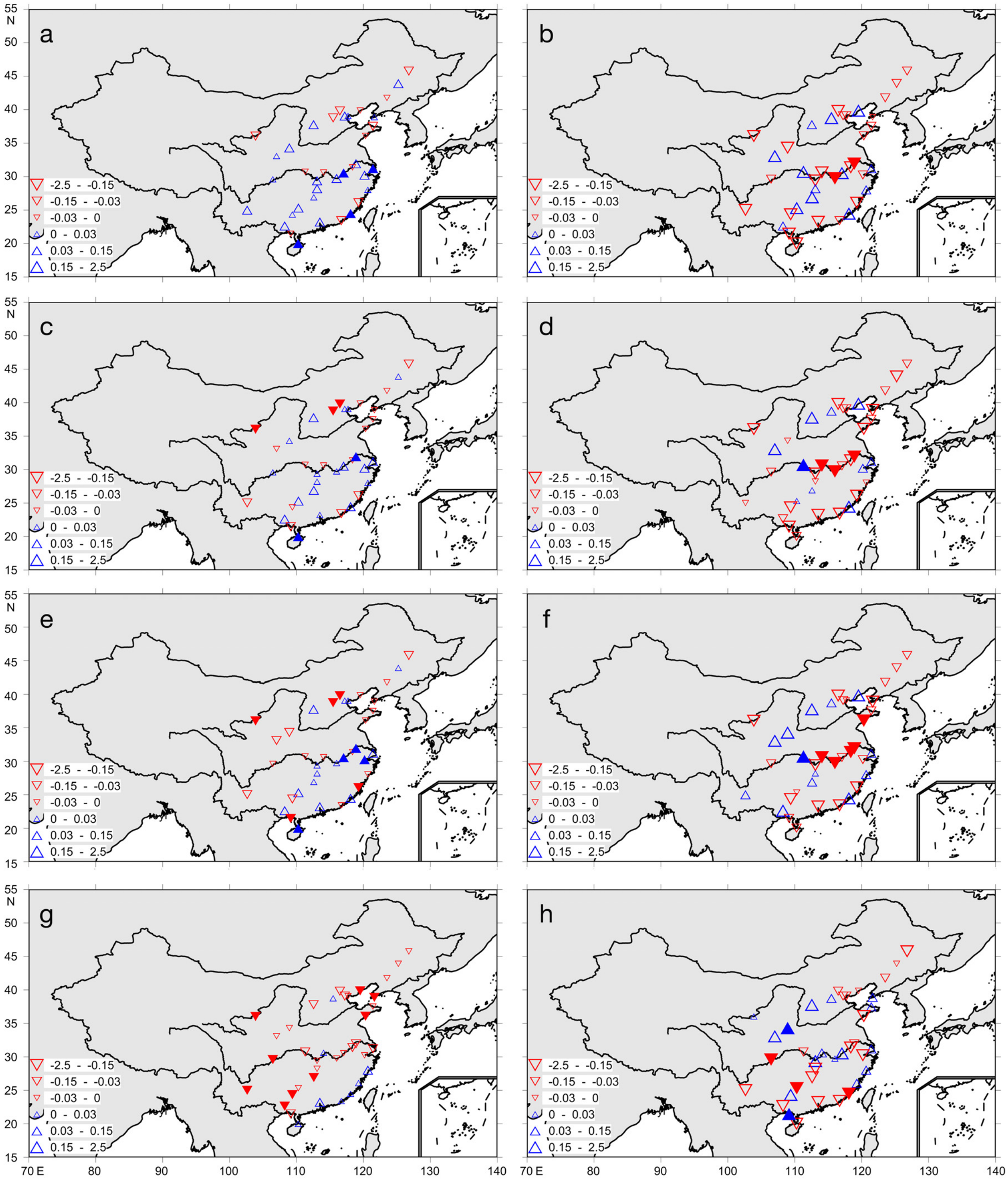

Fig. 11. The spatial distribution of linear trends of normalized anomaly series of annual maximum precipitation in (a,b) 1 day (RX1day), (c,d) 3 consecutive days (RX3day), (e,f) 5 consecutive days (RX5day), and (g,h) consecutive wet days (CWD) of the 38 stations for the periods (a,c,e,g) 1901–2020 and (b,d,f,h) 1901–1950. Unit: decade$^{-1}$. Solid triangles: trends that are significant at the 0.05 confidence level

