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Defining Indices for the Extreme Snowfall Events and Analyzing their Trends in Northern Xinjiang, China

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Abstract

Northern Xinjiang (NX), China, located at middle latitude of Northern Hemisphere, has abundant snowfall and a long period of snow cover. To assess the impacts of climate change in this region and to provide scientific knowledge for the resources and contingency plans, analysis of the spatial and temporal variations in extreme snowfall events (ESEs) in NX was carried out based on five defined ESE indices in this study, i.e. days of heavy snowfall, maximum 1-day snowfall amounts, maximum 1-event snowfall amounts, maximum consecutive snowfall days, and frequency of heavy snowfall events. To reconstruct the snowfall dataset, the relationship between air temperature and snowfall events were compared, and it was found that daily minimum air temperature below 0 °C is the best indicator to select snowfall days. ESEs in NX were taking an increasing proportion in snow events, though snowfall days were decreasing. Consistent increasing trends in all ESE indices were found for the whole NX, while different changes in these ESE indices were found for subregions. With high increasing trends in these ESE indices in most of subregions, Daxigou-Xiaoquzi area and Qitai area were the hot spots for ESEs. Since these hotspots are likely to be influenced by airflow from the Arctic Ocean, the changes in Arctic Ocean and associated atmospheric circulation as a consequence of climate change might be the main reason for the detected increasing trends of the ESEs in NX.

Keywords: Northern Xinjiang, China; extreme snowfall events; defined indices;
1. Introduction

Precipitation during cold weather occurs in the form of snow over the middle to high latitude areas of the world (Marty and Blanchet 2012). Although large accumulation of snow is an important source of water, especially for arid region, and can have substantial positive impacts like reservoirs recharging, snow-induced floods can pose a significant threat (Kunkel et al., 2016). Moreover, isolated extreme snowfall events or large seasonal accumulations can create transportation disruptions with associated impacts on economic and social activities (Kunkel et al., 2016). For example, the super storm in the United States during March 1993 affected 20 states and consequently caused $1.8 billion in economic loss and 270 deaths, and it was ranked as the US’s worst winter storm over the past 100 years (Changnon and Changnon, 2006), implied undesirable impacts of extreme snow hazards on human society. Considering these aspects, thorough understanding of changes of these unusual snowfall events (extreme snowfall events, ESEs) is critically necessary for availability of water resources and human mitigation to snow-related natural hazards (Changnon and Changnon 2006, Sun et al., 2010).

Numerous studies have reported changes in ESEs in different regions of the world. Lower frequency but higher intensity of snow storms were reported in the USA during the twentieth century (Changnon and Changnon, 2006, Changnon,
2007, 2008, Kunkel et al., 2009). Decreasing trends in maximum snow depth and maximum snow water equivalent were found in Japan (Tachibana, 1995, Ishizaka, 2004, Yamaguchi et al., 2011, Kawase et al., 2012). Increasing trends in the frequency of blizzard and heavy snowfall were found in the United Kingdom (Wild et al., 1996, Wild 1996). Slightly increasing trends in the frequency of ESEs were reported in the Swiss Alps over the period 1933–1999, despite at mid-to-low elevation areas there was a marked decrease in snow depth and duration due to warmer temperature (Laternser and Schneebeili, 2003). Increasing trend in the extreme winter precipitation (regarded as snowfall) in north of the Swiss Alps was reported by 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 of Germany. In Austria, the frequencies and maximum intensities of heavy snow events were slightly higher in the period from 1970/71 to 1988/89 than the period from 1938/39 to 1994/95 (Spreitzhofer, 1999).

In Switzerland, decreasing trends in extreme snow was found due to the decrease in the snowfall days relative to precipitation days (Schmidli and Frei, 2005, Marty, 2008, Serquet et al., 2011, Marty and Blanchet, 2012). In the Antarctic region, significant increase in the winter-season precipitation (regarded as snowfall) was reported (Turner et al., 1997, Kirchgaessner, 2011). Generally, increasing trends in ESEs were found in most of the middle to high latitude regions of the world. Because different indicators for ESEs were used in different
studies, the results are difficult to be compared.

Northern Xinjiang (NX), China (Figure 1), is located at the middle latitude of Northern Hemisphere between Altai Mountains and Tianshan Mountains. Ili River Valley, which is situated in the western part of mountain area in NX, is dominated by the warm and wet airflows from the Atlantic Ocean, and rest of the NX area is dominated by the cold and wet airflows from the Arctic Ocean (Yang et al., 2007, Hao et al., 2011). Precipitation occurs due to the uplifting effect of mountains. With long and cold winters, snowfall is the main weather phenomena in this region. Due to abundant snowfall and a long period of snow cover, this region is well-known for plentiful snow resources and frequent snow disasters (avalanche, blowing snow, white disaster, etc.) (Liu et al. 2012, Sun et al., 2010). Therefore, to assess the impacts of climate change on this region and to provide scientific knowledge for the resources and contingency plans, it is important to study the long-term variations in extreme snowfall events (ESEs).

