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Change in precipitation over the Asian continent from 1901–2016 based on a new multi-source dataset

Y. J. Zhan[1,2,3,4], G. Y. Ren[3,5,*], S. Yang[4]

[1]Chinese Academy of Meteorological Sciences, China Meteorological Administration (CMA), Beijing 100081, PR China
[2]University of Chinese Academy of Sciences, Beijing 100049, PR China
[3]Department of Atmospheric Science, School of Environmental Studies, China University of Geosciences, Wuhan 430074, PR China
[4]National Meteorological Information Center, China Meteorological Administration, Beijing 100081, PR China
[5]Laboratory for Climate Studies, National Climate Center, China Meteorological Administration, Beijing 100081, PR China

ABSTRACT: Asia experiences great regional differences in climatic variations, especially precipitation. Examining changes in precipitation will help us understand large-scale hydro-cycle processes against the background of global climate change. We used a new multi-source dataset of historical global land precipitation records developed by the China Meteorological Administration to analyze long-term change in annual and seasonal precipitation in Asia during 1901–2016. To solve the problem of inhomogeneity, the Russian Bias-corrected Monthly Precipitation dataset was also used for Russia. The normalized precipitation anomaly (NPA) was used to analyze spatial and temporal precipitation trend patterns. Regional average time series for the continent and its 6 subregions were obtained by an area-weighted averaging method. Results show that: (1) regional average annual precipitation increased significantly during this period, and the upward trend was mainly related to a shift in cold areas during the mid-20th century; (2) regional average spring and autumn precipitation amounts had similar characteristics to those of the long-term changes in annual precipitation, and winter precipitation increased slightly for the entire period, with a significant jump occurring from 1945–1955; (3) North and Central Asia experienced a significant upward trend in precipitation for every season except summer during 1901–2016, while South Asia witnessed a significant downward trend in winter during the same period; (4) during 1901–2016, the proportion of summer precipitation declined uniformly in most parts of the continent, with a significant decline in cold areas. Although there are still uncertainties related to the observational data, the analysis results will help in understanding the general pattern of precipitation variation and the possible response of these regions to global climate change.

KEY WORDS: Asia · North Asia · South Asia · Climate change · Precipitation · Trend

1. INTRODUCTION

As a major part of Eurasia, Asia is the largest and most populated continent in the world. Asia also features highly complex geomorphological and climatic characteristics known worldwide, including the Qinghai-Tibetan Plateau, which is often called the 'Third Pole' of the earth (Sharma et al. 2016). The Arctic, Indian, and Pacific Oceans surround Asia, leading to the strongest sea–land thermal contrasts in the world and the characteristic Asian monsoon climate. The vast land area, the highest plateau and mountains, and the heterogeneous climate make Asia an ideal continent for investigating large-scale climatology and climate change.

Asia has strong horizontal and vertical gradients in precipitation (Yanai & Li 1994, Qiu 2008, Yao et al. 2012, Sharma et al. 2016). As a result, the distribution of water resources is so uneven that flooding and drought frequently appear simultaneously. The con-

*Corresponding author: guoyoo@cma.gov.cn

sequences of this effect also make the Asian continent susceptible to climatic change and the effects of human activities. The long-term variation in precipitation plays a vital and significant role in local and regional hydrology, agriculture, ecology, industry, and hydroelectric power generation, features that all rely on the timely and sufficient delivery of water in major river systems. It is also a key indicator in monitoring and detection of large-scale climate change.

It is well documented that the global mean surface temperature has risen significantly during the past century (e.g. Jones et al. 2012, Stocker et al. 2013, Sun et al. 2017). Climate warming is expected to cause change in atmospheric moisture and the intensity and distribution of precipitation at both regional and global scales. Theoretically, the higher global temperature facilitates evaporation, adds more moisture to the atmosphere, and finally causes an increase in precipitation (Trenberth et al. 2003). However, change in the components of the water cycle such as atmospheric vapor content can feedback to the change in temperature. An important issue in the science of climate change is whether or not the total annual precipitation in spatial scales larger than a sub-continent has changed over the past 100 yr in response to the observed global warming. Research related to change in precipitation on the Asian continent can therefore significantly contribute to the understanding of global and regional climate change, and facilitate studies of detection and attribution of climate change and of the response of the global water cycle to the increase in surface temperature. It can also provide useful scientific information for Asian countries in support of attempts to better adapt to climate change in the sectors of agriculture, water sources, ecology, environment, and human society.

The characteristics of global and regional precipitation change are more complex than those of surface air temperature, however. Recent research based on various datasets has found that precipitation experienced an increasing trend at mid- and high latitudes of the Northern Hemisphere, but decreased in subtropical regions, especially the Mediterranean region, during the past century (Dore 2005, Zhang et al. 2007, Trenberth 2011, Donat et al. 2013). Because of the poor data coverage in many areas of the world, especially in most parts of Africa, the estimates of global and continental precipitation change face many uncertainties (Stocker et al. 2013, Wan et al. 2013). Gridded precipitation products based on remote sensing data that are frequently used in studies covering global scales or in the Northern Hemisphere have a relatively short time period of records; the instrumental records are often unable to capture large and abrupt variations in precipitation over short distances because of their coarse resolution and orographic effects in the high-elevation areas (Dahri et al. 2016).

The International Panel on Climate Change (Solomon et al. 2007, Stocker et al. 2013) assessed the long-term trends of precipitation in Asia, and reported that both North and Central Asia showed an increasing precipitation trend during the past century, but the precipitation of South Asia decreased during the same time period. Few publications on change in precipitation for Asia as a whole are available, although many studies have analyzed the decadal variability in precipitation and related mechanisms for regions such as East and South Asia. Choi et al. (2009) found that most countries in the Asian-Pacific region had experienced an insignificant increase in summer precipitation, but their data generally covered the coastal areas of Asia, western Pacific, and Australia, and did not examine the change in precipitation over more than 100 yr. The subcontinental region of mainland China has received much attention with regard to the recent change in precipitation because good data coverage is readily available (e.g. Zhang 1993, Liu et al. 2005, Ren et al. 2005, 2012, 2015, Zhai et al. 2005, Wen et al. 2006, Zhou et al. 2009). Researchers have found that the region-averaged annual precipitation percent anomalies or the annual normalized precipitation anomaly (NPA) experienced a weak upward trend in mainland China over the past half century, but almost no long-term change was detectable for the past century or more (Ding & Ren 2008, Ren et al. 2015, 2016). In West, Central, and North Asia, research covering larger-scale regions using surface observational data are relatively scarce. Tanarhte et al. (2012) found that the annual precipitation rate near the Persian Gulf increased by up to 2% decade^{-1} over the period 1961–2000, but decreased in the northern part of West Asia after 1987. The winter and spring precipitation rate declined at most stations in Iran during 1966–2005 (Tabari & Talaee 2011). Western Asia experienced a decrease in precipitation, which is actually part of a remarkable drying trend witnessed in the entire Mediterranean region during the last 100 yr (Stocker et al. 2013). During 1950–2000, most areas in Central Asia experienced increasing precipitation rates except in western Kazakhstan (Xu et al. 2015). In North Asia, Gruza et al. (1999) found that the annual precipitation rate generally decreased over the period 1951–1995, while the analysis by Groisman et al. (2013) showed that the late 20th century precipitation rate was larger than that of the early 20th century but both trends were insignificant. Previous work can help understand the large-scale change in precipitation that occurred on the Asian continent. However, some deficiencies exist in revealing the detailed spatial patterns of long-term change in precipitation. Restricted by the quality of the data and the length of records, previous research mostly focused on the change in precipitation over a relatively short period starting after 1950 and ending before 2010, and on a relatively small spatial domain. Continental-scale studies related to long-term precipitation change, or the analysis of the whole of Asia, are lacking.

In this paper, a new monthly dataset was adopted to analyze the change in precipitation over the Asian continent from 1901–2016. We mainly focused on the long-term trends in precipitation on the continent, with special emphasis on the spatiotemporal characteristics of annual and seasonal precipitation trends for various periods and spatial scales.

2. DATA AND METHODS

The source of data for monthly precipitation indices used for the current analysis was the historic global precipitation dataset of the China Meteorological Administration (CMA) V1.1 (CGP; Yang et al. 2016) and the Russian Bias-corrected Monthly Precipitation (RBMP; Bogdanova et al. 2007) dataset of the Voeikov Main Geophysical Observatory (VMGO). The sources of the CGP consist of 4 original global datasets: GHCN-monthly Version 2 (GHCN, Peterson & Vose 1997), European Climate Assessment & Dataset (ECA, Klein Tank et al. 2002), Historical Instrumental Climatological Surface Time Series Of The Greater Alpine Region (HISTALP, Auer et al. 2007), and US Historical Climatology Network Version 1.1 (USHCN, Boden et al. 1990). In addition, some monthly precipitation data were also obtained from 7 national datasets: the Canadian national climate and weather data archive, the Australian high-quality climate change dataset, the Korean exchange dataset, the Vietnamese exchange dataset, the Chinese datasets of the CMA, and the Russian and Japanese meteorological agencies.

