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Observed changes in temperature and precipitation over Asia, 1901–2020

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ABSTRACT: Asia is the largest continent in the world and home to 4.7 billion people. Climate change on this continent, therefore, attracts a significant amount of attention from scientists and policy-makers. However, observational studies of long-term climate change over the continent as a whole are lacking. Using updated, homogenized observational data from stations in Asia since 1901 and systematic-bias-adjusted data from stations in China after 1950, we analyzed the long-term trends of surface air temperature (SAT) and precipitation in Asia and China from 1901–2020. The results showed that (1) in the 120 yr between 1901 and 2020, the annual mean SAT rose significantly at rates of 0.13 ± 0.01 and 0.14 ± 0.03°C decade^{-1} in Asia and China, respectively. The year 2020 in Asia may have been the warmest year since the beginning of the 20th century. (2) Since 1901, in both Asia and China, the annual mean minimum temperature increased more than twice as fast as the maximum temperature, and the diurnal temperature range (DTR) dropped significantly. (3) From 1901–2019, the annual precipitation anomaly percentage in Asia showed a significant increasing trend at an average rate of 0.52 ± 0.10% decade^{-1}, and the increase was more obvious in high latitudes than in low to mid-latitudes. (4) Since 1901, there has been no significant change in annual precipitation in China, but there was a weak and non-significant decrease in the first half of the 20th century and a significant increase after the mid 20th century. The results presented in this paper can help us understand the spatio-temporal patterns and causes of climate change in the Asian continent and Chinese mainland.

KEY WORDS: Asia · China · Surface air temperature · Precipitation · Change trend · Climate warming · Observational data

1. INTRODUCTION

Asia is the largest continent of the globe, with the world's highest plateau (Qinghai-Tibet Plateau) and mountains (Himalayan-Karakoram Mountains), a typical monsoon climate (South Asia monsoon, Southeast Asia monsoon and East Asia monsoon), the most diverse climate types (all zonal and non-zonal climate types except a continental ice sheet climate), the densest population settlements and the most frequent weather and climatic disasters. More than half of the world's population has been strongly affected by the extremely high spatial and temporal climate variability in Asia.

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In the past 100+ yr, especially in recent decades, the climate in Asia has undergone significant changes, mainly manifested as a general rise in surface air temperature (SAT) (Jones et al. 2012, Rennie et al. 2014, Hausfather et al. 2017, Dong et al. 2018, Menne et al. 2018, Lenssen et al. 2019, Climate Change Center of China Meteorological Administration 2019, 2020), a marked increase in precipitation in middle and high latitudes (Dong et al. 2018, Zhan et al. 2018), and an increased and strengthened trend in certain extreme weather and climate events (Donat et al. 2013, IPCC 2013). The unique characteristics of the natural and human environment make Asian countries (regions) highly sensitive and vulnerable to climate change. Monitoring and studying long-term changes in SAT and precipitation in the continent is thus of great significance, not only for an in-depth understanding of regional and global climate changes and their impacts and risks, but also for formulating response policy to adapt to climate changes (Hawkins et al. 2017).

However, there is a disparity in the level of scientific and technological development in various parts of Asia, and systematic observation and scientific research in most developing countries (regions) still need to be strengthened. This is mainly manifested in the relatively low capacity of climate observation data development and application, the generally poor quality and continuity of historical climate observation data and the widespread existence of data inhomogeneities. With the goal of integrating, improving, and optimizing existing historical climate data, determining how to apply advanced analysis methods and universally applied climate indices to carry out continental-scale climate change monitoring and research and provide scientific information for assessing and coping with climate change has become an urgent task for climatologists in relevant Asian countries (regions).

A few global and Asian land SAT and precipitation historical data sets have been developed since 2012 by the China Meteorological Administration/China University of Geosciences (CMA/CUG) (Wuhan) research group in which most of the authors of this study were involved. The data sets include monthly SAT and precipitation data since 1900 (Ren et al. 2014, Yang et al. 2016, Sun et al. 2017a, Xu et al. 2018, Cheng et al. 2020, Li et al. 2021) and daily SAT and precipitation data since 1950 (Sun et al. 2017a, Zhan et al. 2017, Y. Zhang et al. 2019). Previous studies also noted the systematic bias in the SAT and precipitation data series, which is crucial to the monitoring, detection and attribution of regional climate change. For example, many groups evaluated and corrected the urbanization bias in the SAT data series (e.g. Ren et al. 2008, 2017, Zhang et al. 2010, Ren & Zhou 2014, Tysa et al. 2019, Wen 2020) and the wind-speed-induced under-catch bias of the precipitation data series (e.g. Sun et al. 2013, Y. Zhang et al. 2019, 2020) for China. Some studies were conducted to improve and develop analysis methods for regional climate change monitoring and detection (Ren et al. 2012, Zhan et al. 2019, 2021). Applying the CMA global land and China climate data sets, researchers constructed time series of surface climate variables for the past 100+ yr and extreme climate index series for the past 60 yr for global land (Yang et al. 2016, Sun et al. 2017a, 2019, Xu et al. 2018, P. Zhang et al. 2019, Li et al. 2021), Asia (Zhan et al. 2018, Climate Change Center of China Meteorological Administration 2020, Cheng et al. 2020), China (Ren et al. 2005a, Cao et al. 2013, Wen et al. 2019, Yan et al. 2020, Zhang et al. 2021) and key regions or watersheds (Y. Ren et al. 2017, You et al. 2017, Zhan et al. 2019, Cheng et al. 2020). These earlier works provide the possibility for further development of climate change monitoring, research and assessment in Asia as a whole as well as in key regions of the continent.

Here, by applying the global land SAT and precipitation data sets as well as the relevant methods of climate change monitoring and detection developed through previous research by the CMA/CUG group, we updated and analyzed the time series of SAT anomalies and precipitation anomaly percentages in different periods of Asia. China was chosen as a focal area since it is one of the countries in Asia in which a large amount of observational research on modern climate change has been conducted, and climate change is also a key target for the country to address.

