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Detection, Causes and Projection of Climate Change over China: An Overview of Recent Progress

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ABSTRACT

This article summarizes the main results and findings of studies conducted by Chinese scientists in the past five years. It is shown that observed climate change in China bears a strong similarity with the global average. The country-averaged annual mean surface air temperature has increased by 1.1°C over the past 50 years and 0.5–0.8°C over the past 100 years, slightly higher than the global temperature increase for the same periods. Northern China and winter have experienced the greatest increases in surface air temperature. Although no significant trend has been found in country-averaged annual precipitation, interdecadal variability and obvious trends on regional scales are detectable, with northwestern China and the mid and lower Yangtze River basin having undergone an obvious increase, and North China a severe drought. Some analyses show that frequency and magnitude of extreme weather and climate events have also undergone significant changes in the past 50 years or so.

Studies of the causes of regional climate change through the use of climate models and consideration of various forcings, show that the warming of the last 50 years could possibly be attributed to an increased atmospheric concentration of greenhouse gases, while the temperature change of the first half of the 20th century may be due to solar activity, volcanic eruptions and sea surface temperature change. A significant decline in sunshine duration and solar radiation at the surface in eastern China has been attributed to the increased emission of pollutants.

Projections of future climate by models of the NCC (National Climate Center, China Meteorological Administration) and the IAP (Institute of Atmospheric Physics, Chinese Academy of Sciences), as well as 40 models developed overseas, indicate a potential significant warming in China in the 21st century, with the largest warming set to occur in winter months and in northern China. Under varied emission scenarios, the country-averaged annual mean temperature is projected to increase by 1.5–2.1°C by 2020, 2.3–3.3°C by 2050, and by 3.9–6.0°C by 2100, in comparison to the 30-year average of 1961–1990. Most models project a 10%–12% increase in annual precipitation in China by 2100, with the trend being particularly evident in Northeast and Northwest China, but with parts of central China probably undergoing a drying trend. Large uncertainty exists in the projection of precipitation, and further studies are needed. Furthermore, anthropogenic climate change will probably lead to a weaker winter monsoon and a stronger summer monsoon in eastern Asia.

Key words: climate change, China, detection, causes, climate models, projection

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1. Introduction

Climate change has been studied intensively by Chinese scientists over the last two decades. During this time, the Chinese government has sponsored a series of State Key Research Programs related to basic science and the impact of climate change; for example, the "projection, impact and response policy of global climate change", the "study on global climate change and environmental policy", the "study on response policy and supporting technologies to global environmental change", the "trend of life-supporting environments in 20–50 years to come in China", the "study on mechanism and prediction theories of major weather and climate disasters in China", the "study on life-supporting environmental change and trends

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*Corresponding author: DING Yihui, dingyh@cma.gov.cn of northern China aridification", the "changes in climate and sea level in China and the future trends and impact", the "response of Chinese terrestrial ecosystems to global change", and the "interaction between Chinese agricultural ecosystems and global change" projects. In addition, the Chinese Academy of Sciences also launched some key projects, such as the "study on carbon budget in land and costal zones" and the "western ecosystem and environment and the sustainable exploration of natural resources". Due to the support from state-funded projects and other research projects such as these, great progress has been achieved in the field of climate change, which has also significantly contributed to the development of Earth system science and the formulation of response policies of the country to global climate change.

Under the state key project of the tenth five-year plan—the study on response policy and supporting technologies to global environmental change—a subproject related to regional climate change detection, cause and projection was established, with a goal to further understand observed climate change and its possible causes, and to project future trends of climate potentially induced by anthropogenic increase of atmospheric CO_2 (Ding et al., 2006). Scientists involved in the sub-project have updated historical climate series, including those of the last 1000 years, 100 years and 50 years in China (Wang and Gong, 2000; Ren et al., 2005, 2006; Tang and Ren, 2005; Ding et al., 2006), and have made an effort to attribute the observed change to anthropogenic and natural factors (Zhao et al., 2005a,b). They have carried out a series of simulations using global climate models and regional climate models to obtain the possible climate change scenarios for the next 50 and 100 years to come in East Asia and China (Zhao et al., 2003; Xu et al., 2005; Luo et al., 2005; Ding et al., 2006). The other two subprojects have also assessed the impacts of projected climate change on agriculture, water resources, terrestrial ecosystems, and coastal zones of China, as well as putting forward measures and policies for adaptation to and mitigation of climate change. However, their achievements will not be reported in this paper.

Great uncertainty still exists in studies of climate change, especially in the projection of future climate trends on a regional scale. Major uncertainties have been identified by the scientists involved in the subprojects described above, and they need surely to be tackled in the near future.

This paper presents a brief summary of the research results of the sub-project of climate change science under the state key project of the tenth five-year plan—the study on response policy and supporting technologies to global environmental change. More details are included in the National Assessment Report on Climate Change, which is available from China Science Press in Beijing. Following this introduction, section 2 of the paper outlines the major results of surface climate change as observed in the past, followed in section 3 by a description of research results on the causes of regional climate change. Section 4 presents some modeling results for future climate trends in China, followed finally by some conclusions in section 5.

2. Changes in surface climate

2.1 *Surface air temperature*

Analysis of surface air temperature in China is based on a dataset of 726 stations across the country. Nationwide average temperature anomalies and temperature trends for the periods 1951–2001 and 1905–2001 have been calculated, taking 1971–2000 as the base period. The method of Jones and Hulme (1996) and Jones and Moberg (2003) for constructing the nationwide average surface air temperature anomaly series was adopted. Trends of temperature have been obtained using the least square method. Different to previous analyses, which have shown major differences mainly in the 1910s–1930s (Ding and Dai, 1994; Lin et al., 1995; Chen and Zhu, 1998; Wang et al., 1998, 2002; Zeng et al., 2001; Hu et al., 2003), the inhomogeneity induced by the shifting of stations and changes in instruments has been checked and adjusted in the present work. The inhomogeneity of monthly mean temperature data has been proved to be mainly caused by the relocation of stations and daily observation times. Inhomogeneities of monthly temperature data prior to 1950 have also been checked, and those caused by different daily observation times and changed time systems have been minimized by recalculating monthly mean temperature using maximum and minimum temperatures (Ren et al., 2005; Tang and Ren, 2005).

Annual mean surface air temperature in China has increased significantly, with the trend of change reaching 0.22°C $(10\ \mathrm{yr})^{-1}$ for the period 1951–2001 and 0.08°C $(10\ \mathrm{yr})^{-1}$ for the period 1905–2001. Annual mean temperature has risen by about 1.1°C during the past half century, and 0.8°C during the past century (Fig. 1) (Ren et al., 2005). It is obvious that the warming mainly occurred in two time periods, namely the 1920s–1940s and the 1980s–2001. Annual mean temperature anomalies in the 1990s and the 1940s were 0.37°C and 0.36°C, respectively. The highest temperature record occurred in 1998, and the second highest in 1946. The warming period in the period of the 1920s–1940s in China was much higher than global warming during the same time. It is not yet clear why this

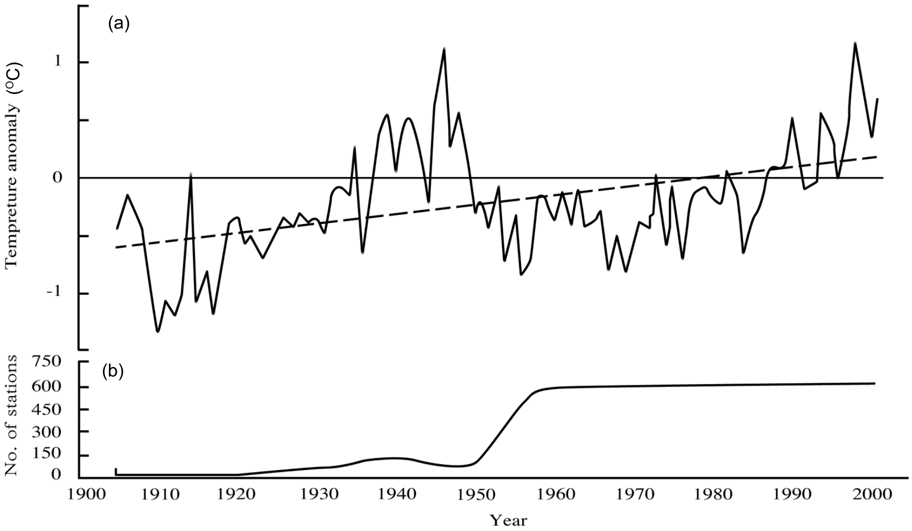

Fig. 1. Change in country-averaged annual mean surface air temperature anomalies in China during 1905–2001: (a) temperature anomalies; (b) number of observation stations. Units: °C (from Tang and Ren, 2005).

warming period occurred in the first half of the 20th century, when anthropogenic effects were not as intensive as they are today.

