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Sensitivity Analysis of Precipitation Pattern as Indicator of Climatic Warming in High Latitudes of Northeast China

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The precipitation pattern is an indicator of climate change. Under the background of climatic warming, many research results on the change in precipitation patterns in different regions have been accumulated. However, there has been insufficient comparison of the sensitivity of rainfall and snowfall to climatic warming. On the basis of temperature and precipitation observational data from 58 meteorological stations in northeast China (Heilongjiang Province) acquired from 1961 to 2016, in this study, we perform a detailed analysis of the spatiotemporal changes in the precipitation pattern and the sensitivity of the pattern to climate change by using statistical methods such as trend, abrupt change, and correlation analyses. According to the results, no significant changes in the patterns of the precipitation amount and frequency were observed in the high latitudes of northeast China from 1961 to 2016. Nevertheless, the ratio of the changes in annual snowfall and precipitation amounts increased significantly in the eastern part of the region. No significant changes were observed in the rainfall amount or frequency patterns at different intensities. However, significant changes were observed in the snowfall amount and frequency patterns at different intensities. The amount and frequency of heavy and moderate snow showed a significant upward trend. The proportion of heavy and moderate snow frequencies increased significantly. In addition, the proportion of light snow frequency decreased significantly. A comprehensive analysis showed that snowfall is sensitive to temperature changes, whereas rainfall is not. The snowfall frequency and the proportion of snowfall frequency are most sensitive to temperature; an increase in temperature mainly affects the frequencies of light, heavy, and moderate snow and the proportion of light snow frequency. The major contribution of this study is that it clarifies the sensitivity differences between rainfall and snowfall to increases in temperature and demonstrates that snowfall frequencies and proportions at different blizzard intensities are the most sensitive indicators to changes in temperature.

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1. Introduction

The precipitation pattern mainly refers to the ratio of the rainfall amount and frequency to the total precipitation amount and frequency. In addition, it refers also to the ratio of the snowfall amount and frequency to the total precipitation amount and frequency, as well as the ratio of the change in the snowfall amount and frequency to the rainfall amount and frequency. The precipitation pattern also includes the ratio of the rainfall amount and frequency (rainstorms or heavy, moderate, and light rain) at various intensities and the ratio of the snowfall amount and frequency (blizzard or heavy, moderate, and light snow) at various intensities and the pattern of the ratio change. A change in the precipitation pattern has a certain value as an indicator of climate change(1) for modeling and predicting the future climate.(2) In the short term, an increase in heavy precipitation will lead to flooding, whereas a continuous and stable decrease in light precipitation may lead to drought.(3,4) Meanwhile, a change in the precipitation pattern will have a significant impact on the process of river icing, snow melt in spring, and surface runoff.(5–8) Temperature is the main factor affecting the change in the precipitation pattern.(9,10) Hence, under the backdrop of climatic warming, changes in the precipitation pattern in different regions have attracted increased attention from scholars worldwide.

The change in the ratio of the snowfall amount to the annual precipitation amount (SA/PA) has been studied in many regions. Researchers generally consider that SA/PA has decreased significantly in most regions. For example, SA/PA in most parts of the world showed a significant downward trend from 1979 to 2017.(11) In Europe, SA/PA decreased at a rate of 1.2%/10a from 1961 to 2010.(12) The ratio of the snowfall amount to rainfall amount (SA/RA) in the western United States also decreased from 1949 to 2004.(13) In New England, SA/PA decreased from 30% in 1949 to 23% in 2000,(6) whereas in the Alps it also showed a significant downward trend with a rate of −1.25%/10a from 1959 to 2010.(14) Moreover, the rates of decline in SA/PA in the Qinghai–Tibet Plateau and Xinjiang were 5 and 10%/10a,(15,16) respectively, whereas in parts of northeast China, SA/PA showed an upward trend.(11,17) After conducting a large amount of research on the change in the proportion of the rainfall amount at different intensities, researchers found that the proportion of the amount of light rain showed a downward trend in many places, whereas the proportion of the rainfall amount at other intensities showed an upward trend or no change.(18–21) For instance, in addition to the decrease in the proportion of the amount of light rain, the proportion of the amount of rain in rainstorms also decreased in north China from 1961 to 2017. Meanwhile, the proportions of moderate and heavy rain amounts increased.(22) From 1961 to 2017, the proportion of the moderate snow amount showed a significant increasing trend in northeast China, whereas the proportion of the light snow amount decreased significantly.(23) From 1961 to 2013, only the proportion of light snow decreased significantly in Liaoning Province in northeast China.(24) From 1961 to 2019, the proportions of blizzard, heavy snow, and moderate snow amounts increased significantly, whereas that of the light snow amount decreased significantly in northern Xinjiang, which is at the same latitude as northeast China.(25) Thus, some research results have been accumulated on the changes in the precipitation pattern, with researchers mainly focusing on describing the changes in the precipitation pattern, and there has been little research on the sensitivity of the precipitation pattern to climatic warming.

The change in the pattern of precipitation frequency has also been investigated, although the amount of research has been limited compared with that on the change in the pattern of the precipitation amount. Hewer and Gough found that the proportion of snowfall frequency to total precipitation frequency (SF/PF) in Toronto decreased by 5.1% from 1849 to 2017.(2) About half of the stations in Switzerland showed a significant downward trend in the proportion of snowfall to rainfall frequency (SF/RF) from 1930 to 2009.(26) In addition, Han *et al.* concluded that the rate of increase in the the proportion of rainfall frequency to total precipitation frequency (RF/PF) in the Antarctic was 4.36%/10a from 1985 to 2015.(27) Regarding the precipitation frequency pattern at different intensities, it has been found that the proportion of light rain frequency showed a downward trend in most regions such as for the Yangtze River basin,(18) for highly urbanized areas in the Pearl River Delta,(19) for the flood season in the Wei River basin,(20) and in Beijing,(21) whereas other rainfall intensities showed a significant upward trend or no change. For example, it was found that the proportion of light rain frequency declined in the flood season in the Bei River basin and the proportion of moderate rain also decreased, whereas those of heavy rain and rainstorms increased.(28) The frequency proportions of light rain and rainstorms decreased in north China, whereas those of moderate rain and heavy rain increased.(22) However, the frequency of light rain did not change significantly in certain regions. For instance, the proportion of frequency of rainstorms only showed a significant downward trend during the flood season (May to September) in the Wu River basin.(29) The frequency of the proportion of blizzards as well as heavy, moderate, and light snow in northeast China increased significantly from 1961 to 2017.(23,24) Furthermore, the frequency proportion of blizzards as well as heavy and moderate snow increased significantly in northern Xinjiang, whereas that of light snow decreased significantly.(25)

Compared with the precipitation amount pattern, there have been few studies on the pattern of precipitation frequency. With the existing research results analyzed, although the characteristics of the change in the precipitation pattern have been focused on in the context of climatic warming, few relevant conclusions have been published about whether rainfall or snowfall is more sensitive to temperature changes or whether the precipitation amount or frequency is more sensitive to temperature changes. The sixth report of International Panel on Climate Change pointed out that atmospheric water vapor increases by about 7% with every 1 °C increase in temperature, resulting in an increase in extreme precipitation events.(30) Some studies have shown that over the past few decades, climatic warming has led to an increase in extreme precipitation events in Siberia, Central Asia, and Poland, including heavy rainfall and heavy snowfall.(31–33) Therefore, an urgent need exists to analyze the sensitivity of the precipitation pattern to temperature changes. Northeast China is the most significant region affected by monsoons in the world. With snowfall and rainfall periods of almost the same length, northeast China is the second largest stable snow area in China and one of the five stable snow areas in Eurasia,(34) and it is distinguished from other snow areas because of its largest annual average snow reserves.(35) The rate of increase in the annual average temperature in northeast China was 0.31 °C/10a from 1961 to 2017, which is higher than the average rate of increase in temperature in the same period for other areas of China and even the world in the last 50 years.(36) Moreover, northeast China is an important commodity grain production base in China with grain output accounting for 10% of the country's output.(37) Therefore, northeast China is an ideal region for analyzing the change in the precipitation pattern under the backdrop of climatic warming and can reveal the sensitivity of the precipitation pattern to temperature changes. Heilongjiang Province is located in the northernmost part of northeast China and is the province with the highest latitude in China. Heilongjiang Province has a typical monsoon climate, with hot and rainy summers and cold and long winters. It is the region of China with the largest amount of snowfall and longest snow cover period. Most importantly, in the past 50 years, the areas showing the greatest warming in the entire northeast region are located in the Xiaoxing'an Mountains, most of the Songnen Plain, and the northern end of the Daxing'an Mountains.(38) The areas showing the greatest warming in the entire northeast region are mainly distributed in Heilongjiang Province. In this study, we selected Heilongjiang Province with the highest temperature rise in northeast China as the study area. The study clarifies the sensitivity differences between rainfall and snowfall to climatic warming by analyzing the characteristics of the change in the precipitation pattern to provide theoretical support for the impact of global climate change and a scientific basis for local economic development.

