

Distribution and trend on consecutive days of severe weathers in China during 1959–2014

SHI Jun^{1,2}, WEN Kangmin^{1,2}, CUI Linli³

1. Ecological Technique and Engineering College, Shanghai Institute of Technology, Shanghai 201418, China;

2. Shanghai Climate Center, Shanghai Meteorological Bureau, Shanghai 200030, China;

3. Shanghai Center for Satellite Remote Sensing and Application, Shanghai 201199, China

Abstract: Based on daily surface climate data and weather phenomenon data, the spatial and temporal distribution and trend on the number of consecutive days of severe weathers were analyzed in China during 1959–2014. The results indicate that the number of consecutive days for hot weathers increased at a rate of 0.1 day per decade in China as a whole, while that for cold weathers, snowfall weathers, thunderstorm weathers and foggy weathers showed significant decreasing trends at rates of 1.4, 0.3, 0.4 and 0.4 day per decade, respectively. Spatially, there were more consecutive hot days and rainstorm days in southeastern China, and more consecutive cold days and snowfall days in northeastern China and western China. Consecutive thunderstorm days were more in southern China and southwestern China, and consecutive foggy days were more in some mountain stations. Over the past 56 years, annual number of consecutive cold days decreased mainly in most parts of western China and eastern China. Consecutive thunderstorm days decreased in most parts of China. The trend of consecutive hot days, snowfall days and foggy days was not significant in most parts of China, and that of consecutive rainstorm days was not significant in almost the entire China.

Keywords: severe weathers; consecutive days; distribution; trend; China

1 Introduction

The combined global land and ocean average temperature shows an linear increase of 0.89°C during 1901–2012 and 0.72°C during 1951–2012, and the increase of global surface temperatures for 2081–2100 will likely be in the range of 0.3–4.8°C relative to 1986–2005 (IPCC, 2013). A changing climate will lead to the changes of extreme weather and climate events in their frequencies, intensities, durations, spatial extents and timings (Xia *et al.*, 2012; Fu *et al.*, 2013; Wang *et al.*, 2014; Ren *et al.*, 2015), and can result in unprecedented death, injury and property damage (IPCC, 2012). During the 2001–2010 decade, our world suffered unparalleled high-impact climate extremes in history, and over 370,000 people died

Received: 2015-10-16 **Accepted:** 2015-12-25

Foundation: National Natural Science Foundation of China, No.41571044, No.41001283; China Clean Development Mechanism (CDM) Fund Project, No.2012043; CAS Pilot Special Project, No.XDA05090204

Author: Shi Jun (1975–), specialized in climate change and meteorological disaster. E-mail: shij@climate.sh.cn

from extreme weather and climate conditions (WMO, 2013). The analysis of the climatic characteristics of weather and climate extremes, including their frequency, intensity and duration, is thus necessary for scientific research of climate change and for developing climate change mitigation and adaptation strategies (de Vyver, 2012).

Severe weathers refer to any hazardous meteorological or hydro-meteorological phenomena which potentially cause major damage, serious social disruption or loss of human life (WMO, 2004). The main severe weathers in China include rainstorm, thunderstorm, snowstorm, dust/sand storm, tornado, gale, extreme temperature, fog, haze, etc. Previous studies have investigated the variation patterns of some severe weathers in China. For example, Yu *et al.* (2012) analyzed the interdecadal variations of thunderstorm, hail and gale in the south of the Yangtze River, Jiang-Huai area, Huang-Huai area and the north of the Yellow River from 1971 to 2000. Fu *et al.* (2013) examined the variability in the frequency of precipitation extremes in China during 1961–2009. Wang *et al.* (2014) investigated the distribution and variability of extreme temperature in the Yangtze River Basin from 1962 to 2011. Zhu *et al.* (2014) studied the spatiotemporal variation patterns of the beginning and ending dates of snowfall and snowfall days in Qinghai Province during 1962–2012. Liu *et al.* (2015) analyzed the spatiotemporal variation of cold surges and their possible driving factors in Inner Mongolia during 1960–2012.

However, there are some insufficiencies in the previous studies. To begin with, the majorities of existing studies are concerned with the frequency change of severe weathers based on monthly or annual data, but few studies focus on the consecutive days of severe weathers based on daily observation data. Then, those findings from early researches do not contain the recent observation data, so they can't reflect the latest changes of severe weathers especially in recent years. Finally, most of previous studies are related to temperature and/or precipitation extremes, and only a minority of researches considers other severe weathers, such as thunderstorm and snowfall (Singh and Patwardhan, 2012; Brooks, 2013; Zhu *et al.*, 2014). The characteristics of these severe weathers are absolutely necessary to engineering design and risk mitigation under global climate change.

In this study, we take the whole of China as study area, using the weather monitoring data from 1959 to 2014, to detect the temporal and spatial patterns in the consecutive days of six types of severe weathers, namely, hot weathers, cold weathers, rainstorm weathers, snowfall weathers, thunderstorm weathers and foggy weathers. The datasets that we used and methods that we employed are described in the next section. The interannual variability, spatial distribution and trend associated with severe weathers are presented in Section 3. This is followed by a discussion of the main findings in Section 4. Finally, we summarize our most important findings and provide conclusions in Section 5.

2 Data and method

2.1 Data

The daily surface climate data and weather phenomenon data provided by the National Meteorological Information Center, China Meteorological Administration (NMIC/CMA) were used to produce the consecutive days of severe weathers in this study. After a comprehensive consideration of the time duration and the missing rate of observation data, 604 among

756 available stations, with relatively complete data series of daily maximum temperature (T_{\max}), daily minimum temperature (T_{\min}), daily precipitation and daily weather phenomenon records of snowfall, thunderstorm and fog, were chosen. The administrative division of China and the distribution of selected meteorological stations are shown in Figure 1. These selected stations have the missing values of less than 10% in daily surface climate data and weather phenomenon data. Erroneous data and outliers of climate elements and weather phenomena was checked to improve the data quality and avoid the negative effects on climatic trend, and the missing data were filled in with the synchronous values of neighboring stations through simple linear regression method or with the climatological standard normals, 1981–2010 of the stations themselves (Zhang *et al.*, 2008). Since 2014, thunderstorm was no longer observed and recorded at meteorological stations of China, so the analysis period of thunderstorm was actually from 1959 to 2013.