The records of GHCN served as the basic data source for building the CGP dataset. When a station was included in both GHCN and other datasets, the station was identified by analyzing the merits of the GHCN and other datasets by comparing the difference and length of monthly records. If the difference was less than 5%, then the stations with longer records were chosen as the data source, and the shorter data series were used to supplement the source records; if the difference was larger than 5%, the data series with the longest records were applied (Yang et al. 2016). The CGP monthly precipitation data has been quality controlled by 2 procedures: detection of abnormal values and a space consistency check (Yang et al. 2016), which is similar to those processes of the GHCN. The CGP dataset contains data from a total of 31 456 observational stations from all over the world, which includes more than half of the stations of the GHCN. Compared to the GHCN dataset, the CGP dataset has a higher station density and a more complete record in mainland China and its neighboring regions (Yang et al. 2016). In mainland China, monthly precipitation records from the national stations of more than 2400 sites were originally used in the new dataset, but we only applied the data of the 800 national reference climate stations and national basic meteorological stations in this work.

However, exploring precipitation changes in Asia is still hampered by a deficiency of the CGP dataset. The monthly precipitation records have not been homogenized except for mainland China. In the region of the former Soviet Union, there were 2 obvious changes in precipitation observational procedure, taking place 1948–1953 and 1966–1967 (Groisman et al. 1991), which resulted in significant inhomogeneities in the observational records. To solve the problem, the RBMP datasets were used in Russia, which encompasses about 76% of the areas belonging to the former Soviet Union. The monthly precipitation data were corrected by using a regression model which considered all known rain gauge measurement biases and metadata about location and environmental conditions over Russia (Bogdanova et al. 2007). There are 457 Russian stations in the RBMP dataset, and these stations can all be found in CGP. However, these stations only contain precipitation data from 1936–2010. To establish the long-term time series of the corrected precipitation data, we blended the CGP data and RBMP data by the methods described below.

If a CGP dataset station was located in Russia, but not included in the RBMP dataset, the station was discarded. In the remaining stations of Russia, the 1936–2010 precipitation data in the RBMP dataset were used. Because the precipitation could be regarded as homogeneous in the period 1901–1947 and 1967–2016, the 1901–1935 and 2011–2016 data in the CGP dataset could be bias-corrected by simply using the average differences between the RBMP and CGP data for the period 1936–1947 and 1967–2010, respectively. For stations with no precipitation record of the same time in the 2 periods, the CGP data were regarded as missing records, and only the RBMP data of 1936–2010 were used (red dots in Fig. 1a). After this step, the issue of the data inhomogeneities in most study areas was largely solved. However, the data were not corrected in the remaining 24% of areas of the former Soviet Union. Some records from Central Asia and Mongolia also had the problem of inhomogeneities; strong winds during the cold season may have resulted in lower catch rates of the gauges before the Tretyakov rain gauges were applied in these regions (Groisman et al. 1991, Zhang et al. 2004).

Stations were further selected for use in this analysis only if 2 conditions were met simultaneously: the World Meteorological Organization (WMO) Station region code was 2, and the stations had to be located within the rectangular region in the range of 40° E to 165° W, 5° to 80° N. In total, 6937 stations were located in this region. The Philippines and Indonesia were not included in the study region because they are considered part of the Oceania sub-region by the WMO, and they are not located on the Eurasian continent. To reduce the influence of missing data, the following steps were applied to select stations and to process the data.

(1) We selected stations that reported at least 10 valid records over all 12 mo of a year during the base period 1961–1990. In this step, a total of 2652 stations were identified (Fig. 1a). These stations were uniformly and densely distributed in the study region except West Asia. The average monthly precipitation in the base period was calculated for every station selected in the previous stage.

(2) For every year with ≥10 valid months of records, the missing monthly precipitation records were filled by the average monthly precipitation obtained in Step 1.

(3) A station had to have records for ≥10 years in 1961–1990, 5 years in 1901–1950, and 5 years in 1991–2016, in order to minimize the impact of missing data in the base period and in the end periods on the analysis results.

(4) A total of 1316 stations were chosen for use in this work (Fig. 1e). These stations were relatively uniformly and densely distributed throughout India, eastern China, Japan, and Thailand, although the coverage was not very good for West Asia, the Arctic region, and western China.

To reduce the biases caused by uneven station density or temporal variations in data coverage, we used the region-average method (Jones & Moberg 2003). Each station was assigned to a regular 5° × 5° latitude–longitude grid box. Each of the total 249 grid boxes of 2652 stations and 220 grid boxes of 1316 stations contained at least 1 station. The temporal variations in the count of grid boxes with stations in the 6 sub-regions are shown in Fig. 1b,f. The total number of grid boxes of 1316 stations in all regions gradually increased before 1936, and increased to an average of more than 180 grid boxes with stations in 1936. After 1940, the number of grid boxes with stations was more than 200 continuously until 2000, but this number fell after 2000. North Asia had the most grid boxes in almost every year, and the number of grid boxes there increased rapidly in 1936 while the number in other regions increased slowly (Fig. 1b,f). The temporal variation of the 249 grid boxes of 2652 stations was similar (Fig. 1b).

The number of stations employed in every grid box is presented in Fig. 1c,g. For the dataset of 1316 stations (Fig. 1g) some grid boxes in West Asia and West China have no stations. There are fewer than 10 stations in Central Asia and Russia. The regions with the best coverage for stations and grid boxes were India, East China, and Japan. For the dataset of 2652 stations (Fig. 1c), nearly all grid boxes in the study region contain stations. However, the years with valid records in West Asia and West China were less than 60 (Fig. 1d) because most stations in these regions had no valid records prior to 1950. To avoid the inconsistency of the coverage of stations, the 1316 long-record station dataset was used for obtaining regional average precipitation series and the spatial pattern of change during the period 1901–2016 in this paper, and the 2652 stations were used to analyze the spatial pattern of change after 1951. Therefore, the records mostly cover more than 60 yr for grid boxes with data except for 7 grid boxes in West Asia, Southeast Asia, and North Asia, meaning that the gridded values provide relatively good coverage for the study period (Fig. 1h).

Above all, the monthly precipitation data for 1316 stations cover most areas of the Asian continent except for West Asia and West China (mostly classified to Central Asia). The other regions have a sufficient temporal and spatial coverage of valid precipitation data records. The grid boxes covered 95, 96, 94, and 88% of the area of North, East, Southeast, and South Asia, respectively, but only covered 64 and 61% of the area of West and Central Asia.

This paper mainly analyzed the annual and seasonal changes in precipitation trends in Asia. The annual total precipitation is the total precipitation

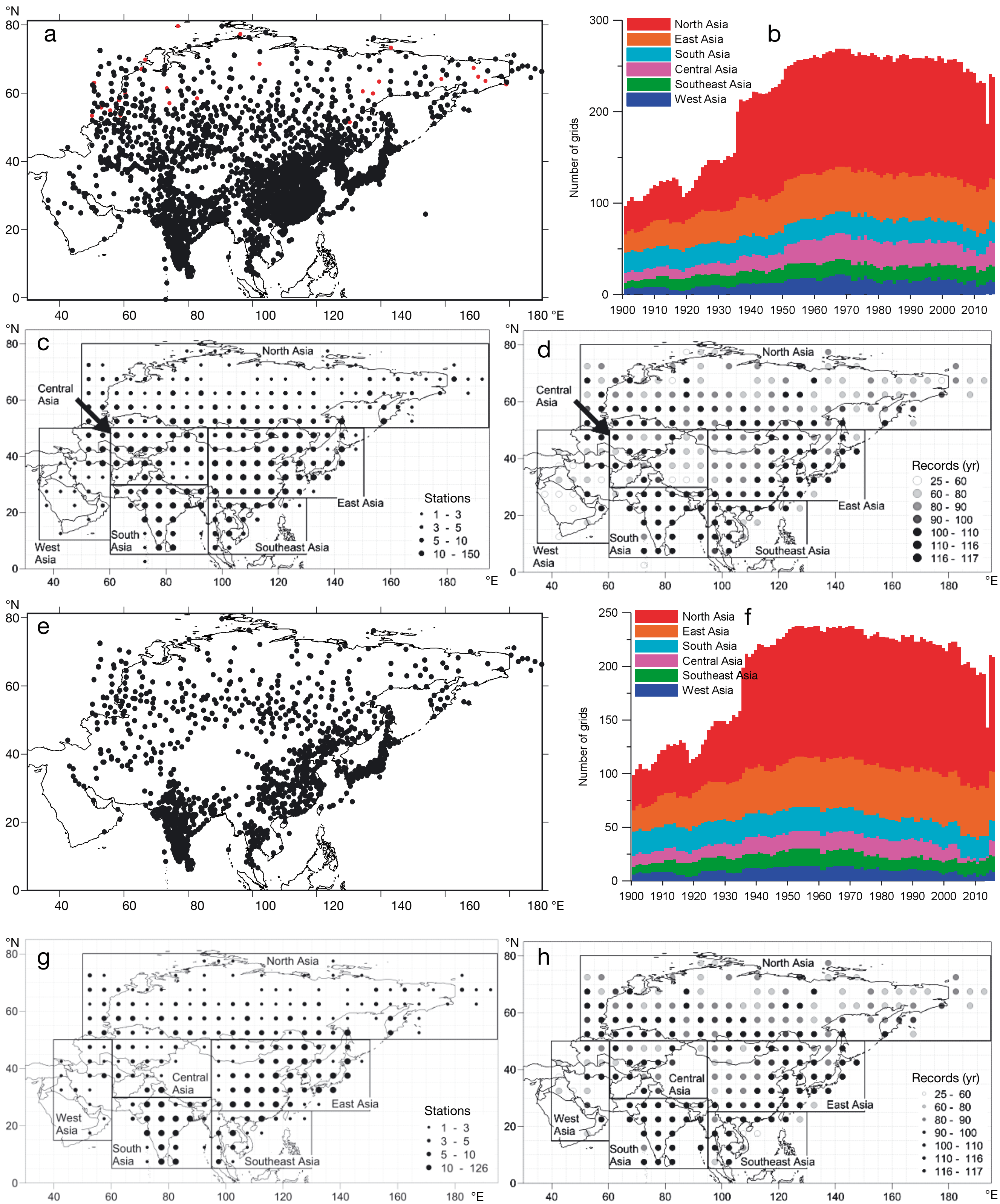

Fig. 1. (a,e) Spatial distribution of precipitation measurement stations in Asia (5–80° N, 40° E–165° W). Red dots in (a) indicate the stations for which RBMP records of 1936–2010 were used. (b,f) Numbers of grid boxes in the 6 sub-regions in 1901–2016; (c,g) number of stations in every grid box, with the bold straight lines showing the boundaries of the 6 sub-regions; (d,h) number of years with valid records in every grid box. (a–d) based on 2652 stations; (e–f) based on 1316 stations

received over 12 mo in any given year (mm). The seasonal total precipitation is the sum of 3 mo of precipitation by season as follows: spring represents March, April, and May (MAM); summer is June, July, and August (JJA); autumn is September, October, and November (SON); and winter is December, January, and February (DJF). The proportion of precipitation in every season is the ratio of seasonal total precipitation to annual total precipitation.

