Nat. Hazards Earth Syst. Sci. Discuss., 1, 7059–7092, 2013
www.nat-hazards-earth-syst-sci-discuss.net/1/7059/2013/
doi:10.5194/nhessd-1-7059-2013

Natural Hazards and Earth System Sciences
Open Access
Discussions

Temporal and spatial variability of extreme snowfall indices over northern Xinjiang from 1959/1960 to 2008/2009

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Received: 18 July 2013 – Accepted: 27 September 2013 – Published: 5 December 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Plentiful snowfall is an important resource in northern Xinjiang. However, extreme snowfall events can lead to destructive avalanches, traffic interruptions or even the collapse of buildings. The daily winter precipitation data from 18 stations in northern Xinjiang during 1959/1960–2008/2009 were selected for purpose of analyzing long-term variability of extreme snowfall events. Five extreme snowfall indices, Maximum 1 day snowfall amount (SX1day), Maximum 1-weather process snowfall amount (SX1process), Blizzard days (DSb), Consecutive snow days (DSc) and Blizzard weather processes (PSb), were defined and utilized to quantitatively describe the intensity and frequency of extreme snowfall events. Temporal trends of the five indices were analyzed by Mann–Kendall test and simple linear regression, and their trends were interpolated using universal kriging interpolation. Temporally, we found that most stations have upward trends in the five indices of extreme snowfall events, and over entire northern Xinjiang, they were all increasing at the 0.01 significance level (MK test), with the linear tendency rates of 0.49 mm $(10\,a)^{-1}$ (SX1day), 0.89 mm $(10\,a)^{-1}$ (SX1process), 0.024 days $(10\,a)^{-1}$ (DSb), 0.14 days $(10\,a)^{-1}$ (DSc), and 0.069 times $(10\,a)^{-1}$ (PSb) respectively. Meanwhile, obvious decadal fluctuations besides long-term increasing trends are identified. Trends in the intensity and frequency of extreme snowfall events show a distinct difference spatially. In general, trends of five indices were found shifting from decreasing to increasing from the northeast to the southwest and from the north to the south of northern Xinjiang. Furthermore, the regions covered by increasing or decreasing extreme snowfall events were identified, implying the hot or cold spots for extreme snowfall events changes. These results may be helpful for northern Xinjiang on the regional and local resource and emergency planning.

1 Introduction

Although change in mean snowfall is an important indicator of climate change, it can be argued that the most damaging and memorable winters are those with extremely large amounts of snow. Extreme snowfall event (ESE) causes serious loss of human life and property in many middle and high latitude countries almost every winter (Marty and Blanchet, 2012). ESEs have severe influences on the production and life. For example, ESEs are often accompanied by extreme snow storms and avalanches which cause hazardous conditions on roads, railways and airports – sometimes even leading to the interruption of major transport routes; extreme surface snow can be a high economic burden for society due to snow load damages to buildings, increased snow removal costs or spring flooding; and in pastoral areas, a great deal of snowfall often leads to grassland being buried, resulting in a large number of deaths of livestock due to lower temperature and lack of forage stock (Wang et al., 2013). In the United States, the super storm during March 1993, affected 20 states with $1.8 billion in economic loss and 270 deaths, being ranked as the US's worst winter storm of the past 100 yr (Changnon and Changnon, 2006), implying undesirable impacts of extreme snow hazards on human society. The recorded snow disaster in China occurred in January 2008, leading to economic loss of about ¥1516 billion and over one hundred deaths (http://www.weather.com.cn/static/html/article/20091117/141218.shtml). Additionally, tremendous snow disasters attacked many places in China. For example, Tibetin was attacted by snow disasters in the winter and spring of 1956–1957, 1965–1966 and 1976–1977, Ili in north Xinjiang in 1969, most north China in 1977, and west mountainous areas of south Xinjiang in 1983. Due to hazardous nature of extreme snow events, thorough understanding changes of snow events is critically necessary for human mitigation to confront snow-related natural hazards.

Actually, there is a bunch of researches devoted to the trends of snowstorms over a variety of regions. A lower frequency but higher intensity of extreme snowfall events was reported in the USA during the twentieth century (Changnon and Changnon, 2006;

Changnon, 2007, 2008; Kunkel et al., 2009), and the trends of snowstorm frequency were downward in the lower Midwest, South, and West Coast, while upward in the upper Midwest, East, and Northeast, and the entire country (Changnon et al., 2006). Maximum snow depth and maximum snow water equivalent are decreasing in Japan (Tachibana, 1995; Ishizaka, 2004; Yamaguchi, 2011; Kawase, 2012). In the UK, Wild et al. (1996) showed the frequency of blizzards during the most recent decades (1880–1989) was increasing. Wild (1996) found the frequency of blizzards and heavy snowfalls greater than 15 centimeters across Great Britain (1861–1995) was in upward trend. For the Swiss Alps, the frequency of ESEs was constant or increased slightly for the period 1933–1999, despite a marked decrease in snow depth and duration at mid-to-low elevations, as a consequence of warmer temperatures (Laternser and Schneebeli, 2003). Such an increase has also been observed for extreme winter precipitation in north of the Alps (Schmidli and Frei, 2005). Strasser (2008) suggested that the predicted variability in climatic extremes may lead to more frequent heavy snowfall in the Bavarian region (Germany). In Austria, both the absolute frequencies and the maximum intensities of heavy snow events were slightly higher from 1970/71 to 1988/89 than during the period from 1994/95 to 1938/39 (Spreitzhofer, 1999). In Switzerland, significant increases were found for heavy precipitation strength and frequence in winter (Schmidli and Frei 2005). Marty (2008) discovered a significant step-like decrease in snow days at the end of the 1980's with no clear trend since then and this abrupt change resulted in a loss of 20 % to 60 % of the total snow days. Serquet et al. (2011) showed clear decreasing trends in snowfall days relative to precipitation days and the decrease in snowfall days was stronger at lower elevations. Marty and Blanchet (2012) found the decreasing trends in extreme snow depth and extreme snowfall in Switzerland. In the Antarctic, the significant increase in the number of winter-season precipitation events were observed (Turner et al., 1997; Kirchgaessner, 2011). Despite using different indicators of ESEs, results from researches above-mentioned show that the trends in all kinds of ESEs are different in regions.

