ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 29, NO. 5, 2012, 958–977

Recent Progress in Studies of Climate Change in China

REN Guoyu*[1] (任国玉), DING Yihui[1] (丁一汇), ZHAO Zongci[1] (赵宗慈), ZHENG Jingyun[2] (郑景云), WU Tongwen[1] (吴统文), TANG Guoli[1] (唐国利), and XU Ying[1] (徐 影)

[1]*Laboratory for Climate Studies, National Climate Center, China Meteorological Administration, Beijing* 100081

[2]*Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing* 100101

(Received 15 October 2011; revised 6 February 2012)

ABSTRACT

An overview of basic research on climate change in recent years in China is presented. In the past 100 years in China, average annual mean surface air temperature (SAT) has increased at a rate ranging from 0.03°C (10 yr)$^{-1}$ to 0.12°C (10 yr)$^{-1}$. This warming is more evident in northern China and is more significant in winter and spring. In the past 50 years in China, at least 27% of the average annual warming has been caused by urbanization. Overall, no significant trends have been detected in annual and/or summer precipitation in China on a whole for the past 100 years or 50 years. Both increases and decreases in frequencies of major extreme climate events have been observed for the past 50 years. The frequencies of extreme temperature events have generally displayed a consistent pattern of change across the country, while the frequencies of extreme precipitation events have shown only regionally and seasonally significant trends. The frequency of tropical cyclone landfall decreased slightly, but the frequency of sand/dust storms decreased significantly. Proxy records indicate that the annual mean SAT in the past a few decades is the highest in the past 400–500 years in China, but it may not have exceeded the highest level of the Medieval Warm Period (1000–1300 AD). Proxy records also indicate that droughts and floods in eastern China have been characterized by continuously abnormal rainfall periods, with the frequencies of extreme droughts and floods in the 20th century most likely being near the average levels of the past 2000 years. The attribution studies suggest that increasing greenhouse gas (GHG) concentrations in the atmosphere are likely to be a main factor for the observed surface warming nationwide. The Yangtze River and Huaihe River basins underwent a cooling trend in summer over the past 50 years, which might have been caused by increased aerosol concentrations and cloud cover. However, natural climate variability might have been a main driver for the mean and extreme precipitation variations observed over the past century. Climate models generally perform well in simulating the variations of annual mean SAT in China. They have also been used to project future changes in SAT under varied GHG emission scenarios. Large uncertainties have remained in these model-based projections, however, especially for the projected trends of regional precipitation and extreme climate events.

Key words: overview, temperature, precipitation, extreme climate, climate change, instrumental records, proxy data, detection, attribution, projection, climate model, China

Citation: Ren, G. Y., Y. H. Ding, Z. C. Zhao, J. Y. Zheng, T. W. Wu, G. L. Tang, and Y. Xu, 2012: Recent progress in studies of climate change in China. *Adv. Atmos. Sci.*, **29**(5), 958–977, doi: 10.1007/s00376-012-1200-2.

1. Introduction

In recent years, under the national key research projects for the "Eleventh Five-Year Period (2006–2010)—Study and Demonstration of Response Techniques to Global Environment Change and Monitoring, Detection, and Prediction of Major Extreme Climate Events and Meteorological Hazards", two research themes have emerged: (1) detection, attribution and projection of regional climate change including extreme weather and climate events changes, and (2) assessment of climate change impact on natural and human systems. To facilitate synergetic studies on fundamental scientific issues of climate change and its

*Corresponding author: REN Guoyu, guoyoo@cma.gov.cn, gyren@homeway.com.cn

impacts, vulnerability, and adaptation, the China Meteorological Administration (CMA), Ministry of Water Resources (MWR), Chinese Academy of Sciences (CAS), and the National Natural Science Foundation of China (NNSF), among others, have also supported related research works.

Following the tradition of previous studies, recent research has focused on (1) investigating the evolutionary behaviors in climate change and variation on different temporal and spatial scales over mainland China, (2) detecting regional climate response signals in the context of global climate change, and (3) projecting future climate change trends and assessing their impacts on agriculture, water resources, and ecological and coastal systems. These recent research efforts have given more attention to changes of frequency and intensity in extreme weather and climatic events, possible causes of regional climate change, development of global climate system models, and climate reconstruction for different historical periods, among others.

Notably, Chinese climate scientists have contributed numerous published scientific findings, many of which have been reflected in Committee of Second National Assessment Report on Climate Change (2011). This article summarizes some of these recent findings related to detection, attribution, and projection of climate change in mainland China, and it briefly discusses some of the existing challenges in these areas of study.

2. Observed mean climate change

2.1 *Temperature change*

Instrument-based observation data in China can be traced back to 1841, although atmospheric observation was interrupted many times in earlier years. Only about a dozen weather stations made observations from the mid-19th century to the beginning of the 20th century, and these stations were mostly distributed along the coastal regions. In the 1920s and 1930s, the Chinese government set up >700 meteorological observatories, but only ∼100 stations retained their observational records; the stations with records of continuous measurements number only a few dozen. Station numbers significantly declined during the 1940s due to war. Complete weather records from most stations are available only after 1950, when a new meteorological station network was gradually set up, filling gaps in western China and other areas in which data were previously sparse.

Zhang and Li (1982) created an average annual mean surface air temperature (SAT) series based on a monthly mean SAT dataset with a five-grade classification system using a region-dividing method according to SAT patterns with data from 137 stations across China. For periods before 1950 when observational records were missing, the available readings were interpolated. But for western areas, where some data were badly insufficient or completely missing, the SAT values from the surrounding areas, including neighboring countries, were interpolated to fill in the gaps. Lin et al. (1995) established the country-averaged SAT series (i.e., the LYT series) for the past ∼100 years in China. Using instrument-based SAT measurements, the SAT graded data, and proxy data for the data-sparse west region, Wang et al. (1998) divided China into 10 regions, with five stations for each region, and created another average annual mean SAT anomaly series for China (i.e., the WYG series), to which they applied an area-weighted method.

Because different methods were used to calculate daily mean temperature prior to 1950, however, serious inhomogeneities in the SAT data series were caused for the early periods. Based on the observations from 616 stations across China, Tang and Ren (2005) constructed a country-averaged annual mean SAT series (i.e., the TR series) using a method for homogenizing the data through calculating the daily and monthly mean values of maximum and minimum temperatures. This approach for establishing the country-averaged annual mean SAT series significantly improved the homogeneity of the data, making it consistent with data that had been used abroad for calculating daily and monthly mean SAT values. Since then, the SAT records before 1950 have undergone further quality control, in which data corrections and remedies have been implemented; 291 more evenly distributed stations were selected to update the country-averaged SAT series (Tang, 2006, hereafter referred to as TD series). In addition, Wen et al. (2006) constructed another mean SAT anomaly series (1901–2003) for China using the University of East Anglia/Climate Research Union (UEA/CRU) global grid data (i.e., the CRU series).

With these SAT sequences extended to 2007, Fig. 1 shows the variation curves of the five major SAT series. Clearly, the curves are generally consistent in terms of variation trends, all showing the two warming episodes in the past 100 years. However, they vary significantly in some segments before 1950. The discrepancies may be partially related to different datasets and statistical methods used in the analyses, among other factors.

Table 1 indicates that the SAT change rates in China from the five series in 1906–2005 range from 0.03°C $(10\ \text{yr})^{-1}$ to 0.12°C $(10\ \text{yr})^{-1}$, with the CRU series giving the highest rate [about ∼0.12°C $(10\ \text{yr})^{-1}$] followed by the TR [0.10°C $(10\ \text{yr})^{-1}$], TD [0.09°C $(10\ \text{yr})^{-1}$], and WYG [0.05°C $(10\ \text{yr})^{-1}$] se-

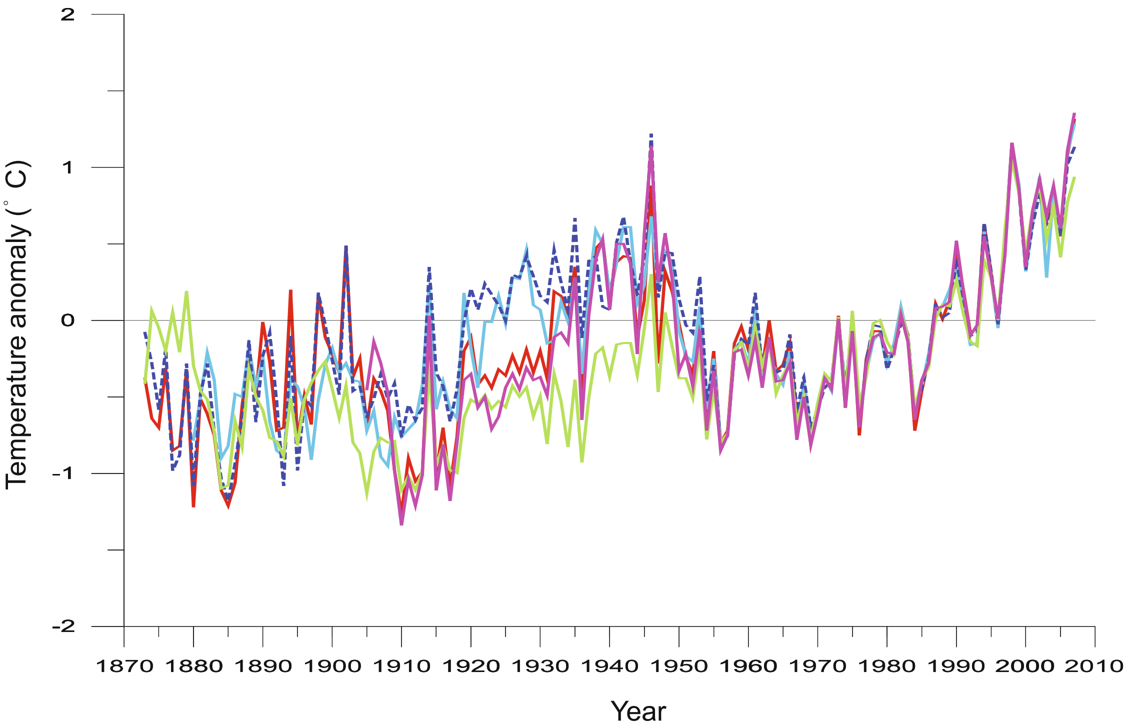

Fig. 1. Region-averaged annual mean air temperature anomalies of China (relative to annual mean values in 1971–2000): light blue: WYG curve (1880–2007); blue dots: LYT curve (1873–2007); pink: TR curve (1905–2007); red: TD curve (1873–2007); green: CRU curve (1873–2007). (Tang et al., 2009. Reproduced with permission of *Advance in Climatic Change Research*.)

ries; the LYT series yielded the lowest rate [0.03°C (10 yr)$^{-1}$]. The main reasons for these discrepancies were the larger differences in SAT changes among these series from 1900 to 1950. Considering all of the mean values of these series, the rate of change in the annual mean SAT in China in the past 100 years was ~0.08°C (10 yr)$^{-1}$. Considering the biases in the estimates, the warming rate was (0.08±0.03)°C (10 yr)$^{-1}$ at a 95% confidence level (Tang et al., 2009).

Table 1. Surface air temperature (SAT) trends in China during the past 100 years [1906–2005 and 1908–2007; units: °C (10 yr)$^{-1}$]. (Tang et al., 2009, Reproduced with permission of *Advances in Climatic Change Research*.)

Series	1906–2005	1908–2007
WYG	0.053	0.059
LYT	0.034	0.042
TR	0.095	0.111
TD	0.086	0.096
CRU	0.120	0.127

Note: WYG: (1880–2007, updated from dataset of Wang et al., 1998); LYT: (1873–2007, updated from dataset of Lin et al., 1995); TR: (1905–2007, updated from dataset of Tang and Ren, 2005); TD (1873–2007, updated from dataset of Tang, 2006); CRU (1873–2007, updated from dataset of Jones et al., 1999).