The precipitation indices commonly used included the original value, anomaly, percent anomaly (PA), and normalized precipitation anomaly (NPA). All anomalies are the yearly total precipitation minus the average annual total precipitation in the base period. The PA is the annual anomaly divided by the average annual total precipitation in the base period, while NPA is the annual anomaly divided by the standard deviation of the annual total precipitation in the base period.

Previous research has mainly used original precipitation values or anomalies (absolute indices) to analyze long-term changes in precipitation. However, the same amount of precipitation in different areas does not have the same meaning. For example, while a month with 200 mm of precipitation in New Delhi may be a common occurrence, the same amount of precipitation in Riyadh could be rarely seen over several decades. For large regions with wide discrepancies in the distribution of precipitation, such as the Asian continent, the change in precipitation amount in arid areas can hardly be detected during the regional average computing process if absolute values of original indices or anomalies are used.

To solve this problem, the relative values of precipitation indices should be used to examine the change in precipitation in a large-scale analysis. However, the use of PA can sometimes seriously magnify the gain in precipitation in extremely dry areas when computing regional averages. For example, Bahrain Station (26.3° N, 50.7° E) only has 0.012 mm of summer mean precipitation during the base period (1961–1990), but its 1992 percent anomaly was as high as +41 570% because the summer witnessed a total rainfall event of 5 mm. Such an abnormally high PA will greatly affect any analysis results of regional averages.

As another relative value index, the NPA also faces a similar problem, but the deviation is not as large. In the former example, the 1992 summer NPA of Bahrain Station was +9.5, which does not create too serious of a problem in the regional average time series. Previous studies also considered NPA as a better indicator to analyze the regional average change (Jones & Hulme 1996, Ren et al. 2015). Therefore, NPA was mainly used in the present analysis to calculate the regional average time series.

The grid area-weighted averaging method was applied to establish the Asian and regional average NPA series (Jones & Moberg 2003). NPA values were calculated based on observational station data, and the grid box values were calculated by averaging all of the station values in each of the grid boxes. Finally, the regional average NPA time series was calculated by area-weighted (using the cosines of the mid-grid latitude as weights) average of all grid box values.

The linear trends of the precipitation index series are the linear regression coefficients between the precipitation and ordinal numbers of time (e.g. $i = 1$, 2, 3, …, 116 for years 1901–2016) obtained by using the least squares method. The 1951–2016 trends, 1981–2016 trends, and the moving linear trends with step lengths of 20, 30, 40, and 50 yr were also calculated to analyze the trend characteristics of varied time periods. In order to calculate the grid trends, the grid boxes had to have at least a 65, 50, or 25 yr record for the 3 periods (1901–2016, 1951–2016, and 1981–2016), respectively; otherwise, the grid boxes were not included in the calculations. The method for calculating moving linear trends was described by Ren et al. (2015). The significance of the linear trends of the NPA series was determined by using a 2-tailed simple *t*-test. In this assessment, a trend was considered to be statistically significant if it was significant at the 95% ($p < 0.05$) level.

To analyze the regional change features of Asian precipitation, the entire region was divided into 6 sub-regions as follows: North Asia (50° E–165° W, 50°–80° N, frigid climate), East Asia (95°–150° E, 25°–50° N, temperate and subtropical monsoon climate), Southeast Asia (95°–130° E, 5°–25° N, tropical monsoon climate), South Asia (60°–95° E, 5°–30° N, tropical monsoon climate), West Asia (35°–60° E, 15°–50° N, tropical and subtropical arid climate), and Central Asia (60°–95° E, 30°–50° N, temperate continental climate) (Fig. 1c). The sub-regions were divided based on a combination of climatic (Kottek et al. 2006), geographical, and political boundaries. Areas within the 6 sub-regions have approximately the same climate types, and the boundaries are located near local geographical boundaries. The average values of the 6 sub-regions were also calculated by the area-weighted averaging method. The sub-regions of West, Central, and East Asia may have the problem of data inhomogeneities in the cold seasons. The problem may be more serious in northern parts of West, Central, and East Asia (NWCEA), which was defined as a rectangular region spanning

50°–110° E, 40°–50° N, due to the generally stronger wind in winter. In order to understand the influence of the possible inhomogeneities on trend analysis, the average values in these sub-regions and the whole of Asia were also examined with the data of the NWCEA region excluded.

3. RESULTS

3.1. Annual NPA change

The spatial distribution and the zonal mean of linear trends of gridded NPA for the periods of 1901–2016, 1951–2016, and 1981–2016 were all examined (Fig. 2). From 1901–2016, the annual total NPA increased significantly in about half of the grid boxes north of latitude 50° N, while it decreased insignificantly in almost every grid box between 20° and 30° N. In other latitudes, the NPA increased in both Central and Southeast Asia, but decreased in the eastern part of China, although these trends were insignificant (Fig. 2a).

The averaged zonal results show that the NPA decreased in the subtropical zone (20°–30° N) and increased less than 0.040 (decade^{-1}) in the tropical (5°–20° N), temperate (30°–50° N), and polar (75°–80° N) zones. The NPA remarkably increased in the frigid climate zone (50°–80° N), and the rate of increase was more than 0.040 (decade^{-1}).

From 1951–2016, the annual NPA also increased in most grid boxes between latitude 50 and 70° N. The NPA decreased in some grid boxes between 20 and 30° N, such as in the Yunnan-Guizhou Plateau and in the Gangetic and Indus plains. In the temperate (30°–50° N) zone, the NPA decreased slightly in most grid boxes east of 100° E, but increased west of 100° E. The zonal average trends were obviously positive because West China experienced a significant increase in precipitation during the period 1951–2016. The zonal averages showed that the annual NPA decreased slightly in the subtropical (20°–30° N) zone and strongly in the polar (70°–80° N) zone. The NPA increased in most grid boxes of the frigid zone (50°–70° N), but the rate of increase of the zonal mean did not exceed 0.10 decade^{-1} (Fig. 2b).

From 1981–2016, the annual NPA still increased in most grid boxes between latitude 50° and 70° N. Like the trends of 1951–2016, the NPA also decreased in some grid boxes between 20° and 30° N such as in the Yunnan-Guizhou Plateau and in the Gangetic and Indus plains. The Indian and Indo-China peninsulas had an increasing NPA in nearly all grid boxes south of 20° N, but the trends were not significant. The NPA increased with trends more than 0.10 decade^{-1} in most grid boxes of Russia, Japan, West China, and Kazakhstan during this period. The zonal averaged NPA obviously increased in most latitudes except for the subtropical (20°–30° N) and polar (75°–80° N) zones (Fig. 2c). Thus, the annual NPA experienced a significant increase in most parts of North Asia, while it tended to decrease in subtropical zones for every temporal scale. The characteristics of zonal change in averaged precipitation were consistent throughout the past century.

The regional average annual NPA time series for the whole of Asia are presented in Fig. 3. The NPA values were negative for most years before 1952. They changed to positive values suddenly around 1953, and remained positive until 1961. After 1961, the NPA exhibited a rising trend with alternating positive and negative values. Overall, the regional average annual NPA increased over the entire period of 1901–2016, with the rate of change being 0.016 (decade^{-1}), which was significant. The NPA time series without the NWCEA region varied in some years, and the linear trend reduced to 0.012 (decade^{-1}), accounting for a ca. 25% reduction of the trend for the whole of Asia. However, the trend without the NWCEA region was still significant ($p < 0.01$), and the characteristics of the change pattern were not much different, implying that the potential inhomogeneities in the data of the region had an influence on the trend estimate of precipitation over the continent, but they may not have substantially changed the overall characteristics of the annual precipitation change in the time period analyzed.

The running linear trends of the regional average NPA are shown in Fig. 4. Most trends that ended before 1950 were negative. In particular, the 30 and 40 yr trends before 1945 were mostly significant. Every trend beginning before 1940 and ending after 1955 was positive, and most of them were also significant. The 20 yr moving trends after the 1950s were characterized by alternatively positive and negative variations, which were all insignificant, with about a 10 yr cycle. The 30, 40, and 50 yr trends increased slightly after 1950, but the trends were all small and insignificant. The sudden increase in the 1940s and 1950s was a major factor related to the increasing running trends for precipitation from 1901–2016. Before the sudden change in the 1940s and 1950s, the precipitation trends in Asia tended to decrease, while afterward they fluctuated with small running trends.

