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CHARACTERISTICS AND TRENDS OF CLIMATIC EXTREMES IN CHINA DURING 1959–2014

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Abstract: The spatial and temporal variations of daily maximum temperature (Tmax), daily minimum temperature (Tmin), daily maximum precipitation (Pmax) and daily maximum wind speed (WSmax) were examined in China using Mann-Kendall test and linear regression method. The results indicated that for China as a whole, Tmax, Tmin and Pmax had significant increasing trends at rates of 0.15℃ per decade, 0.45℃ per decade and 0.58 mm per decade, respectively, while WSmax had decreased significantly at 1.18 $m \cdot s^{-1}$ per decade during 1959—2014. In all regions of China, Tmin increased and WSmax decreased significantly. Spatially, Tmax increased significantly at most of the stations in South China (SC), northwestern North China (NC), northeastern Northeast China (NEC), eastern Northwest China (NWC) and eastern Southwest China (SWC), and the increasing trends were significant in NC, SC, NWC and SWC on the regional average. Tmin increased significantly at most of the stations in China, with notable increase in NEC, northern and southeastern NC and northwestern and eastern NWC. Pmax showed no significant trend at most of the stations in China, and on the regional average it decreased significantly in NC but increased in SC, NWC and the mid-lower Yangtze River valley (YR). WSmax decreased significantly at the vast majority of stations in China, with remarkable decrease in northern NC, northern and central YR, central and southern SC and in parts of central NEC and western NWC. With global climate change and rapidly economic development, China has become more vulnerable to climatic extremes and meteorological disasters, so more strategies of mitigation and/or adaptation of climatic extremes, such as environmentally-friendly and low-cost energy production systems and the enhancement of engineering defense measures are necessary for government and social publics.

Key words: climatic extreme; trend; Mann-Kendall trend; linear regression; vulnerability; China

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1 INTRODUCTION

The average land and ocean surface temperature shows a warming of 0.85 ℃ [0.65 to 1.06 ℃] globally over the period 1880 to 2012 as calculated by a linear trend, and the increase of global mean surface temperatures by the end of the 21st century (2081—2100) relative to 1986—2005 is projected to likely be in the range of 0.3—4.8 ℃ (IPCC[1]). Many studies confirm that the changes in climatic extremes are greater than in mean climate based on observation or simulation (Katz and Brown[2]; Groisman et al.[3]), and changes in climatic extremes are likely to have larger impacts on agriculture, ecology, infrastructure and human activities (Kunkel et al.[4]; Fu et al.[5]; IPCC [6]). According to World Meteorological Organization (WMO)[7], our world suffered unprecedented high-impact climate extremes during 2001—2010, and over 370,000 people died from extreme weather and climate conditions. It has therefore been suggested that climate change research should concentrate on climatic extremes rather than climatic means (von Storch and Zwiers[8]; Hu et al.[9]). Moreover, the analysis of long-term characteristics of climatic extremes is of quite important in assessment of the evolution of these extremes under the condition of changing climate and the adaptation and mitigation strategies in the context of sustainable development[10].

China is a region with complex topography and influenced by a strong monsoon system. Important temporal-spatial variability in both climatic means and climatic extremes is anticipated (Jiang et al.[11]). On the national scale, Xu et al. [12] analyzed variations of

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temperature and precipitation extremes over China in two periods of 1960—1989 and 1990—2007. Wang et al. [13] reviewed the climatological characteristic, variability and trend of extreme climates in China in recent decades. Ren and Zhou [14] evaluated the urbanization effects on extreme temperature indices in China during 1961—2008. Chen and Sun[15] investigated the changes in extreme temperature and precipitation indices using CMIP5 simulations. At the regional scale, Li et al.[16] studied the changes of daily climate extremes with indices of temperature and precipitation in southwestern China during 1961—2008. Wang et al. [17] investigated the recent changes in extremes of temperature and precipitation over the western Tibetan Plateau from 1973 to 2011. Wang et al.[18] analyzed the temporal variability and spatial distribution of temperature extremes in the Yangtze River Basin from 1962 to 2011. Ren et al. [19] investigated the changes in precipitation extremes of South China during 1961—2011.

However, there are some insufficiencies in the existing studies. First of all, most findings from previous studies were based on the observational data without undergoing a strict homogenization test, so they might not reflect the real change of climatic extremes in space or time scales. Moreover, a majority of early researches dealt with the climatic extremes according to administrative divisions of China, but few studies had further studied the characteristics of climatic extremes in different regions of China which were divided according to the characteristics of natural geography and climate. Finally, many previous studies analyzed the monthly or annual variations of extreme temperature and precipitation indices [12,14,16,17], and few concerned about the change of daily extreme values, such as daily maximum temperature (Tmax), daily minimum temperature (Tmin), daily maximum precipitation (Pmax) and daily maximum wind speed (WSmax). Changes in these daily extreme values have severe consequences on human society and natural environment (Wi et al. [20]). For example, Tmax and Tmin can be used as good indicators of peak energy and water consumption, human health and as effective references for infrastructure design and operational standards (Paniagua-Tineo et al. [21]). Pmax represents one of the most important and readily available measures of extreme rainfall and is used frequently as inputs to assessments of flood risk, urban waterlogging and municipal drainage design (Westra et al. [22]), and WSmax is also quite important to sustainable utilization of wind energy and mitigation of disasters caused by extreme winds (Jiang et al.[23]).

This work is aimed to provide an overview on the variations of temperature, precipitation and wind extremes in recent decades over China. The paper is organized as follows. Section 2 describes the datasets and the methods of analysis used in this study. The spatial and temporal variations of temperature, precipitation and wind extremes are presented in Sections 3. Discussions and conclusions are given in Sections 4 and 5.

2 DATA AND METHODS

2.1 *Data*

Tmax, Tmin, Pmax and WSmax data were used to form the series of climatic extremes in this study. These meteorological data were offered by the National Meteorological Information Center, China Meteorological Administration (CMA) (http://www.nmic.gov.cn). In China, the meteorological stations are maintained based on WMO's Guide to the Global Observing System and CMA's Specifications for Surface Meteorological Observation and a series of data quality control methods are employed and the errors are corrected before the release of historical meteorological data (Fischer et al.[24]).