Nevertheless, most of the previous studies in NX only focused on isolated single snow storm event (e.g., Ding et al., 2010, Li et al., 2011, Chen and Cui 2012), statistical behaviors of various ESEs were rarely revealed (Dong et al., 2010, Ding et al., 2011, Wang et al., 2011). Zhang et al. (2014) studied statistical characteristics of the intensity and frequency of heavy snow in Altay area of NX, but their study was simply based on daily precipitation from November to next March, the impact of climate change on snowfall days wasn't considered. Sun et
al. (2010) identified snowfall days in the context of climate change by considering
the precipitation days in which daily air and ground temperature were both below
0 °C as snowfall days. They analysed only the frequency of heavy snowfall days
with daily precipitation more than 5 mm. Literature has revealed that
characteristics of consecutive snowfall events, which were main cause of the
snow-related natural hazards in NX (Zhao et al., 2011), haven't been studied yet.

As mentioned above, the main objectives of this study were: (1) to define
ESE indices which can describe the frequencies and intensities of heavy snowfall
days, as well as those of consecutive snowfall events and; (2) to analyse the
temporal and spatial features of these ESE indices in NX at the regional and
subregional scales in the context of climate change. This research can give an
example to quantify ESEs. It will be helpful for scientists to find proper ESE
indices to study ESEs in middle and high latitude areas. In turn, by using these
consistent ESE indices, the results from different countries could be combined
seamlessly. This research is helpful to assess potential climate impacts on
regional scales and can also be useful for risk management and hazard
adaptation.

2. Data and methods

The daily observed precipitation and temperature datasets (quality controlled)
for NX region were obtained from the China Meteorological Administration. The
meteorological stations in the study area were relatively sparse due to the natural
and anthropogenic reasons, therefore, the record lengths were diverse. In order to select the stations as many as possible, and the dataset as consistent and complete as possible, 25 stations whose daily datasets covered 1961-2010, with missing data less than 5%, were finally selected. The selected meteorological stations are shown in Figure 1 and Table 1. The missing data was completed using conventional statistical methods including (Zhang et al., 2013): (1) missing data of a single day were filled by taking the average of the same days in all selected years; (2) missing values of consecutive two or more days were filled by developing simple linear correlation with neighboring stations (distance <100 Km). The station with missing data was regarded as dependent station, while its neighboring stations (without missing values) as independent stations. Data of dependent station was named by y, and data of independent station by x. Linear regression equation (y=ax+b) were derived using data of dependent and independent stations over the same period of time. The neighboring station which has the highest correlation for the two time series between x and y was selected, and then the related linear regression equation was applied to estimate the missing values of the dependent station. In order to avoid false trends in the time series of daily air temperature and precipitation caused by the changes of meteorological measurements, the RHtestsV3 and RHtests_dlyPrcp software were used to perform homogeneity test and adjustment for the time series of daily air temperature and precipitation. A detail description pertaining to these software
can be accessed from website: http://etccdi.pacificclimate.org/software.shtml.

The results of homogeneity test showed that the daily temperature and precipitation series of all the stations selected in this study were homogeneous.