This article focuses on a description of the updated results and findings obtained from this new analysis. For more detailed information, including introduction of the data and methods along with a discussion (including comparisons with data derived from other global land data sets) of the SAT change in Asia since 1901 and the SAT and precipitation changes in China since 1901, please refer to Sun et al. (2023), Wen et al. (2023) and Zhan & Ren (2023) (all in this special issue). Thus, this study should be regarded as a summative and updated analysis of the previous studies by the CAM/CUG group and other studies in this special issue. Results reported are intended to help deepen the understanding of past climate changes across Asia, and specifically in China, and provide scientific information for Asian countries (regions) to assess and respond to climate change.

2. DATA AND METHODS

2.1. Region and data used

The boundary of the Asian region refers to the scope of the World Meteorological Organization (WMO) Region II, but only includes parts of Indonesia and Malaysia (north of 5° N) in the Indonesian Archipelago. The high latitude zone does not include the region north of 75° N due to a lack of continuous observations (see Fig. 1). The Chinese region includes the mainland and nearby islands.

Monthly SAT (1901–2020) and precipitation (1901–2019) data for the entire Asian region since the beginning of the 20th century were obtained from the CMA National Meteorological Information Center (NMIC) 'Global Land Surface Air Temperature dataset (GLSAT)' and 'Global Land Precipitation dataset (GLP)' (Yang et al. 2016, Sun et al. 2017a, Xu et al. 2018). GLSAT and GLP are the products of multi-source data integrations and generally contain more observations than the source data sets. Obvious improvements in data coverage appear in the Asian continent, especially in China and its neighboring regions. All data, except Asian precipitation records, have been updated to December 2020. Monthly precipitation data were unavailable for 2020 in a few countries at the time when this work began, and therefore in these cases the data is from 1901–2019.

Asian monthly SAT and precipitation data are subject to multiple quality controls. Temperature data, including monthly average maximum, minimum and mean temperatures, have been adjusted for inhomogeneities caused mainly by relocation and instrumentation (Sun et al. 2017b, 2023, Xu et al. 2018). The monthly precipitation data of China and the former Soviet Union have also been homogenized (Zhan et al. 2018). The requirements for data retention before, within and after the reference climate period were the same as those reported in previous studies (Sun et al. 2017b, Zhan et al. 2018, Zhang et al. 2021) in order to assure the robustness of the trend estimate. For Asian precipitation data, for example, only those stations with at least 10 yr of valid records encompassing all 12 months of a year in the reference climate period (1961–1990) were chosen, and at least 5 yr of valid records in 1901–1950 and 1991–2016 were required in order to minimize the effect of missing data on the estimates of anomaly percentages and linear trends (Zhan et al. 2018). The distribution of SAT and precipitation observational stations used in Asia is shown in Fig. 1.

The monthly mean SAT data set for China since the beginning of the 20th century (1901–2020) was developed by Cao et al. (2016) and Wen et al. (2023 in this special issue). Wen et al. (2023 in this special issue) improved the SAT data set by including more stations and homogenizing the supplemental data, for a total of 47 stations distributed relatively evenly across China. The daily precipitation data (1901–2020) is from the 'Sixty-Station Daily Precipitation Dataset in China since 1901', recently developed by the NMIC (Zhan et al. 2022). The data set is composed of the monthly precipitation records of 60 stations across China. Great effort has been made to remedy the early period observations. A detailed description of the Chinese precipitation data can be found in Zhan et al. (2022).

For the post-1960 period, the data of monthly mean SAT and monthly total precipitation in China, which covers about 820 national stations for SAT and 2300 stations for precipitation across the country, are from the 'China Surface Historical Climate Homogenized Dataset' developed by the NMIC. Compared to the data of 1901–2020 (1901–2019 for precipitation), the SAT data of 1961–2020 from the national stations have not only been homogenized, but also corrected for urbanization bias (Wen et al. 2019), and the precipitation data of 1961–2019 have been corrected for under-catch bias induced by wind, evaporation and wetting (Zhang et al. 2020). The monthly data of SAT and precipitation over the past 60 yr, which have been corrected for these systematic biases, can better reflect the characteristics of regional-scale climate trends than the homogenized-only data series in China. The spatial distribution of the SAT and precipitation stations in China since 1961 can be found in the literature (Wen et al. 2019, Zhang et al. 2020).

The SAT data of China since 1901 have been quality controlled and homogenized, but the urbanization bias has not been corrected (but see Wen et al. 2023 in this special issue); the post-1900 precipitation data of China have only been subjected to quality control and a preliminary check and process for inhomogeneities, but no attempt has been made to adjust for under-catch bias (but see Zhan & Ren 2023 in this special issue).

2.2. Analysis methods

For monthly and annual SAT and precipitation data, the temperature anomaly and the precipitation anomaly percentage were calculated from the stations. The 30 yr period from 1961–1990 was adopted as a refer-