Although the daily data span from 1951 to 2014, we excluded those data before 1959 because there are not enough meteorological stations, and early data contain more gaps and missing values (Fu et al.[25]). If a station has more than 10% missing values, this station was removed from our study. As a preliminary result, 604 among 756 available stations, with relatively complete data series, were reserved for further selection. There are some missing data in the daily data. The missing data of one day were filled in by the average value of its neighboring days, and missing data exceeding one day were filled in by the neighboring stations through the simple linear regression method (Zhang et al. [26]). All the nearest observatories with the Pearson correlation significance (P) less than 0.01 level are regarded as reference series for a given station with missing data (Zhang et al.[27]).

Quality control is a necessary step before data analysis, because false outliers can seriously affect the trends. The software package for data homogeneization, named RHtestsV4 (available from http://etccdi.pacificclimate.org/software.shtml), was then applied to daily data to determine where inhomogeneities may occur. It is based on the penalized maximal F test, and uses a two-phase regression model to examine the possible step change points that exist in a time series (Li et al.[16]). Only stations without step change point for all the elements of temperature and precipitation were used in this study. Finally, there are 234 stations remaining after data quality control and homogeneity assessment. The spatial distributions of selected 234 stations are shown in Fig.1.

2.2 *Methods*

2.2.1 THE SEQUENCES OF CLIMATIC EXTREMES

Based on the daily climate data, annual extreme value of maximum temperature, minimum temperature, maximum precipitation and maximum wind speed was selected respectively at each station, and finally four

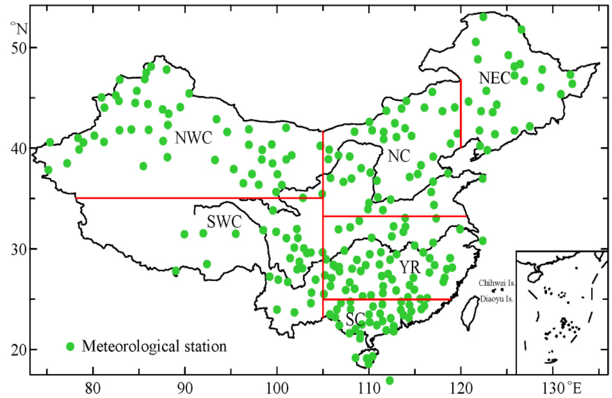

Figure 1. The geographical distribution of meteorological stations and six regions of China. China is divided into six regions, namely, Northeast China (NEC), North China (NC), the mid-lower Yangtze River valley (YR), South China (SC), Northwest China (NWC) and Southwest China (SWC).

series of extreme values, i.e. annual Tmax, Tmin, Pmax and WSmax were formed for each station. The sequences of Tmax, Tmin and Pmax all began in 1959 and ended in 2014, but the sequences of WSmax began in 1972 and ended in 2014, because before 1972, WSmax data contain more gaps and missing values.

For better understanding the regional characteristics of climatic variations, China was further divided into six regions, i.e., Northeast China (NEC), North China (NC), the mid-lower Yangtze River valley (YR), South China (SC), Northwest China (NWC) and Southwest China (SWC) according to natural geography, climate and other published papers (Xu et al.[12];Shi et al.[28]), as shown in Fig.1. The regionalization reflects the boundary of eastern China and western China at 105°E longitude which was adopted by many scholars (Zhang and Zhu [29]), and it also gives a better division between NC and YR, and between YR and SC, with 33°N and 25° N latitude as the dividing line, respectively. Moreover, NWC and SWC were divided by the 35°N latitude, and NEC and NC were divided by the 120°E longitude. These divisions are almost the same as those of existing studies (Li et al.[30]; Zu and Yang[31]).

Annual averaged sequences for each region of China were calculated firstly as simple arithmetic averages based on the series of annual extreme values over all stations in that region, and then the mean annual series of climatic extremes in China were calculated as arithmetic averages of the annual extreme values in six regions of China. This simple procedure was adopted because the locations of the selected stations provide a nonuniform spatial coverage of the country, especially in the west of China.

2.2.2 TREND ANALYSIS AND SIGNIFICANCE TEST

In this paper, two methods, i.e. simple linear regression method and the Mann-Kendall (MK) test, were used to detect the trends of Tmax, Tmin, Pmax and WSmax and to test their significances, respectively. For each station, each region as well as for the whole of China, we calculated the slope of the linear trend using the least squares fitting process, which was widely applied in extreme temperature and precipitation studies (Rahimzadeh et al.[32]; de Lima et al.[33]), and the change magnitude of all climatic extremes were quantified and showed on a decade time scale. The non-parametric MK test was used to verify the statistical significance at the 0.05 level for all the trends. MK test is a rank-based procedure, which is less sensitive to outliers compared with parametric approaches and has widely used to assess the significance of monotonic trends in hydrology and climatology (Hu et al.[9]; Villafuerte et al.[34]).

3 RESULTS

3.1 *Temporal variations and spatial trends of daily maximum temperature*

For China as a whole, mean annual Tmax increased averagely at a rate of 0.15℃ per decade