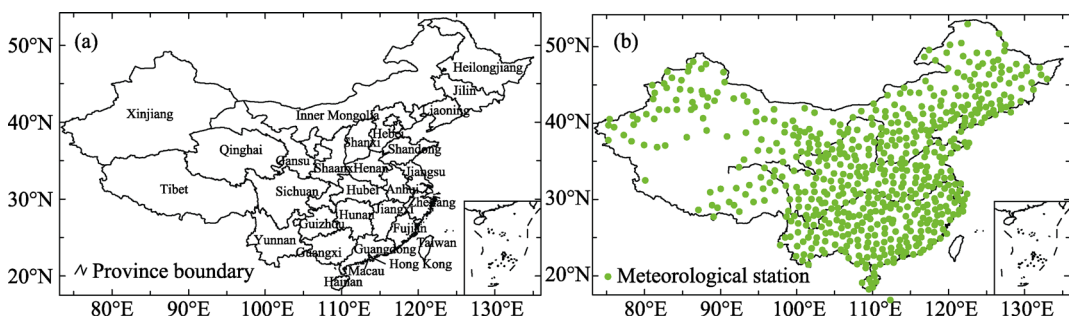


Figure 1 The administrative division (a) and the locations of 604 meteorological stations (b) in this study

2.2 Method

2.2.1 The definition of the days of severe weathers

In this study, hot days are specified as those days with T_{\max} no less than 35°C , and cold days are those with T_{\min} less than -5°C . Rainstorm days are defined as days with daily precipitation no less than 50 mm. The definition of snowfall, thunderstorm and foggy days is in accordance with Standard of the Surface Observation about Meteorology (CMA, 2003), namely, snowfall is a type of precipitation falling from clouds in the form of flakes of crystalline water ice. Thunderstorm is a storm in which there is thunder and lightning and a lot of heavy rain. Fog is a visible mass consisting of droplets of water vapor or ice crystals in the air near the ground, which causes a reducing visibility of less than 1 km (Shi *et al.*, 2010). If the above-mentioned weathers occurred on a same day simultaneously, that day was recorded as the corresponding type of severe weathers respectively.

2.2.2 The sequence of consecutive days for severe weathers

For each type of severe weathers, the sequences for annual average days and annual maximum days of consecutive severe weathers were built in China respectively. Based on the daily sequence of severe weathers, the periods of consecutive days for each type of severe weathers were determined and annual maximum number of consecutive days (or the length of the longest consecutive days in each year) was counted to form the annual sequence of consecutive days at each station. To obtain the sequence of annual average days of consecutive severe weathers in China, annual average days of consecutive severe weathers in each

province was calculated firstly with the station-averaged method, and then annual average days of consecutive severe weathers for China were calculated with the area-weighted average method according to the area of each province. The longest consecutive days for each type of severe weathers were selected directly from 604 stations in each year to obtain the annual maximum sequence of consecutive severe weathers in China.

2.2.3 Distribution and trend of consecutive days for severe weathers

Based on the annual sequence of consecutive days for each type of severe weathers, the average annual consecutive days and the linear trend of annual consecutive days of severe weathers were calculated at each station and in the whole China during 1959–2014. Trend is defined by linear regression coefficient (Niu *et al.*, 2004). The linear trends were calculated with the method of ordinary least squares regression, which was generally used in extreme temperature and precipitation studies (Kruger and Sekele, 2013; de Lima *et al.*, 2013), and the statistical significance was tested at the 0.05 confidence level using a two-tailed t-test (Wang *et al.*, 2013b). According to the longitude and latitude of meteorological stations, the spatial distribution and trend in annual consecutive days of severe weathers were spatialized with the inverse distance weighted (IDW) interpolation technique and were displayed by drawing software Surfer 8. The spatial distribution indicates the general condition of consecutive severe weathers in China, and the spatial trend manifests the linear regression coefficient on a time scale of ten years.

3 Results and analysis

3.1 Temporal characteristics in the consecutive days of severe weathers in China

To understand the temporal variations in the consecutive days of severe weathers, the distributions and trends in annual and decadal average days of consecutive severe weathers, and those in annual maximum days were analyzed for each type of severe weathers in China.

3.1.1 Interannual and interdecadal variations in average days of consecutive severe weathers

During 1959–2014, annual average number of consecutive hot weathers increased at a rate of 0.1 day per decade in China and the trend was significant (Figure 2a). Annual consecutive hot days decreased slightly during 1959–1985 and then increased rapidly. The number of consecutive hot weathers was 2.1, 2.0, 1.8 and 2.0 days per year during 1959–1970, the 1970s (1971–1980), the 1980s (1981–1990) and the 1990s (1991–2000) respectively, but during 2001–2014, it increased to 2.4 days per year in China (Table 1). Annual average number of consecutive cold weathers decreased at a rate of 1.4 days per decade during 1959–2014, and the trend was also significant in China (Figure 2b). Annual consecutive cold days decreased continuously during 1959–2006 and then increased a little in recent years. The number of consecutive cold weathers was 39.6 and 39.0 days per year during 1959–1970 and the 1970s respectively, and during 2001–2014, it decreased to 33.4 days per year (Table 1).

The trend of annual average number of consecutive rainstorm weathers was not significant in China during 1959–2014 (Figure 2c). Consecutive rainstorm days were more in the 1990s and during 2001–2014, both with an average of 0.22 day per year, and they were less in the 1980s, with an average of 0.19 day per year (Table 1). Annual average number of

consecutive snowfall weathers decreased significantly at a rate of 0.3 day per decade in China (Figure 2d). Over the past 56 years, annual consecutive snowfall days increased slightly at first and then decreased continuously. In the 1970s, the number of consecutive snowfall weathers was more, with an average of 5.1 days per year, and during 2001–2014, it was less, with an average of 3.9 days per year (Table 1).

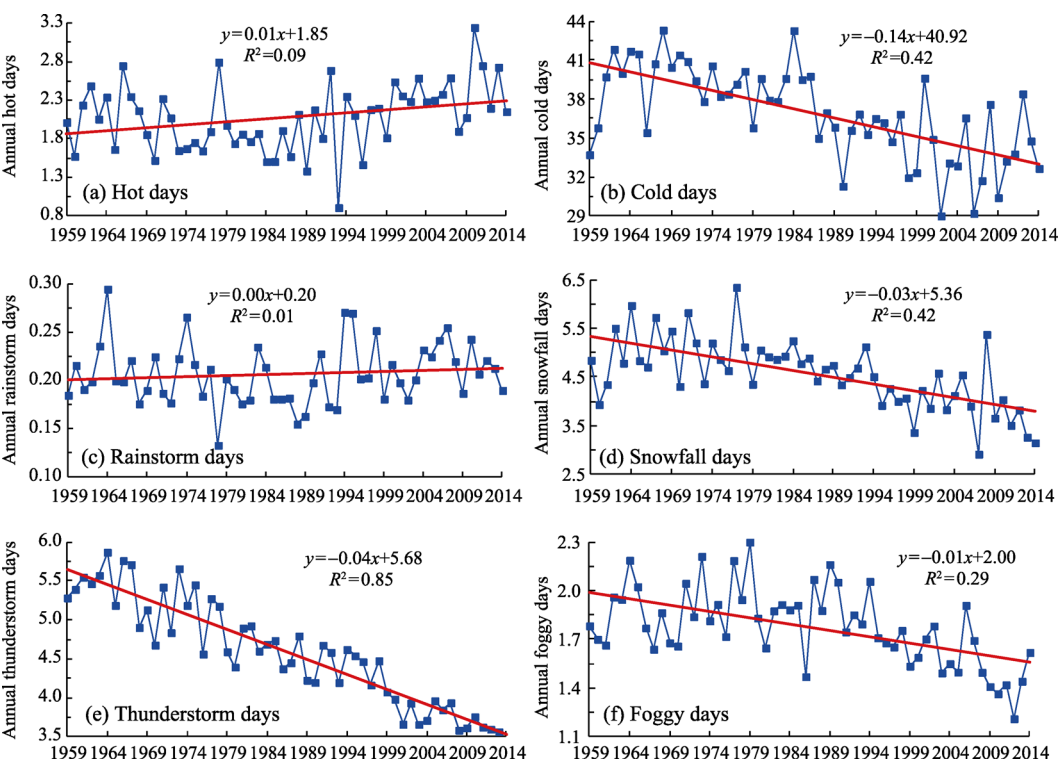


Figure 2 Annual consecutive days of severe weathers in China during 1959–2014 (The blue lines are annual value and the red lines are linear trend)