2. Materials and Methods

2.1 Overview of study area

Heilongjiang Province is located in northeast China, adjacent to Russia to the north, the Inner Mongolia Autonomous Region to the west, and Jilin to the south (Fig. 1). It is located at 121°11′–135°05′ E, 43°26′–53°33′ N and has a total area of about 47.3 × 10^4 km^2. Its topography is characterized by "five mountains, one body of water, one grassland, and three fields".(39) The terrain is generally high in the northwest, north, and southeast and low in the northeast and southwest. It is composed of mountains, terraces, plains, and water. It includes part of the four major water systems of the Heilongjiang, Wusulijiang, Songhuajiang, and Suifenhe rivers. The annual average temperature range is between −5 and 5 °C, and the annual average precipitation

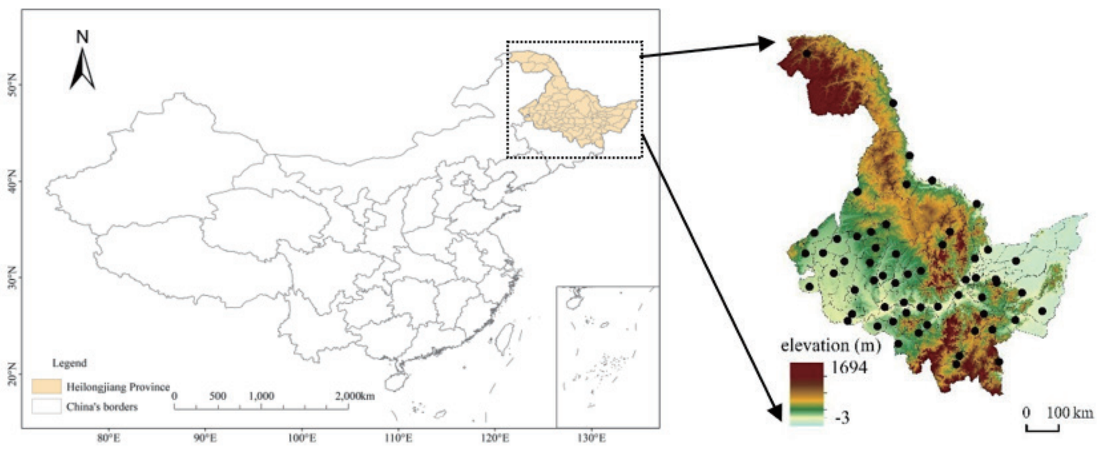

Fig. 1. (Color online) Distribution of meteorological stations in Heilongjiang Province, China.

is around 400–600 mm. The precipitation is generally lower in the west and higher in the east, with less precipitation in the plains and more in the mountainous areas. The rainfall is mainly concentrated in May to August, whereas snowfall is concentrated in November to March. The province has four distinct seasons; the winter is long, cold, and dry, and the summer is short and humid.

2.2 Data sources

The daily precipitation and temperature data used in this study were acquired from the observational data of Heilongjiang Meteorological Bureau. The rainfall data in this article comes from rain sensors, which are suitable for meteorological stations, hydrological stations, agriculture, forestry, national defense and other relevant departments. The rain sensors are used for the telemetry of liquid precipitation, precipitation intensity, and precipitation start and end time. The observational data were successively reviewed by Heilongjiang Meteorological Bureau and China Meteorological Administration (CMA). Any abnormal data were corrected and/or eliminated. The data quality was standardized so that the data could be used directly. In this study, 58 stations, such as Harbin, Suifenhe, and Mudanjiang stations, were selected to provide analysis samples with no missing measurement data, strong data continuity, and a uniform spatial distribution. The time period was from 1961 to 2016 (1961 refers to August 1, 1961 to July 31, 1962), spanning a total of 56 years. In accordance with the industry standard of CMA (2018), taking the 24 h precipitation amount as the classification standard (Table 1), rainfall and snowfall were divided into four intensities as follows: rainstorms and heavy, moderate, and light rain for rainfall, and blizzard and heavy, moderate, and light snow for snowfall.

2.3 Research methods

2.3.1 Trend analysis method

A univariate linear regression equation of the precipitation variable (y) and the corresponding time (x) was established:[(40)]

$$y = ax + b \quad (i = 1, 2, ..., n), \tag{1}$$

where a is the linear regression coefficient indicating the rate of change in the spatial extent of precipitation. A positive or negative value of a indicates that the spatial extent of precipitation is increasing or decreasing over time, respectively.

Table 1
Precipitation classification standard of CMA (mm).

Classification	Rainstorms	Heavy rain	Moderate rain	Light rain	Blizzard	Heavy snow	Moderate snow	Light snow
Precipitation	≥50	25–49.9	10–24.9	0.1–9.9	≥10	5.0–9.9	2.5–4.9	0.1–2.4

2.3.2 Mann–Kendall test

The Mann–Kendall (MK) test is a climate diagnosis and prediction technique. The non-parametric MK test is commonly employed to detect trends in climate and other data, with little interference from abnormal values.(41,42) In addition to its simple and convenient calculation, another advantage of the MK test is that the samples are not required to follow a certain distribution. Using the MK test, we are able to know the exact time of an abrupt change.

The MK test is performed using the following formula, where n and x are the number of samples and the time sequence, respectively:

$$S_k = \sum_{i=1}^{k} r_i \; (k = 2,3,...,n), \tag{2}$$

where

$$r_i = \begin{cases} +1 & \text{if } x_i > x_j, \\ 0 & \text{if } x_i \le x_j. \end{cases} \quad (j = 1, 2, ..., i) \tag{3}$$

The order list S_k is the number of values that are greater at time i than at time j.

The statistic of the MK test is defined by the following formula when the time series is assumed to be randomly independent.

$$UF_k = \frac{[S_k - E(S_k)]}{\sqrt{Var(S_k)}} \quad (k = 1, 2, ..., n) \tag{4}$$

Here, $UF_1 = 0$ and $E(S_k)$ and $Var(S_k)$ are the average value and variance of S_k, respectively. If x_1, x_2, …, x_n are independent individuals with the same continuous distribution, $E(S_k)$ and $Var(S_k)$ are obtained as

$$E(S_k) = \frac{n(n+1)}{4}, \tag{5}$$

$$Var(S_k) = \frac{n(n-1)(2n+5)}{72}, \tag{6}$$

where UF_i is a standard normal distribution, which is calculated at time sequence x of $x_1, x_2, …, x_n$. Given a significance level α, we can examine the normal distribution table. If $UF_i > U_\alpha$, there exists an obvious change in the sequence.

The above process is repeated for the reverse time sequence α of x_n, x_{n-1}, …, x_1 with the conditions of $UB_k = -UF_k$, $k = n, n-1, …, 1$, $UB_1 = 0$.

Positive values of UF or UB indicate an increasing trend, and vice versa. If UF or UB is beyond the critical curve, then an obvious trend exists. The range beyond the critical curve stands for the period with an abrupt change. If *UB* and *UF* have a point of intersection with the critical curve, the year corresponding to the point is the start year of the abrupt change.

2.3.3 Moving average method

The moving average method is also called the rolling average method.(43) Based on the simple average method, the moving average is calculated by sequentially increasing and decreasing the old and new data to eliminate accidental factors and determine development trends. In this study, the 5-year moving average is used to calculate the average anomaly of each element. When the 5-year moving average changes from positive (negative) to negative (positive), the start year of the negative value (positive value) is defined as the transition year. In this study, there are multiple intersection points in the process of the MK test, which can be comprehensively evaluated by combining the transition year determined by the moving average method.