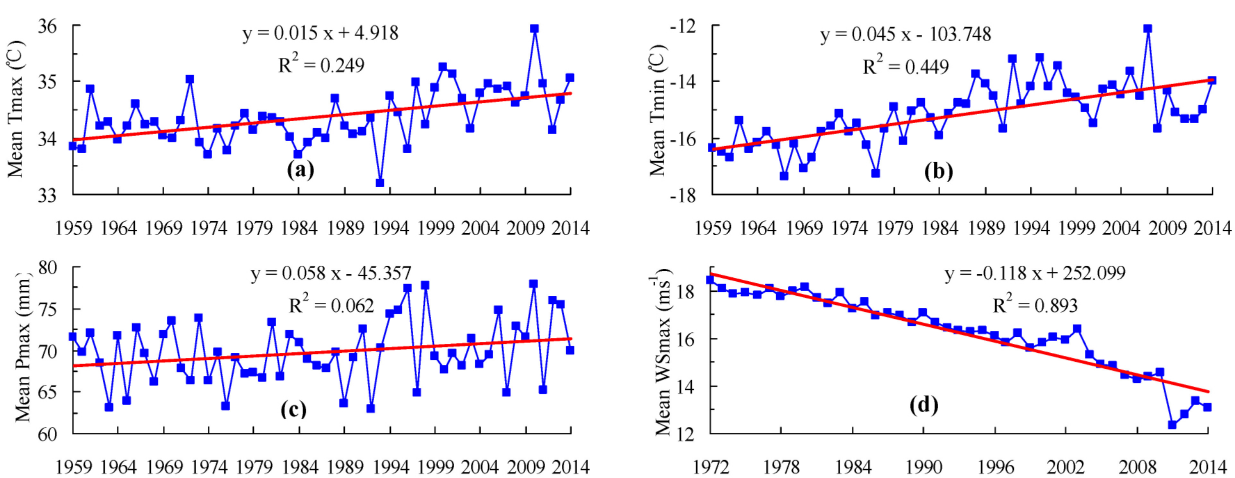

Figure 2. Variations of mean annual (a) daily maximum temperature, (b) daily minimum temperature, (c) daily maximum precipitation and (d) daily maximum wind speed in China (The blue lines are the annual extreme values and the red lines are the linear trends, the same as below).

during 1959—2014 (Table 1), and the trend was significant. Annual Tmax increased slowly during 1959—1980, and in the 1990s(1991—2000) it increased rapidly (Fig.2a). In 1993, mean annual Tmax was the lowest, with the value of 33.2℃, but in 2010, it was the highest, with the value of 35.9℃. The highest Tmax in China was recorded on August 4, 2008 and July 14, 2011 at Turban station, Xinjiang province, both with the values of 47.8℃.

Table 1. Linear trends of climatic extremes over China during 1959—2014.

Climatic extremes	Regions of China						China
	NEC	NC	YR	SC	NWC	SWC	
Tmax[℃·(10 yrs)$^{-1}$]	0.18*	0.15	0.06*	0.12	0.16	0.23	0.15
Tmin[℃·(10 yrs)$^{-1}$]	0.53	0.49	0.37	0.38	0.49	0.43	0.45
Pmax[mm·(10 yrs)$^{-1}$]	−0.48*	−1.02	1.29	2.82	0.64	0.22*	0.58
WSmax[m·s^{-1}·(10 yrs)$^{-1}$]	−1.41	−1.33	−1.13	−1.16	−1.00	−1.07	−1.18

*Variations not statistically significant at the 0.05 level.

During 1959—2014, annual Tmax increased in six regions of China, especially in NC, SC, NWC and SWC, annual Tmax increased at rates of 0.15, 0.12, 0.16 and 0.23℃ per decade respectively, and the trends were all significant (Table 1 and Fig.3). In NEC and YR, the increasing trends of annual Tmax were not significant. During the period from 2001 to 2014, mean annual Tmax was the highest in all six regions, and in three out of six regions, i.e. NEC, NC and YR, mean annual Tmax was the lowest during 1981—1990. In terms of the 234 meteorological stations used in this study, the extreme maximum temperature in NEC, NC, YR, SC, NWC and SWC was 43.7, 43.7, 43.5, 42.2, 44.2 and 43.1℃ respectively during 1959—2014.

Figure 4 illustrates the spatial distribution of trends in annual Tmax during 1959—2014 over China. Annual Tmax increased at rates of 0—0.4℃ per decade at over 75% stations in the past 56 years, and over 40% stations show significant increase, with the most notable increases found in SC, northwestern NC, northeastern NEC, eastern NWC and eastern SWC (Fig.4). There were only 7 stations with significant decrease of annual Tmax, mainly located in western Xinjiang and southeastern NC.

3.2 *Temporal variations and spatial trends of daily minimum temperature*

Mean annual Tmin increased at a rate of 0.45℃ per decade in the past 56 years and the trend was also significant (Table 1). Annual Tmin increased continuously during 1959—1995 and then it decreased slightly (Fig.2b). In the first 14 years of this century, it changed little. Mean annual Tmin was the lowest in 1967, with the value of −17.4℃, and in 2007, it was the highest, with the value of −12.2℃. The lowest Tmin was recorded on February 13, 1969 at Mohe station, Heilongjiang province, with the value of −52.3 ℃.

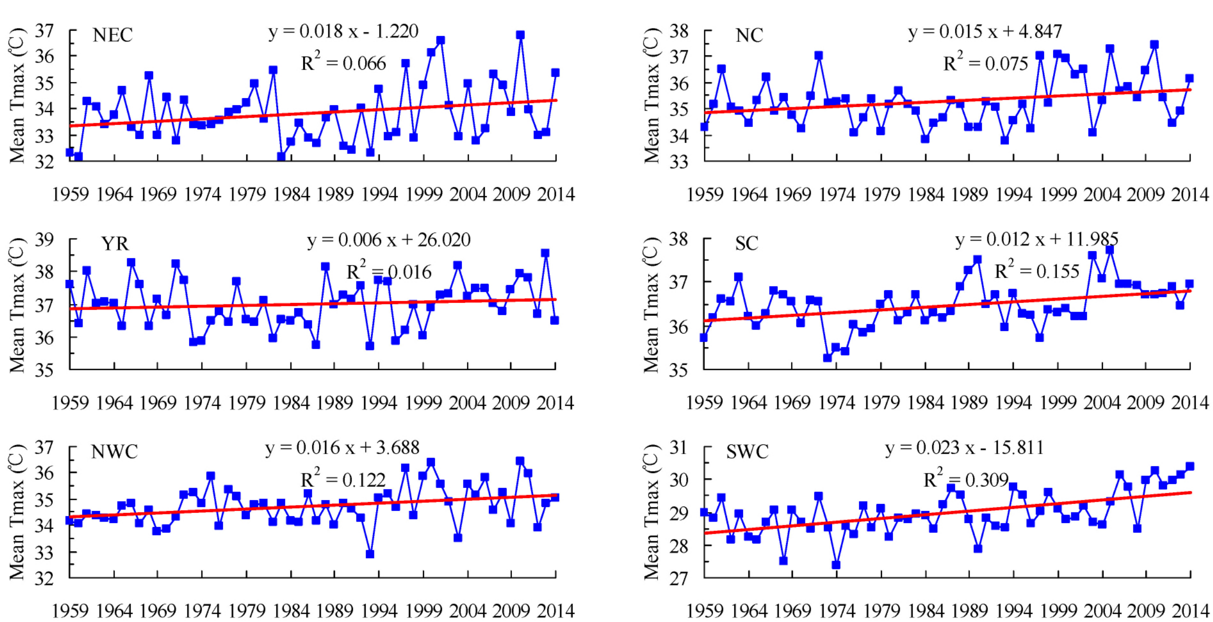

Figure 3. Variations of annual daily maximum temperature in six regions of China during 1959—2014.