In China, many reseaches have been conducted on ESEs in recent years, most of which focused on case studies (e.g. Gao, 2006; Zhao, 2007; Chen et al., 2007; Bai, 2008; Qin and Jin, 2008; Ding, 2010; Li et al., 2011; Chen and Cui, 2012), while relatively fewer studies focused on statistical trends and frequency changes of ESEs (Liu et al., 2010; Dong et al., 2010; Ding et al., 2011; Wang et al., 2011). Comparatively, only fewer studies referred to northern Xinjiang, a subregion of China that has plentiful winter snowfall and is famous for snow-related disasters. Sun et al. (2010) studied the changes in intense snow days over China in recent 40 yr (1961–2000), in which a intense snow day was defined as a day whose daily snowfall (snow water equivalent) was equal to or larger than 5 mm. They found that the frequency of intense snow days increased in northern Xinjiang. Zhao et al. (2010) pointed that in the period form 1961 to 2007, the frequency and intensity of extreme precipitation in winter were increasing in northern Xinjiang. The winter precipitation in northern Xinjiang could be considered as snow because its winter temperature are below 0 °C.

Northern Xinjiang, an autonomous region in northwest China, locating in the Mid-latitude, is one of the most sensitive regions to globe warming. The Tianshan Mountains divide Xinjiang into southern and northern parts. The climate is mostly affected by the westerly current from the Atlantic and Arctic Oceans (Zhang et al., 2012). Winters in northern Xinjiang are longer and colder than other places in China and snowfall event is the main weather phenomena in this region. Due to abundant snowfall and a longer period of snow cover (from the beginning of November to the end of March of the subsequent year, usually), this region is well-known for its plentiful snow resources and frequent snow disasters (e.g., avalanche, wind-blowing snow, snow disaster, etc.) (Liu et al., 2012). Therefore, studying on long-term variation of extreme snowfall event in northern Xinjiang is of very importance. It is a requisite to scientifically assess the impacts of climatic changes on regional ecological environment and to do resource- and emergency-planning. However, previous studies about extreme snowfall events in northern Xinjiang employed different indices, and usually applied thresholds based on local snowfall amount to define extreme snowfall events. Since precipitation is uneven

both in time and space, studying extreme precipitation using the same threshold in a whole year and over a large area may under-estimate them in winter and may make the study results incomparable at regional levels. For example, precipitation more than 10 mm may not be identified as an extreme event in summer, but it may be the case in winter. Besides, daily snowfall exceeding a threshold of 10 mm (snow water equivalent) may be classified into extreme snowfall in one place, but in another place, only daily snowfall exceeding 12 mm can be defined as extreme snowfall events. Obviously, using the same threshold in different seasons and regions is inappropriate. What mentioned above is the main motivation of the present research. The objectives of this study are bi-folds. Firstly, five indices were defined to quantitatively describe ESE frequency and intensity, and secondly, trends of the ESE indices and their spatial variability over northern Xinjiang are analyzed to show their possible responses to globe warming.

2 Data and methods

2.1 Data

The daily precipitation dataset for this study was provided by China National Meteorological Information Center. The precipitation types (sleet, snow, fog, dew, frost, etc.) in the dataset has also been discriminated. Moreover, the temperatures of winter, from December to next February, in northern Xinjiang are all below 0 °C. Mentioned above make it easy to identify snow days and their snowfall amounts. What needs to be mentioned is that the precipitation is usually measured by rain gauge in China. In case of snowfall, the snow amount captured by the rain gauge is taken from observation site to room. When the snow in rain gauge melted at room temperature, the melted-water amount is measured in unit millimeter (mm).

Owing to natural and anthropogenic reasons, in northern Xinjiang, the meteorological stations are relatively sparse and the record lengths are different. Before using the weather data in trend analysis, it is necessary to do preliminary controls on the choice of the record length and on the missing data. Rigorous quality control has been conducted before the data mentioned above was released, and homogenization for the dataset has also been performed using RHtestsV3 software (http://etccdi.pacificclimate.org/software.shtml). Here we selected stations whose winter precipitation data are at least 95 % complete in the period of 1959/1960–2008/2009. The missing data were completed by Jiang et al. (2013) using conventional statistical methods including: (1) if only one day has missing data, the missing data was replaced by the average value of the same day in all selected years; (2) if consecutive two or more days have missing data, the missing data would be processed by simple linear correlation between its neighboring stations (distance < 100 km). Finally, 18 out of 23 national basic meteorological stations were selected for this study. Their winter daily precipitation series range from 1959/1960 to 2008/2009. Detailed information of the meteorological stations and dataset can be referred to Table 1. The location of the selected meteorological stations can be referred to Fig. 1.

2.2 Definition of extreme snowfall indices

To define extreme events, a threshold value must be decided and then used to distinguish the sounded extreme events from a common meteorological dataset (Zhai et al., 1999). At present, the snow grades widely used in China and Xinjiang province are measured by the standards of snowfall and snow cover depth in 12 h or 24 h (Table 2). It has been proved that these standards are very useful for determining the grade of snowfall intensity. However, snowfall is a very uneven weather process in both time and space. Temporally, snowfall can be classified as a continuous and an intermittent process. In case of a continuous process, snowfall lasts for a long time interval and covers a wide range of area with unchanged intensity, which is usually called heavy snowfall. In the case of an intermittent process, snowfall can last for long or short time periods with changing intensity. Spatially, the distribution of meteorological elements of ESEs differs locally. Sun et al. (2010) indicated that China ESEs distributed in four sub-regions. Their ESEs' frequency and intensity changed differently. In order to overcome the drawbacks

mentioned above, we define five indices (Table 3) to quantitatively describe regional ESEs. Maximum 1 day snowfall amounts (SX1day) and Maximum 1-weather process snowfall amounts (SX1process) are the intensity indices, blizzard days (DSb), consecutive snow days (DSc) and blizzard weather processes (PSb) are the frequency indices.