Table 1 Annual consecutive days of severe weathers in China during five periods

Severe weathers	Periods of time				
	1959–1970	1971–1980	1981–1990	1991–2000	2001–2014
Hot days	2.08	1.95	1.77	2.01	2.42
Cold days	39.62	38.99	37.69	35.58	33.43
Rainstorm days	0.21	0.20	0.19	0.22	0.22
Snowfall days	4.95	5.09	4.78	4.26	3.90
Thunderstorm days	5.38	5.06	4.59	4.38	3.72
Foggy days	1.82	1.98	1.89	1.74	1.54

Annual average number of consecutive thunderstorm weathers decreased at a rate of 0.4 day per decade in China, and the trend was also significant during 1959–2013 (Figure 2e). Annual consecutive thunderstorm days decreased continuously in the past 55 years. During 1959–1970, the number of consecutive thunderstorm weathers was more, with an annual average of 5.4 days, and during 2001–2013, it was less, with an annual average of 3.7 days (Table 1). Annual average number of consecutive foggy weathers decreased significantly at

a rate of 0.4 day per decade in China (Figure 2f). Over the past 56 years, annual consecutive foggy days decreased at first and then increased and later decreased continuously. In the 1980s, the number of consecutive foggy weathers was more, and during 2001–2014, it was less, with an annual average of 5.8 days (Table 1).

3.1.2 Interannual variations in the maximum days of consecutive severe weathers

Annual maximum number of consecutive hot weathers increased at a rate of 2.1 days per decade but the trend was not significant in China during 1959–2014 (Figure 3a). The maximum number of consecutive hot days decreased slightly during 1959–1990, and then it increased rapidly. Consecutive hot weathers were the most at Turpan station of Xinjiang in 2008, which were 101 days. Annual maximum number of consecutive cold weathers decreased at a rate of 2.2 days per decade and the trend was significant in China (Figure 3b). The maximum number of consecutive cold days decreased continuously before 2007, and then it increased. Consecutive cold weathers were the most at Wudaoliang station of Qinghai in 1975, which were 138 days.

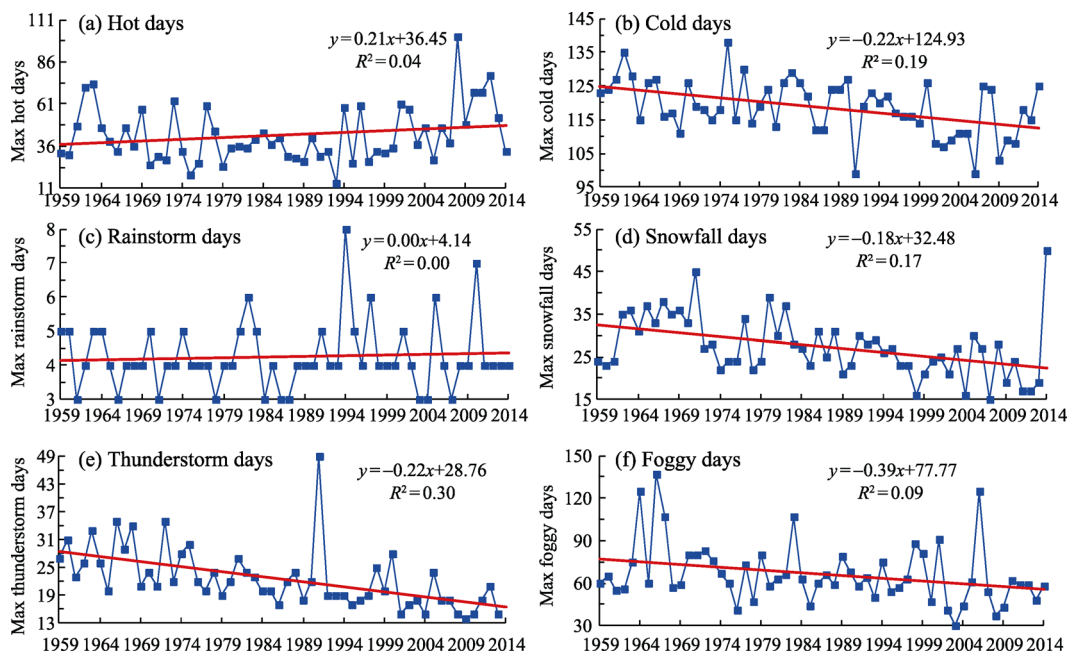


Figure 3 The maximum number of consecutive days for severe weathers in China during 1959–2014 (The blue lines are annual value and the red lines are linear trend)

In the past 56 years, the trend of annual maximum number of consecutive rainstorm weathers was not significant in China (Figure 3c). Consecutive rainstorm weathers were the most at Dongxing station of Guangxi in 1994, which were 8 days. Annual maximum number of consecutive snowfall weathers decreased at a rate of 1.8 days per decade and the trend was significant in China (Figure 3d). Consecutive snowfall weathers were the most at Alashankou (Alataw Pass) station of Xinjiang in 2014, which were 50 days.

Annual maximum number of consecutive thunderstorm weathers decreased significantly at a rate of 2.2 days per decade in China (Figure 3e). The maximum number of consecutive

thunderstorm days decreased continuously over the past 55 years. Consecutive thunderstorm weathers were the most at Xainza station of Tibet in 1991, which were 49 days. Annual maximum number of consecutive foggy weathers decreased at a rate of 3.9 days per decade and the trend was also significant in China (Figure 3f). Consecutive foggy weathers were the most at Mount Emei station of Sichuan in 1966, which were 137 days.