2.3.4 Correlation analysis

Correlation analysis is a statistical method used to discover whether there is a relationship between two variables/datasets and the relatedness and negative/positive correlation of this relationship.(44) The Pearson correlation method is adopted in this study to quantitatively analyze the relationship between precipitation and air temperature. For each pair of variables, Pearson's correlation coefficient (r) is calculated as

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}}, \tag{7}$$

where $\overline{x}$ represents the mean precipitation and $\overline{y}$ is the mean air temperature. A two-tailed Student's t-test is used to examine the significance of the correlation.

2.3.5 Independent sample *t*-test analysis

The independent sample t-test was used to assess the difference in the data of two groups of unrelated samples. It examines whether the difference between the average of the two samples and the population represented by each is significant. The formula is as follows:

$$t = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{\frac{(n_1-1)S_1^2 + (n_2-1)S_2^2}{n_1+n_2-2}\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}}, \tag{8}$$

where S_1^2 and S_2^2 are the two sample variances and n_1 and n_2 are the two sample sizes. The test formula $F = S_1^2 / S_2^2$ obeys the F distribution of ($n_1 - n_2$) degrees of freedom. It can be used to test whether the difference is statistically significant.

3. Results

3.1 Background analysis of temperature change in Heilongjiang Province from 1961 to 2016

From 1961 to 2016, the annual, summer, and winter average temperatures of Heilongjiang Province were 2.83, 20.59, and −17.56 ℃; the corresponding rates of change were 0.32 ℃/10a ($p < 0.05$), 0.25 ℃/10a ($p < 0.05$), and 0.43 ℃/10a ($p < 0.05$), respectively. All results showed significant warming trends, and the warming rate in winter was higher than that in summer. Relative to the 1960s, the annual, summer, and winter average temperatures in the past 10 years have increased by 1.61, 1.26, and 2.13 ℃ [Figs. 2(a)–2(c)], respectively. The results of MK analysis show that the annual, summer, and winter average temperatures of Heilongjiang Province underwent abrupt changes in 1987, 1993, and 1986 (in winter, there are two intersection points of *UF* and *UB*, combined with the 5-year moving average method, with 1986 selected as the abrupt change point), all of which changed from cold to warm periods [Figs. 2(d)–2(f)].

From 1961 to 2016, the annual, summer, and winter temperatures in Heilongjiang Province exhibited a zonal distribution, with higher temperatures in the south and lower temperatures in the north. The annual, summer, and winter temperature trends were 0.10–0.62, 0.01–0.59, and 0.12–0.75 ℃/10a, and the percentages of stations that passed inspections were 96, 93, and 91%, respectively. The warming trend in the north was greater than that in the south. The temperature increase in winter was greater than that in summer. Overall, from 1961 to 2016, most stations in Heilongjiang Province exhibited significant or highly significant upward trends in temperature regardless of whether the entire year, summer, or winter was considered. In summary, the annual, summer, and winter average temperatures in Heilongjiang Province during 1961–2016

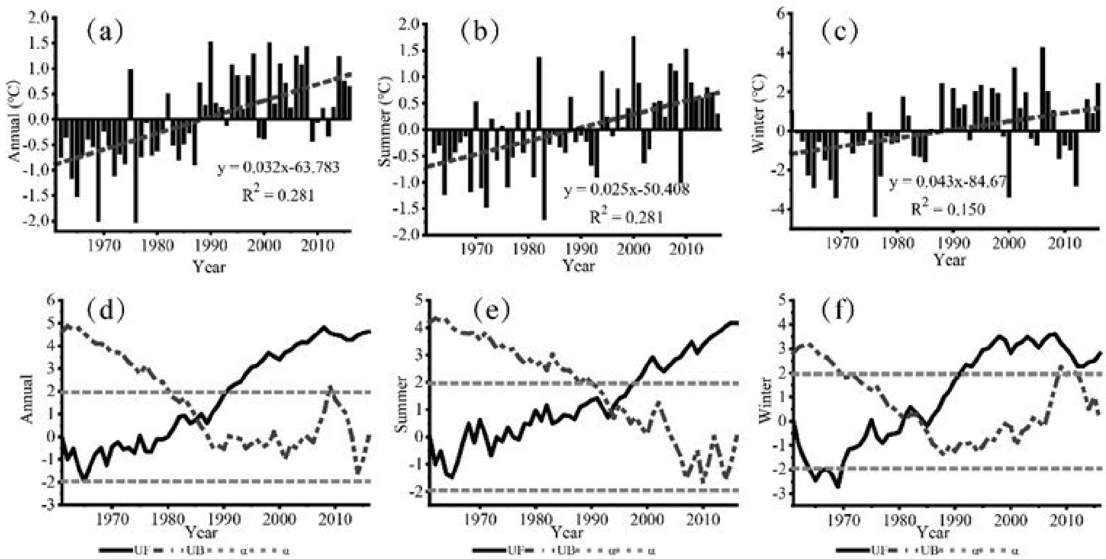

Fig. 2. (a)–(c) Annual, summer, and winter temperature changes and (d)–(f) results of MK test in Heilongjiang Province from 1961 to 2016.

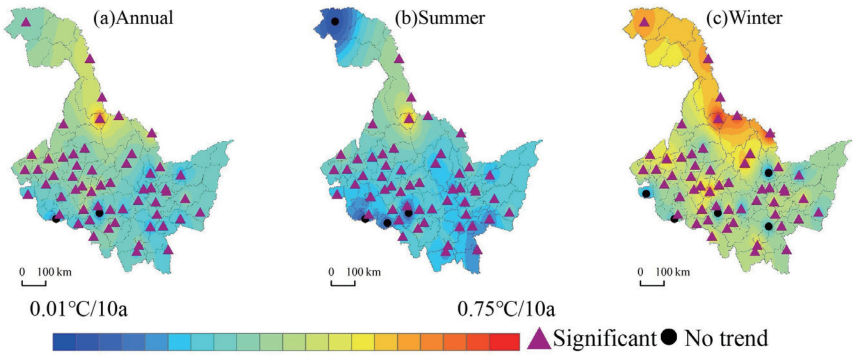

Fig. 3. (Color online) Spatial variations of annual, summer, and winter temperatures in Heilongjiang Province from 1961 to 2016.

showed significant warming trends, and the warming rate in winter was higher than that in summer (Fig. 3).

3.2 Variation characteristics of annual precipitation pattern in Heilongjiang Province from 1961 to 2016

3.2.1 Variation characteristics of pattern of amount of annual precipitation

During the period 1961–2016, the average annual precipitation, rainfall, and snowfall amounts in Heilongjiang Province were 522.14, 468.53, and 53.61 mm, respectively. SA/RA was 10%:90%, that is, snowfall accounted for about 10% of total precipitation and rainfall accounted for 90% of total precipitation. From 1961 to 2016, the rates of change of annual precipitation, rainfall, and snowfall in Heilongjiang Province were 5.34, 2.92, and 2.29 mm/10a ($p < 0.05$) [Figs. 4(a)–4(c)], respectively. Among these values, snowfall showed a significant increasing trend, whereas the trends for precipitation and rainfall were not significant. From 1961 to 2016, the rates of change of the ratios of the amount of rainfall to total precipitation (RA/PA), SA/PA, and SA/RA in Heilongjiang Province were −0.33, 0.33, and 0.42%/10a, respectively [Figs. 4(d)–4(f)]. No significant change was observed, indicating that no significant change occurred in the pattern of the total precipitation amount in Heilongjiang Province from 1961 to 2016.