2.3 Mann–Kendall test

In this study, firstly, based on winter daily precipitation dataset, ESE indices of every selected meteorological station were calculated, and then averaged them as the ESE indices of northern Xinjiang region. We explored the changing features of the indices using the Mann–Kendall (MK) non-parametric test. This test is used to detect the tendency of long period hydro-meteorological data without having to make an assumption about its distributional properties. Moreover, the non-parametric methods are less influenced by the outliers in the data (Lanzante, 1996). In a trend test, the null hypothesis H_0 is that there is no trend in the analyzed time-series, and hypothesis H_1 is that there is a trend in the analyzed data. The MK test is applied by considering the statistic S as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{1}$$

where x are data value at time i and j ($j > i$), n is the length of the time series and

$$\operatorname{sgn}(x_j - x_k) = \begin{vmatrix} +1 \ (x_j - x_k) > 0 \\ 0 \ \ (x_j - x_k) = 0 \\ -1 \ (x_j - x_k) < 0 \end{vmatrix} \tag{2}$$

The Mann–Kendall test has two parameters. One is the significance level that indicates the test strength and the other is the slope magnitude estimate that indicates the direction as well as the magnitude of the trend. Under the null hypothesis, x_i are independent and randomly ordered, the statistic S is approximately normally distributed when $n \geq 8$ with zero mean and variance as $\mathrm{Var}(S) = n(n-1)(2n+5)/18$. The standardized statistical test (Z) was computed by:

$$Z = \begin{vmatrix} \frac{s-1}{\sqrt{\mathrm{Var}(s)}} & S > 0 \\ 0 & S = 0 \\ \frac{s+1}{\sqrt{\mathrm{Var}(s)}} & S < 0 \end{vmatrix} \quad (3)$$

At the given significance level α, if $|Z| \geq Z_{1-\alpha/2}$, the H_0 is rejected, that means the time-series has a trend in the MK test at significance level α. Furthermore, if $Z > 0$, the time-series has an upward trend, and if $Z < 0$, it has a downward trend. When $|Z|$ is greater than 1.28, 1.64 or 2.32, it indicates that the trend of time-series respectively passes the significant test at 90 %, 95 % or 99 % reliability.

2.4 Universal kriging

To explore spatial feature of five ESE indices over northern Xinjiang, the linear tendency rates of each ESE index for 18 meteorological stations were firstly obtained by the simple linear regression analysis, and then they were spatially interpolated with universal kriging.

Kriging spatial interpolation methods are superior to the classical statistical ones, especially when the meteorological stations are relatively rare. They are the main contents of the geostatistical. They take into account the dependence of meteorological elements in space to have an unbiased optimal estimation for limited region variables. Compared to the classical statistical interpolated methods, they consider not only the instance but also the spatial orientation relationships between known sample points and unknown ones by observing the variogram and structural feature of the space random field. They can test the accuracy of the interpolation by the way of cross-validation. There are four indicators can assess their interpolation accuracy, Mean Standardized,

Root-Mean-Square, Average Mean Error and Root-Mean-Square. The semivariogram model meets the following criteria is the best: Mean Standardized is closest to 0, Root-Mean-Square is smallest, Average Mean Error is closest to Root-Mean-Square, and Root-Mean-Square Standardized is closest to 1.

Furthermore, universal kriging, a sub-method of kriging, is applicable to interpolate the regionalized variable which has a dominant spatial trend, while ordinary kriging is applicable to interpolate the space random fields that are second order stationary, meaning that the expectation of the regionalized variable are the same everywhere in the studied region. We explored the linear trends of the ESE indices for selected meteorological stations, and discovered that they had dominant spatial trends. Thus, universal kriging is better than ordinary kriging here.

Universal kriging decomposes the space random variable

$$Z(x) = m(x) + R(x) \quad (4)$$

where $m(x)$ is the drift and $R(x)$ is the surplus. $R(x)$ is a smooth regionalized variable whose mathematical expectation does not change in the study region, while $m(x)$ is contrary to it.

Kriging interpolation steps can be simply described as follows (Tang, 1986). Firstly, verify whether the linear trends of ESE indices follow the normality, if not, transform them with math functions. Secondly, observe how the ESE indices' linear trends vary in space and decide the degree of polynomial used to fit the dominant variation characteristic in space. For example, if the linear trends of SX1day linearly increase from east to west, we can use first order polynomial to fit the dominant variation characteristic, and if they increase from east to west in a quadratic curve, we can use second order polynomial. Thirdly, remove the dominant spatial trend observed in the first step and then interpolate the sample residuals into continuous space dataset with ordinary kriging. Finally, have the dominant spatial trends observed in the second step and the ordinary kringing interpolation for the residual in the third step at summed up at the corresponding place. Their sum is the final universal kriging result.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

3 Results

3.1 Temporal trends and spatial features of the ESE indices

3.1.1 Maximum 1 day snowfall amounts (SX1day)

Upward trends were observed at 17 out of 18 stations, while only one station exhibited a downward trend (Table 4). The highest upward trend occurred at Urumqi station, and the downward trend occurred at Altay station (Table 6). MK significance test for the trends in the time series of the SX1day showed that 10 out of 18 stations had significant upward trends (at $p < 0.05$), accounting for 55.6 % of the total stations (Table 5).