In the past 100 years, climate warming has been more evident in Northeast, North and Northwest China. Similar warming has also been detected in the eastern and southern coastal regions of China and most areas of the Qinghai-Tibetan (Q-T) Plateau. In contrast, the warming in South and Southwest China has been relatively weaker. For the period 1906–2005, which was used by the IPCC AR4 (IPCC, 2007), northeastern China, Xiangjiang, and Taiwan underwent significant warming, but Southwest, South, Central China as well as the eastern rim of the Q-T Plateau underwent decreasing SAT trends to varying extents.

In the past 50 years, the number of weather stations has increased rapidly, providing much better data and coverage. The analyses of these data have shown a more significant warming trend over China in this period. In 1951–2007, the overall annual mean SAT, as obtained from the dataset from the 730 national stations, increased by nearly 1.40°C, with a changing rate of 0.25°C (10 yr)$^{-1}$, indicating an accelerating warming trend in recent decades (Ren et al., 2005a).

The spatial distribution of the annual mean SAT change in 1951–2008 (Fig. 2) indicates warming trends

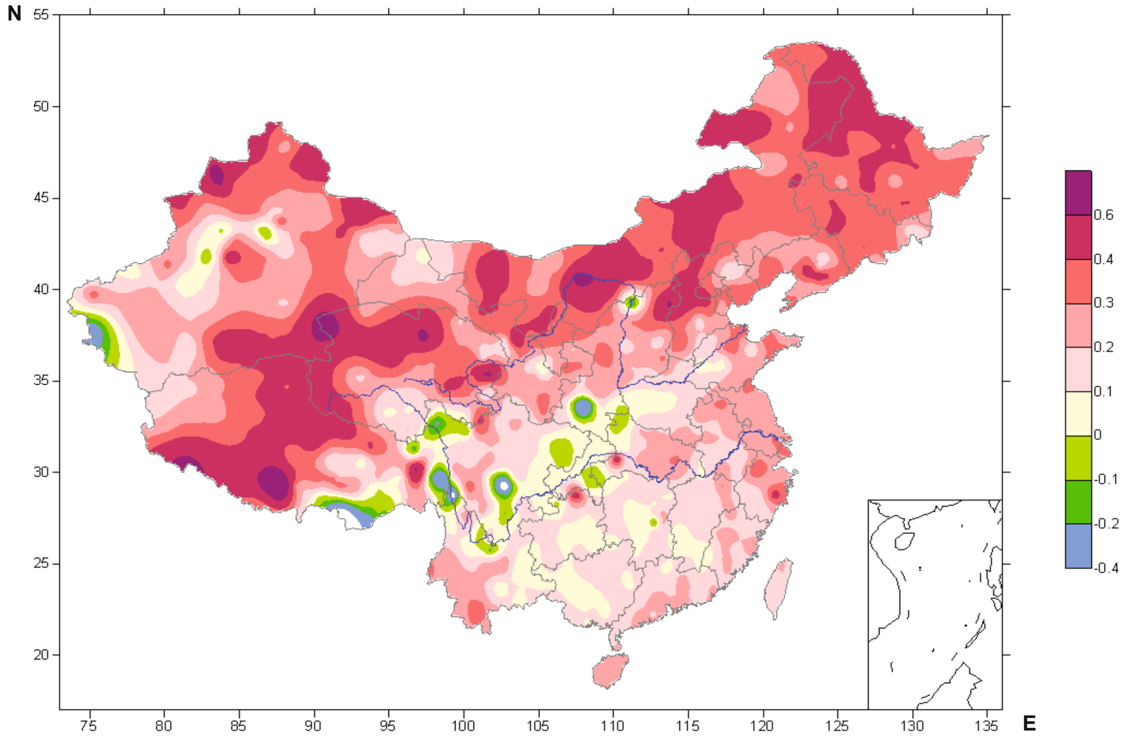

Fig. 2. Station-based distribution of linear trends of annual mean surface air temperature during 1951–2008 [units: °C (10 yr)$^{-1}$].

in most parts of the country, with the most significant warming in the north, especially north of 34°N. In this region, the warming rate is generally >0.30°C (10 yr)$^{-1}$, with the most significant warming in the northern part of North China, the central and eastern Inner Mongolia, the northern part of Northeast China, northern Xinjiang, northeastern Qinghai, and the central Gansu. In these areas the warming rate varied from 0.40°C (10 yr)$^{-1}$ to 0.60°C (10 yr)$^{-1}$. South of 34°N, warming differed among regions. The warming rates in the Yellow River, Yangtze River, and Huaihe River basins ranged from 0.20°C (10 yr)$^{-1}$ to 0.30°C (10 yr)$^{-1}$. Warming was slightly greater in most coastal areas of South China, with a rate of 0.30°C(10 yr)$^{-1}$ to 0.40°C (10 yr)$^{-1}$ in a few areas. The warming rates in areas south of the Yangtze River were generally between 0.10°C (10 yr)$^{-1}$ and 0.20°C (10 yr)$^{-1}$. In addition, warming was relatively faster in the Q-T Plateau, where observation stations are sparse, with rates ranging from 0.20°C (10 yr)$^{-1}$ to 0.50°C (10 yr)$^{-1}$. Less warming occurred in Southwest China, including eastern Yunnan, much of Guizhou, eastern Sichuan, and Chongqing. In this region, there was a cooling trend before the early 21st century. The cooling trend remains in some sporadic areas of the region in spite of the warming trend at most stations in the past 10 years (Ren et al., 2005a).

The seasonal characteristics of average SAT changes over the past 100 years and the past 50 years are also obvious. Since the early 20th century, the mean temperatures across China increased seasonally at rates of 0.19°C (10 yr)$^{-1}$ (winter), 0.16°C (10 yr)$^{-1}$ (spring), and 0.06°C (10 yr)$^{-1}$ (autumn), respectively, while the mean SAT increase in summer was only 0.01°C (10 yr)$^{-1}$. Two warming episodes in the past 100 years occurred in the 1940s and 1990s; the largest positive anomalies appeared in summers with relatively small SAT differences over all seasons for the warming period in the 1940s. The largest positive anomalies appeared in winters with relatively large SAT differences between seasons for the warming period in the 1990s.

With regard to the rapid warming over the past 50 years, significant effects of local human activities, especially the systematic warming biases caused by urbanization in the vicinity of weather stations have been revealed (Ren et al., 2005a, 2008; Zhang et al., 2010). Since the 1950s, rapid urbanization in China has significantly affected SAT observations at most national stations. Without the urbanization effect, the country average annual mean warming for the past 50 years should be less (Ren et al., 2005a). The warming trend of the past 100 years should also be more moderate without the urban heat-island bias, but no analysis has been made so far due to the lack of reference stations in the early 20th century.

Early research generally showed that the annual mean SAT in China in 1951–1989 increased by 0.06°C $(10\ \mathrm{yr})^{-1}$ and that the effect of urbanization on observations from city stations was significant (Zhao, 1991). The latest research has used data from many more observational stations and has applied more sophisticated analysis methods. Results indicate that, in the warming trend of annual mean SAT observed by national reference climate stations and national basic meteorological stations in 1961–2004, urban warming was within (0.06–0.09)°C $(10\ \mathrm{yr})^{-1}$, and even up to 0.10°C $(10\ \mathrm{yr})^{-1}$ for some regions, with a contribution of 27% to the overall warming for annual mean temperature and 18%–38% for seasonal mean temperature over the country on a whole (Ren et al., 2008; Zhang et al., 2010; Ren and Ren, 2011). Therefore, the enhanced urban heat-island effect had significant impacts on the increasing SAT trends as estimated by the observations acquired from the national meteorological stations. This effect is different from that of large-scale land-use change, and it should be considered as a kind of systematic error caused by local human activities, and it should be removed from the current datasets used for studies of climate change.

In addition to the urbanization effect, two other issues affect the analyses of SAT in China. One issue is the insufficiency of the data prior to the 1950s, especially for western regions of the country. The majority of the past analyses did not consider this problem, but it can be solved to some extent using proxy data and records from neighboring countries. Another issue is the inhomogeneity induced by station relocation and instrumentation prior to the 1950s. Although this problem is difficult to solve due to the lack of metadata and reference stations, it does not cause as serious a systematic bias in the estimates of the regional SAT trends as the urbanization effect. Using a combination of methods to detect and adjust the inhomogeneities of SAT data for the period 1900–1950 is expected to produce more reliable analyses.

2.2 *Precipitation change*

Similar to research on SAT change, analyses of precipitation change in China for the past 100 years were also limited by the shortage of early observations. Moreover, because the spatial representation of precipitation data is far lower than for temperature, it is difficult to obtain a country average annual precipitation series of the past 100 years with sufficient credibility, even using proxy data for western regions. Wang et al. (2000) established a seasonal precipitation anomaly series based on data from 35 weather stations east of 100°E. Data used in the work include monthly precipitation amount, precipitation grades and proxy precipitation records. The proxy records are mainly comprised of historical document data from the end of the 19th century and the early 20th century. During 1951–1990, the correlation coefficient of annual precipitation calculated from these 35 stations with that from a more complete dataset of 384 stations was 0.86, indicating that these 35 stations are able to reflect large-scale precipitation variability of the region to a large extent. Recently, the number of stations with the long records in the region was increased to 71 (Pu et al., 2007), representing a better spatial coverage of precipitation data for eastern China over the past 100 years.

Figure 3 shows the curve of annual precipitation anomalies over eastern China in 1880–2007. Annual precipitation in eastern China exhibits no long-term trend; however, decadal to multi-decadal variability is more obvious. The analysis of power spectrum shows that a 26.7-year cycle is statistically significant, so it is not possible to determine whether precipitation in eastern China is correlated with global warming. Seasonal precipitation also shows evident decadal variability, with larger magnitudes in summer and autumn, and seasonal precipitation is more consistent with the annual total precipitation variability. Variations in winter and spring precipitation are smaller. According to annual totals, more precipitation occurred in the 1880s, 1910s, 1930s, 1950s, 1970s, and 1990s over eastern China.

Higher-quality data are available for the past 50 or 60 years, and the recent analyses using these data revealed no significant long-term trends for annual precipitation, in spite of large decadal variability, with an obvious increase from the 1980s to the 1990s (Ren et al., 2005b; Zhai et al., 2005; Chen et al., 2010c). A decrease in annual precipitation in China occurred for the past 10 years mainly due to the evident decrease of precipitation in the Yangtze River basin (Ding et al., 2008; Chen et al., 2010c). In addition, change in snow depth and number of snow days in the eastern and central Q-T Plateau have been analyzed by You et al. (2011). They concluded that the regional average winter (DJF) depth and days of snow cover increased from 1961 to 1990 but decreased from 1991 to 2005, with an insignificant upward trend for the whole period.