A few stations in Heilongjiang Province experienced significant changes in the amounts of total precipitation and rainfall from 1961 to 2016. Only one station in southeastern Heilongjiang Province experienced a significant increase in the total amount of precipitation. No significant change was observed in the amount or rainfall recorded at these stations. Hence, no significant changes were observed in the amounts of total precipitation and rainfall in Heilongjiang from 1961 to 2016. Eighteen stations, which were mainly located in the mid-east of Heilongjiang, showed a significant increase in the amount of snowfall. In addition, only one station had a significant reduction in snowfall (Fig. 5). A significant decrease in SA/PA was observed at 13 stations, which were mainly located in the eastern part of Heilongjiang Province; these were spatially relatively highly concentrated. Meanwhile, Fig. 5 shows that stations with a significant

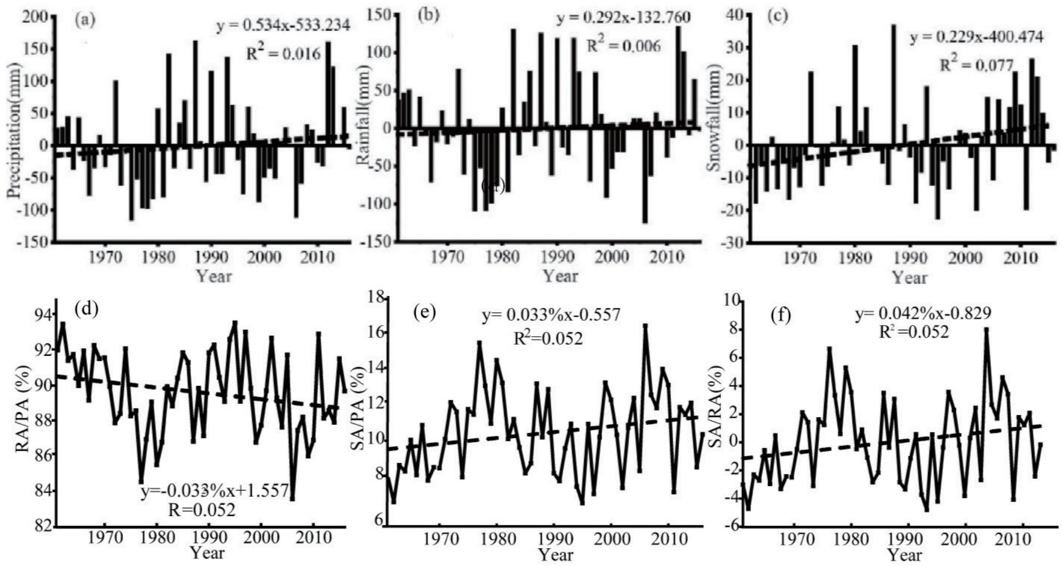

Fig. 4. Temporal variation of precipitation amount pattern in Heilongjiang Province from 1961 to 2016.

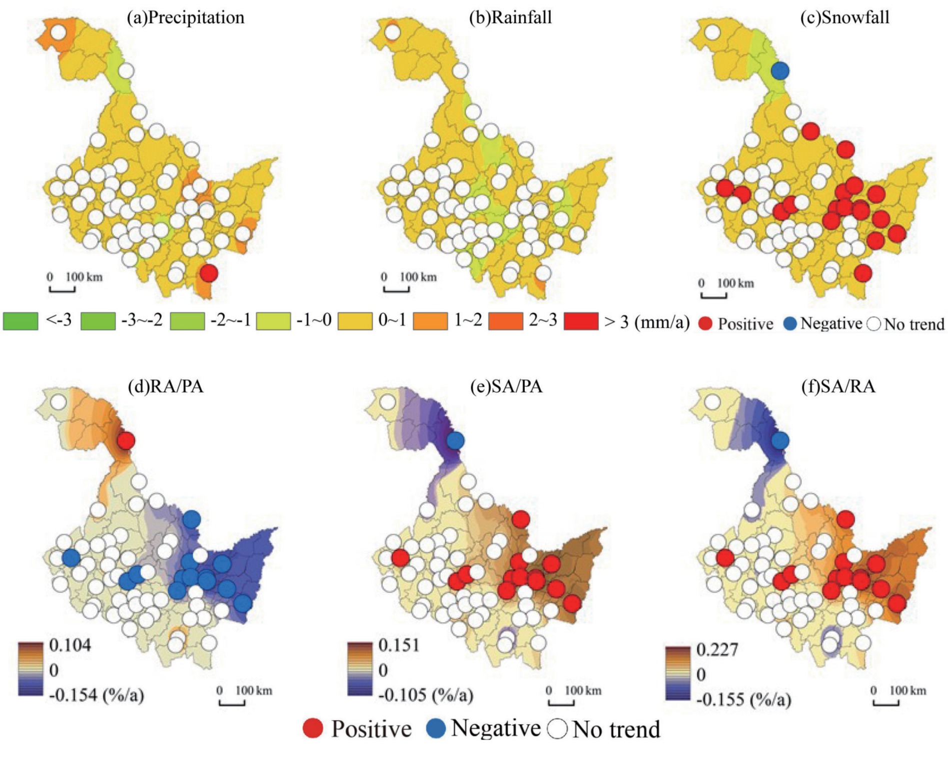

Fig. 5. (Color online) Spatial variation of precipitation amount pattern in Heilongjiang Province from 1961 to 2016.

increase in SA/PA and SA/RA showed a significant decrease in RA/PA. That is, the changes in the patterns of the precipitation amount were significant in the eastern part of Heilongjiang Province from 1961 to 2016 due to the significant increase in the amounts of snowfall received.

3.2.2 Variation characteristics in pattern of annual precipitation frequency

From 1961 to 2016, the average total precipitation, rainfall, and snowfall frequencies in Heilongjiang Province were 105.06, 71.99, and 33.07 times, respectively. The average SF/RF was 32%:68%, that is, the number of snowfalls accounted for one-third of the total instances of precipitation. The rates of change of total precipitation, rainfall, and snowfall frequency in Heilongjiang Province were −0.66, −0.40, and −0.27 times/10a [Figs. 6(a)–6(c)], respectively. RF/PF, SF/PF, and SF/RF were 0.05, −0.05, and −0.03%/10a, respectively (all statistically insignificant) [Figs. 6(d)–6(f)], indicating that the precipitation frequency pattern in Heilongjiang Province did not change during the period 1961–2016.

Few stations in Heilongjiang Province experienced significant changes in the frequencies of the spatial distribution for total precipitation, rainfall, snowfall, RF/PF, SF/PF, and SF/RF from 1961 to 2016. Two stations showed a significant increase in the frequency of precipitation, whereas seven stations experienced a significant decrease. Three stations documented a significant increase and three stations documented a significant decrease in the frequency of snowfall. In addition, five stations documented a significant decrease in the frequency of rainfall [Figs. 7(a)–7(c)]. Four stations in Heilongjiang Province showed a significant increase in SF/PF and SF/RF, whereas two stations showed a significant decrease in SF/PF and SF/RF from 1961 to 2016. The opposite occurred with RF/PF. Because only a few stations experienced significant changes in RF/PF, SF/PF, and SF/RF, no significant regional changes were observed [Figs. 7(d)–7(f)]. As a result, no significant change in the pattern of the frequency of precipitation was observed in Heilongjiang Province from 1961 to 2016.

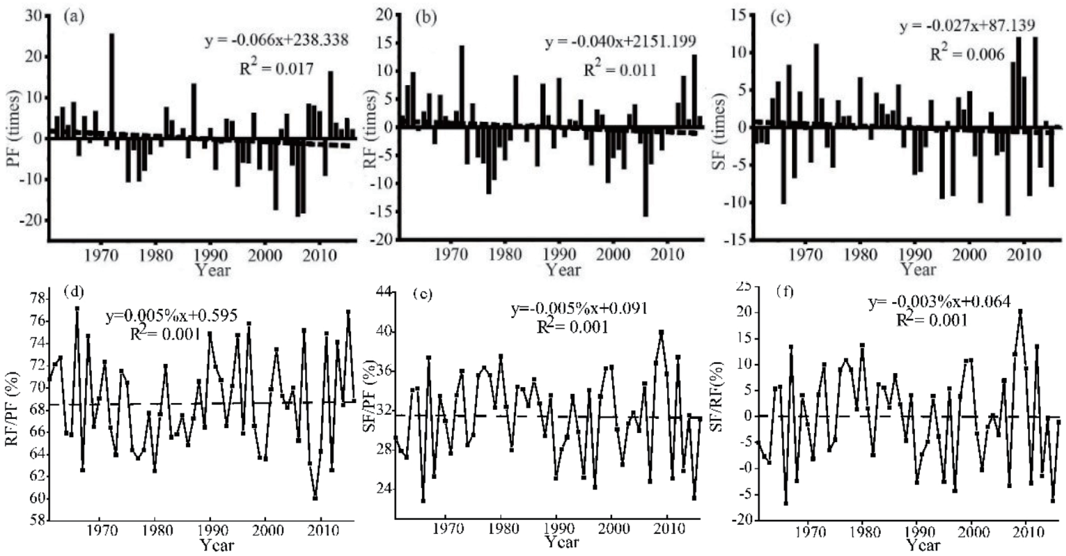

Fig. 6. Temporal variation of precipitation frequency pattern in Heilongjiang Province from 1961 to 2016.