In this dataset, the snowy and rainy days were distinguished and reported strictly beside their daily precipitation amount before 1980, while after 1979, only the daily precipitation amount was reported, and whether it was a rainy or snowy day was not reported. So it is easy to pick out the snowfall days and their daily precipitation before 1980. In order to find the snowfall days in the dataset after 1979, the daily mean, maximum and minimum temperature of snowfall days before 1980 were checked. It was found that although daily mean and maximum air temperature were higher than 0 °C in some snowfall events, but nearly all the snowfall events in NX occurred in the days with minimum air temperature not higher than 0 °C. Table 2 shows the annual average snowfall days during the period of 1961-1979 for stations in NX with distinguished snowy and rainy days, and annual average days of average, maximum and minimum temperature less than 0 °C of snowy days. It was found that though annual average days of average, maximum, and minimum temperature less than 0 °C during snowfall days were less than annual average snowfall days reported in 1961-1979, but annual days of minimum temperature less than 0 °C were nearly same as annual snowfall days. It implies that daily minimum air temperature was found as the best indicator to select snowfall days in NX. Thus, the days with snowfall during 1961-2010 were
selected using these two thresholds: (a) daily precipitation > 0 mm/day, and (b) daily minimum air temperature <= 0 °C. To analyze the impact of climate change on minimum temperature, the long-time trends analysis of days of minimum temperature below 0 °C (DMinTB0) at selected stations was carried out on an annual scale by using modified Mann-Kendall (MMK) trend test. The MMK method was well documented by Hamed and Rao (1998) and Huang et al. (2014). It is a nonparametric approach which is the modified version of the initial Mann-Kendall (MK) test. By taking into account the autocorrelation coefficients (autocorrelation coefficients is correlations between lagged values of the time series data) which were significantly different from zero at the 95% confidence level in the time series data, the MMK test overcomes the persistence of the hydro-meteorological series which affects the results of MK test. The positive value of MMK result (Z value) denotes an upward trend and vice versa. If there was a linear trend in the time series of DMinTB0, the true slope (change per unit time) was estimated by Sen’s slope estimator, a simple nonparametric procedure. The formulas were well documented by Sen (1968) and Tabari et al. (2011). In this study, one year was defined as the months from August to the next July. Heavy snowfall and blizzard are often regarded as extreme snowfall events because they can cause disasters due to high intensity. In NX, heavy snowfall (blizzard) events are referred to those with daily snowfall (snow water equivalent) more than 6 mm (12 mm) (Table 3) (Zhao et al., 2011). Because days of blizzard
events of the selected stations in NX were zero for most of the years in the study period, while days of heavy snowfall events were more than zero for most of the years, therefore, daily snowfall events which can cause disasters in NX were considered as the heavy snowfall events. Thus, only heavy snowfall events were considered in this study. Moreover, snow cover more than 30 cm (water equivalent more than 30 mm) can also cause deaths of animals in pasturing areas and traffic disruption in urban areas, so snowfall events with accumulated snowfall amount more than 30 mm were also regarded as extreme snowfall events. The ESE indices (Table 4) defined in this study were mainly based on snowfall days whose daily snowfall (snow water equivalent) was more than 6 mm, or snowfall events with consecutive snowfall days in which cumulative snowfall (snow water equivalent) > 30 mm. These ESE indices listed in Table 4 were calculated for each station on an annual scale.

For entire NX, temporal trends of ESE indices during the period from 1961 to 2009 were primarily revealed by trend rate (Shi 1996). Trend rate $a_t$ was calculated by simple linear regression as below.

$$x_t = a_0 + a_t t$$

$ t = 1, 2, \ldots, n$  \hspace{1cm} (1)

In this study, $x_t$ are the values of ESE indices in the period of 1961-2009, $t$ value is from 1 to 49. The unit of $a_t$ is the unit of ESE indices per decade. Before calculating the trend rate of these ESE indices in the period of 1961-2009 for NX, extremes in the time series were excluded to avoid the effect of extreme
values on the trend rates. For example, if there is one extremely large value in
the time series, the trend rate might be high due to that extreme value. Thence,
in order to reveal long term trend of a time series, few but high-impact extreme
values within the time series were excluded before performing simple regression
analysis. Here the extreme values are the ESE index values which are less or
more than three times of the standard deviation of the whole ESE index time
series.

Then Rotated EOF (REOF) analysis, applied by Richman (1986), Boone et
al. (2012), and Wang et al. (2015), was also carried out to identify the sub-regions
in NX where ESE indices vary coherently. And the corresponding temporal trends
of ESE indices for each subregion were revealed by trend coefficient (Chen 2012).

Trend coefficient $r_{st}$ was calculated as below.

$$r_{st} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(t - \frac{n+1}{2})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (t - \frac{n+1}{2})^2}} \quad (2)$$

$\bar{x}$ is the mean value of $x_i$, $n$ is the sample length. $r_{st}$ is standardized
coefficient of simple linear regression named as climate trend coefficient, and
represents the general trend of $x_i$ changing over time. It varies from -1 to 1 and
removes the effect of mean variance and units of meteorological elements on the
numerical size of regression coefficient. Thus, it can be compared from location
to location and from element to element, and suits to reveal the spatial feature of
long-term trends in large meteorological element fields.
In this study, ‘scree test’ (Cattell, 1966; Wilks, 2006) was used to separate the ‘signal’ from the ‘noise’. In scree plots, firstly, the eigenvalues were arranged in ascending order and then a curve that connects the eigenvalues was plotted. On this curve a turning point can be found. Up to that turning point on the curve, the corresponding EOFs of the eigenvalues exhibited important signals and were retained, while after that point corresponding EOFs of eigenvalues showed noises and were ignored. The VARIMAX (Kaiser, 1958) method was used to rotate these retained EOFs. The spatial patterns and their corresponding time series obtained after conducting the rotated EOF analysis were named as Principle Component (PC) loadings and PC scores, respectively. Bootstrap method (Hellstrom and Malmgren, 2004, Dubreuil et al., 2014) was used to test the significance of PC loadings at the 95% confidence level. The insignificant loadings were regarded as zero. When significant loadings appeared in more than one PCs for one station, the PC with the highest loading were retained. The station with no significant loading in any PC was included in the closest region. Additionally, PC loadings were also interpolated into continuous surfaces in order to identify coherent subregions of those stations.