3. Observed extreme climate change

Currently a key scientific question has arisen: Are any significant changes in major extreme weather and climate events (i.e., extreme climate events) in a large

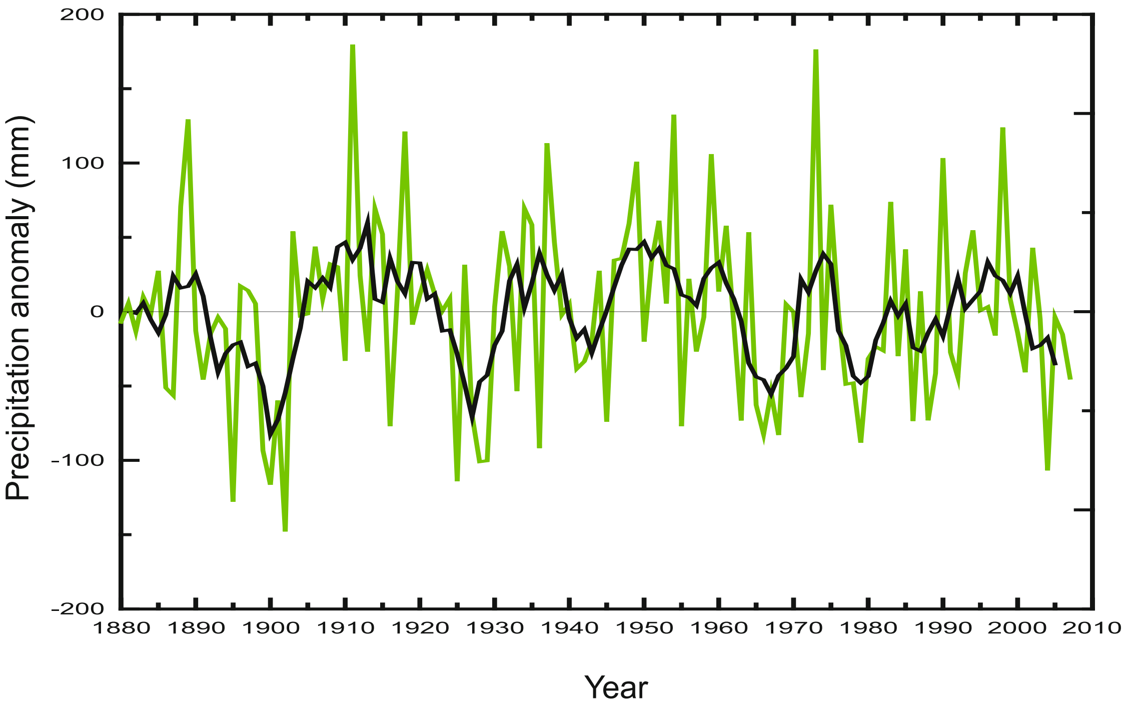

Fig. 3. Region-averaged annual precipitation anomaly (mm) based on 71 weather stations in the eastern China in 1880–2007 (relative to the mean value in 1971–2000); Black line: 5-year smoothing average. (Updated from dataset of Wang et al., 2000 and Pu at al., 2007.)

region like China detectable for the past half a century when significant climate warming occurred globally and across China? Many related studies have been conducted in China, and recent analyses have indicated that changes in the frequency and intensity of major extreme climate events in the country are very complex and that the changing characteristics of different extreme climate events in different regions vary significantly (Gong and Han, 2004; Committee of National Assessment Report on Climate Change, 2007; Ding and Ren, 2008; Ren et al., 2010).

Generally, significant trends in frequency and intensity of the extreme climate events related to temperature have occurred in the country overall; but significant long-term changes have occurred in the extreme climate events related to precipitation only on subregional scales (Table 2). During the past 50 years, frequency and intensity of cold-wave and low-temperature events in China significantly decreased, especially cold-wave events in northern China in the winter half-year and low-temperature and cold injury events in Northeast China in summer (Qian et al., 2007; Ding and Ren, 2008). The number of abnormally cold nights, cold days, and frost days significantly decreased and weakened, and cold climate extremes became more moderate; the number of warm nights and warm days generally increased. However, the frequency of extreme high temperature events across the country did not significantly increase, although these events exhibited significant decadal variability (Sun et al., 2011) and increased to certain extent in Northwest China, North China and the southern part of Northeast China, and decreased in the Yangtze River Basin and southeastern coastal areas after the 1980s (Qian et al., 2007; Ren et al., 2010).

In the southeastern, middle, and lower reaches of the Yangtze River, and in most parts of western China, the frequency and intensity of heavy rain or intense precipitation events increased; however, in North China, the central and southern Northeast China, and parts of Southwest China, intense precipitation decreased and the extent and intensity of meteorological drought increased (Zhai et al., 2005; Yang et al., 2008; Wang and Yan, 2009). Based on the overall average in China, 24-hour maximum precipitation did not significantly change; but it decreased over 1956–1978 and generally increased afterward (Chen et al., 2010c; Fig. 4). Maximum precipitation for three consecutive wet days across the country was broadly consistent compared with 24-hour maximum precipitation (Ren et al., 2010). Intense snowfall events during 1962–2000 decreased over eastern China and increased over northern Xinjiang and the eastern Tibetan Plateau (Sun et al., 2010).

Table 2. Main conclusions and confidence levels of studies of the changes in extreme climate events in China since the 1950s.

Extreme climate event	Period	Observed trend	Confidence level
Rainstorms or intense precipitation events	1951–2008	No significant trend nationwide. It increased in Southeast and Northwest China, however, and decreased in North and Northeast China. The intensity of heavy rain or extreme strong precipitation events generally increased in most regions.	High
Extreme rainfall	1951–2008	The maximum rainfall of one-day and three-day heavy rains increased to some extent, being more evident especially in the south, but insignificant national wide.	High
Extent and intensity of droughts	1951–2008	Meteorological drought index (CI) and ratio of drought extent across the country showed an increasing tendency with a significant trend in North China and the southern part of Northeast China, but decreased in the western China.	High
Frequency of cold wave and low temperature events	1951–2008	It declined and weakened in most areas of the country, particularly evident in the north. From the 21st century, it increased somewhat; but its long-term downward trend continued.	Very high
High temperature events	1951–2008	No significant trend nationwide. But, it increased in North China and saw stronger decadal fluctuations in the middle and lower reaches of the Yangtze River Basin. It has increased since the 1990s.	High
Typical cyclone and typhoons	1954–2008	The number of typhoons landed in China has decreased, and rainfall and its effects associated with TCs also reduced annually.	High
Sand and dust storms	1954–2008	The frequency in the north significantly reduced. There was slight increase after 1998; but it became significantly less relative to that before 1980s.	Very high
Thunder storms	1961–2008	It has significantly decreased in the current study area in the eastern region.	High

Note: The description for the confidence level of assessment findings adopts the provisions by the Working Group II of IPCC Fourth Assessment Report. Very high: 90% chance of being correct; high: ∼80% chance of being correct; medium: ∼50% chance of being correct; low: ∼20% chance of being correct; very low: <10% chance of being correct. CI is a meteorological drought index developed by the National Climate Center (Zou et al., 2010).

In North China and the western part of Northeast China, the climate is generally dry, and the frequency of droughts is normally high. During the past 50 years, however, the frequency of meteorological droughts and drought area percentages in both northern and northeastern China significantly increased (Zou et al., 2010). However, the climate in southern China including the mid and middle reaches of the Yangtze River is normally humid, and more frequent flood events occurred especially in the 1990s. Overall, the frequency of meteorological droughts and the extent of drought regions in southern China remained relatively stable, while the extent of drought regions in the western China decreased (Ding et al., 2008; Zou et al., 2010). Extreme climate change associated with precipitation in the past 50 years had a large negative impact on the densely-populated monsoon region in eastern China. Tropical cyclones (TCs) or typhoons that landed on or affected China did not increase in frequency and intensity. Analyses based on the observational records suggest that TCs actually decreased in number over the past 50 years and that the total TC-induced precipitation in mainland China also significantly declined (Ren et al., 2007; Yang et al., 2009). The small increase in the number of severe TCs making landfall on mainland China in 2000–2010 did not affect this long-term trend overall.

Dust storms in the past 20 years have been less frequent in northern China in general. Although their frequency increased somewhat at the turn of the century, it remained far below that prior to the 1980s (Zhou and Zhang, 2003; Ding and Ren, 2008). Zou et al. (2006) investigated the frequency of severe temperate storms in mainland China over 1954–2004, and they found significant decreases in northeastern, central and western China in winter and spring. This

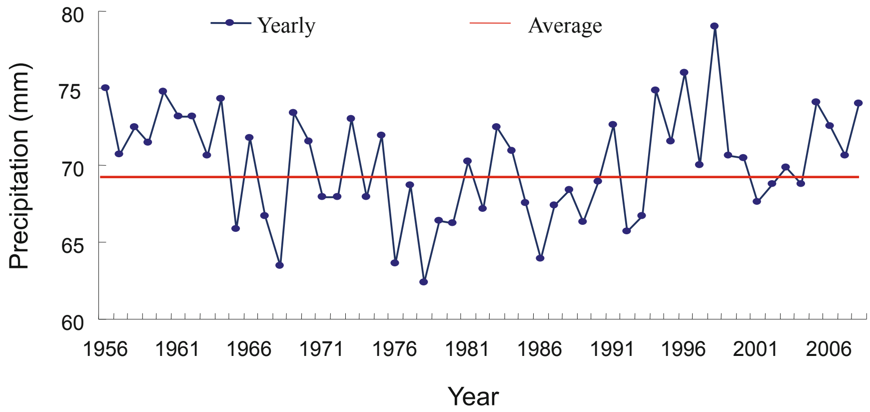

Fig. 4. Region-averaged linear trend of 24-h maximum precipitation in China during 1956–2008 (units: mm). (Chen et al., 2010c. Reproduced with permission of *Advance in Climatic Change Research*.)

result is consistent with the decline of the frequencies of strong wind events and dust storms during approximately the same period (Zhang and Ren, 2003; Chen et al., 2010a; Jiang et al., 2010).

Overall, current research findings indicate that some major extreme climate events and indicators in China have increased while others have decreased. Extreme SAT changed across the country, with the abnormally cold events significantly decreasing in frequency and intensity, while abnormally warm events increased. The changes in extreme temperature events were closely linked to the rising mean SAT. Extreme precipitation, especially intense precipitation, however, was highly regional and seasonal in terms of changes in frequency and intensity. The intensity of intense precipitation appeared to increase in most regions. Changes in the frequency of intense precipitation events were broadly consistent with those of annual total precipitation. The reasons behind the increased intensity of precipitation events remain unknown. TCs affecting the southeastern coast of China tended to decrease, and dust storms in the northern China and thunderstorms in eastern China tended to be significantly less frequent and weaker. Overall, the reasons for temporal change in major extreme climate events over the past 50 years in China are very complicated; they show no overall increase in both frequency and intensity (Ren et al., 2010, 2011).

Detection of extreme climate change calls for more sophisticated indices and statistical methods. The current extreme climate indices, which are not yet fully fledged, need to be improved continuously in line with regional and local circumstances (Feng et al., 2008). Linear trend analyses of extreme climate event series largely rely on the selected time periods. The trends obtained are also sensitive to the extreme values selected at the tails of the frequency distribution. Therefore, the question of how to more accurately calculate and analyze linear trends remains to be further addressed.

It is necessary to enhance the research in detection and adjustment of inhomogeneities of daily data. Because extreme values and extreme climate events are of low probability, the spatial scale of occurrences of any extremes is generally smaller, and samples are limited. Inhomogeneities resulting from various non-natural factors such as station relocation and instrumentation can seriously affect the analyses of extreme climate changes (Li et al., 2004; Yan and Jones, 2008). Over the years, a large number of analyses have been based on observations that were not homogenized. In the future it is highly necessary to assess and adjust the inhomogeneities of daily temperature and precipitation data as appropriate.

Bias in surface observations due to urban effects comprises another important issue. Factors such as the gradually changing environment around weather stations and increasing magnitudes of urban heat islands can significantly affect linear trend estimates of extreme climate index series, especially the extreme temperature index series, in which a systematic bias may be caused by the local human interferences (Ren et al., 2008; Zhou and Ren, 2009). Recently, Zhang et al. (2011) and Zhou and Ren (2011) found a large urban bias in the extreme temperature index series related to daily minimum temperature at a single Beijing station and in a larger region of North China. The urban effects on the upward trends of region-averaged summer days, tropical nights, warm nights and extreme values of minimum temperature, and the downward trends of frost days, cold nights and diurnal temperature range (DTR), for example, were all statistically significant in North China over the period 1961–2008 (Zhou and Ren, 2011). The systematic bias, which may be the main source for uncertainty in changing trends in frequency and intensity of extreme temperature events on local and regional scales or even global scales, obviously need to be removed from the existing daily data series.

In addition, comprehensive analyses of national and regional extreme climate change remain inadequate. Previous studies have generally focused only on a single event or a category of extreme climate events. Moreover, the analyses of change in local severe weather events (e.g., thunderstorms and tornadoes) have been made only at the local level. It is also necessary that studies on the mechanisms and causes of regional extreme climate change be enhanced.