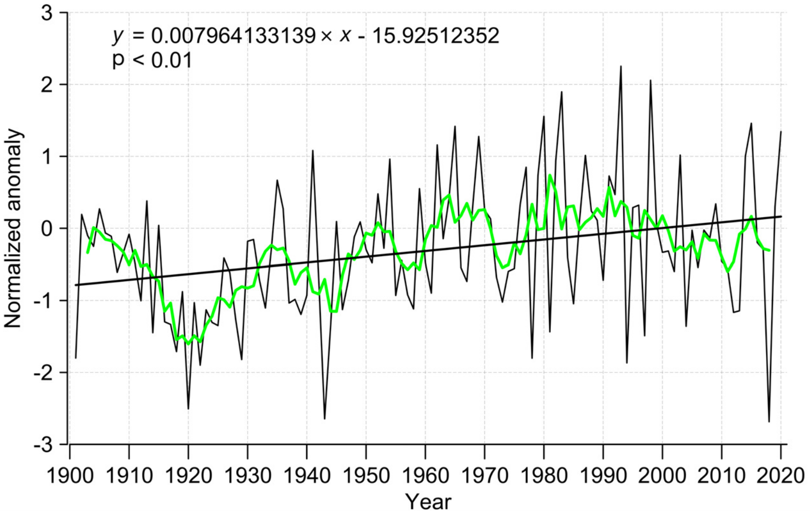

Fig. 12. The annual East Asian summer monsoon index during the period 1901–2020 (black curve). Green curve: 5 yr moving average; black bold straight line: linear trend. Data from Huang & Zhao (2019)

the eastern China monsoon region (e.g. Ren et al. 2000, 2005, Zhai et al. 2005). However, more or less significant increases in precipitation and intense precipitation events in eastern China have been observed over the last decade (Ren et al. 2015, Zhang et al. 2020), due to the abnormally high summer precipitation after 2015 (Ren et al. 2023 in this Special). The significant increase in extreme precipitation at the 38 stations in eastern China since 1951 is consistent with the results of recent studies (e.g. Zhai et al. 2005, 2007, Ren et al. 2015, IPCC 2021). Some studies have attributed the general upward trends in precipitation and extreme precipitation events in mid to high latitude regions to anthropogenic global climate warming (e.g. Zhang et al. 2007, 2013, Sun et al. 2022).

However, the observation that annual extreme precipitation experienced a decrease in the first half of the 20th century may indicate that the recent restorative increase in total and extreme precipitation was also a manifestation of multi-decadal to centenary scale natural climate variability. It may have been related to the long-term variation in the East Asian summer monsoon. The East Asian summer monsoon index (Huang & Zhao 2019) did not experience significant changes during the periods 1951–2020 and 1901–1950 (Fig. 12). However, it increased significantly from the early 1920s to the late 1970s (Fig. 12), when the NAs of most extreme precipitation indices in the study region were generally negative. In contrast, there were correspondences between the decreasing East Asian summer monsoon index and positive trends of extreme precipitation indices during the 1900s to 1920s and the 1980s to 2010s. Therefore, it is possible that the changes in mean and extreme precipitation shown in this study may have been influenced by both human activity and multi-decadal scale natural climate variability.

One of the main uncertainties in this study is the possible influence of urbanization on the long-term daily precipitation data series. Studies have shown that urbanization leads to a reduction in light precipitation and an increase in short-duration intense precipitation at the urban stations of the national observational networks (Li et al. 2011, Liang & Ding 2017, Yang et al. 2017, 2021, Tysa & Ren 2022, Yu et al. 2022). Most of the observation stations used in this study are located in or near urban areas, and this may be an influencing factor for the increasing intense precipitation and decreasing precipitation days in the last decades. If urban expansion has exerted an influence on extreme precipitation records, then the urbanization effect has to be regarded as a systematic bias of the historical observational data that needs to be removed before any studies of regional and global climate change detection and attribution can be conducted (Ren et al. 2016).