3. Results

3.1 Spatial and temporal features of DMinTB0 in NX

3.1.1 Spatial patterns of annual averages of DMinTB0 in NX
In order to get the spatial pattern of annual averages of DMinTB0 in NX (Figure 2), the annual averages of DMinTB0 of selected stations were calculated first, then they were interpolated into continuous surface by Inverse Distance Weighting (IDW) method. DMinTB0's annual averages vary from 101.63 to 301.43 days. In the center of NX, in and around Junggar Basin, DMinTB0 were below 168.23 days. In most of the area around Junggar Basin, the values of DMinTB0 were from 168.23 to 190.43 days, only some small spot areas, such as Hoboksar area and Zhaosu area had higher numbers of DMinTB0 from 190.43 to 212.63 days. The largest values of DMinTB0 existed in the middle of Tianshan Mountain, which were from 234.83 to 301.43, and the largest value of 301.43 occurred in Daxigou station. It revealed that in Daxigou station snowfall occurred nearly in the whole year. Generally, high values of DMinTB0 were found at high altitudes and in the middle region of Tianshan Mountains, such as at Daxigou. Low values of DMinTB0 were found at low altitudes, such as at stations around the Junggar Basin.

3.1.2 Temporal trends of DMinTB0 in NX

The results of MMK trend test and Sen's slope of DMinTB0 for selected stations in NX were showed in Figure 3. The white circle represented the Z values between -1.96 and 1.96 which were not significant. The black inverted triangle represented the Z values less than -2.58 which indicated the significant decreasing trend of DMinTB0 at the 99% confidence level. It was found that 9 out
of 25 stations had significant decreasing trend at the 99% confidence level over
the period from 1961 to 2009, while the rest of stations didn't have significant
trend. The results of Sen's slope ranging from -1.18 to -8.15 days per decade
were showed at each station location (Figure 3). It indicates that the values of
DMinTB0 of all stations were decreasing during the period of 1961-2009 with
large slopes. The largest slope was -8.15 days decade $^{-1}$ and was found at
Balikun station, while the smallest slope was -1.18 days decade $^{-1}$ and appeared
at Qitai station. 4 out of 25 stations experienced decreasing trends with slopes
larger than -2 days decade $^{-1}$. 9 out of 25 stations had decreasing trends with
slopes between -2 and -4 days decade $^{-1}$, 9 out of 25 stations showed decreasing
trends with slopes between -4 and -6 days decade $^{-1}$ and 3 out of 25 stations were
with slopes ranging from -6 to -8.15 days decade $^{-1}$.

3.2 Spatial and temporal features of ESE indices in NX

3.2.1 Spatial patterns of annual averages of ESE indices in NX

The spatial patterns of annual averages of DHS, MASD, MASE, MDSE, and
HSE indices were shown in Figure 4. They were obtained by interpolating the
ESE annual averages of stations into continuous surfaces by using Inverse
Distance Weighting (IDW) method. DHS's annual averages vary from 0.04 to
14.59 days, MASD's from 2.79 to 27.33 mm, MASE's from 3.38 to 42.66 mm,
MDSE's from 0.04 to 1.98 days, and HSE's from 0 to 1.78 times. Low values of
DHS, MASD, MASE, and MDSE were found in the Tacheng, Karamay, Jinghe,
Fuyun, Beitashan, Caijiahu, and Dabancheng areas. High values of DHS, MASD, MASE, and MDSE occurred in the Fuhai, Qinghe, Zhaosu, Daxigou, and Qitai areas. Low values of HSE (Unit: times) were found in the Tacheng, Tory, Karamay, Alashankou, Wenquan, Jinghe, Yining, and Balikun, Habahoe, Altay, Fuyun, and Caijiahu, Xiaquzi, Tianchi and Dabancheng areas. High values of HSE were found in Fuhai, Zhaosu station, and Daxigou area. In whole NX, there were very few HSE events generally. From spatial patterns of these annual averages of all these ESE indices, it was generally found that high values occurred at high altitudes, such as Daxigou, Xiaquzi, and Tianchi areas which were in the region of Tianshan Mountains, while low values appeared at low altitudes, such as Karamay, Jinghe, and Tacheng areas.