4. Historical perspective of contemporary extreme climate change

SAT observation records for the past 100 years are not enough to assess the background of modern climate warming to determine whether the current climate change has exceeded the range of natural climate variability (Jansen et al., 2007). Based on the reconstructed 2000-year temperature series and the 2000-year extreme drought and/or flood events series in eastern China, a preliminary assessment of the abnormalities of climate change in China in the 20th century has been conducted.

4.1 *Temperature changes and uncertainties in the past 2000 years*

In recent years, paleo-climatologists have reconstructed several series of high-resolution SAT changes (including cold/warm patterns) in China or its subregions using such proxy data as historical documents, tree rings, ice cores, lake sediments, and stalagmites (Ge et al., 2003; Yang et al., 2002; Chu et al., 2005; Tan et al., 2003; Thompson et al., 2006; Liu et al., 2007). Because they used different proxy data and reconstruction approaches, these series contain irregularities in temperature variations and even larger discrepancies in some time windows.

The winter half-year temperature changes in eastern China in the past 2000 years reconstructed by Ge et al. (2003) using available instrument-based records and historical documents showed that the temperature anomalies (relative to the mean of 1951–1980) in the 20th century were slightly higher than in the entire warm period in the Song–Yuan dynasties (931–1320 CE), but they were lower than those in the two 100-year warm episodes (1001–1100 CE and 1201–1300 CE) in the Song–Yuan warm period. They were also lower than those in the warmest 100-year episode (651–750 CE) in the Sui–Tang warm period (Ge et al., 2002; Zheng et al., 2002). Viewing China as a whole, the 20th century might have been the warmest segment in the past ∼1000 years, with the 1990s ranking as the warmest decade in terms of mean temperature (Yang et al., 2002). Chu et al. (2005) reconstructed the annual mean SAT time series of the past 1000 years for mainland China using tree-ring data in the west and historical document-based reconstruction in the east from Ge et al. (2002). The SAT series showed the relative warmth of the Medieval Warm Period (MWP) and the marked coldness of the Little Ice Age (LIA). The warmth of the MWP, however, did not seem as evident as previously reported, though the annual SAT at the end of the 11th century and in the mid-13th century might have been higher than that of any decades of the 20th century. The SAT series for the Q-T Plateau in the past 2000 years reconstructed with ice cores by Thompson et al. (2006) showed that a 20th-century warm period existed and temperature increased rapidly, but the MWP and LIA were hardly discernible in this region. This result was supported by a tree-ring based reconstruction of a single site in the Qilian Mountains, northeastern rim of the Qinghai-Tibetan Plateau (Liu et al., 2004).

Ge et al. (2010) systematically collected the 23 high-resolution temperature proxy series published and incorporated them into five different climate subregions (i.e., northeast, central east, southeast, northwest and Q-T Plateau), to assess their respective SAT variations. They showed that, although significant uncertainties existed in the reconstructed temperature series for the periods before the 16th century, the reconstructions for the more recent 500 years gave a higher consistency, especially for the two evident cooling episodes (i.e., 1620s–1710s and 1800s–1860s) and the 20th-century warming period. Notably, the 20th-century warming spatially propagated from west to east and from north to south, namely from the Q-T Plateau, northwest and northeast to the central east and southeast regions. Furthermore, this analysis showed that, in some regions, the warming during the 10th to 14th centuries might be comparable in the magnitude to the warming of the last decades of the 20th century (Fig. 5).

4.2 *Extreme drought/flood events in the past 2000 years*

In records of historical disasters in the past 2000 years, droughts and floods are dominant. Some of these meteorological disasters were so severe in length

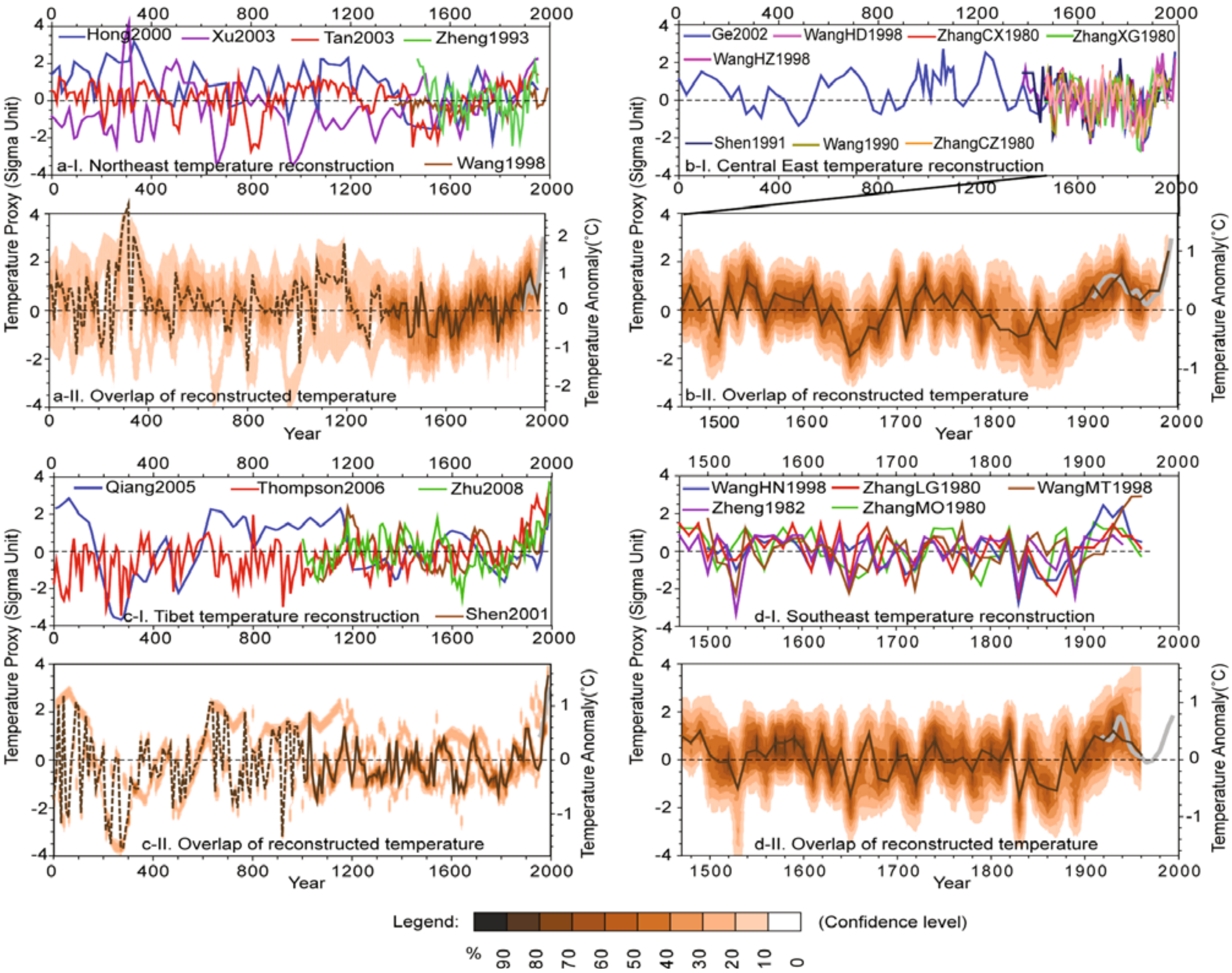

Fig. 5. Reconstructed temperatures and their decadal uncertainty ranges in Northeast (a), Central East (b), Tibet (c) and Southeast (d). (I) Different sources with 10-year resolution; (II) The uncertainty range of reconstruction series. The bold-black curve is the regional temperature coherent series, the part with fewer series is marked with a dashed bold-black curve, and the bold-gray curve is the 10-year smoothed instrumental temperature. The right axes represent the temperature anomaly. (Ge et al., 2010. Reproduced with permission of American Geophysical Union.)

and devastation that they could claimed thousands of human lives. To analyze the occurrence of these extreme events, Chinese paleo-climatologists have preliminarily identified the characteristics of severe floods and droughts nationwide that lasted for at least 3 years during the past 1000–1500 years. Their investigations have shown that, in view of the climatic conditions in the past 1500 years, the droughts in the past 50 years have not been as severe. Even the three well-known megadroughts in the past 300 years (i.e., the 1719–1723, 1875–1878, and 1927–1930) are also dwarfed by those of the far past (Wang and Chen, 1993; Li et al., 1997; Zhang, 2004; Liang et al., 2006; Hao et al., 2010a).

Using historical records on droughts and floods since the Han dynasty (~2000 years BP), Zheng et al. (2006) and Hao et al. (2010b) reconstructed the annual spatial pattern of droughts and floods at 63 stations, based on the reconstructed wet/dry index series for eastern China, in the past 2000 years. Eastern China was divided into three subregions: North China (34°–40°N), Yangtze River-Huaihe River basin (31°–34°N), and Jiangnan (25°–31°N). It was found that, in the past 2000 years, severe droughts and floods have occurred in clusters (Fig. 6). For eastern China as a whole, for example, severe droughts occurred most frequently in the 4th century, the second half of the 8th century, from the second half of the 11th century to the first half of the 12th century, and in first half of the 17th century. Severe floods occurred more frequently in the first half of the 2nd century, the second half of the 3rd century, the first half of the 9th century,

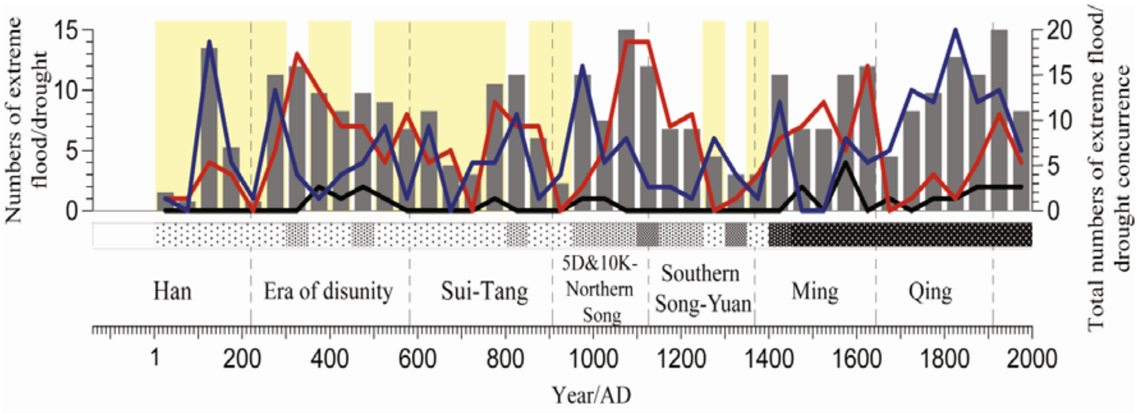

Fig. 6. The numbers of severe flood and/or drought events for each 50-year period during the past 2000 years. Blue line: extreme flood years; red line: extreme drought years; black line: extreme years with drought and flood concurrence in Eastern China; gray bar: total extreme years with flood, drought, and flood and drought concurrence. Yellow bar: the low-confidence involved to the result. The short bars from dark to light in lower panel indicate different confidence levels from full confidence, very high-confidence, high-confidence, medium-confidence, and low-confidence. 5D&10k denote five dynasties and 10 kingdoms.

the second half of the 10th century, the first half of the 15th century, and from the 18th century to the first half of the 20th century. Severe droughts and floods simultaneously occurred relatively frequently in the second half of the 4th century, the second half of the 5th century, the second half of the 16th century, and the second half of the 19th century to the 20th century.

Because of the many gaps in historical records before the northern Song dynasty (~1000 CE), there is more confidence in drought and flood series reconstructed for periods after that time, because more written records are available (Fig. 6).

In addition, when the climate underwent a cooling phase (e.g., Wei, Jin, and North and South dynasties, late Tang dynasty, the first half and mid part of the LIA), severe droughts occurred more frequently in eastern China, with an exception in Qing dynasty (cold period) when severe floods took place more frequently. When the climate was in a warming phase, on the other hand, extreme flood and/or drought events happened generally randomly, with more severe floods in the Han dynasties and more severe droughts in the Song and Yuan dynasties. The frequencies of severe droughts and floods in two other warming phases, the Sui–Tang dynasties and modern times, were near the median level of the past 2000 years.