The warming in the last half century (1951–2001) is very significant, and it is more rapid than the world average. The warming mainly started in the early to mid 1980s. Before that time, temperatures in China fluctuated only within a small range, and no significant trends can be detected. However, starting from the early 1980s, temperatures have steadily risen. 1998 was the warmest year in the past 50 years or so, with the annual mean surface air temperature anomaly reaching 1.13°C. The 1990s was the warmest decade in the latter half of the 20th century.

Seasonal mean temperature for almost all seasons in 1951–2001 shows an upward trend, with the warming in winter being the most obvious. Warming is also significant in spring and autumn, but is very weak in summer. Temperature change in spring and summer is also comparatively similar, with the warming mainly starting after the mid 1990s. On the other hand, temperature change in autumn and winter is more similar, with an obvious warming trend starting until after the early 1980s, and an accelerating warming taking hold after 1987.

Warming in terms of annual mean surface air temperature has mainly occurred in Northeast, North and Northwest China, while most southern parts of the country did not see significant warming. Rising temperatures in winter and spring most significantly contributed to warming in northern China. However, a cooling trend reported in earlier studies is still continuing in southwestern parts of China, with the Sichuan basin and the northern Yunnan-Guizhou Plateau experiencing the most remarkable cooling. Analysis of different seasons shows that the cooling was mainly caused by an obvious drop in seasonal mean temperature in spring and summer. The middle and lower reaches of the Yangtze River also witnessed a cooling trend in summers in the last 50 years. The phenomenon of temperature decrease in Southwest China might have been caused by increased emission of pollutants, such as SO_2, and the resulting acid rain (Li et al., 1995; Hu et al., 2003).

The abovementioned results were all based on a dataset of surface air temperature without any correction for urbanization bias. This might be a problem for most of the meteorological stations located in big, growing cities. In the Beijing region, for example, temperature records from two national basic/reference stations used in constructing temperature series over the past 50 years were significantly impacted by urban warming, especially in the last 20 years. Warming induced by urbanization or enhanced heat island effects in two stations of this city account for around 70% of the total increase in annual mean temperature for the period 1961–2000 (Chu and Ren, 2005). Effects of urbanization on records of nationwide climate stations in other regions, such as North China and a few provinces, is also significant (Ren et al., 2005). These cases indicate the importance of paying more attention to urban heat island effects on long-term mean temperature series in China.

A 1000-year annual mean temperature series has been preliminarily reconstructed (Chu et al., 2005) using 27 tree ring chronologies from seven individual sites

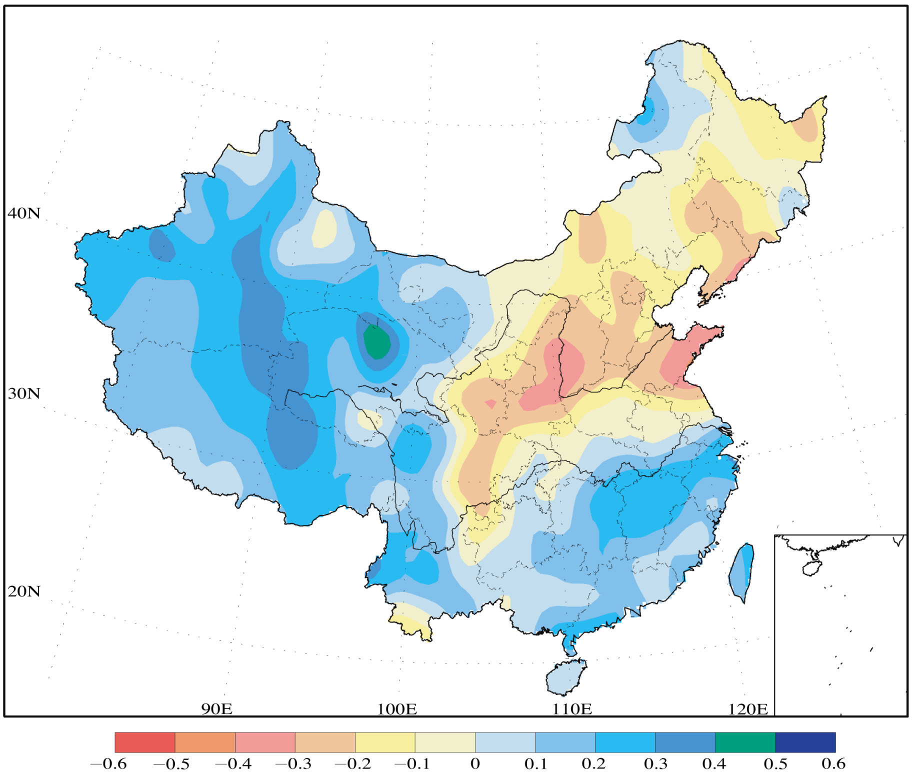

Fig. 2. Trends of precipitation over China (1956–2002). Blue represents positive trend; red represents negative trend. (from Ren et al., 2005)

in western and northeastern China, and the winter-half-year temperature series in eastern China, as reconstructed by Ge et al. (2003). Variability in temperature in China over the past 1000 years is evident. Annual mean temperature in China was generally warmer from A.D. 1000 to A.D. 1310, with a relatively cool episode in the 13th century; and was significantly colder from A.D. 1310 to 1910, with minimum anomalies occurring in the 15th, 17th and 19th centuries. The modern warm period, beginning from the end of the 19th century, looks unusual in terms of the 1000-year variation of annual mean temperature, but it is not significantly warmer than the earlier "Medieval Warm Period" (MWP). The MWP came to an end at approximately the end of the 13th century, and the "Little Ice Age" may then have lasted for a comparatively longer period of time, from the early 14th century to the end of the 19th century. The coldest climate occurred in the mid and late periods of the 17th century and in the 19th century when temperature anomalies dropped to less than −0.4°C. It was also colder in the mid and late period of the 15th century. Some differences between the series of western and eastern China have been detected, and there seems to be no significant warming during the MWP in the temperature series. However, Wang et al. (2002) pointed out that the anomalous warming in the mid 13th century in eastern China was also evident in western China.

2.2 *Precipitation*

Less confidence can be lent to precipitation data prior to the 1950. Data quality for 1951–2001 is good, although no adjustments have been made for the likely bias induced by wind and solid precipitation measurement. In spite of the problems with data, it is still interesting to note that no significant long-term trend in the country-averaged annual precipitation can be detected for the past 100 years. Changing trends in annual precipitation in China are also difficult to detect for the period 1951–2001. If the beginning year is set at 1956, however, a slight increase in average annual precipitation can be seen, with 1998 being the wettest year (Ren et al., 2005).

Large regional differences are notable in precipitation trends between 1956 and 2002 (Fig. 2). An obvious declining trend in annual precipitation occurred in the Yellow River basin and the North China plain, and the largest drop occurred in Shandong Province and southern Liaoning Province. Annual precipitation in the Yellow River, Haihe River, and Liaohe River basins decreased by around 50–120 mm during the time pe-

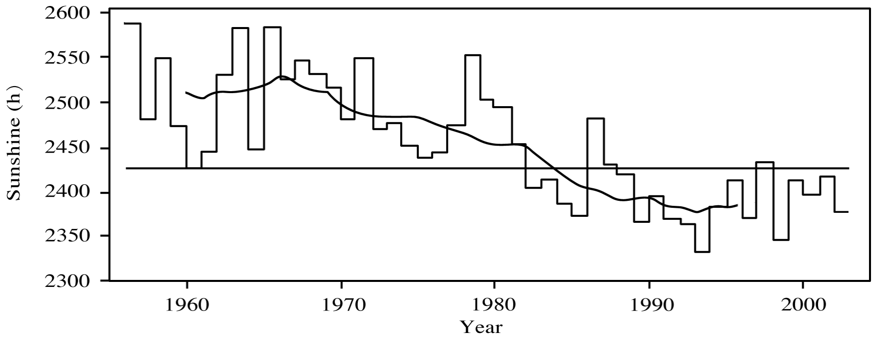

Fig. 3. Change in national average sunshine duration during 1956–2002. Units: h. (from Ren et al., 2005).

riod analyzed. Meanwhile, an insignificant wetting trend in the Yangtze River basin, southeast coastal region and most parts of western China is detectable, though some sites underwent a more significant increase in annual precipitation. The Yangtze River basin and southeast coastal region as a whole witnessed an increase in annual precipitation of around 60–130 mm for the period 1956–2002. The increase mainly resulted from the significant rising summer rainfall, though winter precipitation also tended to rise. Decreases in annual precipitation in the Yellow River basin and the North China plain were mostly caused by less rainfall in summer and autumn. The obvious regional differences in annual precipitation change, in particular the contrast between the south and north, have generally been attributed to a weaker summer monsoon in the East Asian region since the late 1970s (Ding and Dong, 2005).