3.2 Spatial characteristics in the consecutive days of severe weathers in China

3.2.1 Spatial distribution in average annual days of consecutive severe weathers

During 1959–2014, average annual days of consecutive hot weathers were more in north-western and southeastern China, but less in northeastern and southwestern China (Figure 4a). In some areas of eastern Xinjiang, central and southern Anhui, most parts of Zhejiang and Hunan, northern and western Fujian, northern Guangdong, northeastern Guangxi, southeastern Hubei, Jiangxi and Chongqing, the number of consecutive hot weathers was mainly over 6 days per year on average. In northeastern China, eastern and central Inner Mongolia, most parts of Hebei, Shanxi, Shaanxi and Tibet, Ningxia, Gansu, Qinghai, Yunnan, western Sichuan and Guizhou, the number of consecutive hot weathers was less than 3 days per year. At Turpan station of Xinjiang, the number of consecutive hot weathers was the greatest, with

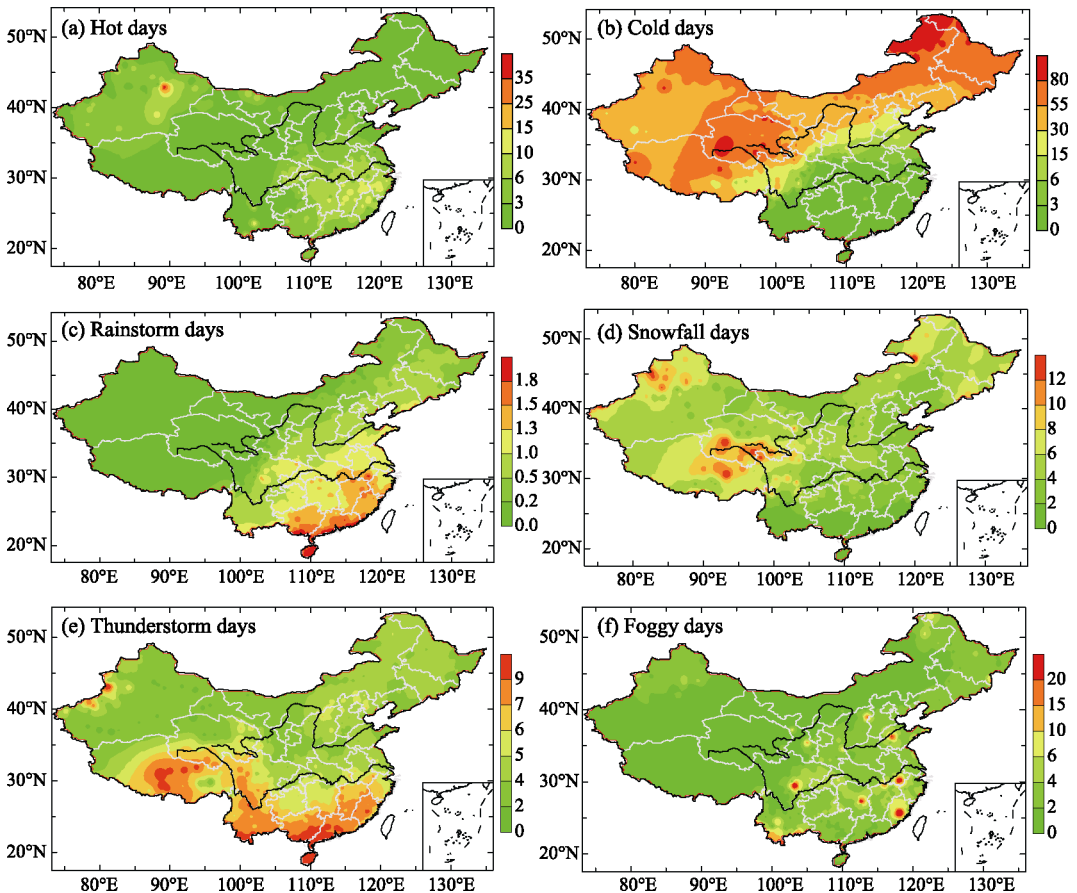


Figure 4 Spatial distribution of annual consecutive days of severe weathers in China during 1959–2014

an annual average of 41 days, and at 103 stations mainly distributed in Tibet, Qinghai, western Sichuan, Yunnan, eastern Jilin and some high mountain stations, there were no consecutive hot weathers during 1959–2014.

Average annual days of consecutive cold weathers were more in northeastern China, Inner Mongolia and western China, but less in southern China over the past 56 years, with obvious differences between northern China and southern China (Figure 4b). In Heilongjiang, Jilin, Inner Mongolia, Ningxia, Xinjiang, Qinghai, the northern parts of Hebei, Shanxi and Shaanxi, most parts of Liaoning, Gansu and Tibet, and northwestern Sichuan, the number of consecutive cold weathers was over 30 days per year on average, especially in Heilongjiang, northern Jilin, eastern Inner Mongolia, most parts of Qinghai, northeastern Xinjiang and some parts of central and western Tibet, it was over 55 days per year. In Fujian, Guangdong, Jiangxi, Hunan, Guizhou, Chongqing, Hubei, Hainan, Guangxi, Yunnan, eastern and southern Sichuan, Shanghai, and the southern parts of Jiangsu and Anhui, the number of consecutive cold weathers was less than 5 days per year. At Wudaoliang station of Qinghai, the number of consecutive cold weathers was the greatest, with an annual average of 115 days, and at 110 stations mainly distributed in Hainan, Guangdong, Guangxi, Yunnan, Chongqing, eastern Sichuan and southern Fujian, there were no consecutive cold weathers during 1959–2014.

Average annual days of consecutive rainstorm weathers were more in southeastern China, but less in western China during 1959–2014 (Figure 4c). In eastern and southern Shandong, southern Henan, most parts of Hubei, eastern Sichuan, eastern and southern Guizhou, southern Yunnan, and regions south of the above-mentioned areas, the number of consecutive rainstorm weathers was over one day per year on average, especially in southern and western Zhejiang, southern Anhui, eastern Hubei, northern and eastern Jiangxi, Fujian, Guangdong, Hainan, central and eastern Guangxi, it was over 1.3 days per year. In Xinjiang, Qinghai, Tibet, the western parts of Sichuan, Gansu and Inner Mongolia, the number of consecutive rainstorm weathers was less than 0.2 day per year. At Dongxing station of Guangxi, the number of consecutive rainstorm weathers was the greatest, with an average of 2.7 days per year, and at 82 stations mainly distributed in Xinjiang, Qinghai, Tibet, and the western parts of Inner Mongolia, Gansu and Sichuan, there was no consecutive rainstorm weathers during 1959–2014.

Over the past 56 years, average annual number of consecutive snowfall weathers was more in northeastern and western China, but less in southern China (Figure 4d). In northwestern Xinjiang, central and southern Qinghai, central and eastern Tibet, some parts of Heilongjiang, Jilin, western Sichuan, eastern Inner Mongolia and southwestern Gansu, the number of consecutive snowfall weathers was over 6 days per year on average, especially in southern Qinghai, north-central Tibet and the Alashankou regions of northwestern Xinjiang, it was over 8 days per year. In central and southern Fujian, Guangdong, Guangxi, Hainan and most parts of Yunnan, the number of consecutive snowfall weathers was less than 2 days per year. At Tulogart station of Xinjiang, the number of consecutive snowfall weathers was the greatest, with an annual average of 17 days, and at 29 stations mainly distributed in Hainan, southern Guangdong and southern Guangxi, there was no consecutive snowfall weathers during 1959–2014.