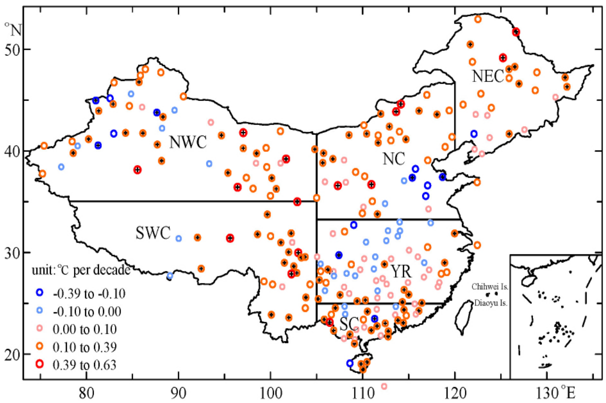

Figure 4. Spatial distribution of linear trends in daily maximum temperature in China during 1959—2014 (+ denotes the trend significant at 95% confidence level, the same as below).

Annual Tmin increased in all six regions of China, and the trends were all significant during 1959—2014 (Table 1 and Fig.5). In NEC, NC, YR, SC, NWC and SWC, annual Tmin increased at rates of 0.53, 0.49, 0.37, 0.38, 0.49 and 0.43℃ per decade respectively. During 1959—1970, mean annual Tmin was the lowest in six regions, which was −33.76, −23.37, −4.66, 2.78, −27.14 and −12.27℃ in NEC, NC, YR, SC, NWC and SWC respectively. In NEC, NC and NWC, mean annual Tmin was the highest during 1991—2000, but in YR, SC and SWC, it was the highest during 2001—2014. The extreme minimum temperature in NEC, NC, YR, SC, NWC and SWC was −52.3, −40.4, −19.4, −4.4, −44.8 and −42.9℃ respectively, in terms of the 234 meteorological stations used in this study.

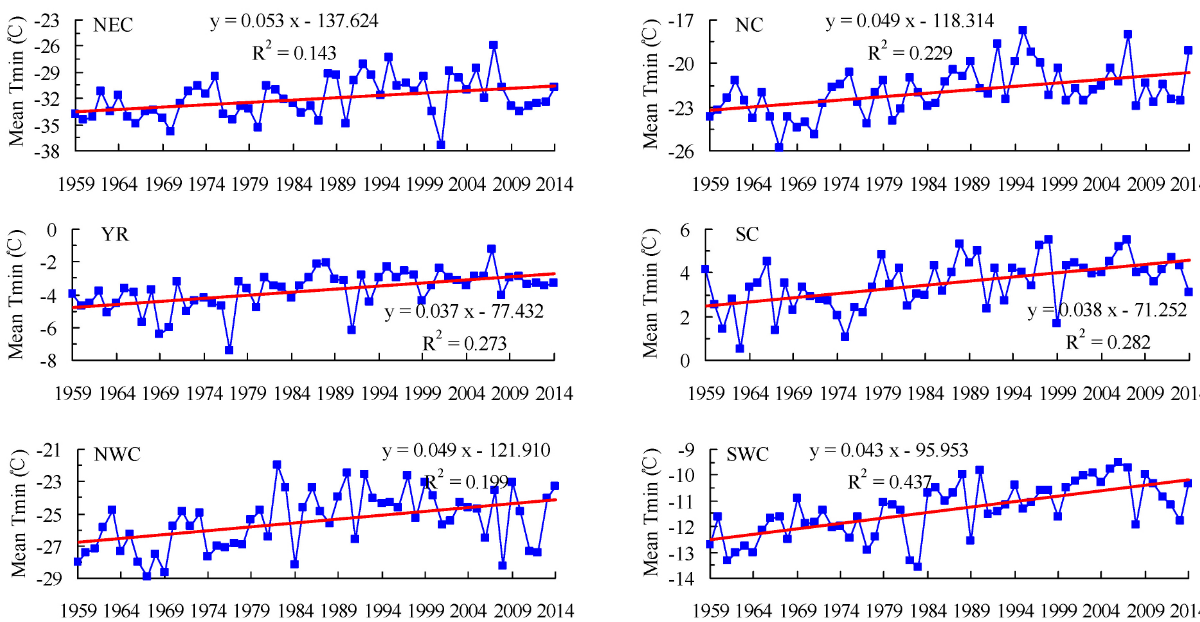

Figure 5. Variation of annual daily minimum temperature in six regions of China during 1959—2014.

Stations with significant increase of annual Tmin account for about 75% of the total stations across China during 1959—2014 (Fig.6). Remarkable increases of annual Tmin can be identified in NEC, northern and southeastern NC and northwestern and eastern NWC, whereas in eastern SWC, SC and YR, there are weak increases of annual Tmin, with the increasing rates of 0.2—0.6℃ per decade in most stations. At some stations in southwestern NC, northeastern NWC and SWC, annual Tmin decreased at rates of 0—0.21℃ per decade though the trend was not significant.

3.3 *Temporal variations and spatial trends of daily maximum precipitation*

Mean annual Pmax also increased significantly at a rate of 0.58 mm per decade in China over the past 56 years (Table 1). Annual Pmax was the greatest in 2010, with the value of 78.0 mm, and in 1992, it was the least, with the value of 62.9 mm (Fig.2c). The greatest daily precipitation was recorded on September 6, 1995

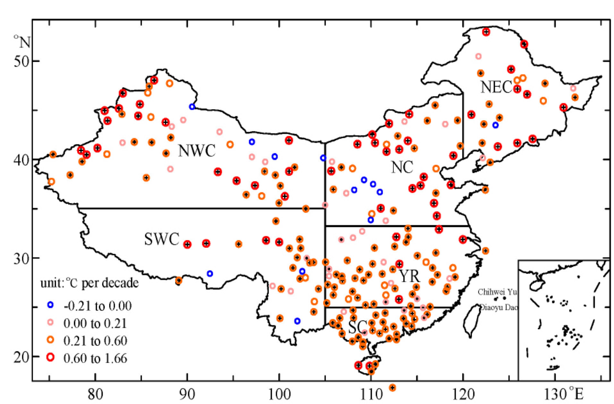

Figure 6. Spatial distribution of linear trends in daily minimum temperature in China during 1959—2014.

at Xisha station, Hainan province, with the value of 633.8 mm.