The linear tendencies of SX1day for 18 stations in northern Xinjiang were analyzed using the linear regression method. It could be found from Table 6 that most stations were characterized by positive tendency except for Altay station. SX1day for Beitashan, Jinghe, Shihezi, Tacheng and Yining significantly increased with the rates of 0.42 mm decade^{-1}, 0.45 mm decade^{-1}, 0.82 mm decade^{-1}, 0.89 mm decade^{-1} and 1.14 mm decade^{-1} at the 0.05 significance levels respectively, and those of Caijiahu, Urumqi and Wenquan significantly increased with the rates of 0.54 mm decade^{-1}, 1.37 mm decade^{-1} and 1.36 mm decade^{-1} at the 0.01 significance level respectively. The SX1day's linear tendencies of the 18 selected stations varied from −0.35 to 1.37 mm decade^{-1} with the regional average of northern Xinjiang 0.49 mm decade^{-1}.

The upward trends in the SX1day could be observed from Fig. 2a. The SX1day was significantly increasing over northern Xinjiang in the long-term view (MK $p < 0.05$). From Fig. 2a, it could be seen that from 1960s to around 1982/1983, all trend values of the SX1day were below the average, and then shifted to above the average in the subsequent period. From the five-year moving average line of the SX1day in Fig. 2a, three peaks and three valleys within the whole increasing trends of the SX1day could be found. Three peaks were around in 1972/1973, 1979/1980 and 1989/1990, and three valleys were around in 1970/1971, 1976/1977 and 1984/1985.

Though the SX1day average of considered winters for entire nothern Xinjiang showed in Fig. 2a was only 6 mm, the variabilities among the 18 selected stations are much greater. The minimum and maximum values of the SX1day in the studied winters for selected stations were displayed in Table 1. These two values varied remarkably among the 18 selected stations. The minimum values were from 0.2 to 3.5 mm, and the maximum values from 7.2 to 33.1 mm.

Figure 3 showed the rough trend of spatial distribution for the linear tendency rates of ESE indices, the white lines in the pictures are the 0 contours. It could be found from Fig. 3a that the most areas of northern Xinjiang were characterized by positive tendency in the SX1day except for the northeast of northern Xinjiang around Altay region. And generally, southern and western parts of northern Xinjiang experienced a larger increasing rate of the SX1day than its northern and eastern parts. Southwest of northern Xinjiang was dominated by the highest positive tendencies.

3.1.2 Maxium 1-weather process snowfall amounts (SX1process)

17 out of 18 stations were found in upward trends, while only one station in a downward trend (Table 4). Urumqi was identified as the station whose upward trend was the highest, while Altay station was observed having the highest downward trend (Table 6). The result of MK significance test for the trends in the time series of the SX1process showed that 11 out of 18 stations had significant upward trends (at $p < 0.05$), accounting for 61.1 % of the total stations (Table 5).

Table 6 showed that most stations had positive tendency in SX1process except for Altay and Qinghe. SX1process for Jinghe and Wusu significantly increased 0.85 mm and 2.14 mm every decade at the 0.05 significance level respectively, and those for Caijiahu, Qitai, Shihezi, Urumqi and Wenquan significantly increased with the rates of 1.03 mm decade^{-1}, 0.88 mm decade^{-1}, 1.80 mm decade^{-1}, 2.55 mm decade^{-1} and 1.72 mm decade^{-1} at the 0.01 significance level respectively. The linear tendencies of SX1process for the 18 selected stations varied from −0.54 to 2.55 mm decade^{-1}, with the regional average of northern Xinjiang 0.89 mm decade^{-1}.

Figure 2b showed the temporal variation of SX1process over northern Xinjiang during winters of 1959/1960–2008/2009. The SX1process was significantly increasing over northern Xinjiang in view of the long-term period (MK $p < 0.05$). The changing characteristics of the SX1process's linear tendency rates could be found similar as that of SX1day.

Figure 2b also showed the average value of SX1process for entire nothern Xinjiang in the studied winters. It was just 10 mm, however, the differences among the stations were greater. Table 1 displayed The minimum and maximum values of the SX1process in the studied winters for selected stations. The two values remarkably varied among the 18 selected stations, the minimum values were from 0.3 to 5.6 mm, and the maximum values from 10.3 to 79.5 mm.

Figure 3b represented the spatial pattern of the SX1process's linear tendency rates over northern Xinjiang during winters of 1959/1960–2008/2009. The distribution pattern of the SX1process's linear tendency rates was found similar to that of SX1day's. The discrepancy between them was that, in the northeast of northern Xinjiang, the downward trend of SX1process dominated a larger area than that of SX1day. The highest positive linear tendency rates occurred in the south of northern Xinjiang.

3.1.3 Blizzard days (DSb)

Except five stations, the DSb of the other 13 stations were increasing (Table 4). Urumqi station had the highest upward trend, while Altay had the highest downward trend, their changing rates were 0.18 days decade^{-1} and −0.09 days decade^{-1}, respectively (Table 6). MK significance test for the DSb's trends showed that 2 out of 18 stations had significant upward trends (at $p < 0.05$), accounting for 11.1 % of the total stations (Table 5).

For the linear tendencies of DSb, most stations were in positive tendency except for Altay, Habahe, Karamay, Qinghe and Tory. DSb for Tacheng and Wenquan significantly increased with the rates of 0.16 days decade^{-1} and 0.08 days decade^{-1} at the 0.05 significance level respectively, and the Urumqi's markedly increased 0.18 days decade^{-1}

at the 0.01 level. The linear tendencies of DSb for the 18 selected stations varied between −0.09 to 0.18 days decade^{-1}, with the regional average of northern Xinjiang 0.02 days decade^{-1} (Table 6).

Temporal variation of the DSb for northern Xinjiang was showed in Fig. 2c. The DSb was dramatically increasing over northern Xinjiang in the long-term view (MK $p < 0.01$). A distribution feature which was similar with that of the SX1day and SX1process could be identified from comparison of Fig. 2c with Fig. 2a and b. The values of DSb were all below the average from 1960s to around 1982/1983 and then shifted to above the average in the subsequent period. For the inter-annual variations, three peaks and three troughs could be obviously found from the five-year moving average line in Fig. 2c. Three peaks were around in 1967/1968, 1979/1980 and 1988/1989, and three valleys were around in 1975/1976, 1984/1985 and 1992/1993. From the mid-1990s onwards, the linear trends of the DSb rapidly increased.