A few sites of tree ring data are available, and they provide an historical perspective of summer or annual precipitation change on a local scale. For example, annual precipitation over the past 1000 years, as reconstructed from tree rings from the eastern rim of the Caidamu basin in the Tibetan Plateau, indicates a wetter climate in the 20th century than any other centuries in history, and much more severe droughts in the mid to late 15th century, late 17th century and early 18th century, than in the 20th century, occurred (Shao et al., 2004). Historical documents also show much more severe droughts in North China during some decades of the time period, corresponding to the Little Ice Age.

2.3 *Other climate elements*

Change in sunshine duration, pan evaporation and wind speed for the last 50 years has also been analyzed. Figure 3 shows changes in nationwide average sunshine duration during 1956–2002. A significant decreasing trend can be seen, especially for the time period from the mid 1960s to the early 1990s. For the whole period analyzed, the decreasing trend is -38 h $(10\ \mathrm{yr})^{-1}$, but it reached approximately -50 h $(10\ \mathrm{yr})^{-1}$ for the period 1966–1993. Sunshine duration began to stop dropping, or went up slightly, from the mid 1990s. Spatial characteristics include the largest decrease having been in the North China plain, including Hebei, Henan and Shandong Provinces, plus an insignificant increase in a few places on the eastern Tibetan Plateau, Gansu Province, western Inner Mongolia and northern Northeast China (Ren et al., 2005).

Since 1956, the country-averaged pan evaporation has had a significant tendency to decrease, with a changing rate of -35 mm $(10\ \mathrm{yr})^{-1}$. The most significant decrease occurred in spring and summer in the North China plain and the lower reaches of the Yangtze River. The largest decrease in pan evaporation in terms of absolute values has been in northwestern China (Ren et al., 2005). From the early 1990s on, however, pan evaporation in China has stopped decreasing and has begun to rise a little. It is evident that the temporal and spatial patterns of change in pan evaporation are very similar those of sunshine duration in China, implying a dominant influence of solar radiation upon observed pan evaporation (Guo and Ren, 2005; Ren and Guo, 2006).

Country-averaged annual mean wind speed has also experienced a tremendous drop during the past 50 years. However, the obvious decrease in wind speed began from the mid 1970s and has not since stopped, as sunshine duration and pan evaporation did in the early 1990s. The largest decrease in wind speed has occurred in Northwest China, while Southwest China and northern Northeast China have witnessed a smaller drop.

2.4 *Extreme climate events*

A mixed picture can be seen for changes in extreme weather and climate events over the past 50 years. As expected, country-averaged daily minimum tempera-

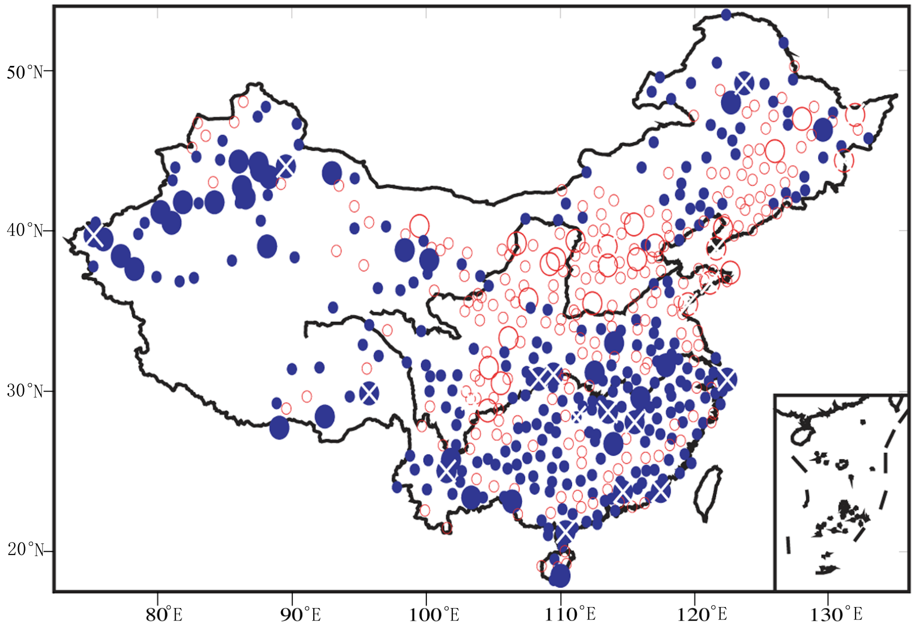

Fig. 4. Trends of days with extreme strong rainfall (25 mm d^{-1}) for 1951–2000 in China. Solid and open circles indicate increases and decreases respectively, and the sizes of the circles are scaled to the strength of the trend (from Ding et al., 2006).

ture and days with a minimum temperature below 0°C have been significantly decreasing since 1950. Due to the fact that a minimum temperature of above 0°C is generally representative of frost-free periods (or $\geqslant 2°$C for operational use), and there has been a decrease in days with a minimum temperature below 0°C, the lengthening of the frost-free period is implied. At the same time, country-averaged daily maximum temperature and days with a maximum temperature above 35°C have not tended to increase significantly, though some places in North China have shown an increasing frequency of heat waves. Days with cold waves in winter in northern and eastern China have undergone a significant decrease over the last 50 years, especially for the period beginning 1970 (Zhai and Ren, 1997; Zhai and Pan, 2003).

Although an obvious increase in days with heavy rain in the Yangtze River basin, and areas suffering from serious drought in the North China plain and southern Northeast China, has been detected for the last 50 years, no significant change in extreme precipitation events can be seen for the country as a whole. Stronger rainfall has been more frequently recorded in western China, including Xinjiang Autonomous Region and most areas of the Tibetan Plateau (Zhai et al., 1999; Gong and Wang, 2000), but less frequently observed in North China and southern Northeast China, where annual total precipitation has undergone a large decrease (Fig. 4). The pattern of a drier North China and a wetter South China has resulted in a difficult situation for water management in the country.

Annual total volume of precipitation induced by tropical cyclones equivalent to the areal rainfall amount, and the total days with torrential precipitation of 50 mm d^{-1} due to tropical cyclones, have both tended to decrease since 1957, although the two years with the largest typhoon-induced rainfall occurred after 1980 (Fig. 5). The frequency of landing typhoons in southeastern coastal areas has also tended to decrease after the early 1980s (Ren et al., 2006). Dust storms, a disastrous weather phenomenon in northern China, have shown a significant decreasing trend in terms of the number of days over the last 50 years, and in the last two decades have occurred at a much lower frequency, in spite of the fact that they have appeared a little more frequently since 1997.

3. Understanding and attributing reasons for climate change in China

Understanding and attributing reasons for climate change is a key issue in international climate research (IPCC, 2001), and there have been many advances in China relating to this field over the last decade. Similar to international studies, most Chinese research has concentrated upon the detection and causes of climate warming in China during the 20th century. Some other studies have focused on understanding the dimming of surface solar radiation in China and the patterns with