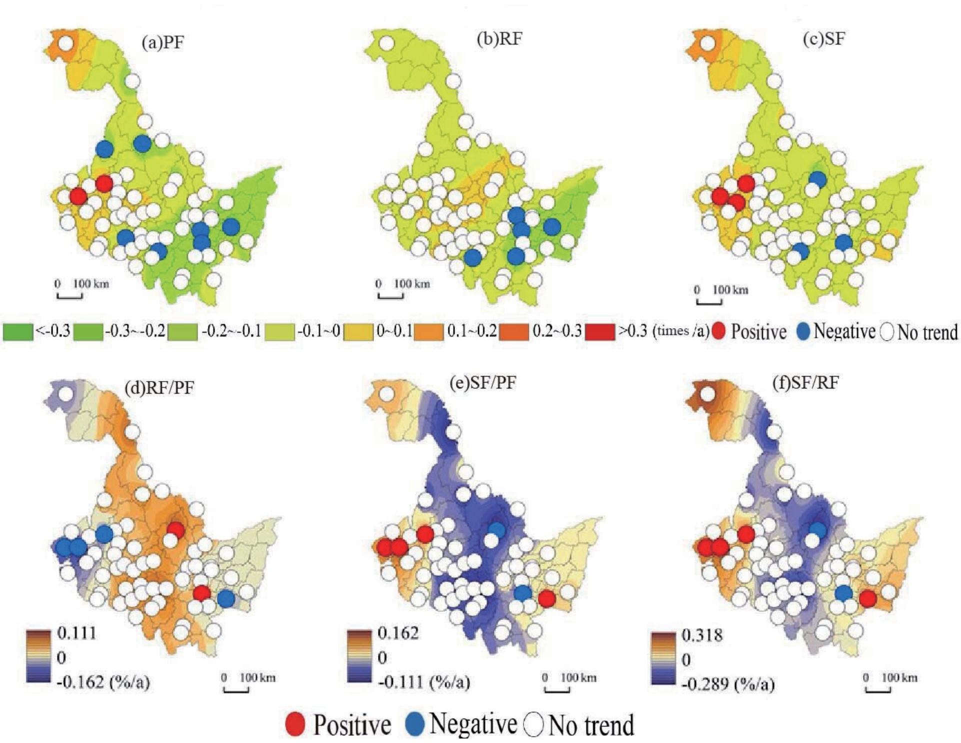

Fig. 7. (Color online) Spatial variation of precipitation frequency pattern in Heilongjiang Province from 1961 to 2016.

3.3 Variation characteristics of patterns of precipitation of different intensities in Heilongjiang Province from 1961 to 2016

3.3.1 Variation characteristics of different intensities of rainfall pattern

3.3.1.1 Variation characteristics of patterns of amount of rainfall at different intensities

In 1961–2016, the average amounts for rainstorms, heavy rainfall, moderate rainfall, and light rainfall in Heilongjiang Province were 40.67, 105.96, 170.28, and 151.62 mm, all of which showed no significant change trend, with rates of change of 1.19, 0.65, 1.66, and −0.58 mm/10a [Fig. 8(a)], respectively. The corresponding proportions were 9%:22%:36%:33%, that is, moderate and light rain each accounted for more than 30% of rainfall precipitation, whereas rainstorms accounted for nearly 10%. The results of the analysis show that the proportions of rainstorms and heavy, moderate, and light rainfall in Heilongjiang Province did not change significantly from 1961 to 2016 ($p > 0.05$), with rates of change of 0.16, 0.03, 0.15, and −0.34%/10a, respectively [Fig. 8(b)]. The rainfall pattern in Heilongjiang Province thus appears not to have changed.

Spatially, few stations in Heilongjiang Province showed a significant change in the amounts of rainstorms as well as heavy, moderate, and light rain, or in the proportion of each type of rainfall to the total amount of annual rainfall from 1961 to 2016 (Fig. 9). A significant increase in

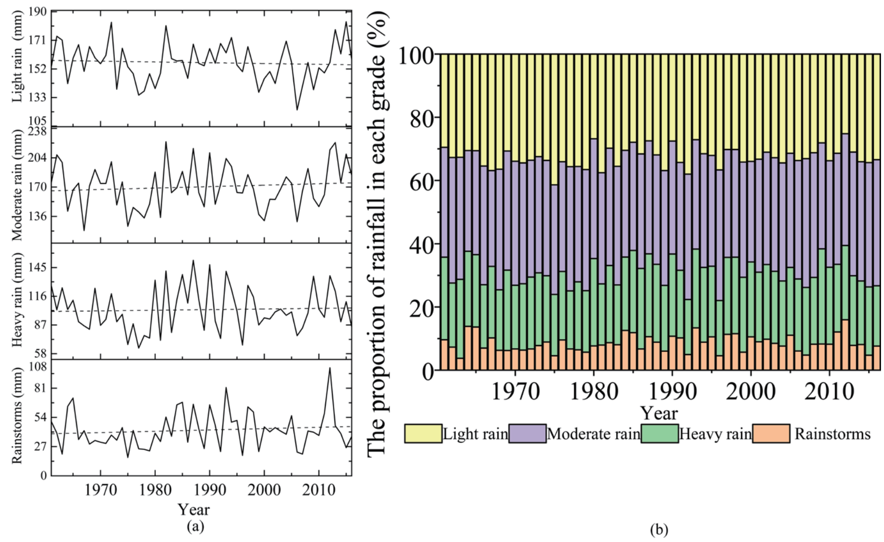

Fig. 8. (Color online) Temporal variation of rainfall amount pattern in Heilongjiang Province from 1961 to 2016.

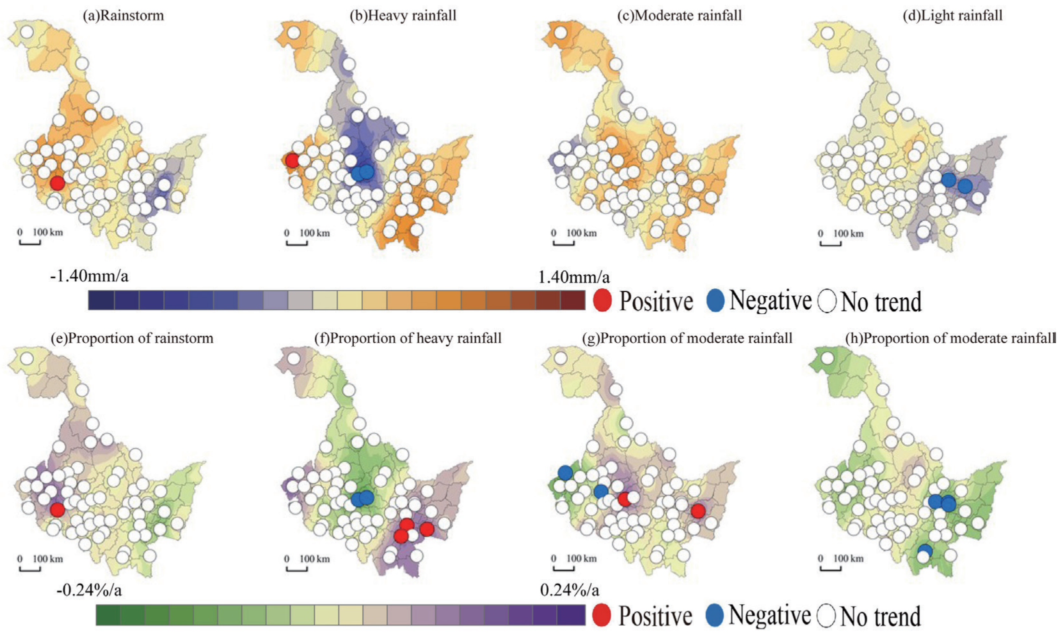

Fig. 9. (Color online) Spatial variation of rainfall amount pattern in Heilongjiang Province from 1961 to 2016.

the amount of precipitation from rainstorms was observed at one station as well as a significant increase in the amount of heavy rain at another station, whereas a significant decrease was observed at two stations. However, no significant change in the amount of moderate rain was observed at any stations, whereas a significant decrease in the amount of light rain was observed at two stations. The proportion of the amount of precipitation in rainstorms changed significantly at only one station, showing an upward trend. The proportion of heavy rain increased significantly at three stations and decreased significantly at two stations. A significant increase or decrease in the proportion of moderate rain was observed at two stations each. Furthermore, the proportion of light rain did not increase significantly at any stations but did decrease significantly at four stations. No significant regional changes were observed because few stations showed significant changes in the proportion of the amount of precipitation rainfall at different intensities. Consequently, no significant change in the pattern of the amount of rainfall was observed at various intensities in Heilongjiang Province from 1961 to 2016.