3.2.2 Temporal trend of ESE indices in NX

Temporal features of regional averages of these ESE indices, DHS, MASD, MASE, MDSE, and HSE, in NX over the period of 1961-2009 were showed in Figure 5. And regional averages of these ESE indices calculated by using direct snowfall measurements before 1980 were also presented in this Figure. It was found that the indices calculated by using direct snowfall measurements are a little smaller than the indices estimated by daily minimum temperature and precipitation, however, their interannual variations are similar. The regional averages of these indices were 2.54 days, 10.20 mm, 14.33 mm, 0.83 days, and 0.13 times, respectively. A peak around 1968/1969 and a valley in 1975 were
found for DHS, MASD, MASE, and MDSE from the five-year-moving averages, and after 1985 all the values of these ESE indices were increasing rapidly. Three peaks and three valleys were found from the five-year moving average of HSE. Three peaks were in 1966, 1981, and 1998, and three valleys were found in 1971, 1990, and 2005/2006. And after 2006, the values of HSE increased rapidly. Comparing the regional average of winters and five-year moving average lines, it was found that all the values of DHS, MASD, MASE, and MDSE were less than its regional average before 1993, and the situation was reversed after the stated year. The values of HSE were fluctuating around the average line and increased gradually. The linear trend formula \(y=ax+b\), and the values of \(R^2\) and \(p\) were presented above the linear trend lines. The values of \(a\) in the formula indicate the rates of linear trends, and their real slopes were unit per year. Increasing trends at the rate of 0.16 days decade \(^{-1}\), 0.61 mm decade \(^{-1}\), 0.83 mm decade \(^{-1}\), 0.038 days decade \(^{-1}\), and 0.0072 times decade \(^{-1}\), were found for DHS, MASD, MASE, MDSE, and HSE, respectively. \(R^2\) is coefficient of determination and it is often used to judge the goodness of fit of a linear trend. Its values vary from -1 to 1. The closer the absolute value of \(R^2\) to 1, the better the fitting degree of regression line to the observed values. The minimum value of \(R^2\) (0.026) was found for HSE, while the maximum (0.24) was found for MASD. The value of \(p\) indicates the significant level of a linear trend. If the value of \(p\) falls within the upper and lower thresholds (0.01 <= \(p\) <= 0.05), this linear trend is significant at the 95%
From the p values of each ESE index’s linear trend, it was found that except for HSE, all the linear trends of the other indices were significant at the 95% confidence level.

Four EOFs must be retained to perform REOF analysis for DHS because four eigenvalues were found up to the turning point on the scree plots of DHS (Figure 6). The scree plots of the other ESE indices weren’t showed here. The explained variance for each retained EOF of these ESE indices and their accumulated variances were listed in Table 5. The explained variance of each EOF for every ESE index indicated that what percentage of the total information of ESE index was represented by that EOF. The larger the value of explained variance is, the more information the corresponding EOF could represent. The accumulated variance is the sum of corresponding explained variances. For example, the accumulated variance at the location of the fourth EOF of DHS was 72.44%. It was the sum of the explained variances for the first (31.53%), second (20.94%), third (12.31%), and fourth (7.66%) EOFs. The larger the values of accumulated variances are, the more information the corresponding retained EOFs could represent. These retained EOFs explained 72.44%, 54.03%, 60.66%, 37.94%, and 89.96% of the variances in DHS, MASD, MASE, MDSE, and HSE, respectively, which indicates that these retained EOFs can represent the main
spatial and temporal variations in these ESE indices. Only three significant EOFs were retained for MDSE, while the other EOFs (considered as noises) were discarded, and because the explained variances of each significant EOFs were relatively smaller than those of the other ESE indices, therefore, the accumulated variances of these retained EOFs of MDSE were smaller than those of the other ESE indices.