The regional average annual NPA time series in the 6 sub-regions were examined (Fig. 5). The NPA in

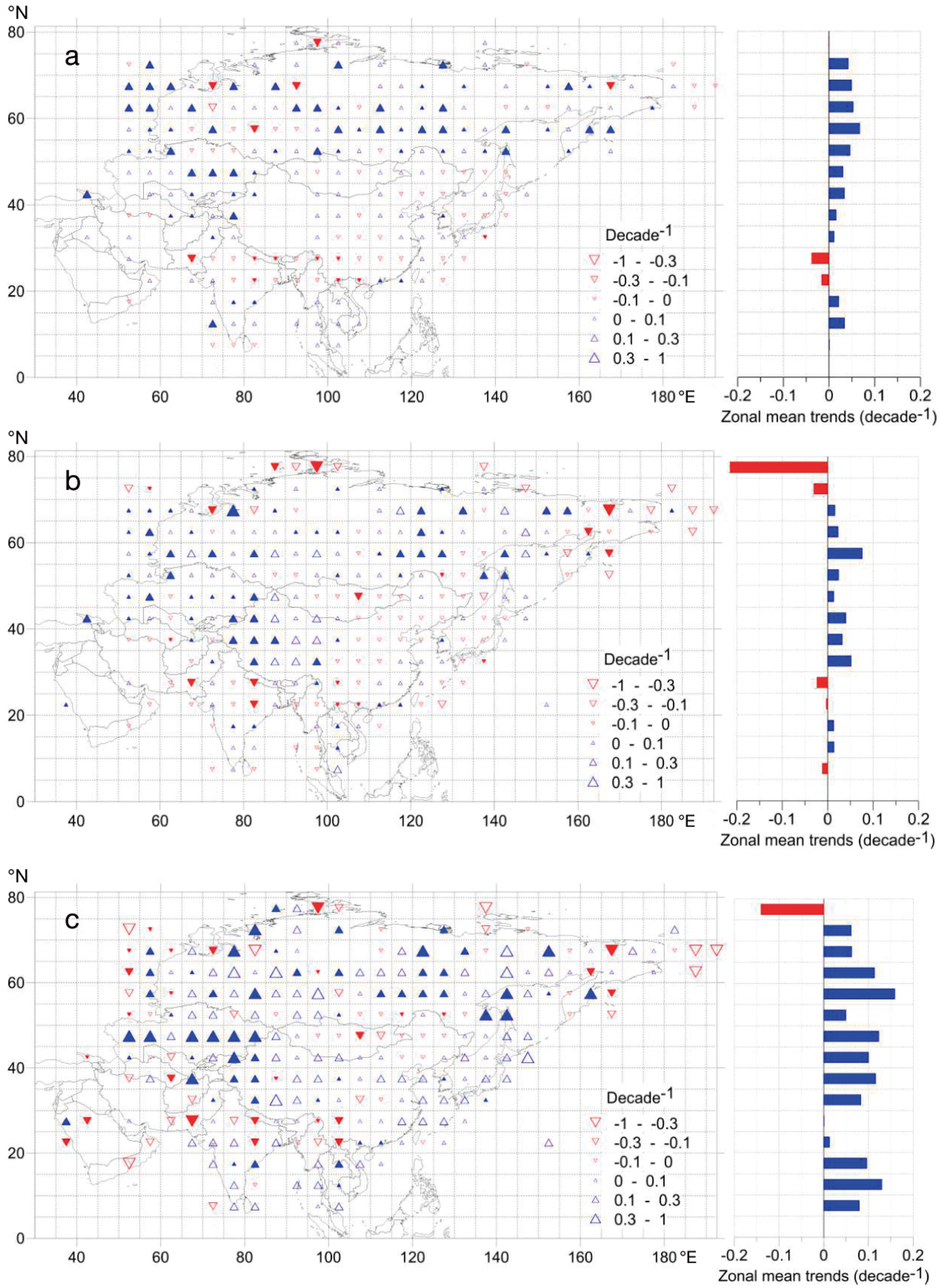

Fig. 2. Spatial distribution and the zonal mean of linear trends of the gridded normalized precipitation anomaly (NPA) for the periods (a) 1901–2016, (b) 1951–2016, and (c) 1981–2016. Data in (a) based on 1316 stations; data in (b) and (c) based on 2652 stations. Red and blue symbols represent negative and positive trends, respectively, and filled symbols represent statistically significant trends

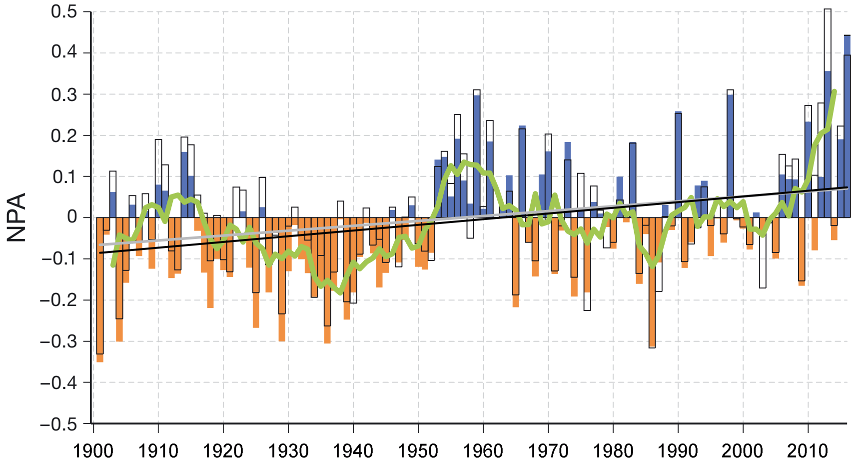

Fig. 3. Regional average normalized precipitation anomaly (NPA) time series in the whole of Asia. Blue and orange bars: positive and negative regional average values of annual NPA, respectively; unfilled portions of the respective bars: regional average values of annual NPA without the northern parts of West Asia, Central Asia, and East Asia (NWCEA region); green line: 5 yr moving average; black and grey lines: linear trends with and without the NWCEA region, respectively

North Asia significantly increased from 1901–2016, especially in the 1930s to 1960s. The change rate was 0.046 (decade^{-1}) for the entire period, about 3 times that of the whole of Asia. The NPA in Central Asia also significantly increased during 1901–2016. A marked decadal increase occurred in the 1950s, and the annual NPA experienced a sudden shift from dry to wet after 2000. Taking out the stations in the NWCEA region, obvious changes appeared in the NPA series of the mid- to high-latitude sub-regions for a few individual years, but the overall linear trends changed little. Specifically, the potential data inhomogeneities of the NWCEA region scarcely affected the NPA series in East Asia, although they may have made the trend slightly smaller in