3.3.1.2 Variation characteristics of patterns of frequency of rainfall at different intensities

From 1961 to 2016, the average frequencies of rainstorms, heavy rain, moderate rain, and light rain in Heilongjiang Province were 0.61, 3.17, 10.98, and 57.22 times, respectively. The frequencies for rainstorms and heavy, moderate, and light rain showed no significant trend, with rates of change of 0.01, 0.02, 0.10, and −0.54 times/10a [Fig. 10(a)], respectively, and corresponding proportions of 1%:4%:15%:80%. It can be seen that 80% of all rainfall occurred in the form of light rain. There was no significant change in the proportion of total rainfall frequency. The change rates were 0.02, 0.06, 0.23, and −0.30%/10a [Fig. 10(b)], which indicate that during the period 1961–2016, the rainfall frequency pattern in Heilongjiang Province appears not to have changed.

Spatially, few stations showed significantly different frequencies of rainstorms as well as heavy, moderate, and light rain along with the proportion of each type of rainfall to the total frequency of annual rainfall in Heilongjiang Province from 1961 to 2016 (Fig. 11). One station experienced a significant increase in the frequency of rainstorms. Two stations showed a significant increase and two stations showed a significant decrease in the frequency of heavy rain. No stations showed a significant change in the frequency of moderate rain, whereas 12

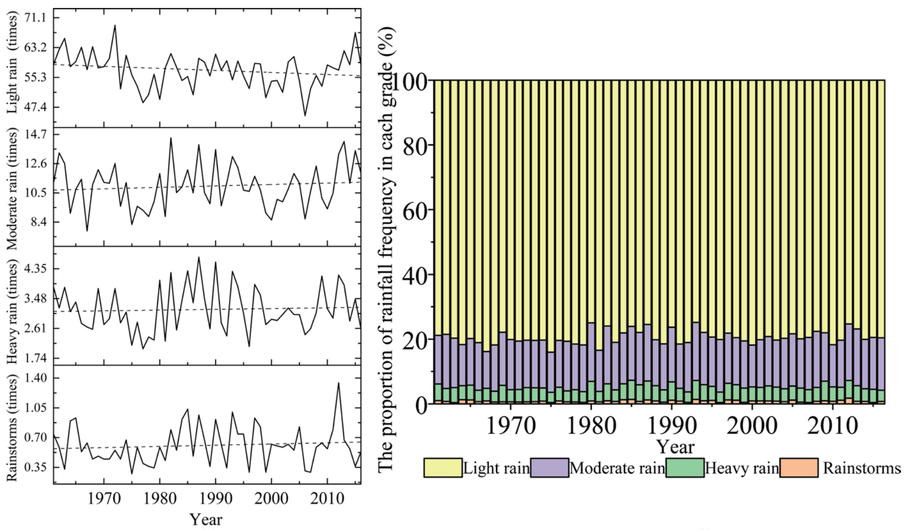

Fig. 10. (Color online) Temporal variation of rainfall frequency pattern in Heilongjiang Province from 1961 to 2016.

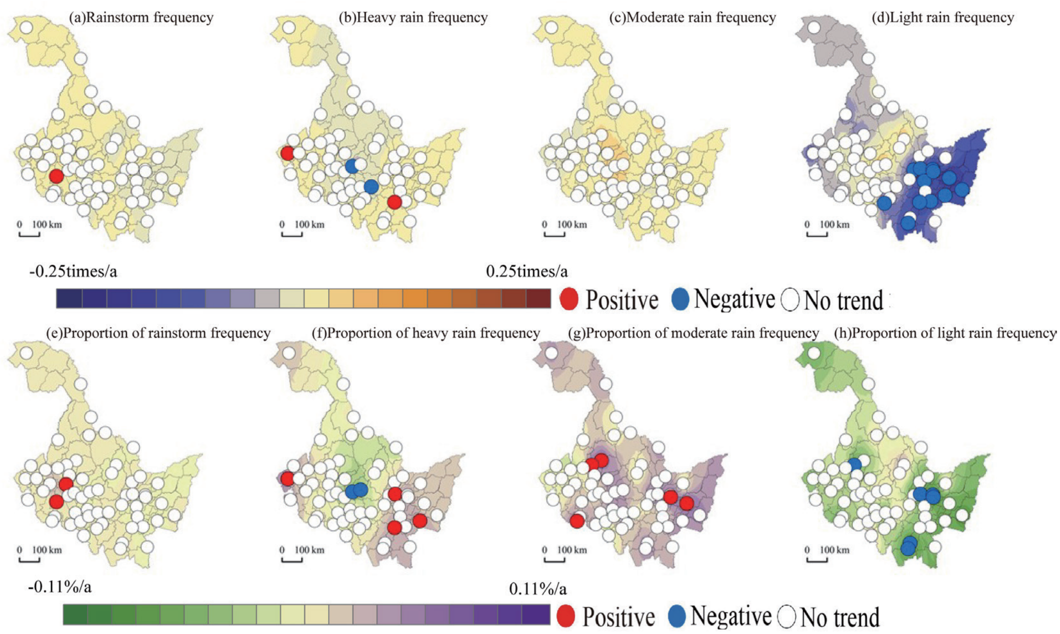

Fig. 11. (Color online) Spatial variation of rainfall frequency pattern in Heilongjiang Province from 1961 to 2016.

stations showed a significant decrease in the frequency of light rain. These changes were distributed in the eastern area of Heilongjiang Province with a rate of change between −2.48 and −1.25 times/10a. Two stations showed a significant increase in the proportion of rainstorm frequency. The proportion of the frequency of heavy rain increased significantly at four stations, whereas it decreased significantly at two stations. The proportion of moderate rain increased significantly at five stations, which were well dispersed throughout the study area. Six stations showed a significant decrease in the proportion of the frequency of light rain. The results showed that few stations experienced significant changes, and no significant regional differences were observed. Therefore, the pattern of rainfall frequency did not change significantly in Heilongjiang Province from 1961 to 2016.

3.3.2 Variation characteristics of different intensities of snowfall pattern

3.3.2.1 Variation characteristics of patterns of amount of snowfall at different intensities

From 1961 to 2016, the amounts of snow falling as blizzards, heavy snow, moderate snow, and light snow in Heilongjiang Province were 12.94, 12.33, 11.39, and 16.95 mm, respectively. The rates of change for blizzards, heavy snow, moderate snow, and light snow in Heilongjiang Province were 0.52 mm/10a, 0.94 mm/10a ($p < 0.01$), 0.56 mm/10a ($p < 0.05$), and 0.29 mm/10a, respectively. The amounts of heavy and moderate snow showed significant upward trends, whereas the amounts of snow falling as blizzards and light snow did not change [Fig. 12(a)]. The

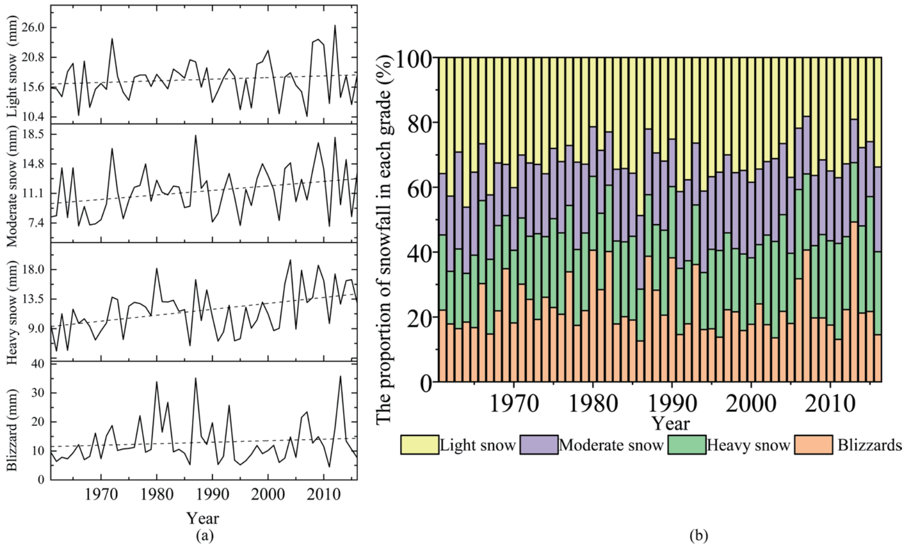

Fig. 12. (Color online) Temporal variation of snowfall amount pattern in Heilongjiang Province from 1961 to 2016.

proportions of snowfall of different grades accounted for 24%:23%:21%:32% of total snowfall. The proportion of light snow was the largest at about 30%, whereas the proportions of other grades accounted for approximately 20%. The change rates of the proportions of blizzards, heavy snow, moderate snow, and light snow were −0.13%/10a, 0.84%/10a ($p < 0.01$), 0.18%/10a, and −0.89%/10a, respectively. The proportion of heavy snowfall experienced a significant increasing trend, whereas the proportions of blizzards, moderate snow, and light snow did not change [Fig. 12(b)]. From the 1960s, the proportion of heavy snowfall has increased by 4.70%. The proportions of snowfall of different grades changed from 21%:22%:21%:36% in the 1960s to 25%:25%:21%:29% in 2007–2016.