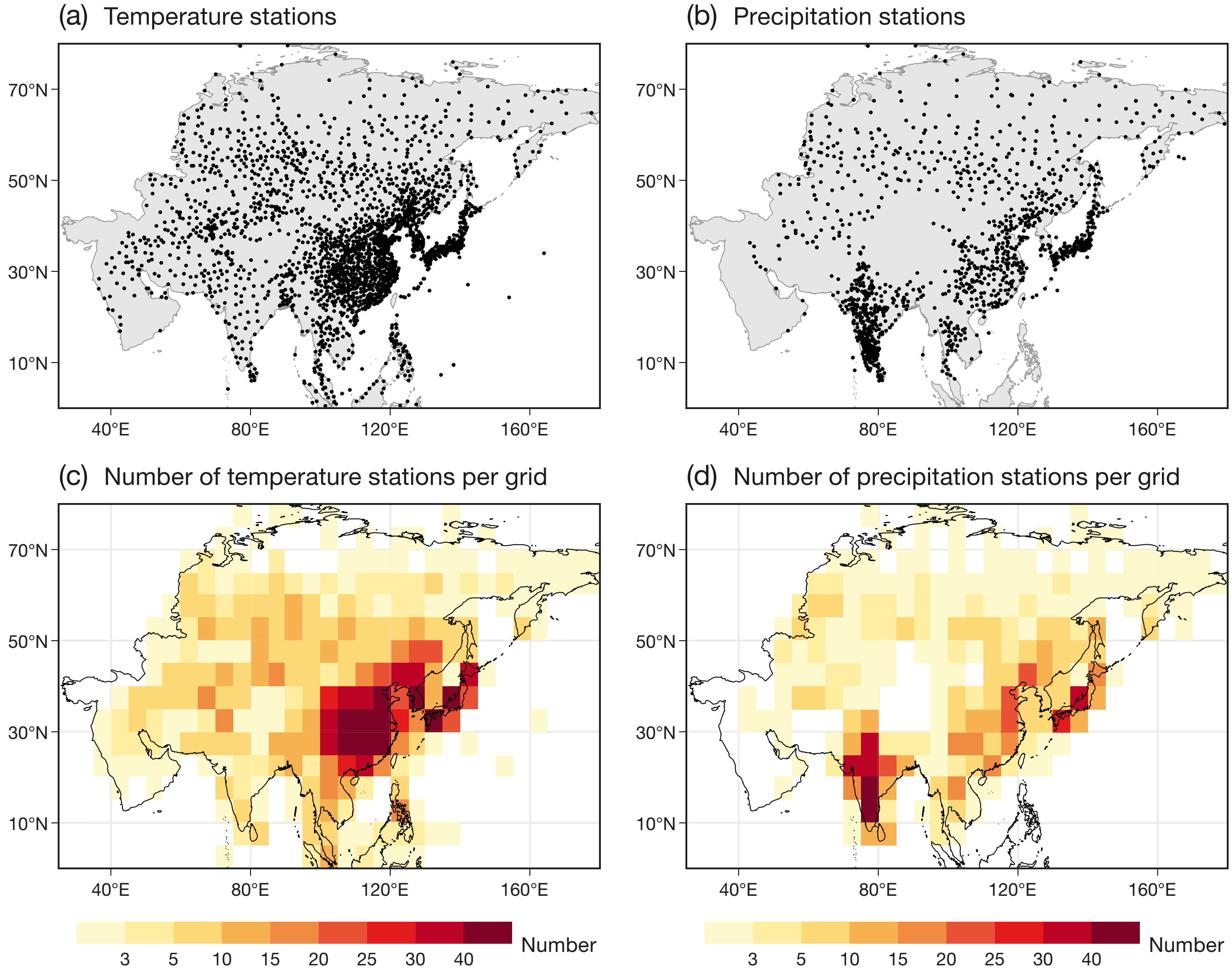

Fig. 1. Study area (Asia) and distribution of observation stations for (a) surface air temperature and (b) precipitation data; 5 × 5° longitude and latitude grids and numbers of stations with (c) temperature and (d) precipitation data. The boundary and longitude/latitude grids (2.5 × 2.5) of China are not shown

ence climate period for calculating the anomalies in the 1901–2020 series, and a reference climate period of the 30 yr from 1981–2010 was adopted for analysis of the 1961–2020 series. Temperature anomaly rather than temperature itself was used because it could, to a large extent, eliminate the influence of varied elevations and geographical units on grid values in grading the observational data (Jones & Hulme 1996). Precipitation anomaly percentage rather than precipitation amount or precipitation anomaly was applied because it can better indicate large-scale patterns of precipitation trends (Zhan et al. 2021).

The temperature anomaly and precipitation anomaly percentage were gridded to form a grid data series. The grid size was 5.0 × 5.0° in Asia and 2.5 × 2.5° in China. The regional average adopts the grid area-weighted averaging method to obtain the time series of the regional average SAT anomaly and precipitation anomaly percentage in different regions. The weight for the area-weighted averaging is the cosine of the mid-latitude of the grid box. For detailed methods of data gridding, area-weighted averaging and data interpolation for drawing isopleth maps, please refer to the related literature (Jones & Hulme 1996, Ren et al. 2005b, Sun et al. 2023 in this special issue, Wen et al. 2023 in this special issue, Zhan & Ren 2023 in this special issue).

In order to examine the trend differences among the different stages with the same end year, 3 periods—1901–2020 (2019), 1961–2020 (2019) and 2001–2020 (2019)—were assigned to calculate the respective SAT and precipitation trends (see Fig. 4 and Table 1). The year 1961 was chosen as the beginning of the analysis period because it is a time point when large-scale construction of climate observational networks began in many Asian countries, and the last 60 yr or so have witnessed rapid and widespread climate warming; the period of 2001–2020 (2019) was used because global and Asian climate experienced a warming slowdown after 2000, especially from 2001–2014. In addition, annual values were ranked to examine the historical positions of the last 5 yr in the varied periods of the last 120 and 60 years for annual mean SAT anomalies (see Table 3). Only the results of annual mean SAT and annual total precipitation are shown in this study. The results of different seasons and sub-regions in Asia and China can be found in Sun et al. (2023 in this special issue), Wen et al. (2023 in this special issue), Zhan & Ren (2023 in this special issue).

Taking into account that the monthly precipitation series may not conform to the assumption of a normal distribution, the long-term trend of SAT and precipitation was estimated by the Sen-Theil method (Sen 1968, Theil 1992), and the significance of the trend was tested by Mann-Kendall (M-K) method (Mann 1945, Kendall 1948). In addition, because the SAT and precipitation data series often have significant autocorrelation, which may affect the results of the significance test (von Storch 1999), the method of Wang & Swail (2001) was used to remove the possible influence of autocorrelation. The long-term change trend is considered to be statistically significant (very significant) at $p < 0.05$ ($p < 0.01$).