Annual Pmax decreased in NEC and NC, but increased in other four regions of China during 1959—2014(Table 1 and Fig.7). In NC, annual Pmax decreased significantly at a rate of 1.02 mm per decade. In YR, SC and NWC, annual Pmax increased significantly at rates of 1.29, 2.82 and 0.64 mm per decade respectively. The variation of annual Pmax was not significant in NEC and SWC in the past 56 years. The decadal characteristics of annual Pmax were not significant in six regions. During 2001—2014, mean annual Pmax was less in NEC and NC, but it was more in NWC and SC. In terms of the 234 meteorological stations used in this study, the extreme values of daily maximum precipitation in NEC, NC, YR, SC, NWC and SWC were 331.7, 315.4, 420.4, 633.8, 79.5 and 362.3 mm respectively during 1959—2014.

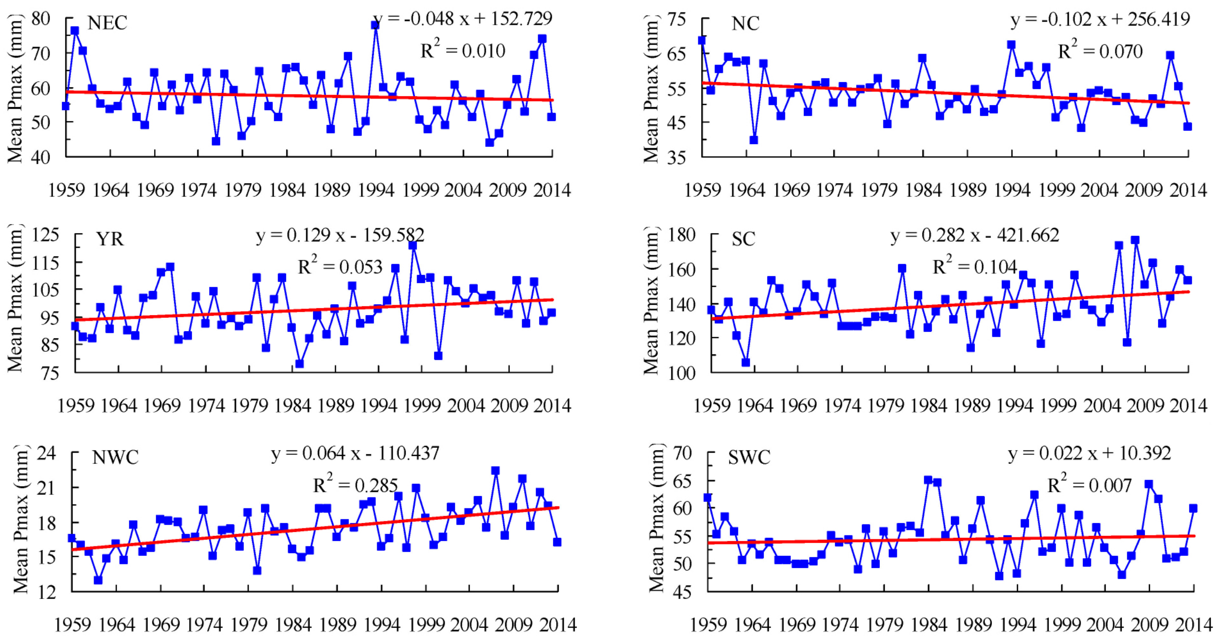

Figure 7. Variation of annual daily maximum precipitation in six regions of China during 1959—2014.

Figure 8 shows the spatial trends of annual Pmax in recent 56 years in China. The most striking characteristic on the trends of annual Pmax is that the number of stations with increase is slightly comparable with that of decrease. Increases of annual Pmax are found at about 75% stations situating in NWC, YR and SC. On the contrary, decreased annual Pmax are observed in NC, southern and eastern NEC, southwestern YR and in parts of SWC and SC. In China, about 14% of the total stations show significant increasing trend of annual Pmax, and 2% stations show significant decrease, far less than those of temperature extremes. Annual Pmax changed (increased or decreased) at rates of 0—2.0 mm per decade in most stations of NWC and SWC, but in YR and SC, especially in SC, it changed at rates of over 2.0 mm per decade in most stations.

3.4 *Temporal variations and spatial trends of daily maximum wind speed*

During 1972—2014, mean annual WSmax decreased at a rate of 1.18m·s^{-1} per decade and the trend was also significant (Table 1). Annual WSmax decreased continuously in the past 43 years and it was the lowest in 2011, with the value of 12.3m·s^{-1} (Fig.2d). The highest WSmax was 140 m·s^{-1} in China, which occurred on January 27, 1975 at Xisha station, Hainan province.

Annual WSmax decreased in all six regions of China during 1972—2014, and the trends were all significant (Table 1 and Fig.9). In NEC, NC, YR, SC, NWC and SWC, annual WSmax decreased at rates of 1.41, 1.33, 1.13, 1.16, 1.00 and 1.07m·s^{-1} per decade, respectively. During 2001—2014, mean annual Pmax

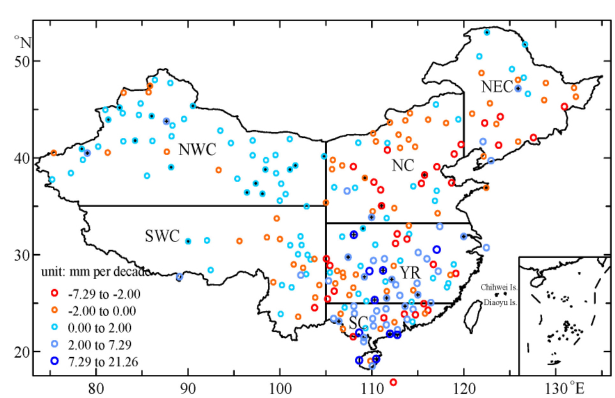

Figure 8. Spatial distribution of linear trends in daily maximum precipitation in China during 1959—2014.

was lower in all six regions, and during 1972—1980, it was higher in all six regions of China. The extreme values of daily maximum wind speed were 38.0, 33.0, 44.7, 140.0, 46.0 and 36.7 m·s^{-1} in NEC, NC, YR, SC, NWC and SWC respectively, in terms of the 234 meteorological stations used in this study.