Few stations in Heilongjiang Province exceeded the 0.05 probability level for the rate of change in the proportions of the amounts of blizzards, heavy snow, and moderate snow to the total snowfall amount from 1961 to 2016 (Fig. 13). Five, thirteen, eight, and nine stations experienced a significant upward trend in the amounts of snow in blizzards and heavy, moderate, and light snow, respectively. The amounts of snow from blizzards and heavy snow in eastern Heilongjiang Province increased at rates of 2.66–7.13 and 1.42–3.87 mm/10a, respectively. The amount of light snow in western Heilongjiang Province increased at a rate of 0.70–1.50 mm/10a. Stations with significant changes in the amount of moderate snow were widely scattered. Two stations experienced a significant increase in the proportion of the amount of snow from blizzards. The proportion of the amount of snow from heavy snow increased significantly at three stations that were at distant locations. The proportion of the amount of snow from moderate snow events increased significantly at two stations, whereas it decreased significantly at one station. A significant increase in the amount of snow from light snow events occurred at only one station, whereas the proportion of the amount of snow from light snow events declined significantly at 12 stations, which were mainly distributed in the eastern part of the study area. The tendency for the changes in the amount of light snow was −3.47–−2.19%/10a. The results

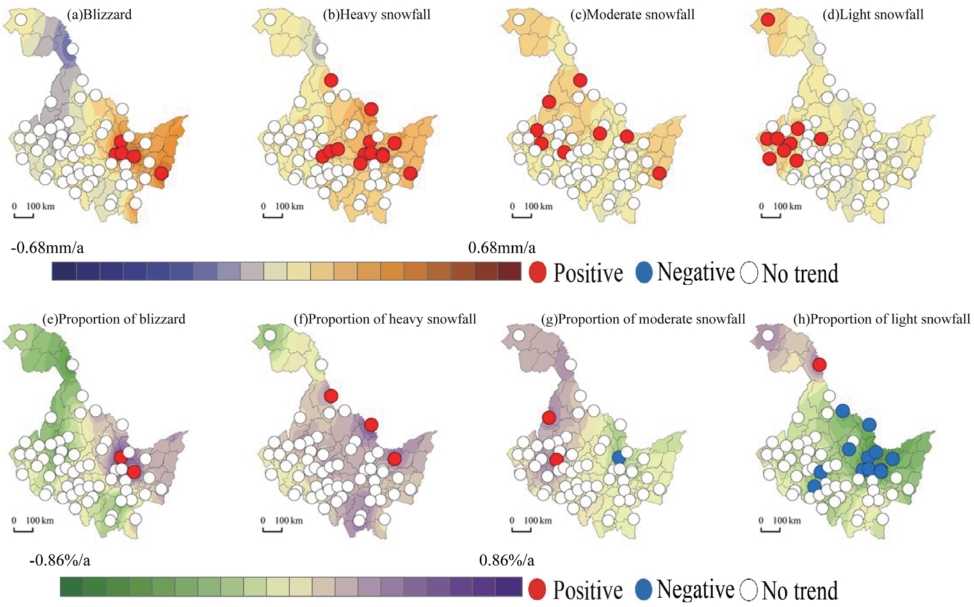

Fig. 13. (Color online) Spatial variation of snowfall amount pattern in Heilongjiang Province from 1961 to 2016.

indicate that the increase in the amount of snow falling in eastern Heilongjiang Province from 1961 to 2016 was mainly caused by the increase in the amounts of snow falling from blizzards and heavy snow events. As a result, the proportions of the amount of snow from light and moderate snow events declined significantly in the east.

3.3.2.2 Variation characteristics of patterns of frequency of snowfall at different intensities

From 1961 to 2016, the average frequencies of blizzards, heavy snow, moderate snow, and light snow in Heilongjiang Province were 0.81, 1.80, 3.30, and 27.17, respectively. From 1961 to 2016, the frequencies of blizzards, heavy snow, moderate snow, and light snow in Heilongjiang Province showed rates of change of 0.04 times/10a, 0.14 times/10a ($p < 0.01$), 0.17 times/10a ($p < 0.05$), and −0.53 times/10a, respectively. The heavy and moderate snow frequencies showed significant upward trends, whereas the blizzard and light snow frequencies did not change [(Fig. 14(a)]. The snowfall of blizzards, heavy snow, moderate snow, and light snow corresponded to proportions of 2%:6%:10%:82% of the total snowfall frequency. Snow fell far more frequently as light snow (80%) than as other grades. The rates of change of the proportions of snowfall frequency for blizzards, heavy snow, moderate snow, and light snow were 0.15%/10a, 0.46%/10a ($p < 0.01$), 0.54%/10a ($p < 0.01$), and −1.15%/10a ($p < 0.01$), respectively. The proportions of heavy and moderate snow frequency demonstrated significant increasing trends, whereas the proportion of light snow frequency showed a significant decreasing trend [Fig. 14(b)]. From the 1960s, the proportions of heavy snowfall and moderate snowfall have increased by 2.58 and 3.02%, respectively, whereas the proportion of light snowfall has decreased by 6.44%. The proportions of snowfall of blizzards, heavy snow, moderate snow, and light snow changed from 2%:4%:8%:86% in the 1960s to 3%:6%:11%:80% in 2007–2016.

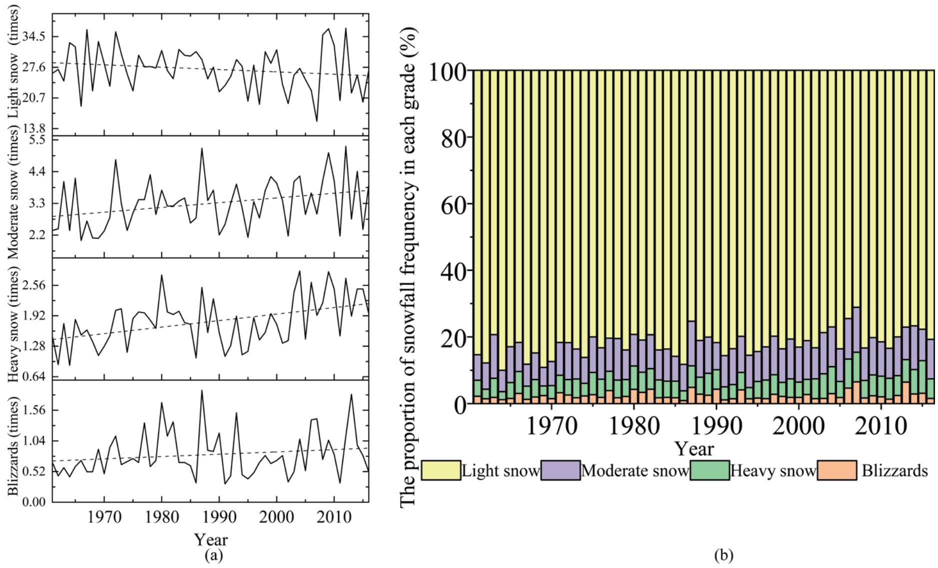

Fig. 14. (Color online) Temporal variation of snowfall frequency pattern in Heilongjiang Province from 1961 to 2016.