After rotating these retained EOFs for every ESE index by VARIMAX method, the subregions for each ESE index were divided according to the PC loadings, and the trend of each ESE index within each subregion was obtained by calculating trend coefficient of the corresponding PC scores. The unit used in this study for trend coefficient was %/10a. The subregions of each ESE index and their corresponding trend coefficients were showed in Figure 7. It indicated that four, four, five, four and six coherent subregions were found for the variations in DHS, MASD, MASE, MDSE, and HSE, respectively. DHS’s subregions were as follows: from Altai Mountain to north part of Junggar Basin (1), from south part of Junggar Basin to the north slope of Tianshan Mountains (2), Zhaosu area (3), Daxigou and Xiaozuzi area (4). All subregions showed increasing trends, highest trend happened in Subregion 2 at the rate of 496.1 %/10a. MASD’s subregions were as follows: Junggar Basin (1), from south part of Junggar Basin to the north slope of western Tianshan Mountains (2), Zhaosu area (3), from Altai Mountain to north part of eastern Tianshan Mountains (4). Subregion 1, 2 and 4 showed
increasing trends, and the highest trend took place in Subregion 2 at the rate of 529.2 %/10a. Subregion 3 was dominated by a decreasing trend at the rate of -11.7 %/10a. The subregions of MASE were as follows: Altai Mountains - Jimunai and Hoboksar area (1), north part of Junggar Basin - north part of eastern Tianshan Mountains (2), Alashankou-Wenquan-Yining-Zhaosu area (3), southern part of Junggar Basin area (4), and Daxigou-Xiaoquzi-Dabancheng-Qitai area in the middle Tianshan Mountains (5). Subregion 1, 3, and 5 were dominated by increasing trends while Subregion 2 and 4 were dominated by decreasing trends. The highest increasing trend was found in Subregion 1 at the rate of 330.5 %/10a, and the highest decreasing trend took place in Subregion 5 at the rate of -168.5 %/10a. The subregions of MDSE were as follows: Altai Mountains-Junggar Basin (1), the west edge and south edge of Junggar Basin (2), west and middle area of the northern slope of Tianshan Mountains (3), east part of NX (4). Subregion 1, 2, and 3 were dominated by increasing trends while Subregion 4 was dominated by a decreasing trend. The highest increasing trend was found in Subregion 2 at the rate of 283.8 %/10a. And the rate of decreasing trend in Subregion 4 was -283.3 %/10a. HSE’s subregions were as follows: from Altai Mountain to north part of Junggar Basin (1), from Junggar Basin to the east part of NX (2), Alashankou-Wenquan-Yining-Zhaosu area (3), Daxigou area (4), Caijiahu-Urumqi-Tianchi-Xiaoquzi-Dabancheng (5), and Qitai area (6). Subregion 2, 4, and 6 showed increasing trend with the highest rate of
344.4 %/10a in Subregion 2, while Subregion 1, 3, and 5 showed decreasing trends with the highest rate of -88.1 %/10a in Subregion 5.

All subregions for DHS showed increasing trends. Except Zhaosu area, all the subregions for MASD were dominated by increasing trends. Subregions in Mountain areas for MASE showed increasing trends and subregions in other areas in NX showed decreasing trends. For MDSE, most subregions in NX were dominated by increasing trends except the east part of NX. Opposite to MASE, the subregions for HSE in Mountain areas showed decreasing trends, while areas in lower elevation showed decreasing trends (Figure 7).

4. Discussions

NX is located in the centre of the Eurasian continent and surrounded by mountains. Climate conditions in this region vary spatially. Large spatial differences in air temperature can directly lead to different beginning and ending dates for snowfall events. In many areas of this region, snowfall often occurs before October and after May, even some stations in mountains can observe snowfall in almost whole year. However, previous studies commonly selected daily precipitation data from December to next February (Zhao et al., 2011) or November to next March (Zhang et al., 2014) to study snowfall events in NX, ignoring the fact that daily air temperature has important effects on precipitation phase. Analysis of snowfall events only in these months might miss snowfall days or regard rainy days as snow ones. Furthermore, due to climate change, the
snowfall duration might also change. In this study, by checking the data from 1961 to 1979 (the phases of daily precipitation were marked in this period), it was found that when daily minimum air temperature was not higher than 0 °C, the precipitation phase was snow. Thus, the daily precipitation (snow water equivalent) with daily minimum temperature not higher than 0 °C (DMinTB0) was regarded as snowfall in our study. Considering climate change, this method is much more accurate to select snowfall days than directly regarding the days in some limited months as snowfall days. Sun et al. (2010) used daily mean air temperature below 0 °C to select snowfall days, the temperature threshold is a little high and some snowfall days might be missed in the study, and moreover, only the days of heavy snowfall (snowfall >= 5 mm/day) were analyzed in their study, which were not enough to characterize features of extreme snowfall events.