Average annual number of consecutive thunderstorm weathers was more in southern and

southwestern China, but less in northwestern China during 1959–2013 (Figure 4e). In most parts of Zhejiang, southern Anhui, southeastern and southwestern Hubei, Hunan, Guizhou, western Sichuan, southern Qinghai, central and eastern Tibet, Yunnan, Guangxi, Guangdong, Hainan, Jiangxi, Fujian and some small parts of western Xinjiang, Gansu, Shanxi and Hebei, the number of consecutive thunderstorm weathers was over 5 days per year on average, especially in central and western Fujian, southern Jiangxi, Guangdong, southern and central Guangxi, Hainan, southern and central Yunnan, central Tibet and some parts of southwestern Sichuan, it was over 7 days per year. In western Inner Mongolia, most parts of Gansu and Xinjiang, Ningxia, northwestern Qinghai, eastern Heilongjiang and some parts of Shanxi, Henan, Liaoning and Shandong, the number of consecutive thunderstorm weathers was less than 4 days per year. At Dongxing station of Guangxi, the number of consecutive thunderstorm weathers was the greatest, with an annual average of 14 days.

During 1959–2014, average annual number of consecutive foggy weathers was more in some mountain stations, but less in most areas of western China and Inner Mongolia (Figure 4f). In some high mountain stations, such as Mount Tai (1533.7 m above sea level), Huang (1840.4 m), Jvxian (1653.5 m) and Emei (3047.4 m) stations, the number of consecutive foggy weathers was over 20 days per year on average. In eastern China and central China, including southern Hebei, eastern and southern Shanxi, central and southern Shaanxi, the eastern parts of Gansu and Sichuan, and the regions south of the above-mentioned areas, the number of consecutive foggy weathers was over 2 days per year. In most parts of Heilongjiang, Liaoning and Yunnan, eastern Jilin, northeastern Inner Mongolia, northwestern Xinjiang, the number of consecutive foggy weathers was also over 2 days per year. In Tibet, Qinghai, western Sichuan, southern and eastern Xinjiang, Ningxia, most parts of Gansu and Inner Mongolia, the number of consecutive foggy weathers was less than one day per year. At Mount Jvxian station of Fujian, the number of consecutive foggy weathers was the greatest, with an annual average of 56 days.

3.2.2 Spatial trend in annual days of consecutive severe weathers

During 1959–2014, consecutive hot weathers varied mainly at rates of -0.4 to 0.5 day per decade (Figure 5a), but the trend was not significant in most parts of China. In some parts of eastern Xinjiang and western and north-central Inner Mongolia, and some southeastern coastal areas, including southern Jiangsu, Shanghai, northern and eastern Zhejiang, southwestern and eastern Fujian, Guangdong, southeastern Guangxi, eastern Hainan, northern Chongqing and some parts of eastern Sichuan, the number of consecutive hot weathers increased significantly at a rate of over 0.2 day per decade. In central and western Shandong, Henan, most parts of Hubei and Hunan, central and northern Jiangxi, northwestern Fujian, western Zhejiang, Anhui, northern Jiangsu, and some scattered areas of Xinjiang, Yunnan, Chongqing and Sichuan, the number of consecutive hot weathers decreased mainly at a rate of $0-0.4$ day per decade, though the trend was not significant.

Except for Hainan, Leizhou Peninsula of Guangdong, and several scattered stations in Heilongjiang and Tibet, the number of consecutive cold weathers decreased in the whole China during 1959–2014, and the trend was significant in west-central Inner Mongolia, most parts of Xinjiang, Qinghai, Tibet and Gansu, western Sichuan, western Shaanxi, Hebei, Shandong, Jiangsu, Anhui, Zhejiang, eastern and southern Henan and eastern Hubei (Figure 5b). There were obvious differences in the decreasing trends of consecutive cold weathers

between northern China and southern China. In regions north of Jiangsu, central Anhui, Henan, southern Shaanxi and those regions west of central Sichuan and Yunnan, the number of consecutive cold weathers decreased at rates of 1.0–3.0 days per decade in most areas, but in regions south of the above-mentioned areas, the number of consecutive cold weathers decreased uniformly at a rate of 0–1.0 day per decade.

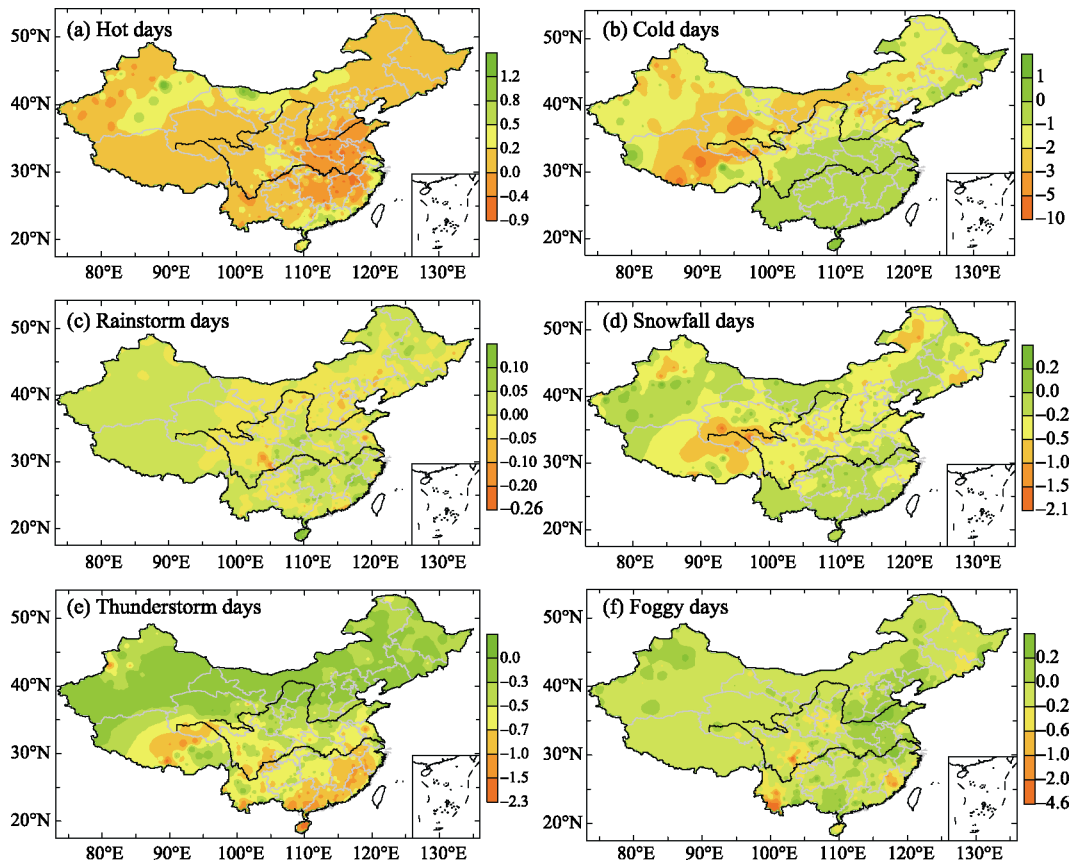


Figure 5 Spatial trend of annual consecutive days of severe weathers in China during 1959–2014