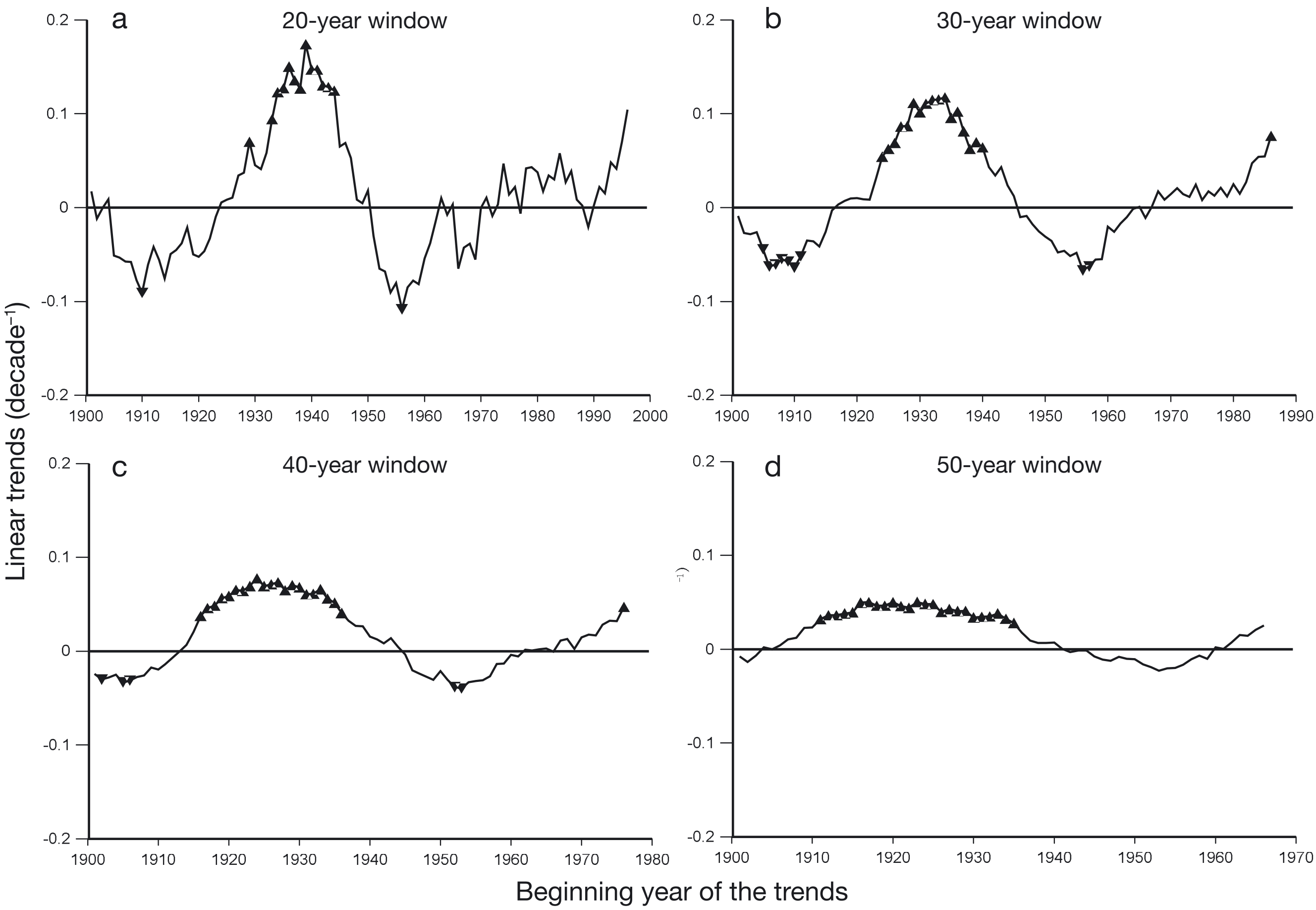

Fig. 4. Annual normalized precipitation anomaly (NPA) running trends for (a) 20 yr, (b) 30 yr, (c) 40 yr, and (d) 50 yr time steps. The solid triangles represent the trends which were significant at the 0.05 confidence level

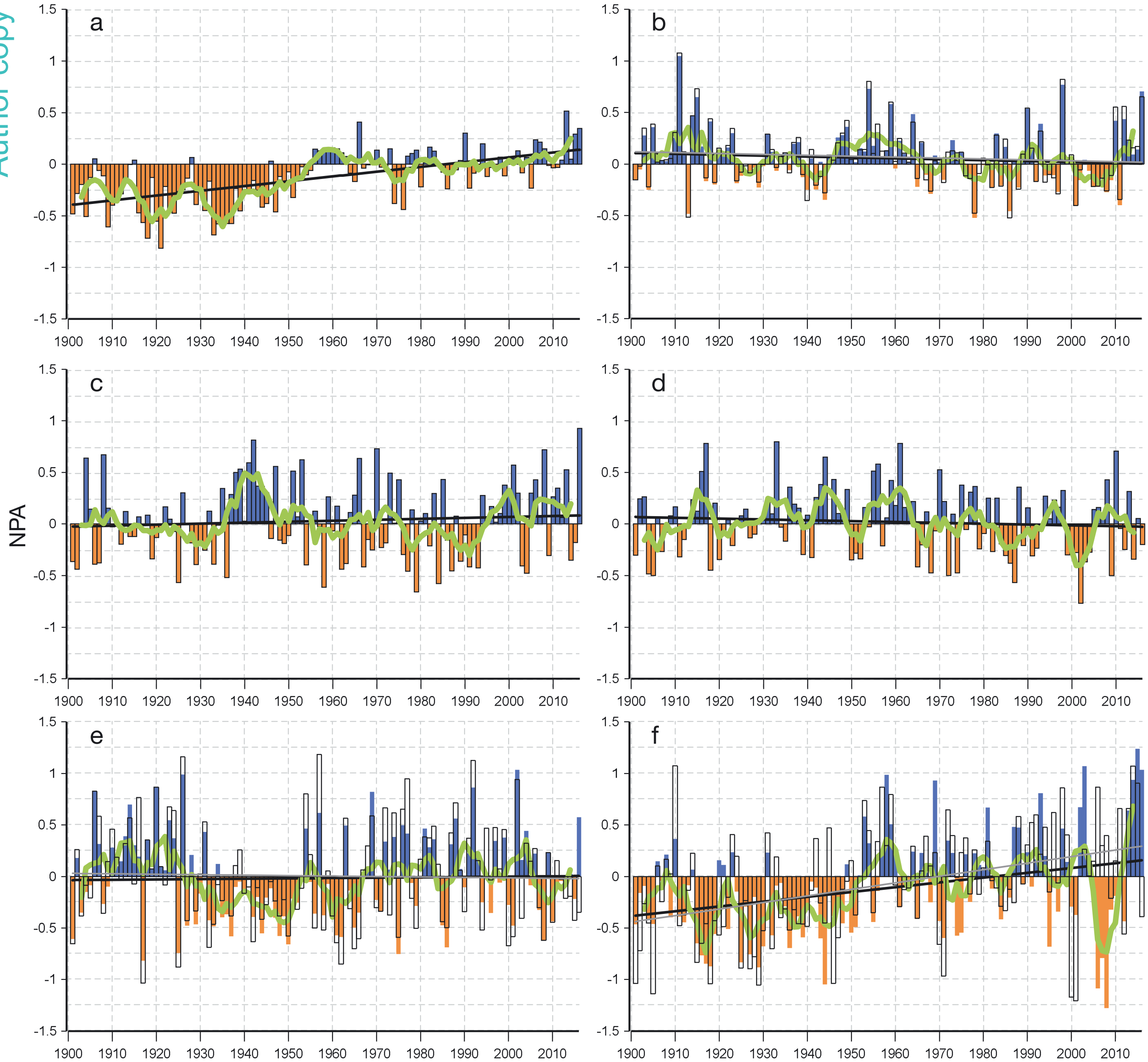

Fig. 5. Regional average annual normalized precipitation anomaly (NPA) time series in (a) North Asia, (b) East Asia, (c) Southeast Asia, (d) South Asia, (e) West Asia, and (f) Central Asia. Blue and orange bars: regional average values of annual NPA; unfilled portions of the respective bars: values without the northern parts of West Asia, Central Asia, and East Asia (NWCEA region) in (b,e,f); green line: 5 yr moving average; black and grey lines (grey line only in b,e,f): linear trends with and without the NWCEA region, respectively

West Asia, with the overall linear trends of these 2 sub-regions unchanged. The NPA in Southeast and West Asia increased slightly, while that in East and South Asia all generally decreased. However, these changes could be better characterized by the decadal and periodic variations rather than linear trends that were all insignificant.

3.2. Seasonal precipitation change

During the period of 1901–2016, the linear trends of the regional average NPA for every season in North Asia and Central Asia all increased, and all are significant except for summer (Fig. 6). The winter NPA in South Asia significantly decreased during

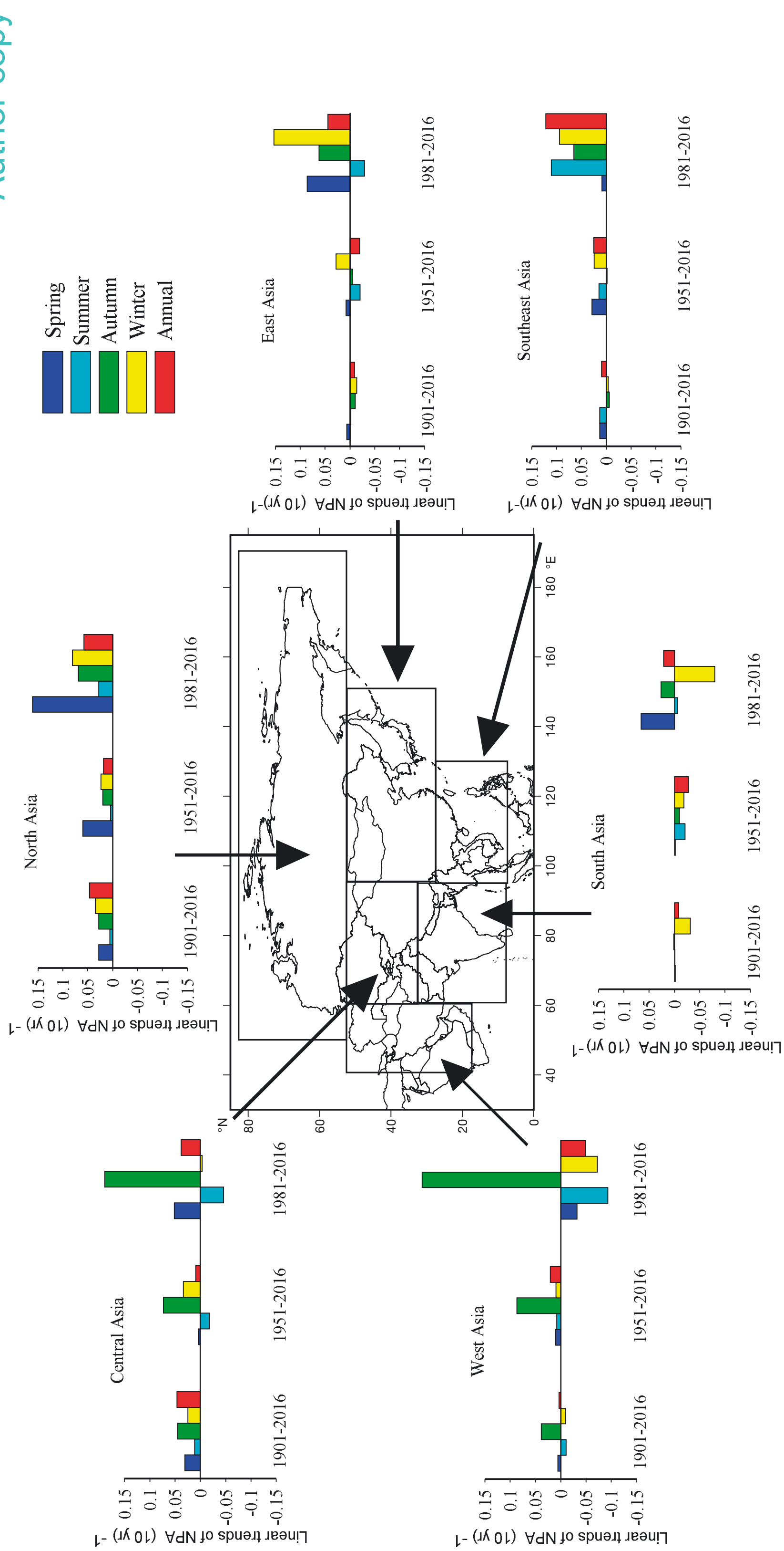

Fig. 6. Linear trends of seasonal and annual normalized precipitation anomaly (NPA) for the periods of 1901–2016, 1951–2016, and 1981–2016 in the 6 sub-regions. Spring: March–May; Summer: June–August; Autumn: September–November; and winter: December–February