3. RESULTS

3.1. Asian temperature

The region-averaged time series of annual mean SAT anomalies in Asia from 1901–2020 shows that since 1901, the annual mean temperature has experienced a significant long-term upward trend, increasing at a rate of 0.13 ± 0.01°C decade−1 (Fig. 2a, Table 1). It is also obvious that the Asian climate warmed slowly before the 1940s, cooled slightly in the period from the early 1950s to the early 1970s and then began to warm rapidly after the late 1970s. The highest annual mean SAT anomalies occurred after 2000, and the lowest regional average temperature appeared in the first 2 decades of the whole period, a temporal characteristic consistent with that of the global surface temperature change (Lenssen et al. 2019, Wang & Clow 2020, Osborn et al. 2021). It is also notable from Sun et al. (2023 in this special issue) that the SAT increase was more remarkable in winter and spring than in summer and autumn over the whole continent.

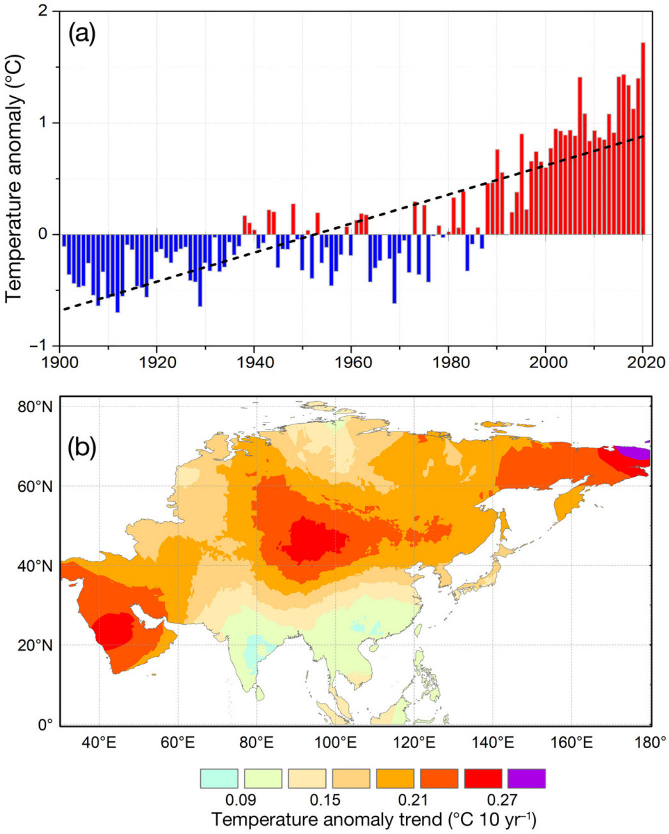

Fig. 2. (a) Time series of mean temperature anomaly in Asia from 1901–2020. The anomaly is the difference from the average of the 1961–1990 base climate period. Dashed line: linear trend. (b) Spatial distribution of the mean temperature anomaly trend in Asia from 1901–2020. The spatial interpolation field data is based on the temperature anomaly trend value on the 5 × 5° grid

Table 1. Trends (±95% CI) of annual mean, maximum and minimum surface air temperature (SAT) and diurnal temperature range (DTR) in Asia in different periods (units: °C decade^{-1}). $^{*}p < 0.05$

	1901–2020	1961–2020	2001–2020
SAT	0.13 ± 0.01*	0.29 ± 0.02*	0.25 ± 0.06
Maximum SAT	0.11 ± 0.01*	0.24 ± 0.02*	0.23 ± 0.07
Minimum SAT	0.18 ± 0.01*	0.32 ± 0.03*	0.27 ± 0.06*
DTR	−0.07 ± 0.00*	−0.08 ± 0.01*	−0.04 ± 0.02

The SAT change trends in 3 different periods of the past 120, 60 and 20 yr were compared (Table 1). Temperatures in the past 120 yr have experienced an upward trend, but the increases were significantly weaker than that during the rapid warming period of 1961–2020, with the latter being nearly twice the warming rate of the whole time period (Osborn et al.

2021, Sun et al. 2023 in this special issue). The minimum temperature increased at a greater rate than the maximum temperature during all 3 periods. The annual mean diurnal temperature range (DTR) showed a significant decline over the past 120 and 60 yr. In the 20 yr period from 2001–2020, the rate of temperature increase in Asia remained high, but only the trend of annual mean minimum temperature was statistically significant, and the decline in DTR slowed down.

In terms of the spatial distribution of Asian annual mean SAT trends in the past 120 yr (Fig. 2b), most areas saw a warming trend. The interior of the continent showed more significant warming than the coastal areas. The most obvious warming occurred in the Russian far east, Central Asia and West Asia, with an aligning feature of waviness from northeast to southwest. The tropical and subtropical monsoon regions, including India, the Indo-China Peninsula and southern China, had the lowest rate of warming in all of Asia. Temperature trends in northern Siberia showed greater diversity, and a small part of the grids saw weak warming of less than 0.12°C decade^{-1}. On the whole, the annual mean warming rate in Asia since 1901 was much weaker than the warming rates in the past 60 and 20 yr (Sun et al. 2023 in this special issue). The spatial patterns of the annual mean SAT trends in Asia shown are consistent with those reported in previous studies (e.g. Sun et al. 2017a, Rao et al. 2018, Osborn et al. 2021).

The annual mean temperature anomaly in Asia was 1.71°C (relative to 1961–1990) in 2020, which was the warmest year in the past 120 yr and obviously higher than the second warmest year of 2016 (Table 2). The years 2019, 2017 and 2018 ranked 5th, 6th and 7th in history, respectively. The regional average annual mean SAT in both 2016 and 2020 broke historical records.