The spatial trend of consecutive rainstorm weathers was less in China as a whole, varied from -0.05 to 0.05 day per decade in most areas, and the trend was not significant except for several scattered stations (Figure 5c). In western, southeastern and northeastern China, including most parts of Xinjiang, Tibet, Zhejiang, Fujian, Anhui and Jiangxi, western Gansu, western Qinghai, western and southeastern Yunnan, southwestern and eastern Sichuan, Chongqing, Hunan, southern Jiangsu, southern and western Hubei, southern Shaanxi, central and eastern Henan, western and northern Heilongjiang, northeastern Inner Mongolia, and some scattered areas of other provinces, the number of consecutive rainstorm weathers increased at a rate of 0 – 0.05 day per decade. In northern China and some areas of northwestern China and southwestern China, the number of consecutive rainstorm weathers decreased at a rate of 0 – 0.05 day per decade in the past 56 years.

Except for some stations in central and southwestern Xinjiang, southern Anhui, northern Jiangxi, Hunan and Guizhou, the number of consecutive snowfall days decreased in whole

China during 1959–2014 (Figure 5d). In some parts of eastern Inner Mongolia, eastern Jilin, central Shaanxi, southeastern Gansu, southern Qinghai, north-eastern Tibet and western Xinjiang, the number of consecutive snowfall weathers decreased significantly at a rate of over 0.5 day per decade. In other regions, the number of consecutive snowfall weathers decreased at a rate of 0–0.5 day per decade, without obvious geographic distribution differences, and the trend was also not significant.

Consecutive thunderstorm weathers showed a decreasing trend in almost entire China during 1959–2013 (Figure 5e), and the trend was all significant except for eastern and southern Xinjiang, northern Qinghai, northwestern Gansu, eastern and western Tibet, western Inner Mongolia, northern Shaanxi, central and northern Shanxi, most parts of Hebei and Liaoning, and some scattered areas of Jilin, Heilongjiang and eastern Inner Mongolia, where the decreasing trend was less than 0.3 day per decade. The decreasing trend of consecutive thunderstorm days was more in southern China than in northern China. In regions south of Shandong, Henan, central Shaanxi, Gansu, central Qinghai and western Tibet, the number of consecutive thunderstorm weathers decreased mainly at a rate of 0.5–1.0 day per decade, but in northeastern, northern and northwestern China, it decreased mainly at a rate of 0–0.5 day per decade.

The spatial change of consecutive foggy weathers ranged from –0.2 to 0.2 day per decade, and the trend was not significant in most areas of China during 1959–2014 (Figure 5f). In western and southern Liaoning, most parts of Hebei, Shandong and Henan, Tianjin, Anhui, south-central Jiangsu, northwestern Zhejiang, northeastern Hubei, southern Shanxi, central and southern Guangxi, some parts of western Xinjiang and eastern Inner Mongolia, and some small parts of other provinces, the number of consecutive foggy weathers increased mainly at a rate of 0–0.4 day per decade, but the trend was not significant in most areas. In other regions, the number of consecutive foggy weathers decreased mainly at a rate of 0–0.6 day per decade, and the trend was also not significant.

4 Discussion

Severe weathers are weather conditions that are hazardous to human life and property. There is great interest to evaluate changes in severe weathers due to their serious and adverse effects on natural ecosystems, social economy and human life (Easterling *et al.*, 2000; Wang *et al.*, 2012; Tang *et al.*, 2013; Compeán, 2013; Saunders *et al.*, 2014). In recent years, the frequent appearance of severe weathers, such as high temperature and heat waves, rainstorm, snowfall and fog have been reported all over the world (Zhao *et al.*, 2013; Chen *et al.*, 2013; Zhang *et al.*, 2015), and some of them have caused enormous damage to agricultural production and social infrastructure, brought about serious disruption to human activities, even personal injury and loss of life (Marengo *et al.*, 2010; Barriopedro *et al.*, 2011; Sun *et al.*, 2014). Insurance statistics revealed that there were 980 documented loss events in 2014, 92% of which were weather-related, including floods, storms, heat waves, droughts, cold waves and wildfires (Munich Re, 2015). Understanding and predicting the variations in severe weathers is thus a major social issue, including, for example, government policy-making, urban infrastructure planning, resources and environment management, and insurance types and premiums.

The types of severe weathers depends on latitude, longitude, terrain and atmospheric conditions (WMO, 2004), and the mortalities and economic losses from severe weathers are higher in developing countries as an expression of the proportion to gross domestic product (GDP) (IPCC, 2012). During 1970–2008, more than 95% of deaths from natural disasters happened in developing countries (IPCC, 2012). China, strongly influenced by the East Asian monsoon, is particularly vulnerable to frequent severe weathers and meteorological disasters, like droughts, floods, storms and heat waves. It is estimated that the economic loss caused by meteorological disasters accounts for as much as 3% to 6% of GDP each year since 1990 (Jiang *et al.*, 2012). The impacts of severe weathers are not only related to the frequencies and extreme values, but also associated with the continuous days. Three or more consecutive days of severe weathers tend to cause more serious consequences than alone. During July and August, 2013, continuous hot weathers hit eastern China, and Shanghai suffered from sustained high temperature. There were 10 consecutive days with T_{\max} exceeding 38°C and 4 consecutive days with T_{\max} over 40°C . Meanwhile, urban electricity peak and water supply had created new historical records, 29.4 million kw and 6.796 million m^3 respectively, and hot weathers also caused a few emergent public health incidents, such as heat stroke, diarrhea and so on (China Meteorological Administration, 2015).

However, the research into consecutive days of severe weathers has been more limited. Zheng *et al.* (2012) examined the trends of extreme weather events in Beijing and results showed that since the 1990s, continuous high temperature days had an increasing tendency. Wang *et al.* (2013a) analyzed the variation characteristics of low-temperature weathers in winter and the results indicated that continuous low-temperature days showed slightly decreasing tendency on decadal scale in Henan Province of China. Huang *et al.* (2012) studied the climate change of lasting fog for 12 hours and 3 days in region around the Three Gorges Reservoir and found that annual mean foggy weathers of lasting for 3 days significantly reduced after impoundment. Ren *et al.* (2015) researched the variations of precipitation extremes in South China and results showed consecutive wet days decreased at -0.05 day per year from 1961 to 2011.