1901–2016. The other seasonal changes in NPA from 1901–2016 in every sub-region were all small and insignificant. The seasonal and annual NPA in the whole study region all increased, and the spring, autumn, and annual trends were significant. During the period of 1951–2016, the seasonal and annual NPA in North Asia, West Asia, and the Asian continent all increased, while the NPA in South Asia decreased in every season. However, only the spring NPA in North Asia and in the whole region, the autumn NPA in Central Asia and West Asia registered a significant increase. During the period 1981–2016, the seasonal and annual NPA in North Asia, West Asia, and the whole region had a similar change to that of 1951–2016. The winter NPA in East Asia also increased significantly. No sub-region had a significantly decreasing seasonal or annual NPA during this recent period (Fig. 6).

The spatial distributions of NPA linear trends for the 4 seasons in the period of 1901–2016 were not all the same as those of the entire year (Fig. 7). In spring, precipitation increased in most land areas north of 40° N, and significantly increased in many grid boxes of Russia; in summer, the seasonal precipitation amount did not change much in any continuous area; autumn precipitation increased significantly in most parts of Russia north of 55° N, and also increased in Central Asia, with Northeast China and Japan experiencing a general downward trend; in winter, Russia had the strongest and most significant increase in precipitation except for the grid boxes east of 140° E, and the region with a significant increase extended southward to 45° N, including Kazakhskiy Melkosopochnik (central Kazakhstan), Mongolia, and the northern part of Northeast

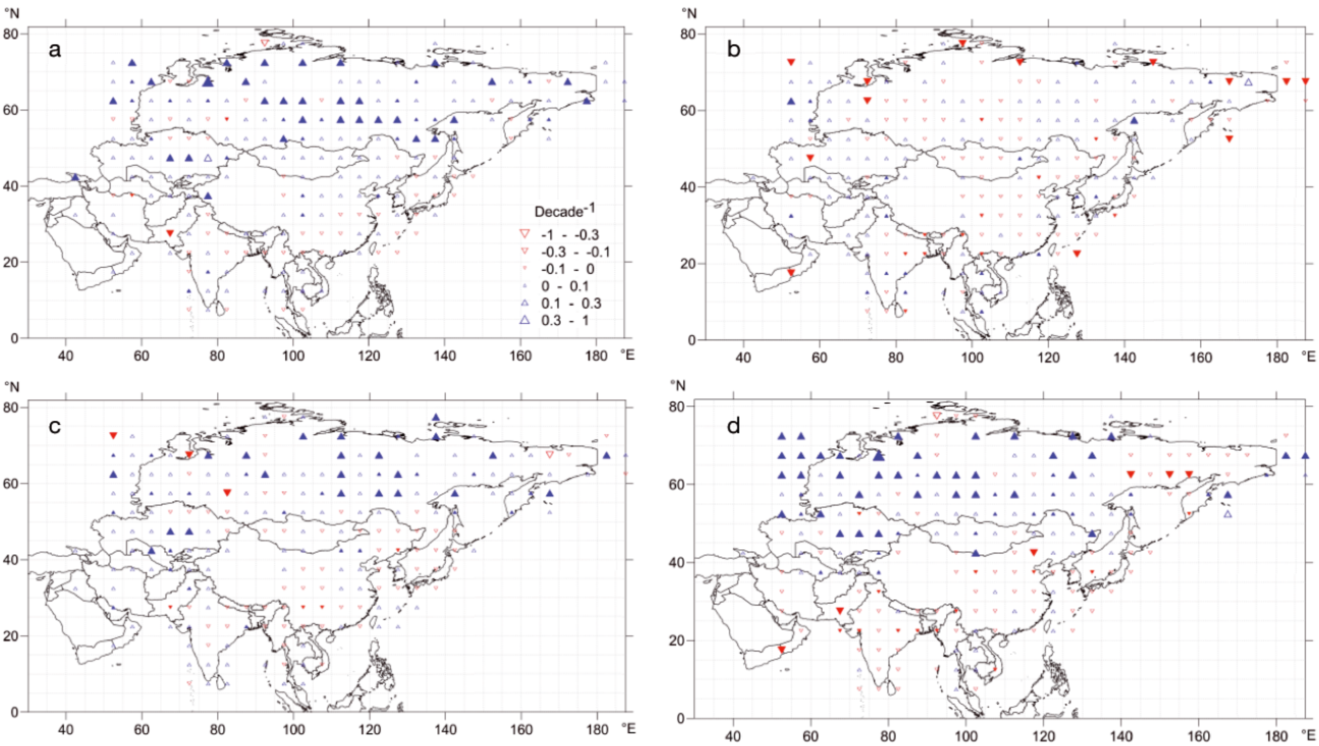

Fig. 7. Spatial distribution of linear trends of gridded seasonal normalized precipitation anomaly (NPA) for the period of 1901–2016 in Asia. (a) Spring, (b) summer, (c) autumn, (d) winter. Filled symbols represent statistically significant trends

China. However, winter precipitation generally decreased in South Asia, with the trend being significant in the northern part of South Asia.

The regional average seasonal NPA time series in the whole region were also not the same (Fig. 8). The spring and autumn NPA significantly increased, with linear trends of 0.016 (decade^{-1}) and 0.011 (decade^{-1}), respectively, during the period 1901–2016. They all declined slightly before 1940 and quickly increased in 1950–1960 and after 2010. The changes in summer were less than those in spring or autumn, with a linear trend of only 0.004 (decade^{-1}) in the period 1901–2016. In winter, the NPA fell dramatically in the 1930s, suddenly rose again in the 1950s, and fluctuated with alternating positive and negative anomalies before 1930 and after 1960. The winter linear trend was 0.001 (decade^{-1}), which did not pass the 0.05 significance test.

The 50 yr running linear trends for seasonal precipitation have shown that the running linear trends in spring and autumn were similar to the annual trend. These trends were significantly negative in several 50 yr periods beginning in the early 20th century. The 50 yr linear trends starting from the mid-1910s and ending to the mid-1990s were all positive, and the trends reached up to 0.020 (decade^{-1}). After this time, the trends fluctuated from negative to positive, and the nearest several 50 yr positive trends were significant. The summer 50 yr running trends all had very small absolute values, with only the 50 yr running linear trends from 1911–1960 to 1921–1970 being significantly positive, while those from 1940–1989 to 1945–1995 were significantly negative. The winter 50 yr running trends were generally negative in the periods starting in the early 20th century, and were all significant when the start year was prior to 1910. However, the 50 yr trends starting later than 1920 became positive, and those with start years from 1930–1945 were mostly significant (Fig. 9).

The proportion of summer precipitation (summer to annual precipitation) declined during 1901–2016 across all of North Asia and most parts of Central Asia and Northwest China. In these areas, the proportions of spring precipitation increased to some extent, and the proportions of autumn precipitation only increased in the Russian Far East. However, in Northeast China, South China, and southern India, the autumn precipitation ratio decreased significantly. In winter, the proportions of precipitation increased significantly in Russia west of 100° E, and decreased in North China, central India, and most parts of West Asia (Fig. 10).