In this study, five ESE indices were defined. They were days of heavy snowfall (DHS), maximum 1-day snowfall amounts (MASD), maximum 1-event snowfall amounts (MASE), maximum consecutive snowfall days (MDSE), and heavy snowfall events (HSE). They represented the main ESEs in NX which can cause disasters. Though different heavy snowfall thresholds were used in the study of Sun et al. (2010) (snowfall >= 5 mm/day) and in the present study (snowfall > 6 mm/day), the consistent increasing trend for days of heavy snowfall was found in both studies. The other ESE indices in NX all showed increasing trends as well. However, the results of MMK trend and Sen's slope of DMinTB0
for each station in NX showed decreasing trend. Because DMinTB0 is an
indicator for snowfall days, the results of MMK trend and Sen’s slope of DMinTB0
indicates that the snowfall days were decreasing. Thence, from what mentioned
above, it can be concluded that even the snowfall days in NX were decreasing,
the ESEs were increasing, and the ESEs in NX were taking an increasing
proportion in snowfall events. Therefore, it is urgent to do research on ESEs in
NX in future.

From the spatial distribution of annual average ESE indices, DHS, MASD,
MASE, MDSE, and HSE (Figure 4), it was found that in the mountain areas, such
as Zhaosu, Daxigou, Xiaoquzi, and Tianchi stations, the values of annual average
ESE indices were higher, while in the basin areas, such as Karamay, Jinghe, and
Tacheng stations, the values of annual average ESE indices were lower. It
implies that mountains have the role of increasing and enhancing snowfall events
due to the uplifting effect of mountains on the airflow.

Trends of DHS, MASD, MASE, and MDSE were positive in the area from
Altai Mountain to northern Junggar Basin. It implies that the days and intensities
of snowfall events with daily snowfall more than 6 mm were increasing in this
area. This might be the reason for the increasing of snowfall events with daily
snowfall more than 6 mm and accumulated snowfall amount more than 30 mm.
In southern Junggar Basin area, MASE was decreasing, while MDSE and HSE
were increasing, it indicates that the frequencies of ESEs was increasing but the
maximum snowfall amounts of ESEs were decreasing, this might be caused by
the decreasing ESE's intensity. In Zhaosu area, MASD and HSE were decreasing,
DHS, MASE, while MDSE were increasing, it implies that the intensity of daily
snowfall more than 6 mm was decreasing, and days of daily snowfall more than
6 mm was increasing in this area. In the east part of NX, MASE and MDSE were
decreasing, while HSE was increasing, it implies that the snowfall events with
accumulative snowfall amount excess 30 mm in this area might be caused by
more consecutive snowfall days with daily snowfall amount lower than 6 mm.
Daxigou-Xiaoquzi area and Qitai area all showed increasing trends in variations
of all the ESE indices. It implies that the ESEs with high daily snowfall intensity
and large accumulated snowfall amount were increasing in this two areas.
Thence, Daxigou-Xiaoquzi area and Qitai area were identified as hot spots for
increasing of ESEs by using rotated EOF method. Because these two subregions
lie in the area which is dominated by the cold and wet airflows from the Arctic
Ocean, it might be the airflow from the Arctic Ocean that caused ESEs in these
two subregions. Though there might be uncertainty when subregions were
divided due to less stations, this study could be a case to study the ESEs at the
middle to high latitudes. The ESE indices defined here can be used for other
regions as well. It will be helpful to compare the studies from the other part of the
world.

5. Conclusions
In this study, five ESE indices were defined for NX based on observed daily precipitation (snow water equivalent) and daily minimum temperature: days of heavy snowfall (DHS, snowfall > 6mm/day), maximum 1-day snowfall amounts (MASD), maximum 1-event snowfall amounts (MASE), maximum consecutive snowfall days (MDSE), and heavy snowfall events (HSE, cumulative snowfall > 30 mm). They were calculated annually for 25 stations selected in NX. The spatial and temporal characteristics of these ESE indices were explored by conducting linear trend and Rotated EOF analysis. According to the results obtained, some important conclusions were found and listed in the following paragraphs.

The high values of annual averages of DHS, MASD, MASE, MDSE, and HSE (Figure 4) were found at high altitudes, such as Zhaosu, Daxigou and Xiaoquzi and Tianchi stations, while small values at low altitudes, such as Karamay, Jinghe, and Tacheng stations. It implies that the uplifting effect of mountains on the airflow was the main reason to cause ESE events.

All the regional averages of these ESE indices over NX, except for HSE, experienced significant increasing trends at the 95% confidence level in the recent 49 years (Figure 5). HSE were fluctuating around the average line and increased slowly. All the values of DHS, MASD, MASE, and MDSE were less than its regional average before 1993, and the situation was reversed after the stated year. It indicates that climate was changing rapidly in NX at the early of 1990s.
The trends of ESE indices in each subregion were significantly different. It implies that there were different reasons for the different trends in each subregion in these ESE indices. It showed the importance to study the ESEs in this region at subregional level.