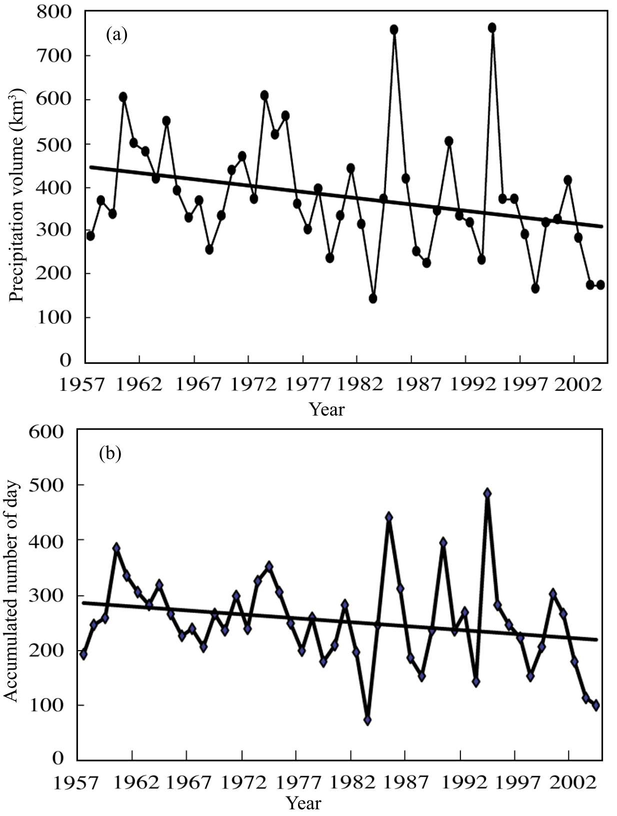

Fig. 5. Variations of tropical-cyclone-induced precipitation in China: (a) variations of total annual volume of precipitation (equivalent to areal rainfall amount); (b) variations of accumulated number of days with torrential precipitation due to tropical cyclones ($\geqslant$50 mm d^{-1}). Units: mm d^{-1}. (from Ren et al., 2006)

wetter/cooler conditions in South China and drier/warmer conditions in North China over the last three decades, rather than averages between 1961 and 1990. In assessing the causes of climate change, both natural and anthropogenic forcings have been considered. The major methods of detection for attributing reasons for climate change in China are multiple climate models and numerical-statistic methods based on observed data (Wang and Shi, 2001; Zhao et al., 2005a,b; Luo et al., 2005; Ding et al., 2006).

3.1 *Detection and causes of annual mean temperature in China for the 20th century*

According to analyses of four sets of observed data in China collected from both domestic and overseas studies (Lin et al., 1995; IPCC, 2001; Wang and Shi, 2001; Tang and Ren, 2005), similar to global warming, it is concluded that warmer conditions have certainly occurred in China in the 20th century, particularly over the last 50 years. Large differences among four observed datasets are evident before 1950 due to insufficient observed data in China. However, four datasets have shown strong agreement, with correlation coefficients of 0.76–0.90. The linear trends of temperature in China for the four datasets from 1900–1999 are 0.35°C (100 yr)$^{-1}$, 0.39°C (100 yr)$^{-1}$, 0.72°C (100 yr)$^{-1}$, and 0.19°C (100 yr)$^{-1}$, respectively. For the latter half of the 20th century (1950–1999), the linear trends are 0.73°C (50 yr)$^{-1}$, 0.77°C (50 yr)$^{-1}$, 0.92°C (50 yr)$^{-1}$, and 0.64°C (50 yr)$^{-1}$, respectively (Zhao et al., 2005a). All evidence points towards a warming trend in China, and is particularly obvious for the last 50 years.

Paleoclimate studies of detection in China for the last 1000 years have indicated consistent characteristics with regard to temperature change in the Northern Hemisphere. The 20th century may well be the warmest in China during the last 1000 years, but some research has argued that the MWP might have been much warmer. As we know, due to limited proxy data in China for the last 1000 years, one can only state with confidence that the 20th century was a warm century during the last 1000 years (Zhao et al., 2005a); whether or not it was the warmest century during this time still needs to be further examined. Also required is more evidence to detect the warming status of the 20th century during the last 1000 years.

Figure 6a shows the evolution of annual mean temperature anomalies in China for the 20th century, as simulated by approximately 40 climate models, of which nine are from China, together with the various human emission scenarios, such as doubled CO_2, a 1% increase in greenhouse gases, increasing greenhouse gases, both greenhouse gases and sulfate aerosols increasing, IS92 scenarios, and SRES scenarios (Zhao et al., 2005a). Figure 6a also shows both observation and model control runs for comparison to the simulations of the various scenarios. Firstly, it is evident that the model control run is not able to simulate the warming trend in China for the 20th century. The correlation coefficient between observations and the control run is −0.02, meaning that there is not a significant relationship between observations and the model control run. Secondly, almost all the models with the various human emission scenarios simulate the warming trend in China for the 20th century to a reasonable degree, especially the obvious warming trend over the last 50 years. The correlation coefficients between observations and the multi-model ensemble mean is 0.47, and the linear trends are 0.71°C (100 yr)$^{-1}$ and 0.90°C (50 yr)$^{-1}$, respectively, which are similar to the observations (see Table 1) (Zhou and Zhao, 2006). Therefore, human emissions very likely explain the warming in China for the 20th century, especially for the last 50 years. The conclusion is in agreement with that of the

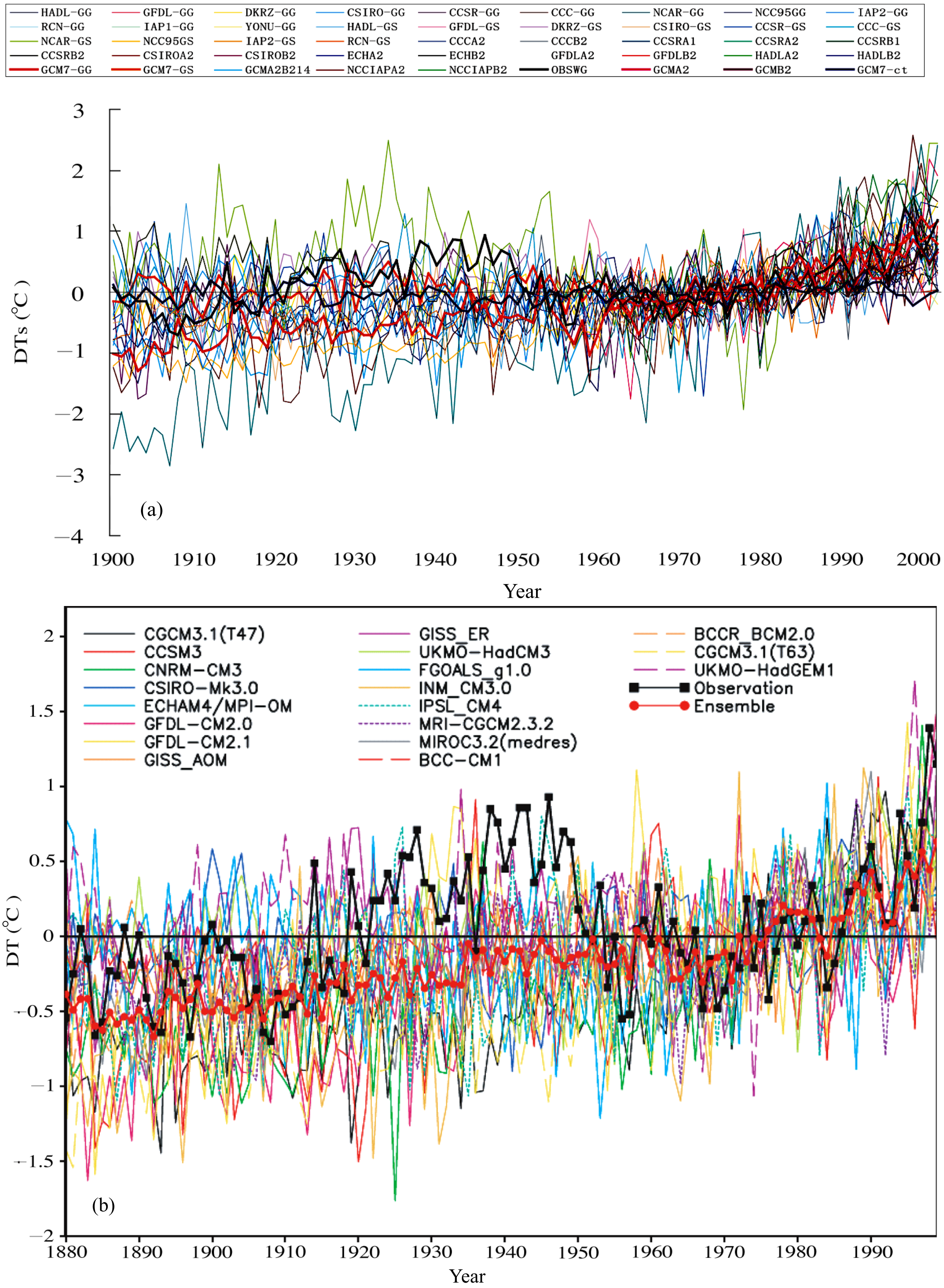

Fig. 6. Evolution of both observed and simulated annual mean temperature anomalies in China for the 20th century, relative to 1961–1990: (a) from around 40 human emission simulations (thick red-GCM7-GG; thick apricot: GCM7-GS; thick claret: GCM7-SRESA2; thick lilac: GCM7-SRESB2; thick black: observation; thick blue: GCM7 control run mean) (Zhao et al., 2005a); (b) from 19 models with all forcings (thick black: observation; thick red: 19-model ensemble mean. Units: °C) (From Zhou and Yu, 2006; Zhou and Zhao, 2006).