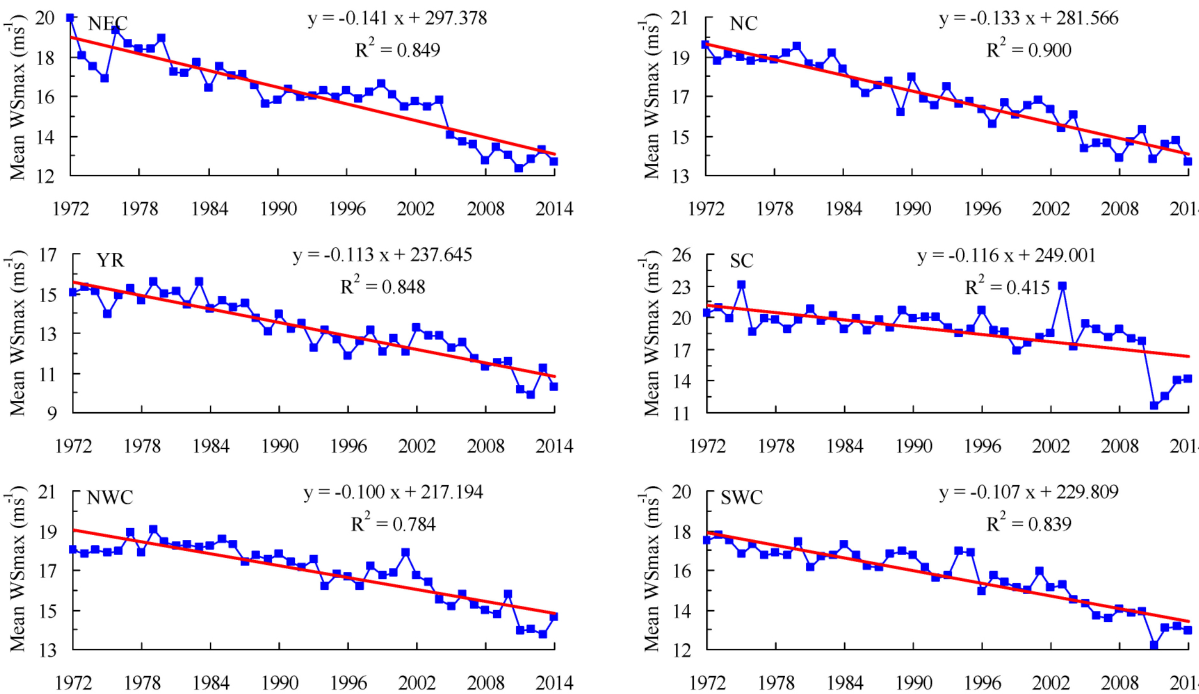

Figure 9. Variation of annual daily maximum wind speed in six regions of China during 1972—2014.

Stations dominated by significant decrease of annual WSmax account for 86% of the total stations in China (Fig.10). Notable decreases of annual WSmax are mostly located in northern NC, northern and central YR, central and southern SC and in parts of central NEC and western NWC, whereas in southern NC, eastern SC and western YR, there are weak decreases of annual WSmax, with the rates of 0—1.2 m·s^{-1} per decade in most stations. In a dozen stations in NWC, western YR and NC and central SC, annual WSmax increased at rates of 0—1.20 m·s^{-1} per decade though the trend was not significant in most stations.

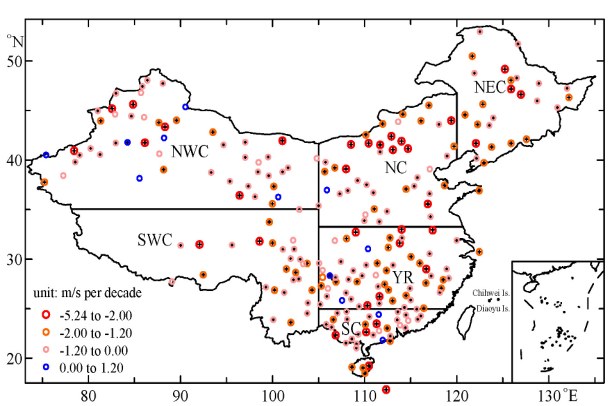

Figure 10. Spatial distribution of linear trends in daily maximum wind speed in China during 1959—2014.

4 DISCUSSION

The total increase of globally averaged surface temperature between 1850—1900 and 2003—2012 is 0.78℃ [0.72 to 0.85℃], and global surface temperature change for the end of the 21st century is likely to exceed 1.5℃ relative to 1850 to 1900 for all RCP scenarios except RCP2.6 (IPCC[1]). Climate warming is always concomitant with changes in climatic extremes, which have more economic, social and environmental impacts than changes in mean climate (de Vyver[10]; Keggenhoff et al.[35]). Recent assessment shows that global disaster loss is on the rise, especially in the fast developing and middle-income countries(IPCC[6]; Munich Re[36]). China, a region with complex topography and strongly affected by the monsoon, is particularly vulnerable to extreme weather and climate disasters (Jiang et al.[11]). Catastrophic weather such as tropical cyclones, floods, heat waves and droughts have been receiving much attention in recent years as a result of the tremendous losses from climatic extremes and/or hydrological and meteorological disasters (Zhang et al.[26]; Zhai and Liu[37]; Wu et al.[38]). The temporal patterns and spatial trends of these extremes are also essential for planning mitigation and adaptation strategies against risks of climate change (Fischer et al.[24]).