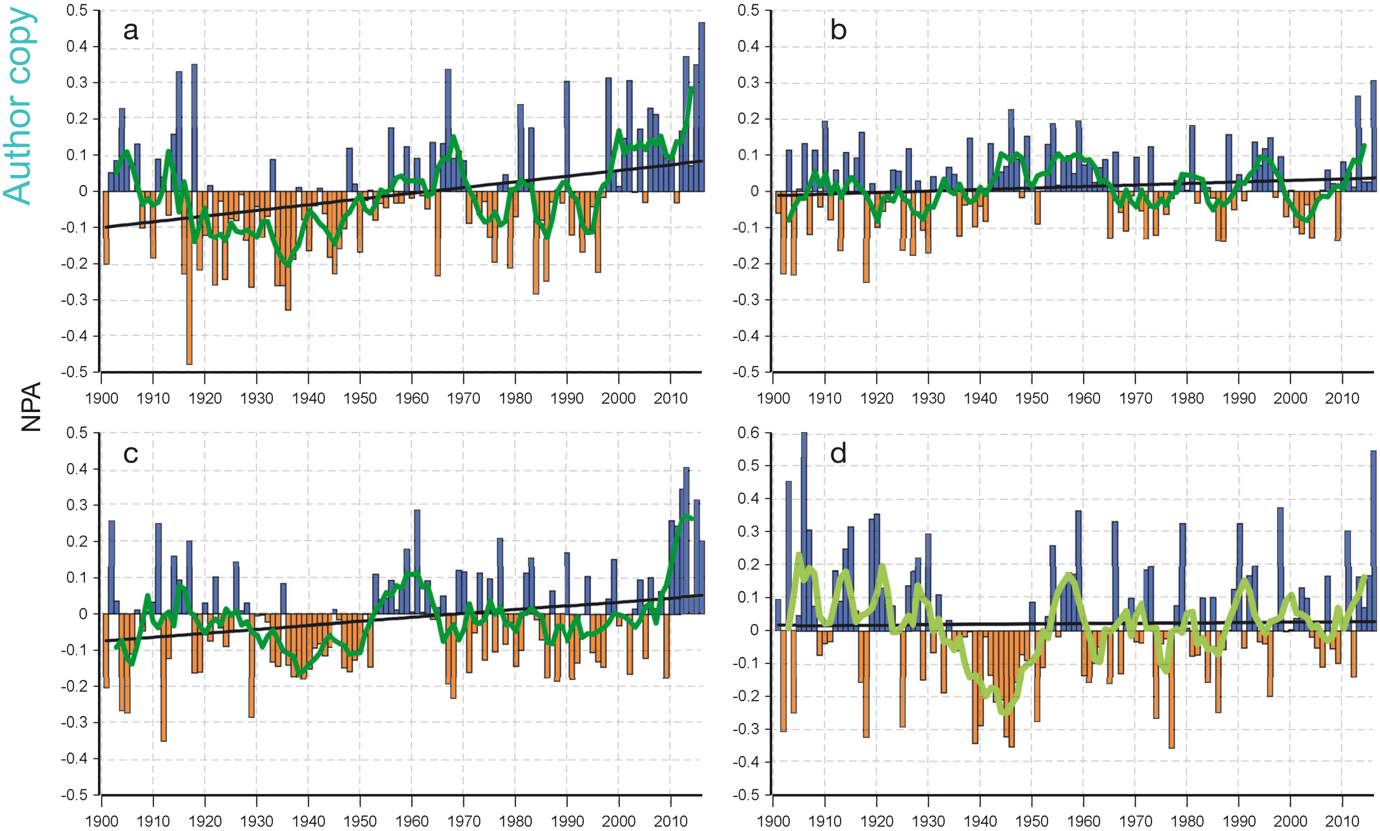

Fig. 8. Regional average seasonal normalized precipitation anomaly (NPA) time series in the whole of Asia. (a) Spring, (b) summer, (c) autumn, (d) winter. Blue and orange bars indicate the regional average values of annual NPA, the green line is a 5 yr moving average, and the black line is the linear trend

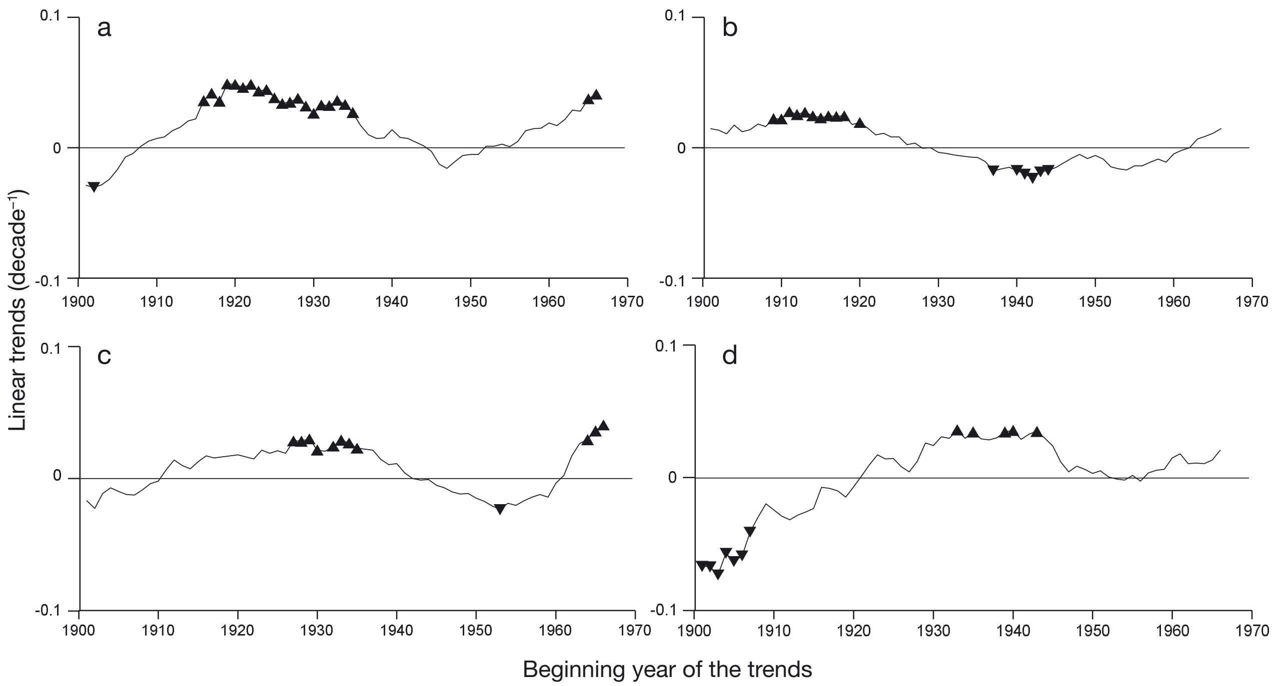

Fig. 9. Seasonal normalized precipitation anomaly (NPA) running trends for a 50 yr step during 1901–2016. (a) Spring, (b) summer, (c) autumn, (d) winter. Solid triangles represent statistically significant trends

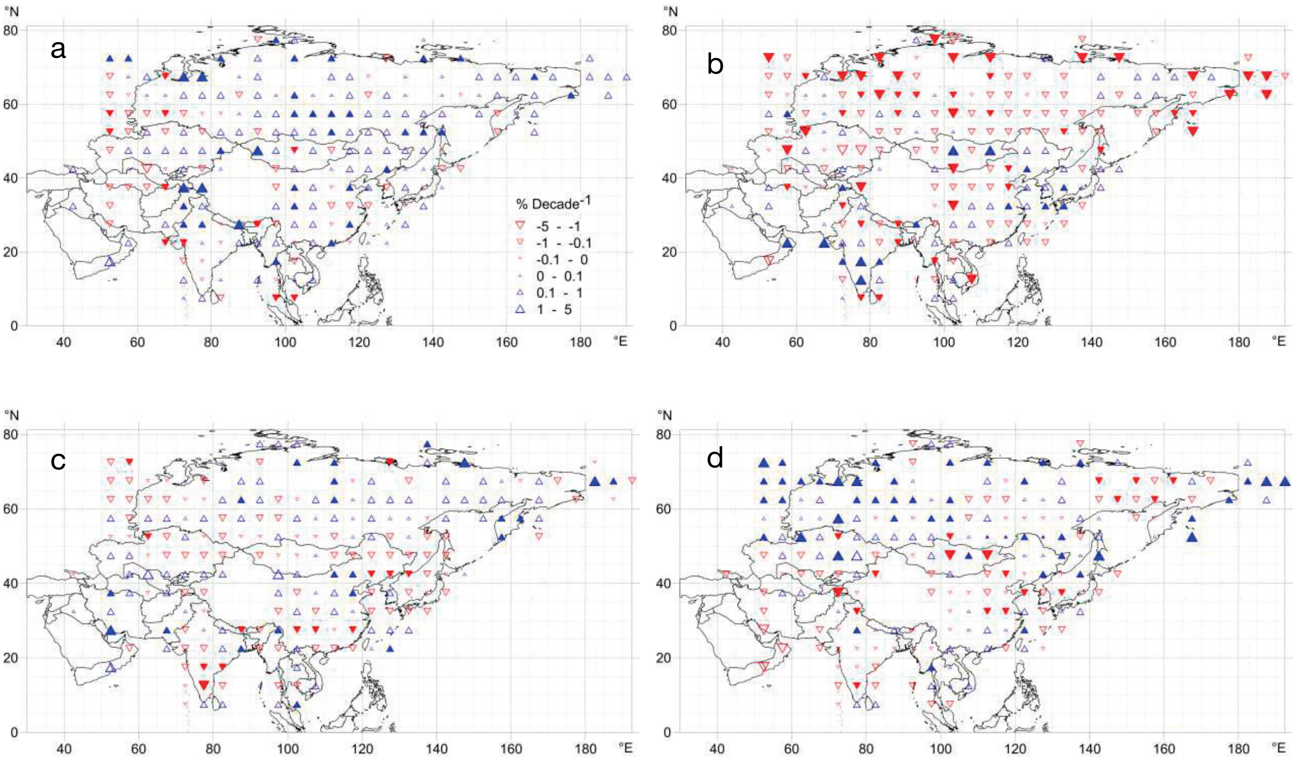

Fig. 10. Spatial distribution of linear trends of gridded seasonal to annual precipitation ratios for the period of 1901–2016 in Asia. (a) Spring, (b) summer, (c) autumn, (d) winter. Filled symbols represent statistically significant trends

4. DISCUSSION

In this study, we analyzed variations in the characteristics of precipitation over the whole of Asia from 1901–2016 by using a new multi-source dataset. This new historical dataset had more valid monthly precipitation data and better data quality than those of single datasets, such as GHCN-D, used in previous works. Our analysis led to some similar conclusions to those of previous studies, but some results reported here are novel and interesting.