5. Possible causes for regional climate change

5.1 *Anthropogenic GHG emissions and natural climate variability*

Comparing the temperature changes simulated by climate models with the observed temperature changes, SAT trends and possible causes for the changes in China over the past 100 years have been analyzed. The anomalies in annual mean temperature from 1880 to 2009 are given in Fig. 7. The observed temperature series (WYG) in Fig. 7 was updated from Wang et al. (1998). The observed temperature anomalies indicate a significant warming trend, and also had obvious decadal variability and quasi-periodic oscillations (Zhao et al., 2009a). Since the early 20th century, the warming trend of annual mean SAT as given by the WYG series has been ~0.05°C $(10\ \mathrm{yr})^{-1}$, which is the lower-than-medium level in the five currently available annual mean SAT series (i.e., CRU, TR, TD, WYG, and LYT).

Figure 7 also shows the outputs from two sets of GCMs. The first set includes seven GCMs commonly used by IPCC: CCC (Canada), CCSR (Japan), CSIRO (Australia), DKRZ (Germany), GFDL (USA), HADL (UK) and NCAR (U.S). Consideration has been given to following four emission scenarios: GHG (GG), GHG and sulfate aerosols (GS), SRES A2, and SRES B2. The annual mean SAT anomaly values in 1900–1990 and 1991–2009 were simulated and projected, respectively (Zhao et al., 2008). The second set includes 19 IPCC AR4 models, which took into account the combined forcings of both the natural factors (i.e., solar and volcanic activities) and human emissions (i.e., GHGs and aerosols). The models were used to simulate the annual mean SAT anomaly in 1880–1999 (Zhou and Yu, 2006; Zhou et al., 2008) and then to poject the SAT change in 2000–2009 under the SRES A1B scenario (Jiang et al., 2008).

Compared to the observation data, the two datasets produced by climate models simulated the

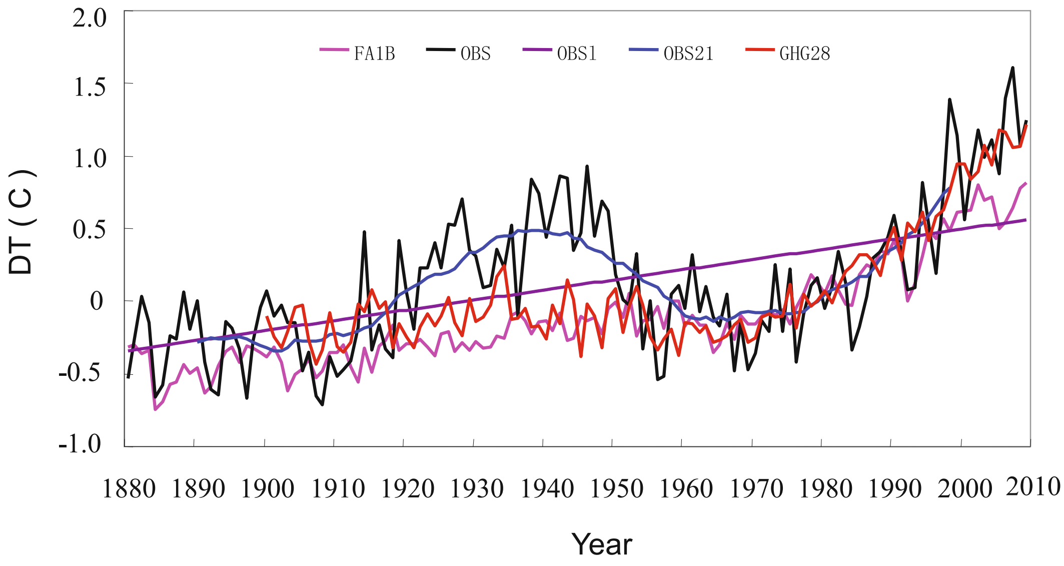

Fig. 7. Observed and simulated evolutions of annual mean SAT anomalies in China over the past 100 years (relative to 1961–1990). Black line: observed changes in annual mean temperature anomaly in China in 1880–2009 with solid black line: linear trend and blue line: smoothed 21-year mean value (calculated based on the data provided by Gong, Wang and Wang, personal communications). Red line: changes of annual mean temperature anomaly in China in 1900–2009 based on the outputs of both simulations and projections from the first set of models ensembles under GG, GS, SRES A2 and B2 scenarios (Zhao et al., 2008). Pink line: variation of annual mean temperature anomaly in China in 1880-2009 based on the outputs of both simulations and projections from the second set of models ensembles (Zhou and Yu, 2006; Zhou et al., 2008; Jiang et al., 2008), taking into account both natural and human emissions under SRES A1B scenarios. (Updated from Zhao et al., 2009a. Reproduced with permission of *Review of Science and Technology*).

warming trend in China for the past 100 years reasonably well. However, they were not able to replicate the significant warming of the annual mean SAT in 1920–1940. The annual mean SAT anomalies for the period from the first and second sets of models were −0.10°C and −0.22°C, respectively. The models were able to replicate the climatic cooling in 1950–1970; the annual mean SAT anomaly for the same period simulated with the two sets of models were −0.18°C and −0.14°C respectively. The climate models also captured the evident warming in 1980–1990 (or 1999) and projected the significant warming from 1991 (or 2000) onward. The linear trend simulated by the first set of models for the past two decades was 0.41°C (10 yr)$^{-1}$, and the linear trend yielded by the second set of models was 0.26°C (10 yr)$^{-1}$, apparently smaller than the warming rate of observation series. The reason for these discrepancies should be addressed in further studies; it may be partially related to the insufficiency of the ocean models to simulate the decadal climate variability. Furthermore, some discrepancies may result from the estimation of the impacts of solar and volcanic activities and from the systematic biases of the observation datasets that originated from urbanization effects as mentioned above.

Considering these uncertainties, the preliminary conclusions can be drawn that the climate models were able to simulate and project the increasing trends of the country-averaged annual mean SAT in the 20th century, especially the significant warming trend in the late 20th century and the beginning of the 21st century. These results indicate that manmade GHG emissions into the atmosphere might have been one of the main influential factors on the surface warming in the past several decades in China. However, it is difficult for the climate models to capture the natural quasi-periodic variations of annual mean SAT in the country. What is more, the simulated and projected climate warming rate was lower than the observed rate for the past two decades, indicating that there are still many issues to be addressed in detection and attribution of regional climate change with existing climate models and observation data.

In addition, natural variability may be an important cause not only of the fluctuation of the country averaged precipitation on the decadal scale in the recent 100 years in eastern China but also of the transforms of the north–south precipitation pattern in the eastern monsoon zone of China (Ding and Ren, 2008). Similarly, the regional differences in the frequency of intense precipitation events might have been mainly related to the natural variability of climate system.

5.2 *Effects of atmospheric dimming/ brightening*

The observational analyses for the past 50 years have shown an evident decrease (dimming) in sunshine duration and total solar radiation reaching the surface up to early 1990s and a slight recovery (brightening) thereafter in mainland China (Ren et al., 2005b; Streets et al., 2008; Zhao et al., 2010). The dimming and brightening process of the atmosphere might have some impacts on the mean temperature, the maximum and minimum temperatures, and the diurnal temperature range (DTR). The SAT increase in 1961–1990 was relatively small in mainland China; the annual mean warming rate was only 0.14°C (10 yr)$^{-1}$, while the 15 years from 1991 to 2005 more significant warming occurred, exhibiting an annual mean warming rate up to 0.65°C (10 yr)$^{-1}$. The multiple model simulations under various scenarios for China have shown a warming trend of (0.18–0.21)°C (10 yr)$^{-1}$ in 1961–1990, apparently higher than the observed values, and the simulated warming rate of the recent 15-year period (1991–2005) was (0.42–0.50)°C (10 yr)$^{-1}$, slightly lower than the observed values. The comparisons indicate that the atmospheric dimming (cooling) and brightening (warming) process might have contributed to the SAT increases in China, but they were not fully taken into account in the climate models (Zhao et al., 2009b).

The observational studies also showed that climate warming is not significant everywhere in China, especially in the Yangtze and Huaihe river basins, where a clear cooling trend was detected in summers, and in the southwestern China where the annual and spring mean SATs decreased or stabilized for the past several decades. The SAT changes in these areas might have been related to the increased concentration of atmospheric aerosols. The increased cloud amount in the Yangtze river basin in summertime might also have affected the SAT change, in particular the seasonal mean surface maximum temperature change (Committee of National Assessment Report on Climate Change, 2007; Ding et al., 2008).

In recent years, observation and climate model studies have shown that the East Asian winter monsoon over the past decades has weakened, while the intensity of the winter Siberian High closely related to the winter monsoon has also significantly declined. The number of days and intensity of strong winds and frequency of cold waves in the winter half-year periods have significantly decreased. These changes have been related to the atmospheric circulation anomalies, but they might have also been the response to the anthropogenic global warming to a certain extent (Committee of National Assessment Report on Climate Change, 2007; Jiang et al., 2010).

6. Projected future trends in climate

Through development and improvement for 20 years, China's climate models have made significant progress. During the ninth 5-year period (1996–2000), a global atmosphere–ocean coupled model intended for use in seasonal climate predictions was developed jointly by the National Climate Center (NCC), CMA, and the Institute of Atmospheric Physics, CAS (Ding et al., 2000; Dong, 2001). Daily coupling over the open ocean surfaces was achieved with the GCM model (BCC-AGCM1.0) and the global ocean circulation model (NCC/LASG L30T63) (Jin et al., 1999) through a flux anomaly coupling scheme (BCC-CM1.0). Since 2004, CMA has been developing a next-generation climate system model, BCC-CSM. The new version of the Climate System Model BCC-CSM1.0 will be also based on the coupled framework (NCAR CSM2), including an atmospheric component model BCC-AGCM2.0.1 (Wu et al., 2008, 2010), land surface component model (CLM3), global ocean circulation component model (POP), and sea ice model (CSIM).

Meanwhile, CMA has also developed BCC-CSM1.1 that incorporates the global carbon cycle, GCM component model BCC-AGCM2.1, land surface model for BCC_AVIM1.0 which is based on AVIM (Ji and Yu, 1999), and improved ocean circulation and sea ice models (based on GFDL MOM4 and SIS, respectively). The next-generation BCC-CSM will also take into account the atmospheric chemistry and aerosols to establish a platform coupling multiple components of the climate system. Verifications of the current climate state and climate change showed that the model has a higher reliability for simulating global and hemispheric climate change; BCC-CSM1.1 is able to capture seasonal, interannual and decadal variability, especially performing well for wintertime. it also has the improved capability in simulating temperature fields and atmospheric circulations.