Changes of extreme temperature and precipitation for the 20th century have also been observed in many parts of the world (Rahimzadeh et al.[32]; Fu et al.[5]; De Lima et al. [33]; Skansi et al. [39]; Chen and Sun [15]; Keggenhoff et al. [35]). Apparently the changes of temperature extremes are associated with global warming. Alexander et al. [40] showed widespread changes in temperature extremes associated with warming, especially for those indices derived from daily minimum temperature all over the world. The analysis of temperature extremes indicated a significant increase for both Tmax and Tmin, and Tmin increased at a higher rate than Tmax (Table 1 and Fig.2). Our results are in agreement with other research results, for example, Li et al. [16] revealed that all temperature extremes showed warming trends in the southwestern China during 1961—2008, and the warming trends in minimum temperature were greater than those related to maximum temperature. Significant warming trends had also been observed for the source region of Yellow River over the period 1960—2006, and this warming was mainly due to the increase of minimum temperature, with significant increase in the magnitude and decrease in the frequency of the low temperature events (Hu et al.[9]).

In the past several decades, China has experienced a pronounced warming and the atmospheric circulation is featured with an inter-decadal transition in the late 1970s (Wang et al.[13]). Over 40% of the total stations showed significant increase of annual Tmax in China in recent 56 years, with the most notable increases in SC, northwestern NC, northeastern NEC, eastern NWC and eastern SWC (Fig.7). As for the changes of annual Tmin, about 75% of the total stations increased significantly, with remarkable increases in NEC, northern and southeastern NC and northwestern and eastern NWC (Fig.8). Our results are in accord with others, for example, Fan et al. [41] reported a significant increasing trend for the highest maximum temperatures and the lowest minimum temperatures in Shanxi during 1959 to 2008, and Gong et al. [42] reported that the maximum temperatures showed increasing trends in a small region near the southern coast of eastern China, and the minimum temperatures were getting slightly higher for most stations in northern and southern China during 1955—2000. Over the western Tibetan Plateau, most extreme indices associated with cold events showed a significant decrease, and warm-related indices all increased from 1973 to 2011 (Wang et al.[17]).

Global warming will lead to an increase in the magnitude and frequency of extreme precipitation through increased atmospheric moisture contents and large-scale storm activities (Allan and Soden [43]; Trenberth [44]; IPCC [1]). After an analysis of the global precipitation extremes, Alexander et al. [40] found that there was a trend toward wetter conditions along with global warming. Since 1950, land regions with an increase of heavy precipitation events are likely more than those with a decrease of heavy precipitation events (IPCC[1]), particularly in tropical and subtropical regions where in general, the relative changes in the intensity of precipitation extremes exceed those in annual mean precipitation (Kharin et al.[45]). The spatial variations of annual Pmax showed no significant trend in most of China during 1959—2014 (Fig.9). The results from Wang et al. [17] also demonstrated that the trends of precipitation extremes in the western Tibetan Plateau were insignificant during 1973—2011. For the source region of Yellow River, no significant changes of rainfall indices had been observed over the period 1960—2006 (Hu et al.[9]). Unlike extreme temperature, the changes of extreme precipitation are spatially incoherent. Only 16% of the total stations showed significant trend of annual Pmax (Fig.9). In terms of the average values of different regions of China, annual Pmax decreased significantly in NC but increased in SC, NWC and YR (Table 1 and Fig.5). This spatial tendency of precipitation extremes may partly explain the water crisis in the northern China and the drained dry in the lower reaches of the Yellow River (Xia et al. [46]; Fu et al.[47]).

Strong wind usually collapses walls and houses, destroys tall buildings and causes casualties and property damages. Annual daily WSmax decreased significantly in China during 1972—2014 (Fig.2d), and in most areas of China, WSmax decreased significantly (Fig.10). The reduction of wind speed was also found over most parts of Heilongjiang province during 1961—2004 (Zou et al.[47]). Chen et al.[48] analyzed the variation tendency of the extreme value of wind speeds over windy regions in Xinjiang and the results indicated a descending trend in the frequency and intensity of extreme strong wind in four out of five regions. Chen et al. [49] investigated the characteristics of maximum wind speed in Jiangsu province and the results showed that average annual maximum wind speed had significant fluctuations and the decreasing tendency was in all regions from 1975 to 2008, though the degree was various. In north China, annual mean wind speeds also decreased at 0.2—0.5 $m \cdot s^{-1}$ per decade in most gauges (Rong and Liang[50]). Shi et al.[51] also indicated that from 1959 to 2010, strong wind days had decreased significantly in the Yangtze River delta.

The spatial and temporal differences in the change of climatic extremes reflect the complexity of climate and topography impacts in China. The changes in climatic extremes are comprehensive effects of a number of factors including atmospheric circulation and geographical environment (Fu et al. [25]). Analysis of changes in the large-scale atmospheric circulation revealed that increases in geopotential height and anticyclonic circulation, together with the weakness of monsoonal flow and vapor transportation over the Eurasian continent had led to the changes of climate extremes in southwestern China (Li et al. [16]). In the Pearl River basin, the change of annual temperature and precipitation extremes was attributed to the changes of Western Pacific subtropical high (WPSH), East Asian summer monsoon (EASM) and wind directions (Fischer et al. [24]). Moreover, factors that influence climatic extremes are different in different regions and periods. Chen et al. [53] suggested that the variations of extreme cold days in winter were closely linked to Arctic Oscillation (AO) in the northern part of eastern China during the period 1961—2011, while in the southern part of eastern China they were strongly related to El Niño-Southern Oscillation (ENSO) after the mid-1980s. Urbanization and land use change also had great impacts on the climatic extremes (Shi et al.[52]). Ren and Zhou[14] reported that the impacts of urbanization on the trends of extreme temperature were statistically significant in mainland China for the time period 1961—2008, and annual-mean urbanization effects for Tmax and Tmin were 0.070 and 0.023℃ per decade respectively in China as a whole.