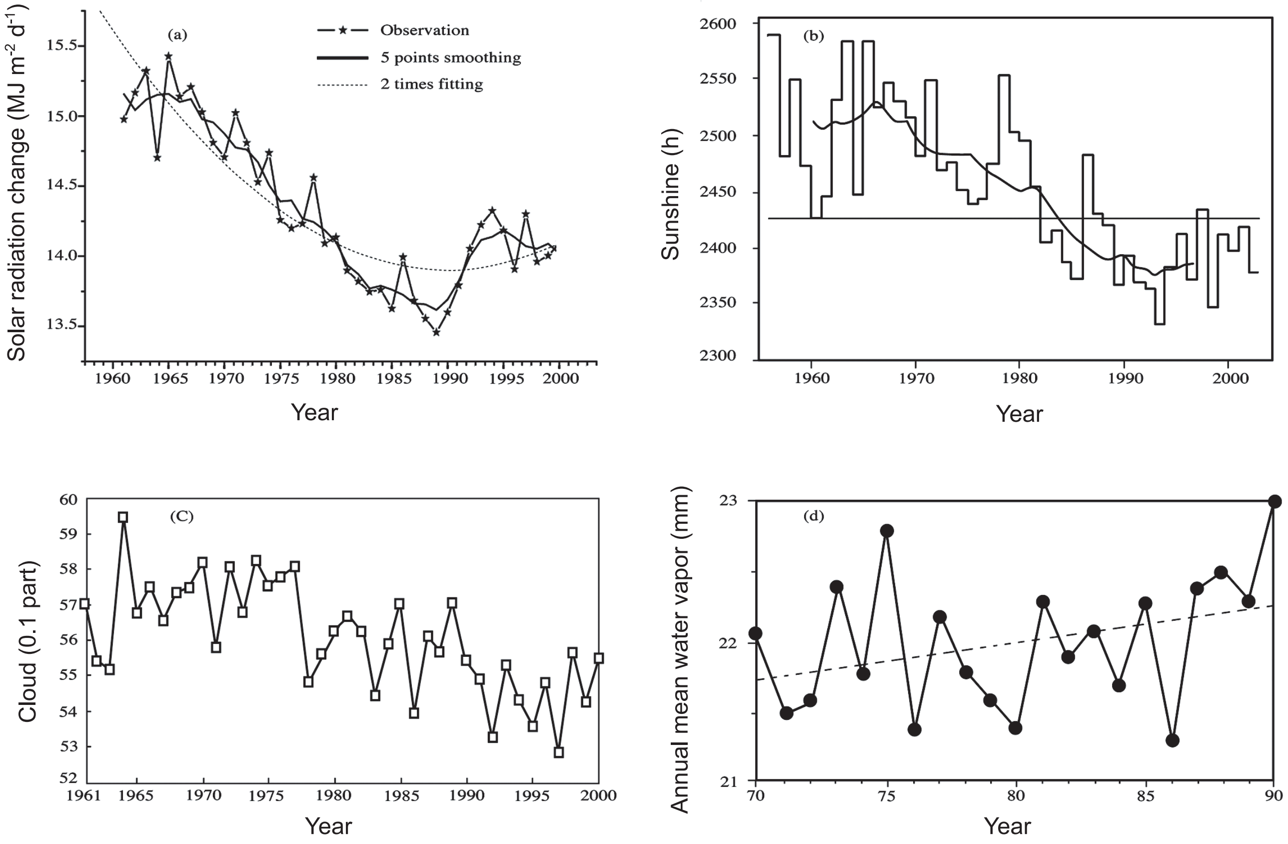

Fig. 7. (a) Surface solar radiation change in China for 1957–2000 (Units: MJ m^{-2} d^{-1}) (Che et al., 2005; Shi et al., 2006). (b) Change of annual mean sunshine time for 1956–2002 (Units: h) (Ren et al., 2005). (c) Total cloud amount change for 1961–2000 (Units: 0.1 part) (Ren et al., 2005). (d) Annual mean atmospheric water vapor change for 1970–1990 (Units: mm) (from Zhai and Eskridge, 1997).

IPCC (2001).

Another study considers all radiative forcing by 19 global climate system models, of which two are from China, to simulate annual mean temperature anomaly changes in China for the 20th century. All radiative forcing included: changes in solar radiation, volcanic activity, greenhouse gases, sulfate aerosols, black carbon, ozone, land use/vegetation changes, and others (see Fig. 6b) (Zhou and Yu, 2006; Zhou and Zhao, 2006). The correlation coefficient of the annual mean temperature anomalies between observation and the multi-model ensemble for the 20th century is 0.55, which is better than when only using human emissions (see Table 1) (Zhou and Zhao, 2006). This implies that solar and volcanic activity, as well as the interactions between air and sea, might be responsible for the temperature change in China during the first half of the 20th century.

The third numerical experiment (E3 in Table 1) uses the NCAR CAM2, driven by observed sea surface temperature and sea ice provided by the Hadley Center. The model simulates annual mean temperature in China during the 20th century with 12-member ensembles (Zhou and Yu, 2006; Zhou and Zhao, 2006). The model has a certain capability to reproduce the colder periods of 1900–1915 and the 1970s, as well as the warmer period of the 1940s, more so than the means of 1961–1990. However, the model does not reproduce the obvious warming trends in China during the second half of the 20th century (see Table 1).

The ensemble means of the human emissions experiments or all radiative forcing experiments are not able to simulate well the warming range in China for the last decades of the 20th century. This implies that simulated ensembles underestimate the real extent of the warming that has taken place in China. It is also evident that the models do not simulate to a reasonable level the warm period in China from 1920–1940 (see Fig. 6). Most of the models and their ensemble average considerably underestimate this warming period, with temperatures being 0.5–1°C lower than observed.

Table 1. Anomaly correlation coefficients (ACC) and linear trends of annual mean temperature in China for the 20th century between observations and numerical simulations (developed from Zhou and Zhao, 2006).

Numerical experiments (E)	ACC	Linear trends (20th century)	Trends (past 50 years)	Trends for 1960–1970	Trends for 1980–1999
CT (control run)	−0.02	0.11°C (100 yr)$^{-1}$	0.11°C (50 yr)$^{-1}$	0.10°C (10 yr)$^{-1}$	−0.02°C (10 yr)$^{-1}$
E1 (approximately 40 models with human emissions)	0.47	0.71°C (100 yr)$^{-1}$	0.90°C (50 yr)$^{-1}$	−0.07°C (10 yr)$^{-1}$	0.38°C (10 yr)$^{-1}$
E2 (19 models with both natural and human forcing)	0.55	0.70°C (100 yr)$^{-1}$	0.85°C (50 yr)$^{-1}$	−0.06°C (10 yr)$^{-1}$	0.24°C (10 yr)$^{-1}$
E3 (12-member ensembles with observed SST and sea ice as input)	0.50	0.33°C (100 yr)$^{-1}$	0.01°C (50 yr)$^{-1}$	−0.12°C (10 yr)$^{-1}$	0.21°C (10 yr)$^{-1}$
Observed mean (4 data)		0.4–0.8°C (100 yr)$^{-1}$	0.5–0.9°C (50 yr)$^{-1}$	−0.55°C (10 yr)$^{-1}$	0.53°C (10 yr)$^{-1}$

3.2 *Possible anthropogenic signals of climate change in China for the last 50 years*

There exists complete and accurate observed data in China for the last 50 years, use of which makes it possible to understand and detect anthropogenic signals of climate change (Zhai and Eskridge, 1997; Wang and Shi, 2001; Wu et al., 2004; Che et al., 2005; Ren et al., 2005; Zhao et al., 2005b; Shi et al., 2006[a]). Based on observed data of annual mean surface solar radiation for 1957–2000—quality-controlled at 122 stations across China (Che et al., 2005; Shi et al., 2006)—and annual mean sunshine from 574 stations (Ren et al., 2005), it is found that surface solar radiation and sunshine decreased (dimmed) from 1961—1990, then increased (brightened) after 1990, although still lower than in the 1960s (see Figs. 7a, b) (Che et al., 2005; Ren et al., 2005; Zhao et al., 2005b; Shi et al., 2006). These phenomena have also been found in other countries (IPCC, 2001).