It is also worth noting that, because the precipitation records observed from the agency 'China Customs' before 1932 applied units of inches and the recording accuracy was set to 0.01 inches (about 0.254 mm), daily precipitation of less than 0.127 mm was discarded as 0. Consequently, the analysis of wet days and their trends could be affected to a certain extent. We used 1.0 mm as the threshold for wet days in this study, and the threshold of the precipitation data with inches as a unit had been set to 0.04 inches (about 1.016 mm), which is slightly higher. Although it is better to use 1.0 mm rather than 0.1 mm as a threshold for wet days, there is still a tiny probability of recording fewer wet days and a greater daily precipitation intensity for the observations before 1932. However, the unit transformation would not substantially affect the analysis of the long-term extreme precipitation trends.

The data for observations made before 1951 was obtained from digitized sources, and differs in spatial and temporal distribution from those made since 1951. Though we excluded all data with obviously inconsistent observational sites, the slight differences in the distribution of data may sometimes produce inhomogeneities in the regional average series of the precipitation indices. We used a 5 yr sliding *t*-test to detect possible breakpoints in amount, frequency, and intensity of the precipitation series from the 38 stations used, as shown in Fig. 13. In general, there was no concentration of breakpoints in the 3 series. The number of stations with breakpoints in each year was less than 5, and there were obviously fewer before 1951 than after 1970. Therefore, there are reasons to believe that the main conclusion of this article will not be fundamentally altered by the minor problems of data inhomogeneity. Of course, data homogenization should be carried out in the future to remove the discontinuous points, though this is a big challenge due to the sparseness of observations for the early 20th century.

Under the East Asian monsoon climate, changes and variability in extreme precipitation are affected by multiple drivers including anthropogenic global warming, ocean–atmosphere variability modes, and the large-scale atmospheric circulation abnormality. Although long-term trends in extreme precipitation over the whole time period were undetectable, the trends after 1950 were obvious, and the decadal to multi-decadal variabilities were marked. The causes and mechanisms of the recent trends and the variabilities in the annual total and extreme precipitation need to be investigated in combination with the usage of reanalysis data and numerical modeling.

## 5. CONCLUSIONS

Based on the daily precipitation dataset for the past 120 yr at 38 stations in eastern China, the characteristics of the spatial and temporal changes in precipitation, wet days, precipitation intensity, and various extreme precipitation indices from 1901 to 2020 have been analyzed. The main findings are as follows.

(1) From 1901 to 2020, wet days and CWD decreased. Annual precipitation and extreme precipitation increased, but only the trend in intense precip-