In estimating the impacts of climate change, a primary concern is the potential changes of severe weathers that could accompany global warming. It has been widely recognized that climate change may increase the likelihood of severe weathers such as heat waves, heavy rainfall, and severe storms over most global land areas (Bender *et al.*, 2010; Kharin *et al.*, 2013; Sillmann *et al.*, 2013; Yang *et al.*, 2014). Research into other severe weathers such as thunderstorm and fog in relationship to global climate change has been more limited. It is thus of great importance and urgency to launch a circumstantial estimate of how frequency and intensity of these severe weathers might change for some time to come due to the global climate change (Brooks, 2013; Akimoto and Kusaka, 2015). The impacts of severe weathers are also to a large extent dependent on the social or eco-environmental vulnerability, resiliency and adaptation and mitigation capacity (Singh and Patwardhan, 2012). Climate change may be most frequently perceived when it is associated with severe weathers, especially where vulnerable populations or high value properties are at risk (IPCC, 2013). Our social vulnerability is increasing as the society gets more and more complex and interconnected, and as personal, industrial and commercial development spreads to high risk areas (IPCC, 2012; Yin *et al.*, 2013). Adaptation policies and efforts such as modifying local infrastruc-

ture to withstand floods and storms, adjusting urban patterns to account for heat waves, as well as establishing emergency planning in our communities and homes, would achieve great benefits from avoiding disaster and risk of severe weathers.

Although provide longer records, climatic datasets based on site observations discourage adequate sampling of the meteorological elements for global and regional applications, especially over desert or mountainous areas in Tibet, Xinjiang and Qinghai province. The interpolation results of severe weathers in western China may not be able to reflect the actual distribution and variation trend due to sparse meteorological stations. Compared with ground observations, space-borne observations provide more homogeneous data (Schulz *et al.*, 2009), especially in the mountainous or oceanic regions. The TRMM lightning imaging sensor (LIS) and precipitation radar (PR) have been applied to resaearch precipitation and lightning in many parts of the world (Prakash *et al.*, 2012; Zhu *et al.*, 2013; Nastos *et al.*, 2013). In addition, reanalysis data can be a potential source of useful data for assessing the long-term changes of some severe weathers in data sparse regions. You *et al.* (2013) showed that both NCEP/NCAR reanalysis data and ECMWF reanalysis data can reproduce the variations of temperature extremes acquired from surface observations, and can be used in the study of climate extremes to certain extent. Further using these space-based observation data and reanalysis data into the study, and adopting the scientific method to carry out the examination of data homogenization and the filling of missing data, is the direction of future efforts.

5 Conclusions

The distribution and trend of consecutive days for six types of severe weathers were analyzed and results indicate that annual consecutive hot weathers increased at a speed of 0.1 day per decade in China, but consecutive cold, snowfall, thunderstorm and foggy weathers decreased at rates of 1.4, 0.3, 0.4 and 0.4 day per decade respectively. The maximum number of consecutive cold, snowfall, thunderstorm and foggy weathers decreased at rates of 2.2, 1.8, 2.2 and 3.9 days per decade respectively. The trend of consecutive rainstorm weathers was not significant in China during 1959–2014.

Spatially, consecutive hot weathers were more in northwestern and southeastern China, but less in northeastern and southwestern China. Consecutive cold weathers and snowfall weathers were more in northeastern and western China, but less in southern China. Consecutive rainstorm weathers were more in southeastern China and less in western China. Consecutive thunderstorm weathers were more in southern and southwestern China, but less in northwestern China. Consecutive foggy weathers were more in some mountain stations and less in most areas of western China and Inner Mongolia.

Over the past 56 years, consecutive cold weathers decreased in most areas of western China, the central and northern parts of eastern China, west-central Inner Mongolia, Hebei, eastern and southern Henan and eastern Hubei. Consecutive snowfall weathers decreased in some parts of eastern Inner Mongolia, eastern Jilin, central Shaanxi, southeastern Gansu, southern Qinghai, north-eastern Tibet and western Xinjiang. Consecutive thunderstorm weathers decreased in most areas of China. The trend of consecutive hot weathers and foggy weathers was not significant in most areas of China, and that of consecutive rainstorm

weathers was not significant in almost the entire China.

References

- Akimoto Y, Kusaka H, 2015. A climatological study of fog in Japan based on event data. *Atmospheric Research*, 151: 200–211.
- Barriopedro D, Fischer E M, Luterbacher J *et al.*, 2011. The hot summer of 2010: Redrawing the temperature record map of Europe. *Science*, 332: 220–224.
- Bender M A, Knutson T R, Tuleya R E *et al.*, 2010. Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricane. *Science*, 327(5964): 454–458.
- Brooks H E, 2013. Severe thunderstorms and climate change. *Atmospheric Research*, 123: 129–138.
- Chen Shangfeng, Chen Wen, Wei Ke, 2013. Recent trends in winter temperature extremes in eastern China and their relationship with the Arctic Oscillation and ENSO. *Advances in Atmospheric Sciences*, 30(6): 1712–1724.
- China Meteorological Administration (CMA), 2003. Standard of the Surface Observation about Meteorology. Beijing: China Meteorological Press, 1–151. (in Chinese)
- China Meteorological Administration (CMA), 2015. China Meteorological Disasters Yearbook (2014). Beijing: China Meteorological Press, 1–238. (in Chinese)
- Compeán R G, 2013. The death effect of severe climate variability. *Procedia Economics and Finance*, 5: 182–191.
- de Lima M I P, Santo F E, Ramos A M *et al.*, 2013. Recent changes in daily precipitation and surface air temperature extremes in mainland Portugal, in the period 1941–2007. *Atmospheric Research*, 127: 195–209.
- de Vyver H V, 2012. Evolution of extreme temperatures in Belgium since the 1950s. *Theoretical and Applied Climatology*, 107: 113–129.
- Easterling D R, Evans J L, Groisman P Y *et al.*, 2000. Observed variability and trends in extreme climate events: A brief review. *Bulletin of the American Meteorological Society*, 81(3): 417–425.
- Fu Guobin, Yu Jingjie, Yu Xiubo *et al.*, 2013. Temporal variation of extreme rainfall events in China, 1961–2009. *Journal of Hydrology*, 487: 48–59.
- Huang Zhiyong, Niu Ben, Ye Limei *et al.*, 2012. An analysis of climatic characteristics of extreme fog in the region around the Three Gorges Reservoir. *Resources and Environment in the Yangtze Basin*, 21(5): 646–652. (in Chinese)
- IPCC, 2012. Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press, 1–582.
- IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press, 1–1535.
- Jiang Zhihong, Song Jie, Li Laurent *et al.*, 2012. Extreme climate events in China: IPCC-AR4 model evaluation and projection. *Climatic Change*, 110(1): 385–401.
- Kharin V V, Zwiers F W, Zhang X *et al.*, 2013. Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Climatic Change*, 119(2): 345–357.
- Kruger A C, Sekele S S, 2013. Trends in extreme temperature indices in South Africa: 1962–2009. *International Journal of Climatology*, 33(3): 661–676.
- Liu Xianfeng, Zhu Xiufang, Pan Yaozhong *et al.*, 2015. Spatiotemporal changes of cold surges in Inner Mongolia between 1960 and 2012. *Journal of Geographical Sciences*, 25(3): 259–273.
- Marengo J, Rusticucci M, Penalba O *et al.*, 2010. An intercomparison of observed and simulated extreme rainfall and temperature events during the last half of the twentieth century (Part 2): Historical trends. *Climatic Change*, 98: 509–529.
- Munich Re, 2015. Topics Geo Natural Catastrophes 2014: Analyses, Assessments and Positions. 1–67.
- Nastos P T, Kapsomenakis J, Douvis K C, 2013. Analysis of precipitation extremes based on satellite and high-resolution gridded data set over Mediterranean basin. *Atmospheric Research*, 131: 46–59.
- Niu Tao, Chen Longxun, Zhou Zijiang, 2004. The characteristics of climate change over the Tibetan Plateau in the last 40 years and the detection of climatic jumps. *Advances in Atmospheric Sciences*, 21(2): 193–203.
- Prakash S, Mahesh C, Gairola R M *et al.*, 2012. Comparison of high-resolution TRMM-based precipitation products during tropical cyclones in the North Indian Ocean. *Natural Hazards*, 61: 689–701.