Several attribution analyses have explored the changes in clouds, atmospheric water vapor and dust that have had physical feedback processes with surface solar radiation. Firstly, according to observed annual mean total cloud amounts from 466 stations across China from 1961–2000, it is evident that total cloud amount has experienced a reducing trend over the last 40 years. The total cloud amount was reduced by around 0.4 times the total from 1977–1995 (see Fig. 7c) (Ren et al., 2005). This implies that the reduction in total cloud amount cannot explain the dimming surface solar radiation. Secondly, based on observed data of annual mean dust-storm days from around 600 stations across China over the last 50 years, annual mean dust-storm days were reduced by around −13 days (52 yr)$^{-1}$ (Climatic Assessment Division of the National Climate Center, 2006, personal communication). Therefore, the dimming surface solar radiation does not depend upon the level of dust-storm days either. Thirdly, consideration is given to atmospheric water vapor in China. Calculating the annual and seasonal atmospheric water vapor from both surface and sounding observation at 378 stations across the country from 1970–1990, it is found that atmospheric water vapor increased obviously over the last few decades (see Fig. 7d). The linear trend is 1.2% (10 yr)$^{-1}$. The correlation coefficient between atmospheric water vapor and surface air temperature in China is 0.61, which reached the 99% confidence level (Zhai and Eskridge, 1997). This means that the warming climate in China caused the increasing atmospheric water vapor and, therefore, it might be a reason for the dimming surface solar radiation.

With the developing economy and increasing levels of industrial emissions in China, air pollution has become a serious problem. Sulfate and black carbon aerosols have increased significantly with time, and atmospheric aerosol optical depths have increased obviously (Wang and Shi, 2001; Che et al., 2005; Zhao et al., 2005a,b; Shi et al., 2006). These phenomena were more serious before 1990, but since 1990 policy-makers and the public have paid more attention to improve air pollution and atmospheric pollutants have decreased with time. This implies that the change in anthropogenic aerosols in the atmosphere might be a reason for the dimming surface solar radiation before 1990 and the brightening after 1990.

Further studies of the dimming of surface solar radiation in China have used global and regional cli-

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[a] Shi, G., H. Tadahiro, Z. Chen, B. Wang, J. Zhao, H. Che, and L. Xu, 2006: Qualify detection of surface solar radiation data and its impacts on the long-term change trends. *Journal of Geophysics*, submitted.

mate models nested to atmospheric chemical models to provide additional evidence. Most studies have used global or regional climate models to consider the effects of sulfate aerosols or black carbon, or greenhouse gases plus sulfate aerosols, black carbon and organic carbon on climate change in China (Wang and Shi, 2001; Wu et al., 2004; Zhao et al., 2004; Zhao et al., 2005b). As examples, three numerical simulations are shown in Fig. 8. As simulated by the models, the increasing anthropogenic aerosols bring an increasing atmospheric aerosol optical depth and a reducing (dimming) of surface solar radiation. It is estimated that the atmospheric aerosol optical depth is around 0.6–0.8 in the Sichuan basin and along the Yangtze River valley, and the surface air temperature is cooler by around −0.2–0.5°C for two simulations, or slightly warmer for one simulation (Figure not shown) than the control runs or present time. However, two models do not simulate the significant warming over North China (see Fig. 8a). Only one model with both increasing greenhouse gases and anthropogenic aerosols simulates to a reasonable level the warming in North China (Figure not shown). For rainfall simulations, two models with anthropogenic aerosols do not reproduce the floods along the Yangtze River valley, nor the droughts in North China (see Fig. 8b). One model with both greenhouse gases and anthropogenic aerosols reproduces the rainfall pattern in China, but it does not simulate well the severe droughts over Shandong Province, and underestimates the wet range along the Yangtze River valley (Figure not shown).

The climate characteristics of the more frequent floods with the cooler weather along the Yangtze River valley and the sustaining droughts with the warmer weather in North China for the last 25 years, more so than the period 1961–1990, are evident. Plenty of evidence has revealed the role of natural climate variability, such as: decadal and interdecadal variability of the East Asian summer monsoon; the periodicities and transitions of rainfall and temperature change in China; abrupt (fast) climate change; the impacts of the NAO (North Atlantic Oscillation), the AO (Arctic Oscillation), the AAO (Antarctic Oscillation), the PDO (Pacific Decadal Oscillation), and ENSO; and snow cover on climate patterns in China. The upper part of Table 2 summarizes these studies (Wang, 2001; Zhao et al., 2005b), while the possible anthropogenic signals are given in the bottom part of Table 2. It can be seen from Table 2 that the increasing greenhouse gases contribute to the enhancement of the East Asian summer monsoon, and to the warm and wet climates of China. The black carbon and land use changes might produce the weakening of the East Asian summer monsoon with the pattern of floods in the South China and droughts in North China. The sulfate aerosols might bring the lower temperature and floods along the Yangtze River valley. Causal analyses of anthropogenic factors, such as greenhouse gases emitted into the global atmosphere, sulfate aerosols and black carbon, as well as "atmospheric brown clouds" produced in local areas is contradictory. Therefore, there still does not exist a consensus on the possible mechanisms that have caused the patterns climate change in China for the last 25 years. More research should be carried out in future.

3.3 *Understanding anthropogenic effects on climate change in China*

Causal analysis of climate change is based on demonstration that the detected observed change is consistent with model-estimated responses to both natural and anthropogenic forcings, as well as demonstration that the detected observed change is not consistent with alternative, physically plausible explanations that exclude these forcings.

As proposed above, a broad range of climate variables have indicated evidence of possible anthropogenic signals in China. As summarized in Table 3, the observed and simulated evidence of climate change in China for the 20th century have shown a significant contribution by anthropogenic activity. It is very likely that greenhouse gas forcing has been the dominant cause of observed warming in China over the last 50 years. Climate warming that brings both increasing atmospheric water vapor and increasing anthropogenic aerosols might be a reason for the dimming surface solar radiation in China. We cannot, however, answer definitely whether anthropogenic forcing has caused changes in patterns of rainfall, floods/droughts, the East Asian monsoon, nor typhoons/tropical cyclones. Further studies are needed.

4. Projections of future climate change over China

4.1 *Surface air temperature*

In recent years, a number of new atmosphere-ocean general circulation models (AOGCMs) that have included the effects of: greenhouse gases only (GG); greenhouse gases plus aerosols (GS); and the SRES A2 and B2 scenarios, have made projections of climate change for the 21st century. Using these AOGCM simulations, we analyzed future climate change over China (Hu et al., 2000; Xu, 2002; Zhao and Xu, 2002; Bueh et al., 2003; Zhao et al., 2003; Xu et al., 2003a,b,c; Kimoto, 2005; Xu et al., 2005). In recent years, Chinese researchers have also developed an atmosphere-ocean-land general circulation model with a high resolution

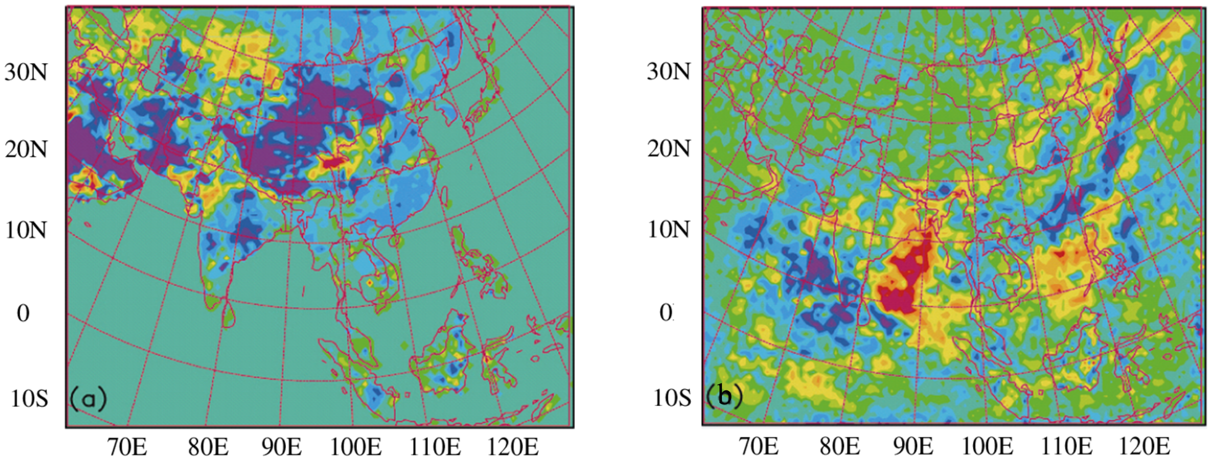

Fig. 8. Geographical distributions of annual mean temperature (left, units: °C) and precipitation (right, units: mm). (a) and (b) as simulated by the TEACOM regional climate model with black carbon (sensitivity minus control) (from Wu et al., 2004).