The variabilities among the stations were much bigger, although the DSb average of studied winters for entire nothern Xinjiang showed in Fig. 2c was only 0.13 days. The minimum and maximum values of DSbs remarkably varied among the 18 selected stations, the minimum values all were 0 days, and the maximum values were between 0 and 6 days (Table 1).

The spatial distribution of linear tendency rates of the DSb was illustrated in Fig. 3c. Generally, in more than a half area of northern Xinjiang, DSb experienced a positive trend except for the northeast region of northern Xinjiang, and the linear tendency rates became larger from the northeast to southwest. The highest rate was in the southwest of northern Xinjiang.

3.1.4 Consecutive snow days (DSc)

Rising trends were discovered at 17 out of 18 stations, only one station exhibited a declining trend (Table 4). Wusu station had the highest rising trend which was 0.28 days decade^{-1} (Table 6). MK significance test for the DSc's trends showed that

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

7 out of 18 stations had obviously upward trends (at $p < 0.05$), accounting for 38.9 % of the total stations (Table 5).

Table 6 indicated that most stations except for Qinghe and Tory were characterized by positive trends in the DSc. DSc of Habahe, Hoboksar, Qitai and Urumqi markedly increased with the rates of 0.24 days decade^{-1}, 0.15 days decade^{-1}, 0.16 days decade^{-1} and 0.18 days decade^{-1} at the 0.05 significance level respectively, and Caijiahu, Karamay and Shihezi with the rates of 0.26 days decade^{-1}, 0.20 days decade^{-1} and 0.22 days decade^{-1} at the 0.01 significance level respectively. The DSc's linear tendencies of the 18 selected stations varied between −0.02 and 0.28 days decade^{-1}, and the regional average of northern Xinjiang 0.14 days decade^{-1}.

Figure 2d showed the long-term variation in the DSc over northern Xinjiang. The DSc was significantly increasing over northern Xinjiang from the long-term view (MK $p < 0.05$). Temporal distribution feature of the DSc was found to be similar with that of the SX1day, SX1process and DSb. The values of the DSc were all below the average from 1960s to around 1982/1983 and then shifted to above the average in the later period. The linear tendency rates were rapidly increasing with only a lower value in around 1984.

The average of DSc in studied winters for entire nothern Xinjiang showed in Fig. 2d was only 2 days, however, the variabilities among the 18 selected stations were much greater. From Table 1, we saw that the the minimum and maximum values of DSc remarkably varied among the 18 selected stations, the minimum values were from 0 to 1 days, and the maximum values were between 2 and 10 days.

The spatial distribution of the DSc's linear tendency rates over northern Xinjiang was depicted in Fig. 3d. From the figure we could see that the most areas of northern Xinjiang were characterized by positive tendency in the DSc except for two small areas in the east and northwest of northern Xinjiang. Generally, the central part of northern Xinjiang experienced a larger increasing rate of the DSc than its west and east sides, and the linear tendency rates were greatly increasing from north to south of northern

Xinjiang. The south of northern Xinjiang was dominated by the highest positive tendencies.

3.1.5 Blizzard weather processes (PSb)

14 out of 18 stations had upward trends for the PSb, while four had downward trends (Table 4). The highest upward trend occurred at Yining station, and its PSb increased 0.28 times decade^{-1}. MK significance test for the PSb's trends showed that 4 out of 18 stations had significant upward trends (at $p < 0.05$), accounting for 22.2 % of the total stations (Table 5).

Except for Altay, Hoboksar, Qinghe and Tory, most stations were characterized by positive trends in the PSb (Table 6). PSbs for stations such as Caijiahu, Jinghe, Urumqi, Wenquan and Yining were significantly increasing with the rates of 0.11 times decade^{-1}, 0.09 times decade^{-1}, 0.22 times decade^{-1}, 0.16 times decade^{-1} and 0.28 times decade^{-1} at the 0.05 significance level respectively. The PSb's linear tendencies of the 18 selected stations varied from −0.08 to 0.28 times decade^{-1}, with the regional average of northern Xinjiang 0.07 times decade^{-1}.

Increasing trend for the PSb over northern Xinjiang was illustrated in Fig. 2e. The PSb was significantly increasing over northern Xinjiang from a long-term view (MK $p < 0.05$). The temporal distribution feature of the PSb was similar with that of the SX1day, SX1process, DSb and DSc. The values of PSb were all below the average from 1960s to around 1982/1983 and then shifted to above the average during the subsequent period. The PSb increased from 1960s to 1980/1981, with the lowest around 1984/1985, and from then, it rapidly increased.

The variabilities among the 18 selected stations were much greater, though the PSb average of studied winters for entire nothern Xinjiang showed in Fig. 2e was only 0.4 times. The minimum and maximum values of the PSb for selected stations were showed in Table 1. The two values remarkably varied among the 18 selected stations. The minimum values all were 0 times, and the maximum values were from 1 to 5 times.

The spatial distribution of the PSb's linear tendency rates over northern Xinjiang was illustrated in Fig. 3e. Positive trends in the PSb dominated the most area of northern Xinjiang except for a long strip in the north-south direction in the north of northern Xinjiang. Generally, the linear tendency rate was greatly increasing from the north to south and from the east to west, and the highest positive trends were in the southwest of northern Xinjiang.

3.2 Classification of the variation of the ESE indices

The SX1day and SX1process were the alternative indicators that described the intensity of ESEs, while the DSb, DSc and PSb were the alternative indicators depicting the frequency of ESEs. Based on the spatial patterns of the trends of the five ESE indices' linear tendency rates, we identified the hot-spots where all the five ESE indices increased or the intensity and frequency of ESEs were all increasing, and identified the cold-spots where all the five ESE indices decreased or the intensity and frequency of ESEs were all decreasing. The results were showed in the Fig. 4a and b, respectively. From Fig. 4a it could be found that more than half of northern Xinjiang, the west and south of northern Xinjiang, was dominated by the upward trends of ESEs' intensity and frequency, hence, this area was identified as the hot-spots. The Fig. 4b showed that only a small area in the east of northern was dominated by the downward trend of ESEs' intensity and frequency, this area was identified as the cold-spots.