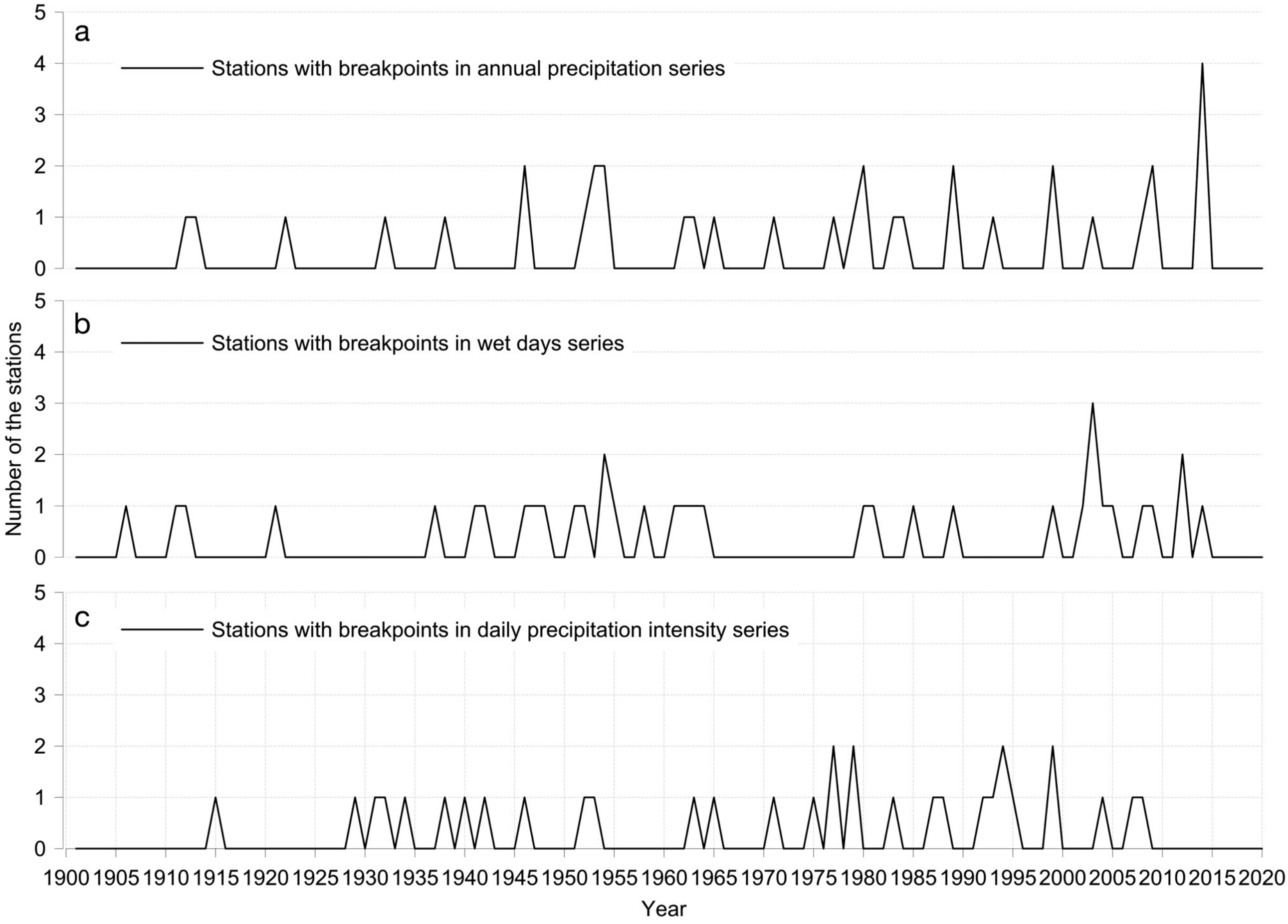

Fig. 13. Variation in the number of stations with discontinuities in the time series of (a) annual precipitation, (b) wet days, and (c) precipitation intensity at the 38 stations used from 1901 to 2020

itation intensity was significant. Precipitation, wet days, precipitation intensity, and extreme precipitation indices all showed obvious periodic variabilities. In general, quasi-periodicals of about 15 to 20 yr or longer were detected in precipitation and wet days, while precipitation intensity and extreme precipitation indices showed characteristics of first decreasing but then reversing after 1951

(2) From 1901 to 1950, CWD increased slightly, but all the remaining precipitation indices decreased. The decreasing trend of extreme precipitation indices such as intense precipitation, rainstorm precipitation, and maximum precipitation in 1 day, 3 consecutive days, and 5 consecutive days were significant at the 0.05 confidence level. During the period of 1951 to 2020, however, precipitation intensity and all extreme precipitation indices increased significantly, except for wet days and CWD, which showed a decreasing trend

(3) From 1901 to 2020, the precipitation and extreme precipitation indices decreased in most parts of northern China, while they increased consistently in the southern region. The spatial pattern over the period 1951–2020 was similar to that of the whole period, but the changes in 1901–1950 were very different. Precipitation and most of the extreme precipitation indices increased in North China and the eastern part of Northwest China, but generally decreased in the Yangtze River Basin and the southeast coastal areas

Overall, several extreme precipitation indices tended to decrease in the first half of the 20th century, and the opposite trends were visible after 1951. There were few significant trends in precipitation extremes at the 38 stations in eastern China over the past 120 yr.

*Acknowledgements*. This work was supported by the Ministry of Science and Technology (MOST) National Key R&D Program (No. 2018YFA0605603), China Meteorological Administration Innovation and Development Project (No. CXFZ2022J050), and China Meteorological Administration Youth Innovation Team 'High-Value Climate Change Data Product Development and Application Services' (No. CMA2023QN08).

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*Geesthacht, Germany*
*Reviewed by: 3 anonymous referees*

*Submitted: September 14, 2022*
*Accepted: May 24, 2023*
*Proofs received from author(s): August 15, 2023*