Table 2. Effects of both natural climate variability and anthropogenic factors on floods/cooling along the Yangtze River valley and droughts/warming over North China for the last 25 years, relative to 1961–1990 (From Zhao et al., 2005b).

Natural climate variability	Contribution to Asian summer monsoon	Climate consequence in China
PDO+ENSO	Weaker	North China drought/ South China floods
AO in spring	Weaker	Strong rainfall over Yangtze River valley and southern Japan
Periodicity and transition of temperature and precipitation	Weaker	Wetter/cooler over Yangtze River valley, droughts in North China
Abrupt climate change	Weaker	Floods over Yangtze River valley
IOD (Indian Ocean Dipole)	Significant	Insignificant
Eurasian snow cover	stronger	Inconsistent
Tibetan Plateau snow cover	Weaker	North China drought/ South China flood
Anthropogenic factors	Contribution to Asian summer monsoon	Climate consequence in China
Greenhouse gases increasing (global warming)	Stronger	Warmer and wetter
Sulfate aerosols increasing	Weaker	Lower temperature and floods in Yangtze River basin
Black carbon aerosol increasing	Weaker	Droughts in North China/ floods in South China
Greenhouse effects + aerosols (brown clouds) increasing	Likely weaker in the last 25 years	Warmer/drier in North China, floods along Yangtze River valley
Land use change (vegetation degeneration)	Weaker	Droughts in North China, floods in South China

Table 3. Detection of climate change in China during the 20th century and projection for the 21st century due to human emissions (based on this paper and those of Zhao et al., 2005a, b; and Ding et al., 2006).

Climate phenomenon	Observed evidence during 20th century	Simulated evidence with anthropogenic emissions during 20th century	Projected climate change due to human emissions in 21st century
Increase of surface air temperature	Trends: 0.5–0.8°C (100 yr)$^{-1}$ Distributions: obvious warming obvious warming of 0.8°C (100 yr)$^{-1}$ in North China	Trends: 0.3–1.6°C (100 yr)$^{-1}$ 0.6–1.6°C (50 yr)$^{-1}$ 0.6–0.9°C (50 yr)$^{-1}$ Distributions: of 0.5–1.8°C (100 yr)$^{-1}$ in North China (approx. 40 simulations)	3.0–5.0°C (100 yr)$^{-1}$, Distributions: obvious warming of 4.5–7.5°C (100 yr)$^{-1}$ in North China (approx. 40 projections)
Increase of $T_{\max}$	Trends: 0.5°C (49 yr)$^{-1}$	Trends: 0.5–0.8°C (50 yr)$^{-1}$ (about 12 simulations)	Trends: 4.1–5.0°C (50 yr)$^{-1}$ (about 12 projections)
Increase of $T_{\min}$	Trends: 1.4°C (49 yr)$^{-1}$	Trends: 0.7–1.0°C (50 yr)$^{-1}$ (about 12 simulations)	Trends: 4.1–4.9°C (50 yr)$^{-1}$ (about 12 projections)
Other warming evidence	17 warm winters since 1986; longer hot summer spells in some parts of China	12 warm winters since 1986; nine warmer summers for 1993–2002 (approx. 40 simulations)	98–99 more warmer winters and 100 warmer summers in 21st century than averages of 1961–1990
Precipitation change	Trends: 3% (99 yr)$^{-1}$; 2% (49 yr)$^{-1}$	−14–21% (100 yr)$^{-1}$; −6–29% (50 yr)$^{-1}$ (approx. 40 simulations)	11%–17% (100 yr)$^{-1}$ (approx. 40 projections)
Patterns of floods/droughts	More floods along Yangtze River valley, and more droughts in Huabei for the last 25 years	Wetter/cooler along Yangtze River valley, and drier/warmer over North China for 1976–2000 minus 1961–1990 (about 5–6 simulations)	Wetter by 10%–20% in northwest; wetter by 15%–25% in northeast; wetter by 10%–15% in Huanan; drier by 0%–2% in Yangtze delta and Bohai coasts (around 10 or more projections)
Heavy rain and rainstorms	Increasing along Yangtze River and parts of South China; decreasing along Huaihe River and middle and lower branches of Yellow River	No obvious change	Increasing along Yangtze River, parts of South China and the northwest and northeast; decreasing over parts of Liaoning (about 2–3 projections)
East Asian winter monsoon	Weakened	Weakened (one AOGCM with SRES)	Weakening (one model with SRES)
East Asian summer monsoon	Weakened obviously	Weakened (one AOGCM with SRES)	Enhancing (one model with SRES)
Typhoon/tropical cyclone influence	Decreasing by linear trend: −3.9 times (50 yr)$^{-1}$ (1951–2000)	Decreasing by linear rend: −3.0 times (50 yr)$^{-1}$ (1951–2000) (one AOGCM with SRES)	Annual total typhoon numbers decreasing by −5–10 times (100 yr)$^{-1}$ (one AOGCM with SRES) annual total typhoon numbers increasing (one regional model with CO_2 increasing)

Continued.

Climate phenomenon	Observed evidence during 20th century	Simulated evidence with anthropogenic emissions during 20th century	Projected climate change due to human emissions in 21st century
SST over ENSO regions	Niño 3.4: 0.33°C (53 yr)$^{-1}$	0.83°C (53 yr)$^{-1}$ (one AOGCM with SRES)	More warm anomalies than warm pool (one AOGCM with SRES)
SST over warm pool	Warming	Warming (one AOGCM with SRES)	Warming (one AOGCM with SRES)
Surface solar radiation	Dimming by 3.1 W m^{-2} (10 yr)$^{-1}$	Weakening effects (2–3 simulations with black carbons)	No calculations
Atmospheric water vapor	Increasing by 1.2% (10 yr)$^{-1}$	No simulations	No calculations

of T63 (named NCC/IAP T63) to simulate climate change over the past 100 years and to project future climate change (Xu, 2002).

Figure 9 shows the time evolution of the annual average temperature anomaly for the 20th and 21st century relative to the years 1961–1990, as projected by 40 AOGCMs. It indicates that the models including greenhouse gases (GG, GS, A2, B2) simulated the warming trend, with strong similarities between observed and simulated results. This means that the one of reasons for 20th century warming in China is likely to be increasing levels of greenhouse gases produced by anthropogenic emissions, especially for the last 50 years. The results indicate that temperatures will further increase by 1.5–2.1°C by 2020, by 2.3–3.3°C by 2050, and by 3.9–6.0°C by 2100. Linear trends in temperature during the 21st century will be larger in China than global equivalents, and lower than the East Asia region.

In terms of seasonality, under the SRES scenarios A2 and B2, temperatures will increase in all four seasons, most obviously in winter and spring, and by relatively less in summer and autumn. Temperatures will increase by 5.6°C and 4.0°C over the whole of China by the end of 21st century and by 2050, respectively.

For the geographical distributions of annual average temperature for the year 2020, 2050 and 2070, the results show temperatures increasing by 1.2–1.8°C in 2020 under the GG scenario, especially in Northeast and western areas of China. The warming is smaller under the GS scenario (1.0–1.5°C), with the largest increase predicted for North China, Northwest China, and the northern part of Northeast China. Under the A2 and B2 scenarios, the temperature increase is predicted to be 0.6–1.8°C and 0.9–2.1°C, respectively. The warming will be larger in 2050, with temperatures predicted to increase by 2.4–3.9°C under GG, 1.5–3.0°C under GS, 1.8–3.9°C under A2, and 1.8–3.3°C under B2. The temperature increase is double compared to 2020. The warming is most obvious over North China, Northwest China and Northeast China.

There are different warming conditions from south to north over the whole of China. The warming is obviously larger in North than in South China. Along the same latitude, the temperature increase is smaller in eastern coastal areas as compared to inland areas.

4.2 *Precipitation*

The reasons for precipitation change are more complicated than those for temperature by human activity. There are different future trends depending on different models and scenarios, particularly for greenhouse gases plus aerosol scenarios (GS). However, in summary, precipitation increases with most of the model simulations under the GG, A2 and B2 scenarios; precipitation increase will be 20% over China under GG and A2 by the end of 21st century, and 10% under B2. Figure 10 shows the change of annual average precipitation anomalies from 1900–2100, as predicted by seven models under different scenarios. The results indicate that precipitation will increase according to most models and scenarios, especially under GG and A2, but will decrease according to some models, particularly in the first half of the 21st century.