In Daxigou-Xiaoquzi area and Qitai area, all these ESE indices showed increasing trends. It implies that the days and intensities of snowfall events with daily snowfall more than 6 mm were increasing in this area. This might be the reason for the increasing of snowfall events with daily snowfall more than 6 mm and accumulated snowfall amount more than 30 mm. Policymakers should focus on these two areas to make measures to avoid snowfall disasters.

Acknowledgments

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References


Sun J.Q., H.J. Wang, W. Yuan, H.P. Chen, 2010: Spatial-temporal features of


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Fig. 6  Changes of the EOF’s eigenvalues in ESE index DHS with natural number series.

Fig. 7  Coherent subregions and their related trends for the variations in ESE indices, DHS, MASD, MASE, MDSE, and HSE.
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<table>
<thead>
<tr>
<th>No.</th>
<th>Station</th>
<th>No.</th>
<th>Station</th>
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Table 2. Annual average snowfall days reported during 1961-1979 for stations in NX with distinguished snowfall and rainfall days, and annual average days of average, maximum, and minimum temperature not higher than 0°C of these snowfall days.

<table>
<thead>
<tr>
<th>Station No.</th>
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<th>Days of daily average temperature not higher than 0°C of these snowfall days</th>
<th>Days of daily maximum temperature not higher than 0°C of these snowfall days</th>
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<td>27.74</td>
<td>23.95</td>
<td>17.47</td>
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Table 3  Snowfall Grading standard for China and Xinjiang (Zhao et al., 2011).

<table>
<thead>
<tr>
<th>Snowfall grade</th>
<th>12 hours snowfall (mm)</th>
<th>24 hours snowfall (mm)</th>
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<tr>
<td></td>
<td><strong>China</strong></td>
<td><strong>Xinjiang</strong></td>
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<tr>
<td>Light snowfall</td>
<td>0.1&lt;x&lt;=0.9</td>
<td>0.2&lt;x&lt;=2.5</td>
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<tr>
<td>Moderate snowfall</td>
<td>0.9&lt;x&lt;=2.9</td>
<td>2.5&lt;x&lt;=5.0</td>
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<tr>
<td>Heavy snowfall</td>
<td>2.9&lt;x&lt;=5.9</td>
<td>5.0&lt;x&lt;=10.0</td>
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<tr>
<td>Blizzard</td>
<td>x&gt;5.9</td>
<td>x&gt;10.0</td>
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### Table 4  
Indices for extreme snowfall events defined based on water equivalent.

<table>
<thead>
<tr>
<th>ID</th>
<th>Indicator name</th>
<th>Definitions</th>
<th>Units</th>
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<tr>
<td>DHS</td>
<td>Days of heavy snowfall</td>
<td>Number of heavy snowfall days (daily snowfall &gt; 6 mm) during a period</td>
<td>days</td>
</tr>
<tr>
<td>MASD</td>
<td>Maximum 1-day snowfall amounts</td>
<td>Maximum daily snowfall during a period</td>
<td>mm</td>
</tr>
<tr>
<td>MASE</td>
<td>Maximum 1-event snowfall amounts</td>
<td>Maximum snowfall amount of snowfall events during a period</td>
<td>mm</td>
</tr>
<tr>
<td>MDSE</td>
<td>Maximum consecutive snowfall days</td>
<td>Maximum days of snowfall events during a period with daily snowfall is more than 6 mm</td>
<td>days</td>
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<td>HSE</td>
<td>Heavy snowfall events</td>
<td>Frequencies of snowfall events during a period with accumulative snowfall amount excess 30 mm</td>
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</table>
Table 5  EOFs retained for each ESE indices, DHS, MASD, MASE, MDSE and HSE, and their associated explained variance (%) and accumulated variance (%).

<table>
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<th>ESE indices</th>
<th>Explained variance (%)</th>
<th>Accumulated variance (%)</th>
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<td>DHS</td>
<td>31.53 20.94 12.31 7.66</td>
<td>31.53 52.47 64.78 72.44</td>
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<tr>
<td>MASD</td>
<td>19.96 17.54 9.42 7.11</td>
<td>19.96 37.50 46.92 54.03</td>
</tr>
<tr>
<td>MASE</td>
<td>29.70 12.62 10.21 8.13</td>
<td>29.70 42.33 52.53 60.66</td>
</tr>
<tr>
<td>MDSE</td>
<td>19.45 10.09 8.40   /</td>
<td>19.45 29.54 37.94   /</td>
</tr>
<tr>
<td>HSE</td>
<td>50.88 18.48 10.90 2.93</td>
<td>50.88 69.36 80.26 83.19 89.96</td>
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