In the climate simulation experiments targeting the 20th century, 22 IPCC AR4 coupled models (Zhou and Yu, 2006) and BCC-CSM1.0 gave good results. Under combined forcings of natural and human factors, most models can successfully replicate the actual evolution of the global mean temperature in the past century. The correlation coefficients of multi-model ensemble outputs and observed temperature series (Jones et al., 1999) can reach 0.87. The 20th-century warming is

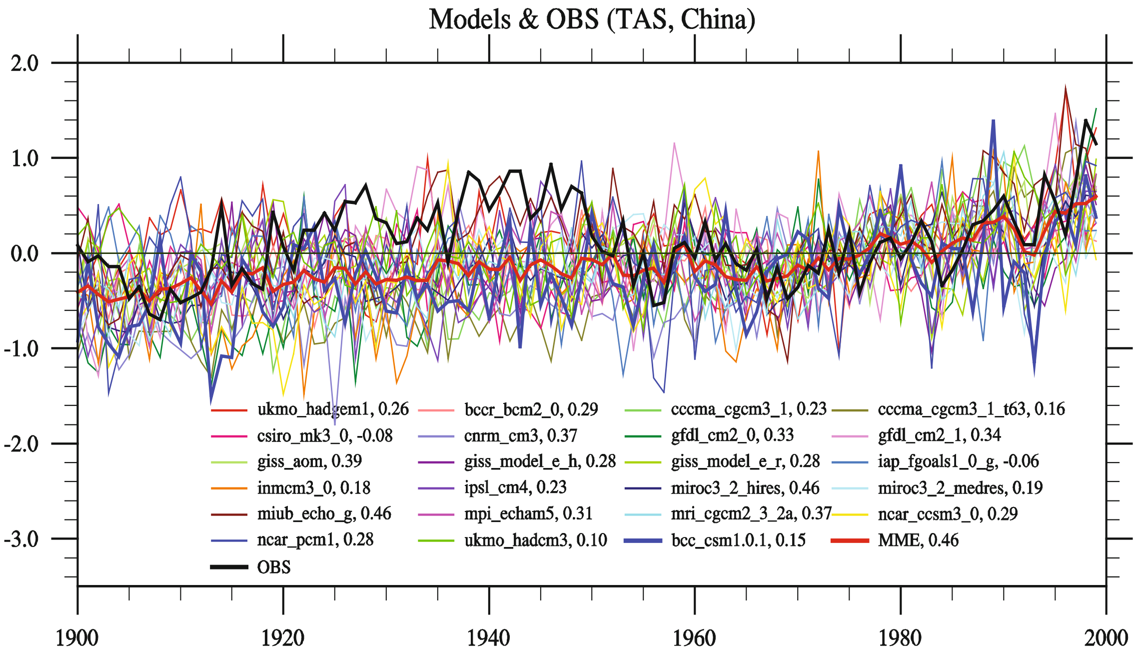

Fig. 8. Annual mean temperature anomalies variations in China (relative to 1961–1990) from 22 global climate models that participated in 20C3M tests for CMIP3 (Zhou and Yu, 2006) and from BCC-CSM1.0. Correlation coefficients of the simulated temperature anomalies with the observations are given after the names of the models.

responsible for this higher correlation coefficient. The warming trend from the multi-model ensembles was 0.067°C (10 yr)$^{-1}$, which was well among the observed rates from 0.03°C (10 yr)$^{-1}$ to 0.12°C (10yr)$^{-1}$. The inclusion of yearly changes of natural forcing factors including solar activity and volcanic aerosols significantly improved the coupled model performances.

However, the differences of the simulations from observation vary largely from model to model, especially in the first half of the 20th century. Variance analysis showed that the external forcings could explain 60% of the global mean temperature change in the 20th century, while the internal variability (noise) from the interactions of the sea-land–air-ice coupling system was responsible for the remaining 40%. For interannual variability, the coupled model did not correspond to the actual observations. Further analysis suggested that the model better captured the temperature change in the second half of the 20th century than in the first half of the century overall. This was partially due to more reliable forcing data (GHG gases and aerosols). The role of GHG gases may also be more significant (Zhou and Yu, 2006). The correlation coefficient of BCC-CSM1.0 outputs to observations is 0.75, which approaches the multiple model average.

Comparing the BCC-CSM1.0 simulations of the annual mean SAT anomaly variations in China in the 20th century with the outputs from the 22 models participating in CMIP3, models varied largely before 1970s, but almost all model simulations were close to observations after 1970s (Wang et al., 1998). The simulations of most models and observations were positively correlated, among them the correlation coefficient of ECHO-G was the highest, reaching 0.44. UKMO-HadCM3 had a lower correlation coefficient, and CSIRO-MK3.0 even gave a negative correlation. The correlation coefficients of BCC-CSM1.0 and FGOALS_g1.0 were 0.15 and −0.06, respectively. The correlation of multi-model ensemble average with the observation series for China was 0.46, which was lower than the global average, but it was statistically significant at the 95% confidence level. In addition to ECHO-G, the multi-model ensemble average was better than any single model simulation, but the ensemble outputs significantly reduced the amplitude of the SAT anomaly series.

The global mean temperature in the 21st century projected by BCC-CSM1.0 model showed a further warming trend, with the amplitude equivalent to IPCC AR4 multi-model average. Under the lower emission scenario (SRES B1), the simulated global annual mean temperature in the next 100 years will increase ∼1.8°C; under the medium level scenario (SRES A1B), the temperature will increase ∼2.4°C by the end of this century. However, under the high-emission scenario (SRES A2), global warming will be up to 3.2°C. Figure 8 shows that the global mean temperature increase as simulated by BCC-CSM1.0 for the 20th century is higher than the multi-model average. The main reason for the larger warming was that BCC-CSM1.0 model did not contain the impacts of interannual variations of aerosols on warming (only considering the average seasonal climate changes). Otherwise, the global mean temperature change would have been more consistent with the multi-model average.

Figure 9 shows several integrated surface temperature variations in China from global climate models. Under SRES B1 and A2, by late 21st century the country average annual mean SAT will increase approximately 2.5°C and 4.6°C relative to 1980–1999, which was significantly larger than the global average. By 2020, under SRES B1, China's annual mean SAT increase will be in a range of 0.6°C–1.8°C, and the maximum warming will take place in Northeast and western China; under SRES A2, annual mean SAT will increase within a range of 1.2°C–1.8°C. By 2050, annual mean SAT for China will significantly increase, with the maximum warming still found in North, Northwest and Northeast China, generally consistent with those identified as the so-called hot-spots in Northeast, Northwest and East China and the Q-T Plateau (Xu et al., 2009).

The global climate models did not show any strong capability to replicate the observed precipitation changes in China. Therefore, the global models were used to project a precipitation trend with only a low level of confidence. The projected frequency of extreme climate events associated with precipitation remained unsatisfactory. However, most of the global climate models showed that in the future the annual precipitation might increase in most parts of China, especially in northern and western China under all GHG emission scenarios, and that both frequency and intensity of extreme precipitation events might also increase (Zhou et al., 2008; Chen and Sun, 2009; Chen et al., 2010b). Frequency of intense snowfall events were projected to decrease over southern China and to increase over northern China by the mid-21st century, but a decreasing trend might be experienced over Northeast China by the end of the 21st century (Sun et al., 2010).

Chinese scientists also simulated the trends of future climate change using regional climate models under different GHG emission scenarios (Gao et al., 2001, 2011; Xu et al., 2006; Shi and Gao, 2008). Nesting RegCM3 into NCAR/NASA global model FvGCM/CCM3, the simulation outcomes showed that under SRES A2, the winter mean temperature will increase evidently in the late 21st century, which is warmer in the northern China than in the southern China, with the highest temperature increase found in Northeast China, but its overall amplitude is lower than that derived from global models. The summer warming magnitude will be higher in the western China, but relatively lower in eastern China. Annual precipitation will increase in Northeast and Northwest China and the Yellow River-Huaihe River basins, but precipitation will undergo little change or even a decrease in the rest of the country. The areas with significant precipitation decreases will be located in the Q-T Plateau and Yunnan province, among others. The number of days with daily precipitation >20 mm (here defined as heavy rainy days), will generally increase in China, even by >10% in most parts of China, but they will decrease in some parts of Southwest China (Shi and Gao, 2008).

In both global climate models and regional models, larger uncertainties were found in the projected trends of future climate change in China under various GHG emission scenarios. The projected trends of regional precipitation variations bear even lower confidence. Similarly, the projected frequency and intensity variations of heavy precipitation events still remain unsatisfactory. The possible causes for the less reliable projections are due to the complexity of nonlinear interactions between various components of the climate system on multiple scales, the limited understanding of weather and climate behavior and change, and the limited computation and information processing resources (IPCC, 2007; Jiang et al., 2011). Climate system models cannot truly replicate the observed climate variations, and they usually fail to capture the widely interested climate variability on a decadal scale and beyond, leaving large uncertainties in model-based future projections. The question of how to reduce the uncertainties in future climate projections needs to be regarded as a major challenge in current climate change studies.

7. Conclusions

In the past several decades, Chinese scientists have conducted numerous studies on detection, attribution, and projection of regional climate change, in particular of mainland China, and they have made substantial progress as well as major contributions to the field of atmospheric science. The major findings of the studies include the following:

(1) The annual mean SAT in China increased at a rate varying from 0.03°C $(10\ \text{yr})^{-1}$ to 0.12°C $(10\ \text{yr})^{-1}$ in the past 100 years (1906–2005 or 1908–2007). The trend of climate warming nationwide has been more rapid since 1951, with the annual mean temperature increasing up to 0.25°C $(10\ \text{yr})^{-1}$, with the highest rate being detected after the 1980s.

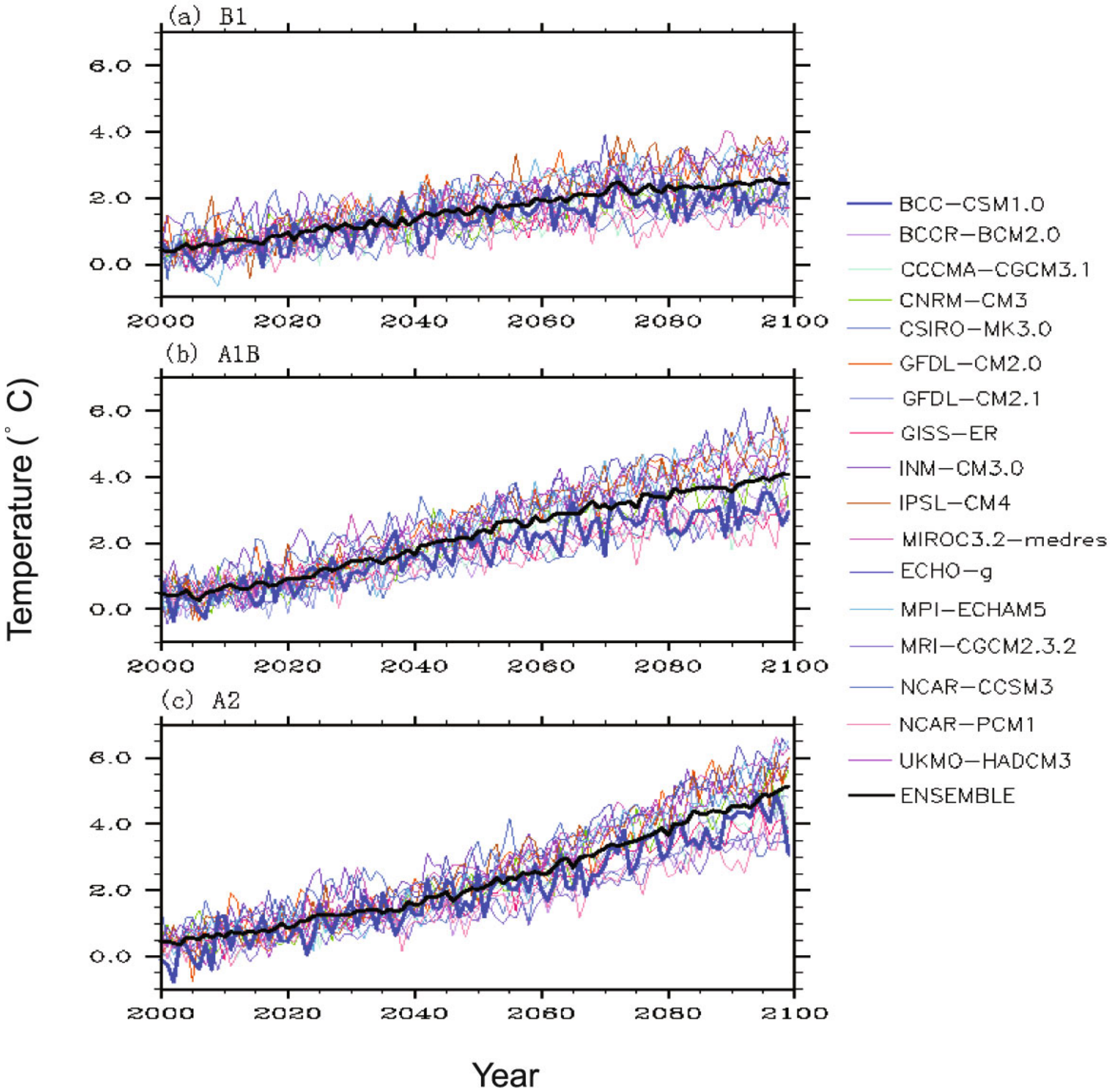

Fig. 9. Region-averaged annual mean surface air temperature anomalies of China derived from IPCC AR4 global climate models and from BCC-CSM1.0 under B1, A1B and A2 GHG emission scenarios, relative to 1980–1999 (units: °C).