4 Discussions

In our previous work (Jiang et al., 2013), the trends of extreme precipitation in Xinjiang were analyzed, however, it just based on the annual scale and ignored the fact that extreme precipitation events seasonly change. In the winter of Xinjiang, snowfall is the main precipitation form, and in the winter of northern Xinjiang, a subregion of Xinjiang, snowfall is the only form of precipitation because it is very cold and the snowfall can't

melt until next spring, and this situation often causes snow disasters. What mentioned above urges us to analyze temporal and spatial variability of the ESEs in northern Xinjiang and we did it in this study.

This study revealed that positive trends were dominated in the five ESE indices that represented extreme heavy snowfall over northern Xinjiang. Increasing trends in the five indices indicated that extreme snowfall became heavier and stronger in this region. A similar result had been gained by Zhao et al. (2010). In their study, consistently increasing trends in extreme snowfall had been detected, although different definition of extreme snowfall was used in the study. In addition, Sun et al. (2010) also found that the frequency of heavy showfall ($\geq 5\,\text{mm}\,\text{day}^{-1}$) in northern Xinjiang was significantly increasing.

For decadal variation, all ESE indices showed a shift starting from the middle of 1980s. In addition to decadal fluctuations, three peaks and three valleys of the ESE indices over northern Xinjiang could be found. Variations became more violent since the middle of 1980s and even much greater in 1990s. This is consistent with the results of Zhao et al. (2010).

The trends in extreme precipitation were in good agreement with the variation of precipitation (Yang et al., 2008; Yang, 2003; Zhang et al., 2011). Previous studies revealed a wetting tendency in northern Xinjiang during the most recent winters (e.g., Xin et al., 2009; Zhang et al., 2010). Min and Qian (2008) found that the precipitaion of four seasons in China had the trendency that tended to extreme precipitation, especially in winter. Trenberth (1998) revealed that the rising temperature leaded to a stronger water vapor circulation, and in order to keep balance with the evaporation, the precipitation would also increase. So, as the winter precipitation increases, the possibilities of extreme strong snowfall would correspondingly increase.

Generally, only a small area in the northeast of northern Xinjiang was dominated by the decreasing trends of the ESE indices. The upward trends of ESE indices, SX1day, SX1process, DSb and PSb, became obvious from the north to south and from the northeast to southwest in northern Xinjiang, while the upward trends of the DSc was greater in middle than both the west and east sides. This is consistent with the researches on extreme precipitation in winter revealed by Zhao et al. (2010) and Wang et al. (2012). The terrain and airflow may be the main causes to this spatial pattern of the ESE indices. Owing to the barrier and uplift effects of Altai and Tianshan Mountains on the Atlantic and Arctic airflow flowing, more precipitation/snowfall appeared in the windward while less in the leeward. The northern slope of the Tainshan Mountains in the windward received more snowfall than the southern slope of the Altai Mountains in the leeward. As a result, ESE intensity and frequency over Altai region were low, and even in a relatively decreasing trend.

Xinjiang is a typical arid region in China, though in the globe warmin context, the increase in winter extreme snowfall could help alleviate the severity and losses generated by drought disasters, while the harmful aspects of extreme snowfall, e.g., traffic disruption and loss of life and property, however, should also not be neglected.

5 Conclusions

Extreme snowfall events can lead to serious impacts on our environment and society. This paper analyzed the frequency and intensity's trends of the ESE characterized by five indices in northern Xinjiang, an arid land locating in northwestern China. The spatial patterns of the trends of the five ESE indices were also studied. The following important conclusions were obtained.

1. Increasing trends of the max 1 day snowfall amounts (SX1day), max 1-process snowfall amounts (SX1process), blizzard days (DSb), consecutive snow days (DSc) and blizzard weather processes (PSb) were identified at above 72 % of the total meteorological stations selected in this study. And the trends were all significantly increasing ($p < 0.05$) over the entire northern Xinjiang region. These tendencies indicated that extreme snowfall events in northern Xinjiang became heavier and more frequent.

2. Positive tendencies in the five ESE indices dominated the most area of northern Xinjiang except for a small area in the north of northern Xinjiang. Generally, the linear tendency rates of the five ESE indices in northern Xinjiang were greatly increasing from the north to south and from the east to west. And the higher positive tendencies occurred in the south and west of northern Xinjiang (Ili River valley).

3. More than half of northern Xinjiang, the west and south of northern Xinjiang, was dominated by the upward trends of ESEs' intensity and frequency, hence, this area was identified as the hot-spots. The frequency and intensity of the five ESE indices were all significantly increasing ($p < 0.05$) in Urumqi station. Only a small area in the east of northern Xinjiang is dominated by the downward trend of ESEs' intensity and frequency.

4. Most of ESE indices showed a shift starting from the middle of 1980s. In addition to the decadal fluctuations, the variation with three peaks and three valleys for the ESE indices of northern Xinjiang were identified. The variation became dramatic since the middle of 1980s and greater in 1990s.

Acknowledgements. The present research was financial supported by the National Key Basic Research Development Program (973 Program) of China (No. 2010cb951001) and the National Natural Science Foundation of China (No. 41171378). The authors are grateful to Earth System Science Data Sharing Platform, Xinjiang and Central Asian scientific data sharing platform, for China and Xinjiang boundary data.

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Table 1. Detailed information of 18 meteorological stations selected for this study and the minimum and maximum values of ESE indices.