Table 2. Ranking of warm years in terms of annual mean surface air temperature (SAT) for the past 5 yr (2016–2020) from the historical series in Asia (1901–2020)

	2020	2016	2019	2017	2018
Ranking	1	2	5	6	7
SAT anomaly (°C)	1.71	1.43	1.40	1.34	1.13

3.2. Asian precipitation

The time series of the regional average precipitation anomaly percentages in Asia from 1901–2019 showed that annual precipitation exhibited a significant upward trend ($p < 0.05$), with an increase of 0.52 ± 0.10% decade^{-1} (Fig. 3). After the early 1950s, annual precipitation was mostly higher than that of the previous 50 yr. The period from 2010–2019 was the decade with the highest average annual precipitation in the past 119 yr. The year 2016 was the wettest year in the continent for the entire period analyzed. From 1918–1952, the Asian continent experienced a period of more than 30 yr of decreased precipitation, with a continental-scale drought occurring in the 1930s and 1940s. Three relatively wet periods of 1906–1916, 1953–1961 and 2010–2019 witnessed higher than normal regional average annual total precipitation in the continent.

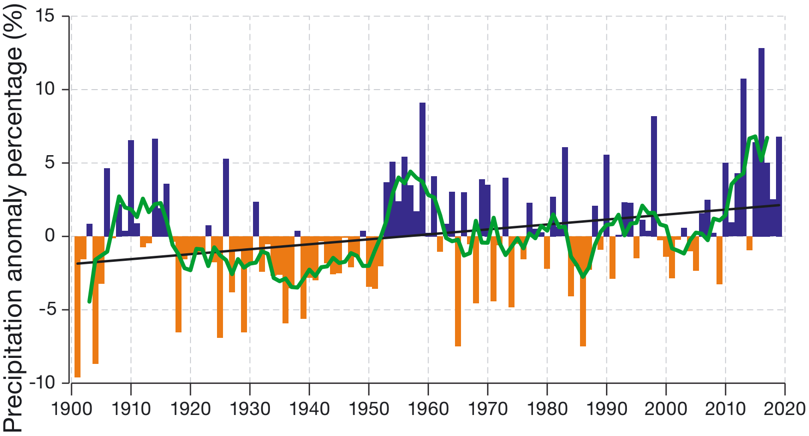

Fig. 3. Time series of regional average annual precipitation anomaly percentage in Asia from 1901–2019. The base climate period is 1961–1990. Green line: 5 yr moving average; black line: linear trend

There were large differences in the annual precipitation anomaly percentage changes in Asia during the 3 periods of 1901–2019, 1961–2019, and 2001–2019 (Fig. 4). From 1901–2019, the annual precipitation in most areas north of 50° N experienced an increasing trend, but the precipitation between 20 and 30° N showed a consistent decrease; precipitation generally decreased in eastern China and increased in Central and Southeast Asia, but the trends of increase and decrease were generally not significant except for southern Central Asia. From 1961–2019, the spatial characteristics of annual precipitation changes were similar to those of the entire period, but there was a significant decrease in the high latitudes of Asia along the coastal zone of the Arctic Ocean, and precipitation in Central and Southeast Asia generally increased. Since the beginning of the