(2) Climate warming was more evident in northern China than in southern China, and the most rapid warming occurred in Northeast, North and Northwest China, and the Q-T Plateau. No significant changes in the annual mean SAT have been detected in Southwest China. Climate warming was more evident in winter and spring than in other seasons, and the warming trend in summer was found the weakest almost everywhere. Interestingly, in the Yangtze River and Huaihe River basins, the summer mean temperature even dropped slightly. These characteristics were visible in the past 100 years and/or over the past 50 years.

(3) In China, rapid urbanization, particularly in the past 50 years, has had significant impacts on most of the long-term SAT records. In the country average annual mean SAT series from 1960 to 2004, as obtained based on the commonly used dataset of national stations, at least 27% of the warming could be attributed to the urbanization effect. Removal of the systematic bias will significantly reduce the increasing rate of SAT in China.

(4) In the past 100 years and/or past 50 years, no significant trends were detected in annual mean precipitation in the country overall, but relatively evident decadal or multi-decadal oscillations were notable. Since early 1950s, precipitation has decreased in North and Northeast China, but increased in most parts of South and West China, particularly in North-

west China.

(5) In the past 50 years intensity of some major extreme climate events across China increased but others decreased without showing consistent trends. However, coherent changes were found in the frequency of extreme temperature events in various regions in China, with evidently less and weakened abnormal cold events, and more and intensified abnormal warm events. But changes in frequency of intense precipitation events were regional and seasonal dependent. A decreasing trend was found in frequency of tropical cyclones or typhoons landing on and affecting the southeastern coastal areas. The frequency and intensity of dust storms in the northern China and thunderstorms over a few areas investigated in eastern China decreased.

(6) From the perspective of paleoclimate reconstructions, the annual mean SAT since the 1950s might have reached the highest level for the past 400–500 years, but it may not have exceeded the amplitude of climate warming in some episodes of the Medieval Warm Period. The occurrence of major historical drought and/or flood events in eastern China was clearly marked with stage features. Severe drought events mainly concentrated in the 4th century and the second half of the 8th century, from the second half of the 11th century to the first half of the 12th century, and in the first half of the 17th century. The frequency of extreme drought and/or flood events in eastern China in the 20th century did not surpass the highest level in the past 2000 years, but approached the level of "normal years."

(7) The analysis of the causes of climate change in China in the past 100 years indicates that increase of GHG concentration in the atmosphere might have been a main factor for significant climate warming in most parts of the country. However, climate warming was not evident in some areas, and cooling was evident in summers, especially in the Yangtze River-Huaihe River basins, which might have been related to the increase of aerosol concentration and more clouds in the atmosphere. Natural variability might have a lesser impact on SAT change, but it might have been a major driver for variations in precipitation amount and frequency of intense precipitation events.

(8) The global climate models used for IPCC AR4 performed well at simulating the annual mean SAT trend in China in the 20th century. Especially for the period since 1970s, almost all models yielded a similar trend of faster climate warming and generally reproduced spatial and seasonal characteristics of climate warming, demonstrating higher confidence in simulating SAT trends in China.

(9) Under SRES B1-A2, IPCC AR4 multi-model ensemble simulations projected that the annual mean SAT in the next 100 years will increase by ~1.8°C–3.2°C across the globe and by ~2.5°C–4.6°C in China. Although the regional climate models were subject to more careful verifications and tests, their projections of mean SAT under different GHG emission scenarios were similar to those from global climate models.

(10) Thus far, the global and regional climate models have not performed well in capturing basic changes in precipitation and extreme climate events, especially changes in frequency and intensity of precipitation events on a regional scale. Currently, confidence in the model's projections of the future precipitation trends in China is low.

Acknowledgements. The authors of this paper thank HAO Zhixin, ZHU Jieping, FENG Guolin, GONG Zhiqiang, REN Yuyu, ZHOU Yaqing, ZHANG Aiying, ZHOU Jiangxing, ZOU Xukai, CHEN Yu, XIN Xiaoge and SHI Ying for their contributions. This study is supported by the Ministry of Science and Technology of China (Grant Nos. 2007BAC29B02, 2007BAC03A01 and GYHY201206012).

REFERENCES

Chen, H., J. Sun, X. Chen, and W. Zhou, 2010b: CGCM projections of heavy rainfall events in China. *International Journal of Climatology*, doi: 10.1002/joc.2278.

Chen, H. P., and J. Q. Sun, 2009: How the "best" models project the future precipitation change in China. *Adv. Atmos. Sci.,* **26**(4), 773–782, doi: 10.1007/s00376-009-8211-7.

Chen, H. W., Y. Xin, P. X. Chen, Y. P. Li, X. J. Yu, and S. Q. S. L. Wang, 2010a: Variation of extreme wind speeds and gale frequency over the windy regions in Xinjiang. *Climatic and Environmental Research*, **15**(4), 479–490. (in Chinese)

Chen, Y., X. Y. Chen, and G. Y. Ren, 2010c: Variation of extreme precipitation over the Chinese large river basins. *Advances in Climate Change Research*, **6**(4), 265–269. (in Chinese)

Chu, Z. Y., G. Y. Ren, X. M. Shao, and H. B. Liu. 2005: A preliminary reconstruction of mean surface air temperature over the past 1000 years in China. *Climatic and Environmental Research*, **10**(4), 826–836. (in Chinese)

Committee of National Assessment Report on Climate Change, 2007: *China's National Assessment Report on Climate Change*. China Science Press, Beijing, 80–105. (in Chinese)

Committee of Second National Assessment Report on Climate Change, 2011: *Second National Assessment Report on Climate Change*. China Science Press, Beijing. 710pp. (in Chinese)

Ding, Y. H., and G. Y. Ren, 2008: *Introduction to Cli-*

mate Change Science of China. China Meteorological Press, Beijing, 281pp. (in Chinese)

Ding, Y. H., and Coauthors, 2000: *Improvement of High Resolution Regional Climate Model and its Application in Experiment on Simulation of Persistent Rainstorm Events in East Asia*. China Meteorological Press, Beijing, 217–231.

Ding, Y. H., Z. Y. Wang, and Y. Sun, 2008: Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences, *Int. J. Climatol*, **28**, 1139–1161

Dong, M., 2001: *NCC General Circulation Model—Basic Principles and Use Instructions*. China Meteorological Press, Beijing, 152pp. (in Chinese)

Feng, G. L., and Coauthors, 2008: Latest advances of climate change detecting technologies. *Acta Meteorologica Sinica*, **66**(06), 892–905 (in Chinese)

Gao, X. J., Z. C. Zhao, Y. H. Ding, and R. H. Huang, 2001: Climate change due to greenhouse effects in China as simulated by a regional climate model. *Adv. Atmos. Sci.*, **18**, 1224–1230.

Gao, X. J., Y. Shi, and F. Giorgi, 2011: A high resolution simulation of climate change over China. *Science China* (*D*), **54**, 462–472, doi: 10.1007/s11430-010-4035-7.

Ge, Q. S., and Coauthors, 2002: Winter-half-year temperature changes in eastern China over the past 2000 years. *Quaternary Sciences*, **22**, 166–173.

Ge, Q. S., J. Y. Zheng, X. Q. Fang, Z. Man, X. Q. Zhang, P. Y. Zhang, and W.-C. Wang, 2003: Winter half-year temperature reconstruction for the middle and lower reaches of the Yellow River and Yangtze River, China, during the past 2000 years. *The Holocene*, **13**, 933–940.

Ge, Q. S., J. Y. Zheng, Z. X. Hao, X. M. Shao, W. C. Wang, and J. Luterbacher, 2010: Temperature variation through 2000 years in China: An uncertainty analysis of reconstruction and regional difference. *Geophys. Res. Lett.*, **37**, L03703, doi: 10.1029/2009GL041281.

Gong, D. Y., and H. Han, 2004: Extreme climate events in northern China over the last 50 years. *Acta Geographica Sinica*, **59**(2), 230–238. (in Chinese)

Hao, Z. X., and Coauthors, 2010a: 1876–1878 severe drought in North China: Facts, impacts and climatic background. *Chinese Science Bulletin*, **55**, 3001–3007, doi: 10.1007/s11434-010-3243-z.

Hao, Z. X., J. Y. Zheng, and Q. S. Ge, 2010b: Changes of extreme drought/flood events in eastern China over the past 2000 years. *Climatic and Environmental Research*, **15**(4), 388–394. (in Chinese)

IPCC, 2007: *Climate Change 2007*: *The Physical Science Basis. Contribut ion of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996pp.

Jansen, E., and Coauthors, 2007: Palaeo-climate. *Climate Change 2007: The Physical Science Basis*, Solomon et al., Eds., 463–497.

Ji, J. J., and L. Yu, 1999: A simulation study of coupled feedback mechanism between physical and biogeochemical processes at the surface. *Chinese J. Atmos. Sci.*, **23**(4), 439–448. (in Chinese)

Jiang, D. B., Y. Zhang, and X. M. Lang, 2011: Vegetation feedback under future global warming. *Theoretical and Applied Climatology*, **106** (1–2), 211–227, doi: 10.1007/s00704-011-0428-6.

Jiang, Y., Y. Luo, Z. Zhao, and S. Tao, 2010: Changes in wind speed over China during 1956–2004. *Theoretical and Applied Climatology*, **99** (3–4), 421–430, doi: 10.1007/s00704-009-0152-7.

Jiang, Z. H., X. Zhang, and J. Wang, 2008: Projection of climate change in China, in the 21^{st} century by IPCC-AR4 models. *Geographical Research*, **27**(4), 787–799. (in Chinese)

Jin, X. Z., X. H. Zhang, and T. J. Zhou, 1999: Fundamental framework and experiments of the third generation of IAP/LASG world ocean general circulation model. *Adv. Atmos. Sci.*, **16**, 197–215.

Jones, P. D., M. New, D. E. Parker, S. Martin, and I. G. Rigor, 1999: Surface air temperature and its changes over the past 150 years. *Rev. Geophys.*, **37**, 173–199.

Li, Q. X., X. N. Liu, H. Zhang, T. C. Peterson, and D. R. Easterling, 2004: Detecting and adjusting temporal inhomogeneity in Chinese mean surface air temperature data. *Adv. Atmos. Sci.*, **21**, 260–268.

Li, Z. Y., S. L. Wu, W. F. Yang, J. W. Chen, Y. X. Wang, and X. Yu, 1997: Long-term variation of drought/flood in Xi'an area. *Climatic and Environmental Research*, **2**(4), 356–360. (in Chinese)

Liang, E. Y., and Coauthors, 2006: The 1920s drought recorded by tree rings and historical documents in the semi-arid and arid areas of northern China. *Climatic Change*, **79**, 403–432.

Lin, X. C., S. Q. Yu, and G. L. Tang, 1995: Series of average air temperature over China for the last 100-year period. *Chinese J. Atmos. Sci.*, **19**, 525–534. (in Chinese)

Liu, X. H., D. H. Qin, X. M. Shao, T. Chen, and J. W. Ren, 2004: Tree-ring based reconstruction of the past 1000 year temperature change over the Qilian Mountains. *Sciences in China* (*D*), **34**(1), 89–95.

Liu, X., X. Shao, L. Zhao, D. Qin, T. Chen, and J. Ren, 2007: Dendro-climatic temperature record derived from tree-ring width and stable carbon isotope chronologies in the middle Qilian Mountains, China. *Arctic, Antarctic, and Alpine Research*, **39**, 651–657.