No.	Station	Lat	Lon	Ele	SX1day (mm)		SX1process (mm)		DSb (days)		DSc (days)		PSb (times)	
		(° N)	(° E)	(m)	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
1	Alashankou	45.18	82.57	336.1	0.2	33.1	0.3	55.4	0	1	0	4	0	1
2	Altay	47.73	88.08	735.3	2.9	15.1	3.1	37.9	0	3	1	6	0	3
3	Beitashan	45.37	90.53	1653.7	1.2	8.7	1.3	13.5	0	0	1	2	0	1
4	Caijiahu	44.20	87.53	440.5	0.4	9.6	0.9	14.5	0	0	0	3	0	2
5	Fuhai	47.12	87.47	500.9	0.5	7.2	1.1	10.3	0	0	0	2	0	1
6	Habahe	48.05	86.40	532.6	1.6	13.0	1.8	35.1	0	1	1	5	0	2
7	Hoboksar	46.78	85.72	1291.6	0.3	7.8	0.5	12.3	0	0	0	4	0	1
8	Jinghe	44.62	82.90	320.1	0.6	9.3	0.8	13.0	0	0	0	4	0	1
9	Karamay	45.62	84.85	449.5	0.3	10.0	0.6	15.5	0	1	0	3	0	1
10	Qinghe	46.67	90.38	1218.2	1.6	15.3	2.0	22.6	0	1	1	5	0	2
11	Qitai	44.02	89.57	793.5	0.6	12.1	0.7	12.1	0	1	0	3	0	2
12	Shihezi	44.32	86.05	442.9	0.3	19.6	0.4	38.0	0	1	0	3	0	2
13	Tacheng	46.73	83.00	534.9	2.5	25.3	4.3	45.0	0	3	1	5	0	5
14	Tory	45.93	83.60	1077.8	1.2	10.7	2.1	19.7	0	1	1	4	0	2
15	Urumqi	43.78	87.65	935.0	0.3	17.6	0.9	29.9	0	2	0	5	0	3
16	Wenquan	44.97	81.02	1357.8	0.6	15.7	0.9	21.3	0	1	0	3	0	2
17	Wusu	44.43	84.67	478.7	0.7	11.7	2.8	44.0	0	1	0	10	0	1
18	Yining	43.95	81.33	662.5	3.5	26.3	5.6	79.5	0	6	1	6	0	5

Table 2. Snowfall grading standard for China and Xinjiang.

Snowfall grade	Criteria for the classification			
	12 h snowfall (mm)		24 h snowfall (mm)	
	China	Xinjiang	China	Xinjiang
Light snowfall	0.1 ~ 0.9	0.2–2.5	0.1 ~ 2.4	0.3–3.0
Moderate snowfall	1.0 ~ 2.9	2.6–5.0	2.5 ~ 4.9	3.1–6.0
Heavy snowfall	3.0 ~ 5.9	5.1–10.0	5.0 ~ 9.9	6.1–12.0
Blizzard	≥ 6.0	≥ 10.1	≥ 10	≥ 12.1

Table 3. Indices of extreme snowfall events.

ID	Indicator name	Definitions	Units
SX1day	Max 1 day snowfall amounts	Maximum of the daily snowfall in winter	mm
SX1process	Max 1-process snowfall amounts	Maximum of the cumulative snowfall in a weather process in winter	mm
DSb	Blizzard days	Number of the blizzard days in a winter	days
DSc	Consecutive snow days	Number of consecutive snow days when daily snowfall ≥ 10 mm in winter	days
PSb	Blizzard weather processes	Times of weather processes whose cumulative snowfall exceeds 10 mm in winter	times

Table 4. Numbers and percentages of stations with upward and downward trends.

ID	Upward		Downward	
	Number of stations	Percentage	Number of stations	Percentage
SX1day	17	94.4	1	5.6
SX1process	17	94.4	1	5.6
DSb	13	72.2	5	27.8
DSc	17	94.4	1	5.6
PSb	14	77.8	4	22.2

Table 5. Results of MK significance test at the 0.05 significance level.

ID	Upward		Downward		No trend	
	Number of stations	Percentage	Number of stations	Percentage	Number of stations	Percentage
SX1day	10	55.6	0	0.0	8	44.4
SX1process	11	61.1	0	0.0	7	38.9
DSb	2	11.1	0	0.0	16	88.9
DSc	7	38.9	0	0.0	11	61.1
PSb	4	22.2	0	0.0	14	77.8

Table 6. Linear tendency rates of 5 extreme indices for each station and entire northern Xinjiang. Bold and italics characters represent the linear trends are significant at the 0.05 level and the 0.01 level respectively.

No.	Stations and region	Linear tendency rates				
		SX1day (mm (10 a)$^{-1}$)	SX1process (mm (10 a)$^{-1}$)	DSb (day (10 a)$^{-1}$)	DSc (day (10 a)$^{-1}$)	PSb (times (10 a)$^{-1}$)
1	Alashankou	0.76	1.12	0.03	0.16	0.04
2	Altay	−0.35	−0.54	−0.09	0.16	−0.08
3	Beitashan	**0.42**	0.38	0	0.01	0.01
4	Caijiahu	*0.54*	*1.03*	0	*0.26*	**0.11**
5	Fuhai	0.13	0.37	0	0.11	0.04
6	Habahe	0.05	0.67	−0.03	**0.24**	0.06
7	Hoboksar	0.25	0.42	0	**0.15**	−0.01
8	Jinghe	**0.45**	**0.85**	0	0.13	**0.09**
9	Karamay	0.19	0.49	−0.003	*0.20*	0.02
10	Qinghe	0.09	−0.07	−0.06	−0.01	−0.04
11	Qitai	0.42	*0.88*	0	**0.16**	0.08
12	Shihezi	**0.82**	*1.80*	0.03	*0.22*	0.11
13	Tacheng	**0.89**	1.22	**0.16**	0.03	0.14
14	Tory	0.14	0.44	−0.02	−0.02	−0.03
15	Urumqi	*1.37*	*2.55*	*0.18*	**0.18**	**0.22**
16	Wenquan	*1.36*	*1.72*	**0.08**	0.12	**0.16**
17	Wusu	0.40	**2.14**	0.02	0.28	0.04
18	Yining	**1.14**	0.50	0.12	0.14	**0.28**
19	Northern Xinjiang	*0.49*	*0.89*	*0.02*	*0.14*	*0.07*