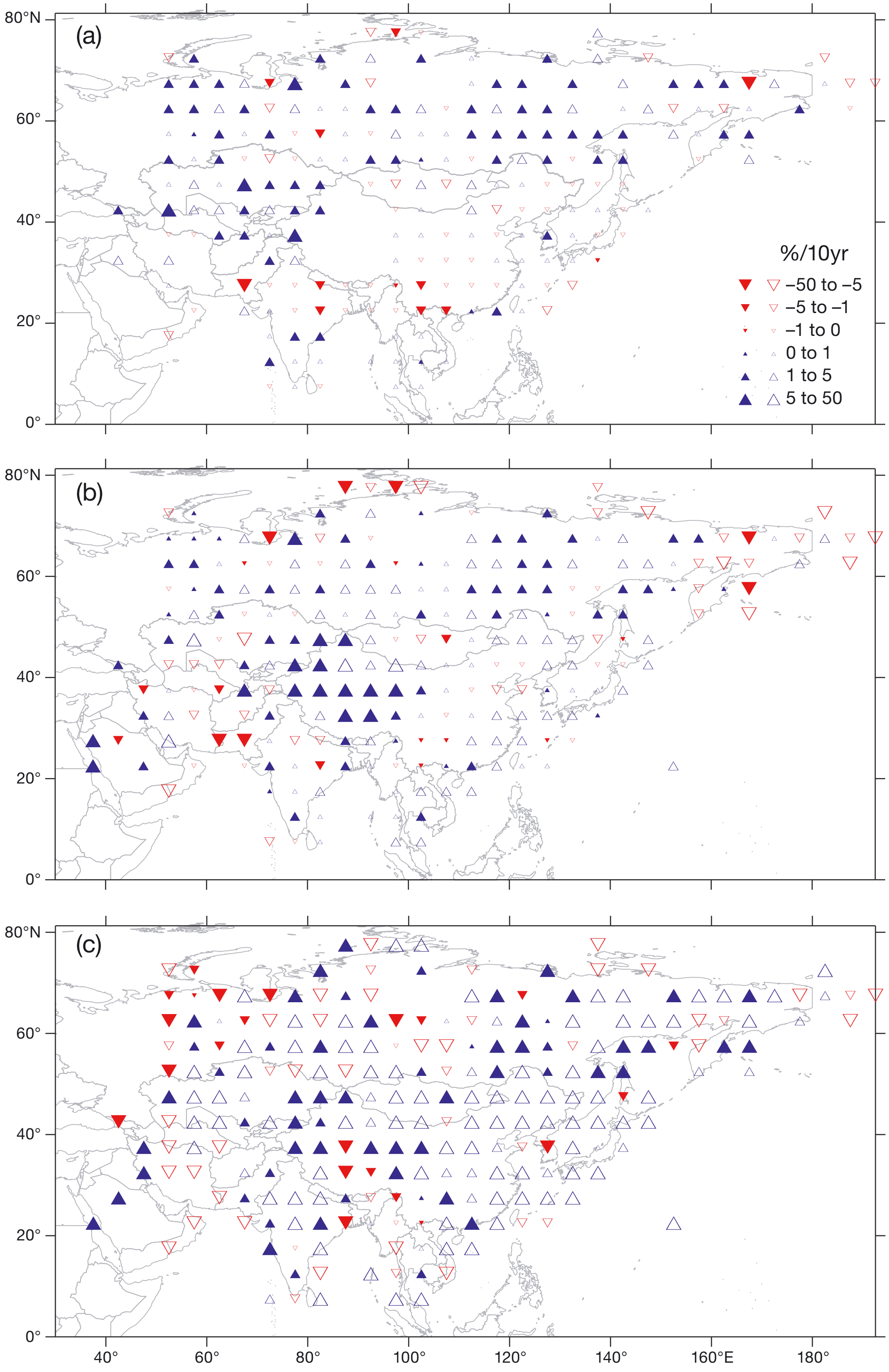

Fig. 4. Trends of annual precipitation anomaly percentage in Asia from (a) 1901−2019, (b) 1961−2019 and (c) 2001−2019. Blue: increase; red: decrease. The size of the triangle indicates magnitude of the trend; filled triangles: significant ($p < 0.05$); hollow triangles: not significant ($p > 0.05$)

21st century, annual precipitation in the regions of eastern Siberia, Mongolia, East and South Asia has increased significantly, while the changes in other regions have witnessed both increases and decreases, though more grids experienced upward trends, and the increasing rates are larger than those of the 2 longer periods.

The above-mentioned trends and spatial characteristics of precipitation changes in Asia are consistent with the results of Zhan et al. (2018) for the period 1901–2016. However, the upward trend in Asian regional average precipitation shown here is statistically significant ($p < 0.05$) as compared to the earlier analysis. The more significant positive trend of the regional average precipitation on the Asian continent estimated in this study can be related to the fact that annual precipitation from 2017–2019 was obviously higher than the normal value (Fig. 3).

3.3. Temperature and precipitation in China

From 1901–2020, annual mean SAT rose significantly at a rate of 0.14 ± 0.03°C decade^{-1} in China; the rate of warming was slow before the mid-1980s, but accelerated from that time to the end of the 1990s; thereafter, China entered a period of warming slowdown (Fig. 5). The warmest year in the past 120 yr was 2007, with an annual SAT anomaly of 1.4°C, and the coldest year was 1936, with an anomaly of −1.0°C. The country's average annual mean maximum temperature rose at a rate of 0.07 ± 0.03°C decade^{-1}, and the annual mean minimum temperature increased at a much higher rate (0.19 ± 0.02°C decade^{-1}), leading to a large and significant decrease in annual mean DTR at a rate of −0.13 ± 0.02°C decade^{-1} (Wen et al. 2023 in this special issue). The decline of DTR was not obvious before the 1950s, but it was highly significant afterward (Wen et al. 2023 in this special issue).

The regional average annual mean SAT increasing trend in China from 1901–2020 obtained here by using the new long-term observational records is slightly smaller than that (0.15°C decade^{-1}) obtained by Cao et al. (2013) for the period 1909–2015, but it is close to that of Li et al. (2010) for the period from 1900–2015 (0.12°C decade^{-1}). The difference from Cao et al. (2013) may have been related to the different periods and numbers of stations used by the 2 analyses.

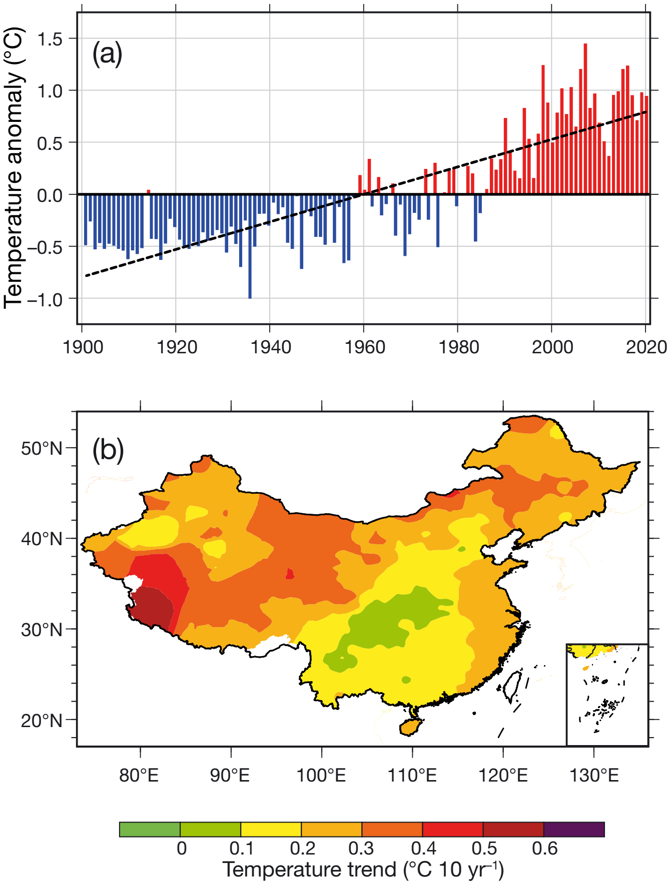

Fig. 5. (a) Time series of annual mean temperature anomaly in China from 1901–2020. The anomaly is the departure from the average of the reference climate period (1961–1990). Dashed line: linear trend. (b) Spatial distribution of annual mean temperature trend after the adjustment of urbanization bias for national reference and basic stations in China from 1961–2020