The analysis revealed a large and significant change in precipitation in North Asia characterized by a significant increase in annual and seasonal precipitation during 1901–2016. The conclusion was similar to findings that precipitation had increased globally in the mid- and high latitudes based on previous studies (e.g. Trenberth 2011, Stocker et al. 2013). The possible reason for the increasing precipitation might be that as the high-latitude regions became warmer, the moisture levels in the atmosphere increased, thereby increasing the probability of precipitation (Boer 1993, Allen & Ingram 2002).

Nevertheless, we could not eliminate the probability that observation errors produced a false increase in precipitation rates. Most precipitation gauges had difficulty in capturing and measuring precipitation accurately, especially winter snowfall. The influence of the wind makes observations of precipitation smaller than the actual precipitation rate, and this deviation (so-called 'undercatch bias') is much greater in snowfall observations (Groisman & Legates 1995, Yang et al. 2005, Bogdanova et al. 2007, Ren et al. 2016). On the other hand, the near-surface wind speed has declined over the past decades in mid- to high latitudes of Asia (e.g. Ren et al. 2005, Jiang et al. 2010, Vautard et al. 2010, You et al. 2010, Guo et al. 2011). This implies that the catch rates of the rain gauges as applied in most countries and regions experienced an increase. North Asian precipitation mainly arrives as snowfall except in summer, so a decrease in wind speed and the resulting rise in the catch rates of the gauges might be causing a false upward trend in precipitation, especially for winter snowfall.

The bias-corrected precipitation data of the VMGO helped to remove biases over Russia during 1936–2010 to a large extent, and the 1901–1935 and 2011–2016 records were also corrected in this paper. The corrected and uncorrected precipitation in North Asia, however, all showed an increase in annual precipitation from 1933–1956, which was also revealed by global zonal mean analyses based on the Global

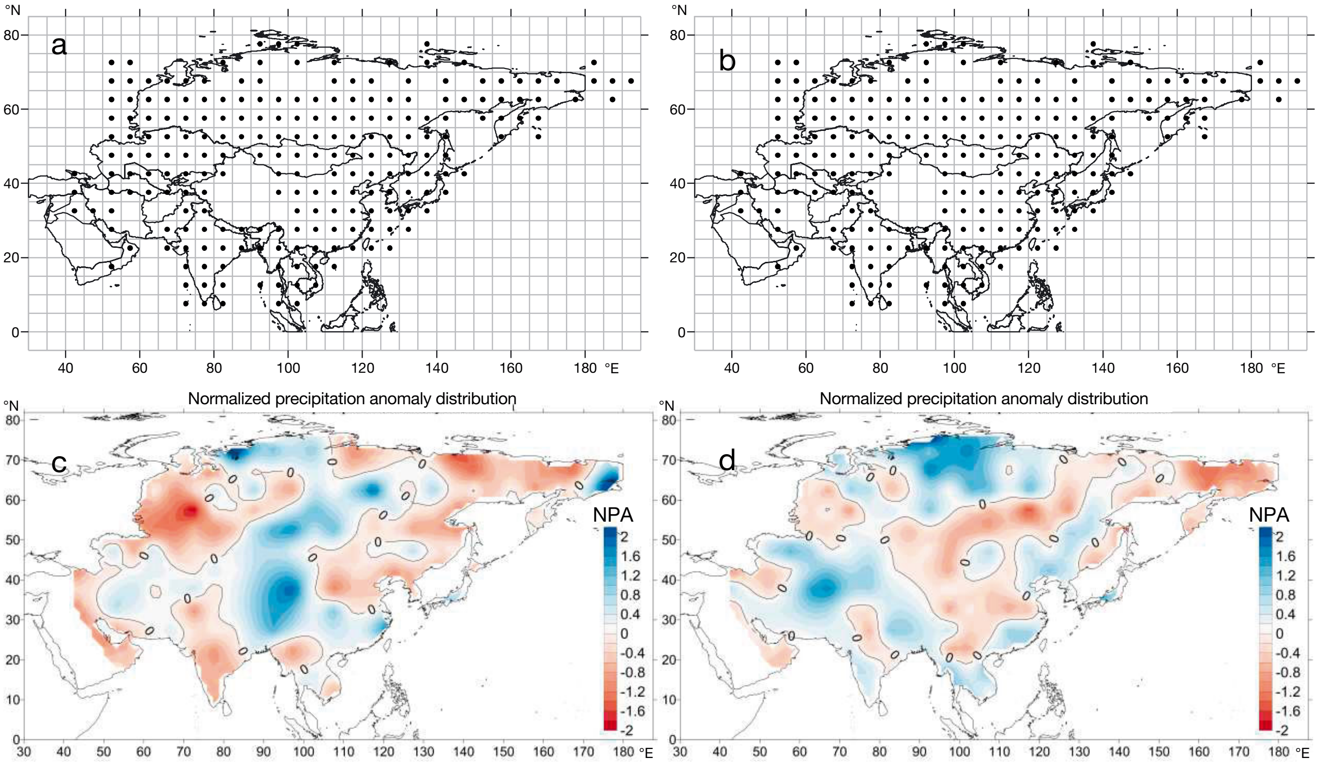

Fig. 11. Grid boxes used to calculate the regional average normalized precipitation anomaly (NPA) values in the whole of Asia for (a) 1952 and (b) 1953, and the spatial distribution of annual NPA in (c) 1952 and (d) 1953

Precipitation Climatology Project (GPCP) dataset (New et al. 2001), indicating that the increase in precipitation in this region may have been a large-scale change. However, the precipitation data in other areas, especially the NWCEA region, were not corrected, although the biases might be relatively small. An examination of the regional series with and without the NWCEA region confirmed that the linear trends of the regional average NPA series in the whole of Asia and the 3 sub-regions containing parts of the NWCEA region were not changed much, although we could not rule out the possibility that the inhomogeneities and systematic errors in the observational data in these cold areas caused false increasing trends of annual and winter precipitation. This problem introduced up to ~25% uncertainties to the estimation of the linear trend of annual NPA in Asia. Further investigation of this issue is needed to reduce the uncertainty.

In addition to the general increase in precipitation over the Asian continent during the past century, a precipitation shift toward a higher level could be found from 1952–1953. This abrupt change was partly in accordance with the analysis by Groisman et al. (2013), but most former studies have not reported an obvious change because of the relatively poor data coverage for the period before 1956 (Gruza et al. 1999). To eliminate the cause of data coverage differences during 1952 and 1953, we examined the grid boxes used to calculate the regional average time series of both of these years (Fig. 11a,b). Clearly, the 1953 grid boxes did not experience a major shift when compared with the 1952 grid boxes, indicating that the sudden change was not derived from variation in data coverage and density. Comparing the NPA spatial distribution of 1952 to that of 1953 (Fig. 11c,d), one can further see that the change in precipitation rate had a strongly negative NPA in the West Siberian Plain and East Siberia in 1952, but the NPA of these areas had a small absolute value in 1953. The datasets (for example, GHCN) used by former studies had very sparse station density in these areas, especially in the plain areas near the Arctic, so that they were less able to detect the precipitation change in the high-latitude areas of Asia (Gruza et al. 1999, Yang et al. 2016). The use of the new multi-source precipitation dataset might have been a reason that we were able to detect the shift and to explain the discrepancies compared to previous studies.

Although the CGP dataset had better station density and record length in China and North Asia, the data coverage was still poor in West Asia, and the early part of the 20th century in western China, which might cause major data uncertainties. Further improvement in processing the spatial and temporal data coverage is underway, but much work is needed to obtain the missing records, and it is almost impossible to fill the data gaps of early years in most parts of western China and West Asia. Uncertainties might also result from the problems with analysis methods. The discrepancies to previous studies could be partly derived from the use of NPA rather than the original precipitation values or anomalies in this analysis. Compared to those absolute-value indices, NPA as used in this paper could better highlight the trends in precipitation change in areas with low precipitation, while the trends might be erased in the process of calculating regional averages using the original precipitation values or their anomalies (Jones & Hulme 1996). The assessment of the applicability of precipitation indices at different spatial and temporal scales, with data that vary in quality, or with different application scenarios, should be part of further quantitative analyses.

5. CONCLUSIONS

A new multi-source dataset was used in this paper to analyze changes in precipitation amounts over the Asian continent during 1901–2016. The main conclusions are as follows:

(1) The regional average annual precipitation in the region has increased significantly. Precipitation prior to the early 1950s was considerably lower than after, however, there were still uncertainties with the data from mid- to high-latitude regions. Large and significant increases mainly occurred in cold areas such as North and Central Asia, with a significant increase occurring in the mid-20th century. The zonal mean annual precipitation of tropical, temperate, and frigid zones tended to increase while that of the sub-tropical zone tended to decrease.

(2) The characteristics of change in the average spring and autumn precipitation over the Asian continent were similar to the annual change. The amount of precipitation in summer increased slightly. The amount of winter precipitation decreased significantly in the 1930s and increased significantly from 1945–1955, and after 2010, with a slight upward trend for the entire period of 1901–2016.

(3) North and Central Asia experienced a significant increase in precipitation for every season except summer during 1901–2016. West Asia showed a significant upward trend in autumn precipitation, and South Asia showed a significant decrease in winter precipitation during the period 1901–2016. No significant changes in seasonal precipitation were observed during 1901–2016 in the other Asian regions.

(4) During 1901–2016, the summer precipitation ratio declined uniformly and significantly in cold areas, and the other 3 seasonal precipitation ratios increased more or less. The autumn precipitation ratio decreased in Northeast China, South China, and southern India.

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