Pu, B., S. W. Wang, and J. H. Zhu, 2007: Spatial pattern of seasonal precipitation over the eastern part of China. *Acta Scientiarum Naturalium Universitatis Pekinensis*, **43**, 620–629. (in Chinese)

Qian, W. H., J. L. Fu, W. W. Zhang, and X. Lin, 2007: Changes in mean climate and extreme climate in China during the last 40 years. *Advances in Earth Science*, **22**(7), 673–684. (in Chinese)

Ren, F., Y. Wang, and X. Wang, 2007: Estimating tropical cyclone precipitation from station observations. *Adv. Atmos. Sci.,* **24**(4), 700–711, doi: 10.1007/s00376-007-0700-y.

Ren, G. Y., M. Z. Xu, Z. Y. Chu, Z. H. Chen, A. Y. Zhang, J. Guo, H. Z. Bai, and X. F. Liu, 2005a: Changes of surface air temperature in China during 1951–2004. *Climatic and Environmental Research*, **10**(4), 717–727. (in Chinese)

Ren, G. Y., and Coauthors, 2005b: Climate changes of mainland China over the past half century. *Acta Meteorologica Sinica*, **63**(6), 942–956. (in Chinese)

Ren, G. Y., Y. Chen, X. K. Zou, Y. Q. Zhou, X. L. Wang, Y. Jiang, F. M. Ren, and Q. Zhang, 2010: Definition and trend analysis of an integrated extreme climatic index. *Climatic and Environmental Research*, **15**(4), 354–364. (in Chinese)

Ren, G. Y., Y. Q. Zhou, Z. Y. Chu, A.Y. Zhang, J. Guo, and X.Y. Liu, 2008: Urbanization effect on observed surface air temperature trend in North China. *J. Climate*, **21**(6), 1333–1348.

Ren, G. Y., Guan, Z. Y., Shao, X. M., and D. Y. Gong, 2011: Change in climatic extremes over mainland China. *Climatic Research*, **50**(1–2), 105–111, doi: 10.3354/cr01067.

Ren, Y. Y., and G. Y. Ren, 2011: A remote-sensing method of selecting reference stations for evaluating urbanization effect on surface air temperature trends. *J. Climate*, **24**(7), 3179–3189

Shi, Y., and X. J. Gao, 2008: Influence of greenhouse effect on eastern China climate simulated by a high resolution regional climate model. *Chinese J. Atmos. Sci.*, **32**(5), 1006–1018. (in Chinese)

Streets, D. G., C. Yu, Y. Wu, M. Chin, Z. C. Zhao, T. Hayasaka, and G. Y. Shi, 2008: Aerosol trends over China, 1980–2000. *Atmospheric Research*, **88**, 174–182

Sun, J., H. Wang, W. Yuan, and H. Chen, 2010: Spatial-temporal features of intense snowfall events in China and their possible change. *J. Geophys. Res.*, **115**, D16110, doi: 10.1029/2009JD013541

Sun, J. Q., H. J. Wang, and W. Yuan, 2011: Decadal variability of the extreme hot event in China and its association with atmospheric circulations. *Climatic and Environmental Research*, **16**(2), 199–208. (in Chinese)

Tan, M., T. Liu, J. Hou, X. Qin, H. Zhang, T. Li. 2003: Cyclic rapid warming on centennial-scale revealed by a 2650-year stalagmite record of warm season temperature. *Geophys. Res. Lett.*, **30,** 1617–1620.

Tang, G. L., 2006: A study of temperature change during instrumental observation period in China. M. S. thesis, Institute of Atmospheric Physics, Chinese Academy of Sciences. 76pp. (in Chinese)

Tang, G. L., and G. Y. Ren, 2005: Reanalysis of surface air temperature change of the last 100 years over China. *Climatic and Environmental Research*, **10**, 791–798. (in Chinese)

Tang, G. L., Y. H. Ding, S. W. Wang, G. Y. Ren, H. B. Liu, and L. Zhang, 2009: Comparative analysis of the time sequences of surface air temperature in China in the last 100 years. *Advances in Climate Change Research*, **5**(2), 71–78. (in Chinese)

Thompson, L. G., and Coauthors, 2006: Abrupt tropical climate change: Past and present. *Proc Natl. Acad. Sci.* (USA), **103**, 10536–10543.

Wang, S. W., and Z. H. Chen, 1993: A preliminary study on severe droughts/floods in the Yangtze and Yellow Rivers for the last 2000 years. *Diagnostic Research on Regularity of Drought/Flood Disasters in the Yangtze and Yellow Rivers and Their Economic Impacts*. Wang and Huang, Eds., China Meteorological Press, Beijing, 67–75. (in Chinese)

Wang, S. W., D.Y. Gong, J. L. Ye, and Z. H. Chen, 2000: Seasonal precipitation series of eastern China since 1880 and the variability. *Acta Geographica Sinica*, **55**, 281–293. (in Chinese)

Wang, S. W., J. L. Ye, D. Y. Gong, J. H. Zhu, and T. D. Yao, 1998: Construction of annual mean temperature series for the last one hundred years in China. *Journal of Applied Meteorological Science*, **9**, 392–401. (in Chinese)

Wang, Y., and Z. W. Yan, 2009: Trends in seasonal total and extreme precipitation over China during 1961–2007. *Atmospheric and Oceanic Science Letters*, **2**(3), 165–171.

Wen, X. Y., S. W. Wang, J. H. Zhu, and D. Viner, 2006: An overview of China climate change over the 20th century using UK UEA/CRU high resolution grid data. *Chinese J. Atmos. Sci.*, **30**, 894–904. (in Chinese)

Wu, T. W., R. C Yu, and F. Zhang, 2008: A modified dynamic framework for atmospheric spectral model and its application. *J. Atmos. Sc.,* **65**, 2235–2253.

Wu, T. W., and Coauthors, 2010: The Beijing Climate Center Atmospheric General Circulation Model (BCC_AGCM2.0.1): Description and its performance for the present-day climate. *Climate Dyn.*, **34**, 123–147, doi: 10.1007/s00382-008-0487-2.

Xu, Y., X. J. Gao, and F. Giorgi, 2009: Regional variability of climate change hot-spots in East Asia. *Adv. Atmos. Sci.*, **26**(4), 783–792, doi: 10.1007/s00376-009-9034-2.

Xu, Y. L., and Coauthors, 2006: Analysis of response to climate change in China under SRES B2 scenario using PRECIS. *Chinese Science Bulletin*, **51**(17), 2068–2074.

Yan, Z., and P. D. Jones, 2008: Detecting inhomogeneities in daily climate series using wavelet analysis. *Adv. Atmos. Sci.*, **25**(2), 157–163, doi: 10.1007/s00376-008-0157-7.

Yang, B., A. Braeuning, K. R. Johnson, and Y. F. Shi, 2002: General characteristics of temperature variation in China during the last two millennia. *Geophys. Res. Lett.*, **29**, 1324, doi: 10.1029/2001GL014485.

Yang, J. H., Z. H. Jiang, P. X. Wang, and Y. S. Chen, 2008: Temporal and spatial characteristic of extreme precipitation event in China. *Climatic and Environmental Research*, **13**(1), 75–83. (in Chinese)

Yang, Y. H., M. Ying, and B. D. Chen, 2009: Climate change characteristics of land-falling tropical cyclones over the past 58 years. *Acta Meteorologica Sinica*, **67**(5), 689–696. (in Chinese)

You, Q. L., S. C. Kang, G. Y. Ren, K. Fraedrich, N. Pepin, Y. P. Yan, and L. J. Ma, 2011: Observed changes in snow depth and number of snow days in the eastern and central Tibetan Plateau. *Climate Research*, **46**, 171–183, doi: 10.3354/cr00985.

Zhai, P. M., X. B. Zhang, H. Wan, and X. H. Pan, 2005: Trends in total precipitation and frequency of daily precipitation extremes over China. *J. Climate*, **18**, 1096–1108.

Zhang, A. Y., G. Y. Ren, J. X. Zhou, Z. Y. Chu, Y. Y. Ren, and G. L. Tang, 2010: Impacts of urbanization on trends of surface air temperature change in China. *Acta Meteorologica Sinica*, **68**(6), 957–966. (in Chinese)

Zhang, D. E., 2004: Variation of dry-wet climate and severe drought events as revealed in the climate records of China over the past 1000 years. *Science and Technology Review*, **22**(8), 47–49. (in Chinese)

Zhang, L., and G. Y. Ren, 2003: Change in dust storm frequency and the climatic controls in northern China. *Acta Meteorologica Sinica*, **61**(6), 744–750. (in Chinese)

Zhang, L., G. Y. Ren, J. Liu, Y. Q. Zhou, Y. Y. Ren, A. Y. Zhang, and Y. W. Feng, 2011: Urban effect on trends of extreme temperature indices at Beijing Meteorological Station. *Chinese J. Geophys.*, **54**(5), 1150–1159, doi: 10.3969/j.issn.0001 5733.2011.05.002. (in Chinese)

Zhang, X. G., and X. Q. Li, 1982: Some characteristics of temperature change in the 20^{th} century in China. *Acta Meteorologica Sinica*, **40**, 198–208. (in Chinese)

Zhao, D., Y. Luo, G. Gao, C. H. Zhu, and Y. B. Shen, 2010: Long-term changes and essential climatic characteristics of sunshine duration over China during 1961–2007. *Resources Science*, **32**(4), 701–711. (in Chinese)

Zhao, Z. C., 1991: The changes of temperature and the effects of urbanization in China in the last 39 years. *Meteorological Monthly*, **17**(4), 14–17. (in Chinese)

Zhao, Z. C., Y. Luo, Y. Jiang, and Y. Xu, 2008: Projections of surface air temperature change in China for the next two decades. *Journal of Meteorology and Environment*, **24**(5), 1–5. (in Chinese)

Zhao, Z. C., S. W. Wang, Y. Luo, and Y. Jiang, 2009a: Uncertainty analysis of climate warming during the last 100 years. *Review of Science and Technology*, **27**(23), 41–48. (in Chinese)

Zhao, Z. C., Y. Luo, Y. Jiang, and D. G. Streetse, 2009b: Impacts of dimming and brightening on warming in China. *Scientific Research Monthly*, **8**, 34–37.

Zheng, J. Y., Q. S. Ge, and X. Q. Fang, 2002: Seeing the 20th century warming from temperature changes of winter-half-year in eastern China for the last 2000 years. *Acta Geographica Sinica*, **57**, 631–638. (in Chinese)

Zheng, J. Y, W. C. Wang, Q. S. Ge, Z. M. Man, and P. Y. Zhang, 2006: Precipitation variability and extreme events in eastern China during the past 1500 years. *Terrestrial Atmospheric and Oceanic Sciences,* **17**, 579–592. (in Chinese)

Zhou, T. J., and R. C. Yu, 2006: Twentieth century surface air temperature over China and the globe simulated by coupled climate models. *J. Climate,* **19**, 5843–5858.

Zhou, T. J., and Coauthors, 2008: Progress in climate change attribution and projection studies. *Chinese J. Atmos. Sci.*, **32**(4), 906–922. (in Chinese)

Zhou, Y. Q., and G. Y. Ren, 2009: Urbanization effect on trends of mean maximum, minimum temperature and diurnal temperature range in North China. *Plateau Meteorology*, **28**(5), 1158–1166. (in Chinese)

Zhou, Y. Q., and G. Y. Ren, 2011: Change in extreme temperature events frequency over mainland China during 1961–2008. *Climate Research*, **50**(1–2), doi: 10.3354/cr01053.

Zhou, Z. J., and G. C. Zhang, 2003: Strong dust storm events of northern China over 1954–2002. *Chinese Science Bulletin*, **48**(11), 1224–1228. (in Chinese)

Zou, X., L. V. Alexander, D. Parker, and J. Caesar, 2006: Variations in severe storms over China. *Geophys. Res. Lett.*, **33**(17), L17701, doi: 10.1029/2006GL026131.

Zou, X. K., G. Y. Ren, and Q. Zhang, 2010: A study of meteorological drought index and its trend. *Climatic and Environmental Research*, **15**(4), 371–378. (in Chinese)