The average SAT in the last 5 yr in China has been warmer than the average of the past 120 and 60 yr. Annual mean SAT anomalies in 2016 were 1.23 and 0.99°C for the past 120 yr and the past 60 yr, respectively, but those in 2019 were 0.98 and 1.05°C for the past 120 yr and the past 60 yr, respectively. 2016 was the 3rd (2nd) warmest year in the past 120 yr (last 60 yr in the 120 yr series), and 2019 was the 9th (6th) warmest year in the past 120 yr (last 60 yr in the 120 yr series) (Table 3). Recent 120 yr SAT series did not consider the urbanization bias in the observational data of the stations, while the recent 60 yr data series as obtained from all national stations was constructed using the urbanization-bias-corrected data; the number and distribution of observational stations used in the 2 series are quite different so the results obtained are slightly different, though the rankings are roughly similar, indicating that the regional average SAT in the past 5 yr was relatively high. The SAT anomaly series in the past 120 and 60 yr have also

Table 3. Ranking of warm years in terms of annual mean temperature anomaly for the past 5 yr (2016–2020) from the historical series and corresponding annual mean temperature anomaly values (°C) in China (1901–2020 and 1961–2020)

	2016	2017	2018	2019	2020
120 yr series	3	12	20	9	13
Last 60 yr of 120 yr series	2	8	15	6	7
60 yr series of national stations	6	2	12	4	7
Anomaly in 120 yr series	1.23	0.95	0.71	0.98	0.94
Anomaly in 60 yr series of national stations	0.99	1.07	0.74	1.05	0.93

adopted different reference periods so the anomaly values are not comparable, but this difference does not affect the historical rankings of regional average annual mean SAT anomalies.

The spatial distribution of the annual mean SAT trends of the national stations from 1961–2020 shows regional differences in climate warming (Fig. 6). The data have been corrected for the urbanization bias of the urban station SAT series. The annual mean SAT increased in most of the north, and the east coast and the Qinghai-Tibet Plateau exceeded 0.20°C decade^{-1}. The warming in these regions was the most remarkable; the annual mean warming in most of central China, northwestern China and southwestern China was relatively small, with a warming rate at some stations of less than 0.10°C decade^{-1}. The extent of the regions with a low annual warming trend expanded compared to that shown by using homogenized-only SAT data (Wen et al. 2019). In the northeastern-most area of north China and the western Himalayan Mountains, data are lacking, and the abnormally high values at the 2 stations need to be investigated further.

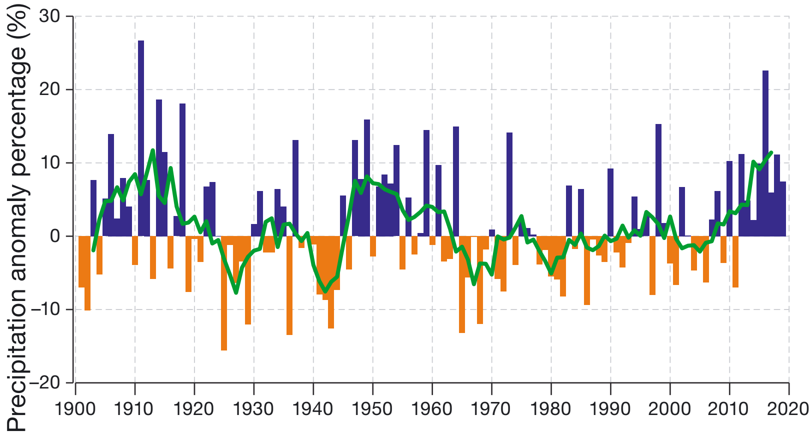

Fig. 6. Time series of regional average annual precipitation anomaly percentage of 60 stations in China from 1901–2019. The precipitation anomaly is the departure from the average of the 1981–2010 reference climate period

Since 1901, the country's average annual precipitation has not shown a significant trend, but decadal to multi-decadal variabilities are apparent. Annual precipitation in the periods of 1901–1920, the mid-1940s to early 1960s and post-2010 were higher than normal and higher than the rest of the whole period (Fig. 6). The years 1911 and 1925 had the highest and lowest precipitation in the entire period, respectively; 1924–1929 and 1938–1944 had continued low precipitation. Precipitation in China has increased significantly since 2007. Each of the last 8 yr had annual precipitation well above normal, with 2016 being the second-largest precipitation year in the past 120 yr. It is also interesting to note that the 2 periods of higher precipitation (1903–1923 and 1945–1964) in the past 120 yr each lasted about 20 yr. Due to the sparseness of observations in the early years in the west, the result shown in Fig. 6 mainly reflects the precipitation change in the eastern monsoon region of the country (Zhan & Ren 2023 in this special issue).

The regional average annual precipitation anomaly percentage in China has significantly increased since 1961 (1.2% decade^{-1}) (Fig. 7a), and the 10 yr average annual precipitation anomaly percentage from 2010–2019 was 5.2%, which is higher than any other decade in the 60 yr period. In terms of regional patterns in precipitation change, the annual precipitation anomaly percentage showed a clear increasing trend in Northwest China and most parts of the Qinghai-Tibet Plateau, central and northern northeast China, east China and south China. The increase in western northwest China was even more significant, which exhibited a maximum trend of more than 6% decade^{-1} (Fig. 7b). However, the annual precipitation anomaly percentage in most parts of north China, central China and southwest China have shown a decreasing trend. Among these regions, the lower reaches of the Yellow River, the Bohai Rim area and most of Yunnan province have experienced significant decreases in precipitation.