Temperature extremes exert significant influences not only on natural processes but also on multiple aspects of social and economic activities (Zhang et al. [26]; Zhai and Liu[37]). A growing body of research results shows that extreme high temperatures and continuous heat waves can destroy agricultural production, increase the consumption of energy and water, and also have negative impacts on human welfare and even on human health (Kunkel et al.[4]; Zhang et al.[26]; Shi and Cui[54]; Sun et al.[55]). According to IPCC[1], it is virtually certain that there will be more frequent hot extremes and fewer cold extremes in most of the land areas on daily and seasonal timescales as global mean temperatures increase, and it is very likely that heat waves will appear with a higher frequency and longer duration. Sun et al. [55] estimated that since the early 1950s, anthropogenic influence had resulted in a over 60-fold increase in the likelihood of the 2013 hot summer in Eastern China, and similarly hot summers were projected to become more frequent in the future, with half of summers being hotter than the 2013 summer in the next two decades even under RCP4.5. Chen and Sun [15] studied the changes of temperature indices and also found that in China, warm events would be increased and stronger, and cold events would be lessened and weakened in the future.

By the end of the 21st century, precipitation extremes will very likely become more frequent and more intense in most of the mid-latitude landmasses and in humid tropical regions as global average surface temperature increases (IPCC [1]). Allan and Soden [43] found that the observed amplification of precipitation extremes was greater than that from model prediction, which means that simulation and projection of changes in future precipitation extremes in response to man-made global warming may be underestimated. Semadeni-Davies et al. [56] studied the effects of increasing heavy precipitation and potential urbanization and found that peak flow volumes and consequent flood risk would be increased for a watershed in Sweden. A study on the changes of precipitation indices indicates that in general extreme precipitation increases faster than total precipitation and China will undergo more frequent and intensified extreme precipitation events (Chen and Sun[15]). Yang et al. [57] analyzed the climatic extremes and their changes over China, and results showed under the high emissions scenario of RCP8.5, the linear changes of heavy precipitation days (daily precipitation >20 mm) and the contribution of heavy precipitation days (>95th percentile) to annual total precipitation are 2.9 days and 9.9% during the period 2006—2099. Because the distribution of extreme precipitation shows a larger space difference, the detection of regional extreme precipitation is very important to assess the consequences of hydrology, such as flooding and droughts (Rahimzadeh et al. [32]; Trenberth [44]; Zhai and Liu [37]), and it will greatly contribute to the development of appropriate adaptation and mitigation strategies to deal with the negative impacts from precipitation extremes.

The rapid growth of population and industrialization in coastal areas and major river basins has augmented the damage potentials of climatic extremes and other natural disasters in recent decades in China. During the 20 years from 1994 to 2013, meteorological disasters on average caused more than 2,000 deaths and nearly RMB 300 billion yuan of direct financial losses per year in China, which accounted for 55% of the deaths and 87% of the direct economic losses from natural hazards respectively (Wu et al. [38]). Future climate change will lead to more climatic extremes in China (Sun et al.[55]; Chen and Sun [15]). A higher frequency of climatic extremes, combined with a growth of population, wealth and infrastructure in areas vulnerable to such extremes, will collectively make China more vulnerable to climate change and will greatly exacerbate the loss problem in China (Shi and Cui [56]). Identifying this societal vulnerability has important significance for understanding the country's economy, guiding the government policies, planning the future mitigation activities including ways for societies or communities to adapt to and mitigate the effects of climate change.

In general, it is hard to reduce the probability and severity of natural hazards. Consequently, for most hazards we can only decrease their risks by reducing exposure and/or vulnerability of society and ecosystems (Shi and Cui[54]). Changnon and Easterling[58] showed that U.S. federal policy about extreme climate events had shifted from an emphasis on structural defenses to scientific space planning, exposure reduction, and risk sharing mechanisms. Disastrous outcomes will only increase, unless better ways are found to reduce the effects by improving forecasts and early-warning systems, combined with strengthening community preparedness and resilience. Despite the increase of population in disaster-prone areas, global deaths from storms and floods declined by 16% and 43% respectively during the decade 2001—2010, thanks mainly to better early-warning systems, increased preparedness and undoubtedly decreased physical vulnerability (WMO [7]). Policy implications for China may include investing and promoting environmentally-friendly and low-cost energy production systems, redesigning production systems and infrastructures to avoid losses from climatic extremes, improving capability in monitoring and warning of climatic extremes, enhancing engineering defense measures based on changes in extreme events and encouraging research for a better understanding of the characteristics and impacts of weather and climatic extremes and the vulnerabilities of human and natural ecosystems (Zhai and Liu[37]; Ly et al.[59]).

5 CONCLUSIONS

The variations of daily maximum temperature (Tmax), daily minimum temperature (Tmin), daily maximum precipitation (Pmax) and daily maximum wind speed (WSmax) was investigated in this paper. For China as a whole, annual Tmax, Tmin and Pmax increased significantly at rates of 0.15℃, 0.45℃ and 0.58mm per decade respectively, whereas annual WSmax decreased at 1.18m·s^{-1} per decade during 1959—2014. On the regional average, Tmax increased significantly in North China (NC), South China (SC), Northwest China (NWC) and Southwest China (SWC), and Pmax decreased in NC but increased in NWC, SC and the mid-lower Yangtze River valley (YR). Tmin increased in all regions of China and WSmax decreased in all regions of China.

Spatially, over 40% stations showed significant increase of annual Tmax, with the most notable increases in SC, northwestern NC, northeastern Northeast China (NEC), eastern NWC and eastern SWC. Stations with significant increase of annual Tmin accounted for about 75% of the total stations across China, with the remarkable increases in NEC, northern and southeastern NC and northwestern and eastern NWC. Annual Pmax showed no significant trend at most of the stations in China, and only 16% of the total stations had significant increasing or decreasing trend. About 86% of the total stations showed significant decrease of annual WSmax, mostly located in northern NC, northern and central YR, central and southern SC and in parts of central NEC and western NWC.

Negative consequences of climatic extremes are results of both the changes in frequency and intensity of extremes and the vulnerabilities of societies or elements exposed. With global climate change and rapidly economic development, in addition to the complex topography and strongly affected by the East Asian monsoon, China has become more vulnerable to climatic extremes and disasters, so more strategies of mitigation and/or adaptation of climatic extremes, including environmentally-friendly and low-cost energy production systems, redesign of infrastructure and production systems, improvement in monitoring and warning, enhancement of engineering defense measures and intensive research of climatic extremes and climate services, are quite useful and necessary for government and the social publics in the future.

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