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

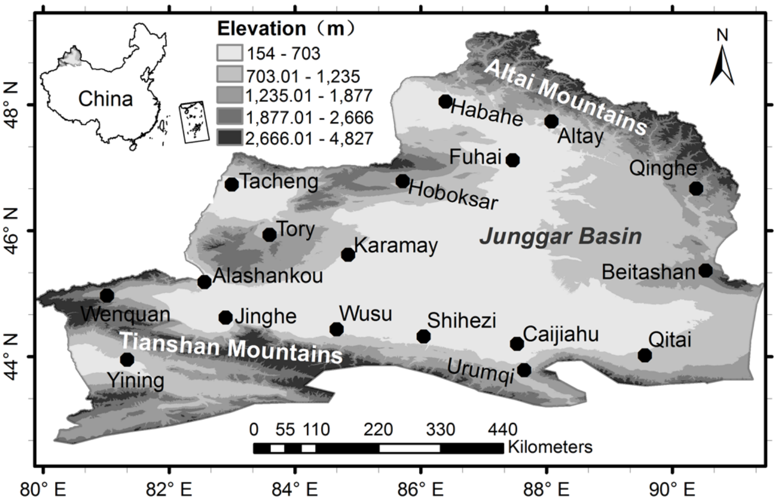

Fig. 1. Location of 18 meteorological stations in northern Xinjiang, and the inset shows the location of northern Xinjiang in China.

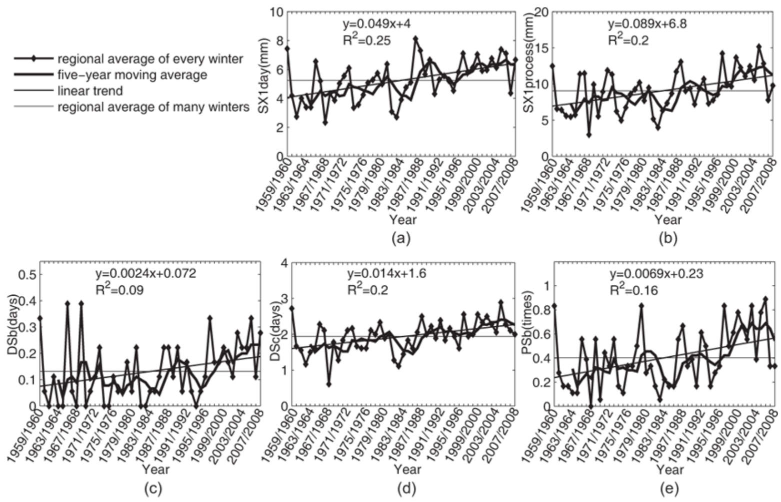

Fig. 2. Temporal trends in ESE indices, SX1day **(a)**, SX1process **(b)**, DSb **(c)**, DSc **(d)** and PSb **(e)** in northern Xinjiang.

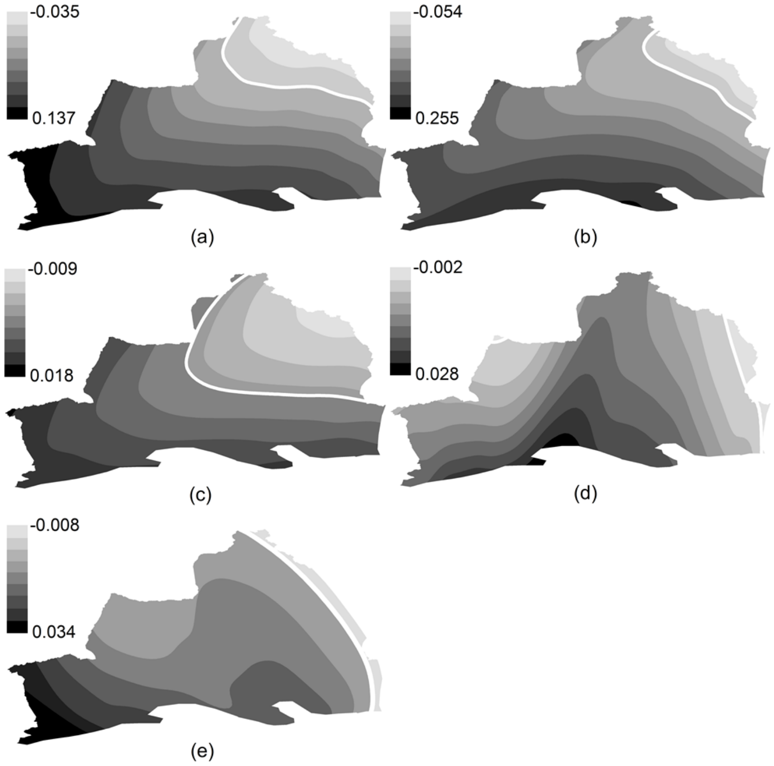

Fig. 3. Spatial patterns of trends in ESE indices, SX1day **(a)**, SX1process **(b)**, DSb **(c)**, DSc **(d)** and PSb **(e)**. The white lines in the pictures are the 0 contours.

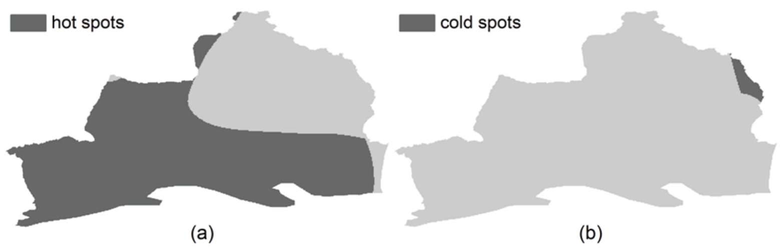

Fig. 4. The hot-spots **(a)** and the cold-spots **(b)** of ESE variation.