- Ren Zhengguo, Zhang Mingjun, Wang Shengjie *et al.*, 2015. Changes in daily extreme precipitation events in South China from 1961 to 2011. *Journal of Geographical Sciences*, 25(1): 58–68.
- Saunders M, Tobin B, Sweeney C *et al.*, 2014. Impacts of exceptional and extreme inter-annual climatic events on the net ecosystem carbon dioxide exchange of a Sitka spruce forest. *Agricultural and Forest Meteorology*, 184: 147–157.
- Schulz J, Albert P, Behr H-D *et al.*, 2009. Operational climate monitoring from space: The EUMETSAT Satellite Application Facility on Climate Monitoring (CM-SAF). *Atmospheric Chemistry and Physics*, 9: 1687–1709.
- Shi Jun, Cui Linli, He Qianshan *et al.*, 2010. The changes and causes of fog and haze days in eastern China. *Acta Geographica Sinica*, 65(5): 533–542. (in Chinese)
- Sillmann J, Kharin V V, Zwiers F W *et al.*, 2013. Climate extremes indices in the CMIP5 multimodel ensemble (Part 2): Future climate projections. *Journal of Geophysical Research: Atmospheres*, 118: 2473–2493.
- Singh A, Patwardhan A, 2012. Spatio-temporal distribution of extreme weather events in India. *APCBEE Procedia*, 1: 258–262.
- Sun Ying, Zhang Xuebin, Zwiers F W *et al.*, 2014. Rapid increase in the risk of extreme summer heat in eastern China. *Nature Climate Change*, 4: 1082–1085.
- Tang Xiangling, Lv Xin, Xue Feng *et al.*, 2013. Progress and prospect of extreme climate events in arid Northwest China. *International Journal of Geosciences*, 4(1): 36–42.
- Wang Huijun, Sun Jianqi, Chen Huopo *et al.*, 2012. Extreme climate in China: Facts, simulation and projection. *Meteorologische Zeitschrift*, 21(3): 279–304.
- Wang Jijun, Pan Pan, Hu Caihong, 2013a. Spatial-temporal change characteristics of continuous low temperature weather during winter in Henan Province. *Meteorological and Environmental Sciences*, 36(4): 1–5. (in Chinese)
- Wang Qiong, Zhang Mingjun, Wang Shengjie *et al.*, 2014. Changes in temperature extremes in the Yangtze River Basin, 1962–2011. *Journal of Geographical Sciences*, 24(1): 59–75.
- Wang Shengjie, Zhang Mingjun, Wang Baolong *et al.*, 2013b. Recent changes in daily extremes of temperature and precipitation over the western Tibetan Plateau, 1973–2011. *Quaternary International*, 313/314: 110–117.
- WMO, 2004. Workshop on Severe and Extreme Events Forecasting: Final Report. Toulouse, France, 26–29 October 2004: 1–25.
- WMO, 2013. The Global Climate 2001–2010: A decade of climate extremes. WMO–No.1103. World Meteorological Organization, Geneva, Switzerland. 1–110.
- Xia Jun, She Dunxian, Zhang Yongyong *et al.*, 2012. Spatio-temporal trend and statistical distribution of extreme precipitation events in Huaihe River Basin during 1960–2009. *Journal of Geographical Sciences*, 22(2): 195–208.
- Yang Shili, Feng Jinming, Dong Wenjie *et al.*, 2014. Analyses of extreme climate events over China based on CMIP5 historical and future simulations. *Advances in Atmospheric Sciences*, 31: 1209–1220.
- Yin Zhan'e, Yin Jie, Zhang Xiaowei, 2013. Multi-scenario-based hazard analysis of high temperature extremes experienced in China during 1951–2010. *Journal of Geographical Sciences*, 23(3): 436–446.
- You Qinglong, Fraedrich K, Min Jinzhong *et al.*, 2013. Can temperature extremes in China be calculated from reanalysis? *Global and Planetary Change*, 111: 268–279.
- Yu Rong, Zhang Xiaoling, Li Guoping *et al.*, 2012. Analysis of frequency variation of thunderstorm, hail and gale in eastern China from 1971 to 2000. *Meteorological Monthly*, 38(10): 1207–1216. (in Chinese)
- Zhang Qigao, Xu Chong-Yu, Zhang Zhi *et al.*, 2008. Climate change or variability? The case of Yellow River as indicated by extreme maximum and minimum air temperature during 1960–2004. *Theoretical and Applied Climatology*, 93: 35–43.
- Zhang Suping, Chen Yang, Long Jingchao *et al.*, 2015. Interannual variability of sea fog frequency in the Northwestern Pacific in July. *Atmospheric Research*, 151: 189–199.
- Zhao Chun-Yu, Wang Ying, Zhou Xiao-Yu *et al.*, 2013. Changes in climatic factors and extreme climate events in Northeast China during 1961–2010. *Advances in Climate Change Research*, 4(2): 92–102.
- Zheng Zuofang, Zhang Xiuli, Ding Haiyan, 2012. Change trend of extreme weather events in Beijing area in recent 50 years. *Journal of Natural Disasters*, 21(1): 47–52. (in Chinese)
- Zhu Runpeng, Yuan Tie, Li Wanli *et al.*, 2013. Characteristics of global lightning activities based on satellite observations. *Climatic and Environmental Research*, 18(5): 639–650. (in Chinese)
- Zhu Xiaofan, Zhang Mingjun, Wang Shengjie *et al.*, 2014. Spatiotemporal variation patterns of the beginning and ending dates of snowfall, and snowfall days in Qinghai Province during 1962 to 2012. *Chinese Journal of Ecology*, 33(3): 761–770. (in Chinese)