In contrast to previous studies, including those using the same station network data without under-catch bias correction (Ren et al. 2015) and

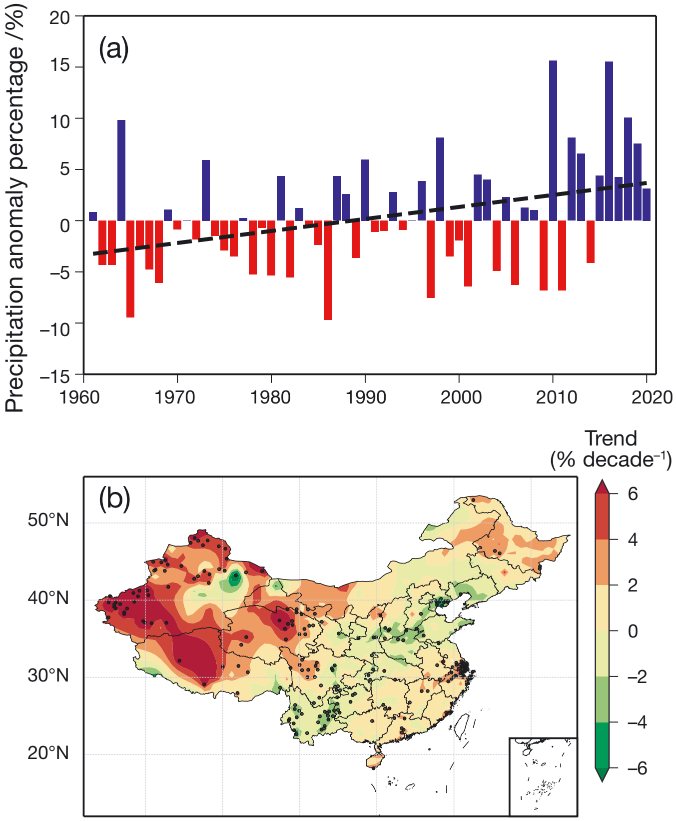

Fig. 7. (a) Time series and (b) spatial distribution of the trend in annual precipitation anomaly percentage in China from 1961–2020. Dashed line in (a) shows the linear trend; reference climate period for calculating the anomaly is 1981–2010. Dots in (b) indicate stations at which the trends passed the significance level test ($p < 0.05$)

the analysis using the same station network data with under-catch bias correction (Zhang et al. 2020), the results obtained in this study showed a significant increase in annual precipitation anomaly percentage in China as a whole. This may be mainly related to the update of data to 2020 in this analysis. In the past 6 yr, annual precipitation has been consistently high (Figs. 6 & 7a), which may have made a significant contribution to the positive trend in precipitation in the past 60 yr.

4. SUMMARY AND OUTLOOK

This article updates the analysis of SAT and precipitation changes in Asia and China since the early and mid-20th century. The annual mean SAT in different regions showed a significant upward trend, and climate warming in high latitudes and the Qinghai-Tibet Plateau (high altitude) was more obvious. The rate of SAT increase was faster in winter and spring. Across the entire Asian region, 2020 was the warmest year of the past 120 yr. Since 2000, mainly due to rapid warming in high latitudes, annual mean SAT changes in Asia were characterized by a continuous upward trend; however, a slowdown of climate warming in China, especially in northern and southeastern regions, is also prominent, though the characteristics of slowed warming on the Qinghai-Tibet Plateau are not as obvious. The overall SAT change in Asia is similar to that of high-latitude regions of the continent.

Since the beginning of the 20th century, the annual precipitation anomaly percentage in Asia has shown a significant increase. The increase mainly occurred in high latitudes, Central Asia, western China and other smaller regions. In the monsoon regions of East Asia and South Asia, precipitation changes in the past 120 yr were characterized by a decreasing trend. The spatial consistency of precipitation changes in the past 60 yr has been low, but the overall change has shown an upward trend in the past 20 yr. The phenomenon of excessive precipitation in the monsoon region of eastern China in the past 10 yr is rare in the past 60 yr. Since 2012, the annual precipitation in China has been higher than normal for 8 consecutive years.

This article not only updates the SAT and precipitation time series of the nested regions in the past 60 yr but also reports results of the latest analysis of the SAT and precipitation changes in Asia and China in the past 120 yr by incorporating more complete and long-term climate data. These data reveal the characteristics of multi-decade-scale variability and the status and particularity of the current climate in the history of instrumental observations. This analysis will enable a more in-depth understanding of the temporal and spatial patterns and causes of climate change and variability in Asia and China, and can provide scientific information for the attribution, projection and impact assessment of climate change in the different regions.

The uncertainty in the monitoring and analysis of SAT and precipitation changes in Asia is mainly related to the spatial coverage and quality of historical observational data (Kennedy et al. 2011, Huang et al. 2020). The uncertainty is likely to be large in regions with insufficient observations, including North Asia, Central Asia and South Asia (Fig. 1c,d) (Thorne et al. 2016). The sparse observational sites and discontinuous records in the period before the early 1960s, for example, is likely to have affected the estimates of averages and trends in Asia and China. Even in the recent 6 decades, the spatial coverage of data is seriously inadequate in the western part of China, including the Qinghai-Tibet Plateau, which may have an impact on climate change monitoring and research results across the country. However, the uncertainty of data coverage and its change with time would be much smaller than the estimates of the trends, mainly due to the relatively even distribution and higher completeness of the early data in both Asia and China, since the first year of the analysis was 1901 rather than the mid-19th century (Brohan et al. 2006).

Except for the recent 60 yr of SAT and precipitation data series, the urbanization bias in temperature data in all regions, as well as systematic biases in precipitation data mainly due to under-catch related to wind speed change, have not been adjusted, and this may have, to a certain extent, affected the estimates of regional average long-term trends in SAT and precipitation (Sun et al. 2013, Zhang et al. 2021). These systematic biases may have affected the determination of extreme climate years and the SAT ranking of the past 5 yr.

Obviously, further study is needed to resolve these issues. However, the uncertainties together would account for less than half of the estimated trends in both temperature and precipitation data series, as reaffirmed in previous analyses involving global land and the Chinese mainland (Brohan et al. 2006, Wen et al. 2019, Y. Zhang et al. 2020, P. Zhang et al. 2021). These uncertainties, as mentioned above, are assessed in the other papers published in this special issue.

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