5. Conclusions

The following conclusions can be drawn:

(1) The main feature of climate change in China during the last 100 years is climate warming, which is consistent with the global warming trend. Based on an analysis of observed maximum and minimum

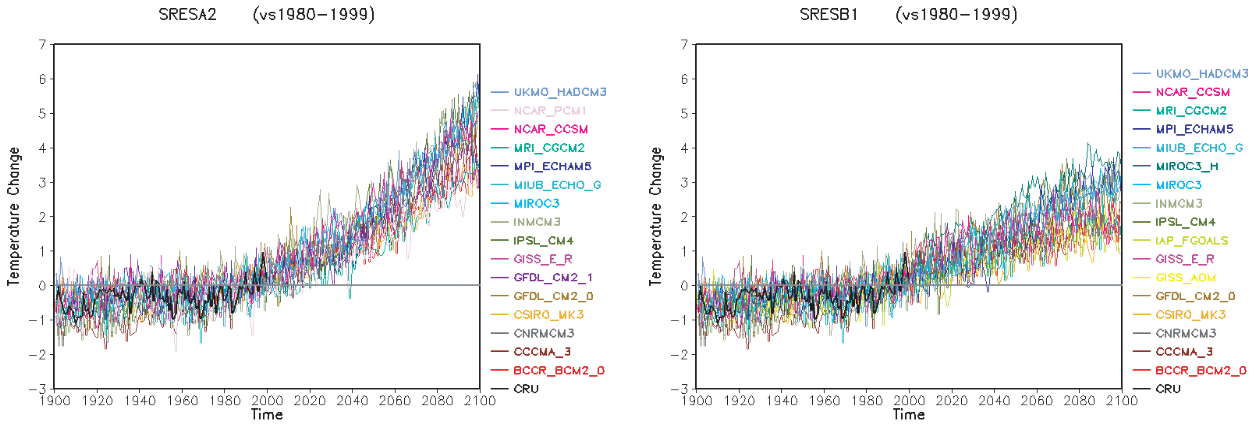

Fig. 9. Simulated and projected temperature change in China (1900–2100) by multi-models with various human emission scenarios. Thick black curve-observation, provided by Wang and Gong (2000); thick red curve-average under GG scenario; thick orange curve-average under GS scenario; thick brown curve-average under A2 and B2 scenarios; thick yellow curve-simulated result by NCC/IAPT63.

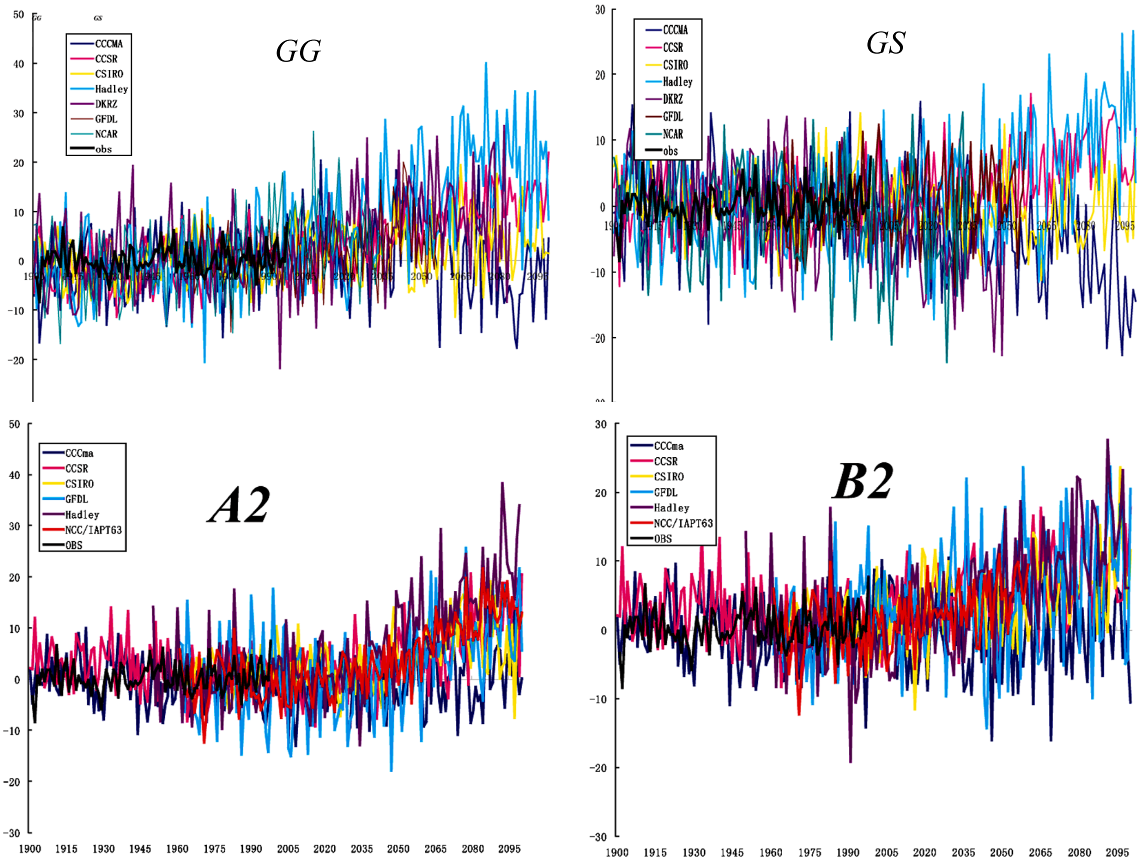

Fig. 10. Change in precipitation according to different models and emission scenarios of greenhouse gases and aerosols from 1900–2100 year. (Units: %; from Ding et al., 2007).

temperatures during the period 1905–2001, mostly in East China, the mean temperature increase rate is 0.81°C (100 yr)$^{-1}$. However, if daily mean temperature from stations in western China and some proxy data are included, the mean temperature increase rate for 1880–2002 is 0.58°C (100 yr)$^{-1}$. Therefore, the warming rates are different due to different data sources and analysis methods. Overall, the warming range in China for the last 100 years is taken as 0.5–0.8°C, slightly higher than the global warming range (0.6±0.2°C). During this period, there occurred two warming episodes: 1920s–1940s and 1980s–present.

There has been no long-term trend for precipitation over the last 100 years in East China. However, since the mid 1950s, precipitation in China has shown a slight increase, consistent with the global trend. The interdecadal change in precipitation amount in China has two dominant modes of 20 and 80 years. North China experienced much precipitation in the period from the 1950s to the late 1970s and then shifted to reverse precipitation conditions in the period from the 1980s to 1990s. In Northwest China, precipitation has started increasing significantly since the mid 1980s, most significantly in Xinjiang Autonomous Region [precipitation increase rate of 10%–15% (10 yr)$^{-1}$].

(2) As the climate has warmed up, the intensity and frequency of occurrence of extreme weather and climate events have increased, including a rise of extreme minimum temperature, a decrease in temperature diurnal variation, and an increase and intensification in extreme precipitation events. In the 1990s especially, the total precipitation amount, extreme precipitation amount and intensity of precipitation events tended to increase. The area and intensity of drought events has also increased. In addition, the frequency of occurrence of heat waves in summer has increased, the number of frost days has decreased, the frequency of cold waves has decreased, the probability of occurrence of snow disasters has increased, and dust storms have tended to decrease.

(3) Based on detection and projections using climate models developed by international communities and China, China will continue to warm throughout the 21st century, especially in winter and in North China, and will be subject to wetter conditions, especially in Northeast and Northwest China, due to an increase greenhouse gas emissions. Future climate conditions in China will be considerably different from those of the 20th century.

Warming will continue over China in the 21st century by 3–5°C, and will be more obvious than in the 20th century, especially in North China and Northwest China. Annual mean temperatures will increase by 1.5–2.1°C in the year 2020, by 2.3–3.3°C in the year 2050, and by 3.9–6.0°C in the year 2100. Synthesizing all scenarios, the results show that it will possibly become wet over most parts of China, particularly in the northeast and northwest, and it will possibly become dryer over central parts of China. For example, the precipitation increase is most obvious in western China. Especially under GS scenarios, precipitation will increase by 20% in Northwest China, but decrease south of the Yangtze River. In the year 2050, the precipitation increase will become more obvious with greenhouse gases increasing, and is likely to increase by 15%–40%. With human emissions increasing, the winter monsoon will weaken over East Asia, while the summer monsoon will intensify. Table 3 Comprehensively summarizes main results of detection, simulations and projections.

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