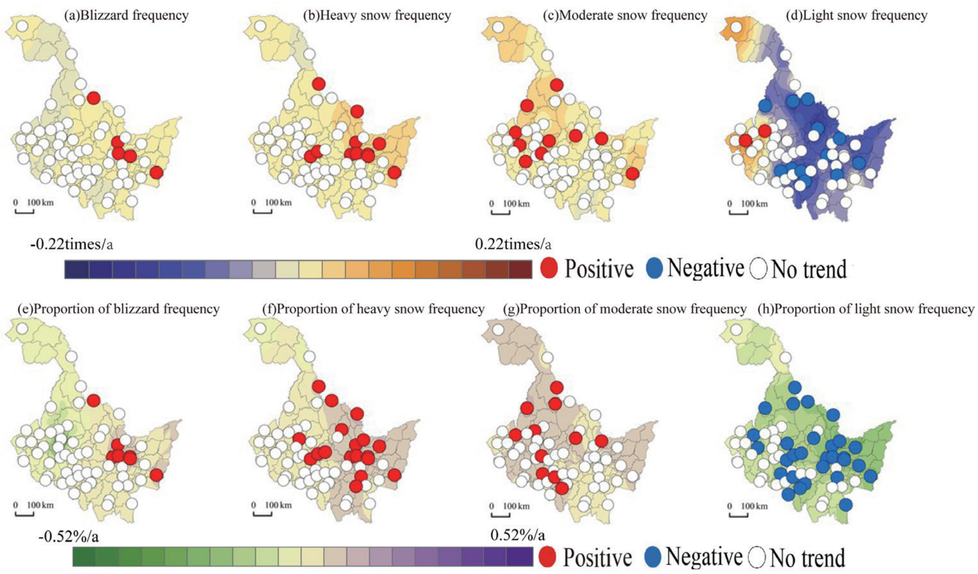

Fig. 15. (Color online) Spatial variation of snowfall frequency pattern in Heilongjiang Province from 1961 to 2016.

Many stations in Heilongjiang Province showed significantly different frequencies of blizzards, heavy snow, moderate snow, and light snow, as well as their proportions in the total snowfall frequency from 1961 to 2016 (Fig. 15). Blizzard and heavy snow frequencies increased significantly at 5 and 11 stations, respectively, with rates of 0.15–0.32 and 0.22–0.62 times/10a; these stations were mainly distributed in eastern Heilongjiang Province. The frequency of moderate snow increased significantly at 10 stations with a rate of 0.20–0.51 times/10a, and these stations were concentrated in the western part of the province. The frequency of light snow increased significantly at two stations and decreased significantly at 12 stations with rates of −2.19–−0.92 times/10a; these stations were primarily distributed in the mid-east portion of the study area. The proportions of blizzard and heavy snow frequencies increased significantly at seven and 18 stations, respectively. These mainly occurred at stations distributed in the east. The rates were 0.38–1.10 and 0.56–1.34%/10a, respectively. The proportion of the frequency of moderate snow increased significantly at 11 stations, which were mainly distributed in the west, and changed at rates of 0.80–1.32%/10a. The proportion of the frequency of light snow decreased significantly at 29 stations; these were mainly distributed in the east and changed at rates of −2.59–−1.09%/10a. The results showed that the pattern of snowfall frequency changed significantly at various intensities in Heilongjiang Province from 1961 to 2016. The proportion of the frequency of blizzard and heavy snow increased, whereas that of light snow decreased in the east. The proportion of the frequency of moderate snow increased in the west.

3.4 Relationship between temperature and precipitation pattern

3.4.1 Sensitivity analysis of annual precipitation pattern to temperature

3.4.1.1 Correlation analysis with temperature

The correlation coefficients between the temperature in each season and the indicators of precipitation from 1961 to 2016 were calculated (Table 2). The results show that no significant correlation existed between total amounts of precipitation, rainfall, and snowfall as well as RA/PA, SA/PA, SA/RA, and temperature. Among the indicators of precipitation frequency, the frequencies of total precipitation, rainfall, and snowfall, RF/PF, SF/PF, and SF/RF were significantly correlated with the temperature in different periods. Specifically, the frequency of total precipitation had a significant negative correlation with the winter temperature. The frequency of snowfall and the frequencies of the proportion of snowfall to rainfall had a significant negative correlation with both autumn and winter temperatures. Other snowfall indicators had no significant correlation with the average temperature of each season.

Table 2
Correlation coefficients between precipitation pattern and temperature in Heilongjiang Province, 1961–2016.

	Spring	Summer	Autumn	Winter		Spring	Summer	Autumn	Winter
Precipitation	−0.02	0.06	0.06	−0.07	PF	−0.02	−0.17	−0.19	−0.35**
Rainfall	−0.01	0.05	0.06	−0.05	RF	0.01	−0.04	0	−0.02
Snowfall	−0.03	0.06	0.03	−0.11	SF	−0.05	−0.20	−0.28*	−0.48*
RA/PA	0.02	−0.05	−0.01	0.05	RF/PF	0.06	0.15	0.25	0.40**
SA/PA	−0.02	0.05	0.01	−0.05	SF/PF	−0.06	−0.15	−0.25	−0.40**
SA/RA	−0.02	0.05	0.01	−0.04	SF/RF	−0.06	−0.15	−0.25	−0.42**

Note: * and ** here and below indicate testing at probability levels of 0.05 and 0.01, respectively.

3.4.1.2 Comparison before and after abrupt temperature change

The annual temperature in Heilongjiang Province showed an abrupt change in 1987. Taking 1987 as the boundary, changes in the patterns of the amount of precipitation and the frequency of precipitation were analyzed (Table 3). No difference was found among all indicators.

3.4.2 Analysis of sensitivity of precipitation of different intensities to temperature

3.4.2.1 Correlation analysis with temperature

The correlation coefficients between indicators of precipitation of different intensities and temperature in each season from 1961 to 2016 were calculated (Table 4). The results show that different intensities of indicators of rainfall, regardless of whether the rainfall amount or frequency is considered, had no significant correlation with the average temperature of each season. A significant correlation was observed between the snowfall indicators and temperature.

Table 3
Results of independent sample t-test analysis of precipitation pattern.

	Precipitation	PF	Rainfall	RF	Snowfall	SF
Before 1987a	a	a	a	a	a	a
After 1987a	a	a	a	a	a	a
	RA/PA	RF/PF	SA/PA	SF/PF	SA/RA	SF/RF
Before 1987a	a	a	a	a	a	a
After 1987a	a	a	a	a	a	a

Note: “a” means no significant difference.

Table 4
Correlation coefficient between rainfall and snowfall patterns and temperature in Heilongjiang Province, 1961–2016.

	Element value				Proportion			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Rainstorms	0.03	0.03	0.08	−0.19	0.03	0.01	0.05	−0.23
Heavy rain	−0.06	0.05	0.03	−0.07	−0.12	0.05	−0.01	−0.08
Moderate rain	−0.01	0.07	0.06	0.05	0	0.05	0.01	0.24
Light rain	0.04	−0.01	0.04	0.03	0.08	−0.09	−0.05	0.08
Rainstorm frequency	0.02	0.04	0.08	−0.18	0.02	0.04	0.08	−0.20
Heavy rain frequency	−0.06	0.04	0.04	−0.07	−0.08	0.06	0.03	−0.08
Moderate rain frequency	−0.01	0.08	0.07	0.06	−0.03	0.14	0.09	0.11
Light rain frequency	0.03	−0.09	−0.03	−0.03	0.05	−0.12	−0.08	−0.02
Blizzards	−0.17	0.05	0.05	0.02	−0.20	0.02	0.08	0.08
Heavy snow	0.13	0.15	0.14	−0.01	0.28*	0.18	0.18	0.11
Moderate snow	0.09	0.04	−0.03	−0.08	0.18	0.00	−0.08	0.08
Light snow	0.03	−0.05	−0.13	−0.35**	0.00	−0.13	−0.18	−0.21
Blizzard frequency	−0.13	0.06	0.11	0.05	−0.10	0.17	0.24	0.23
Heavy snow frequency	0.13	0.16	0.13	−0.03	0.19	0.31*	0.32*	0.29*
Moderate snow frequency	0.09	0.06	−0.02	−0.09	0.17	0.29*	0.23	0.34**
Light snow frequency	−0.08	−0.26*	−0.34**	−0.54**	−0.13	−0.32*	−0.32*	−0.36**

Note: * means significantly correlated. ** means extremely significantly correlated.

A significant negative correlation was found between the amount of light snow and the winter temperature. The frequency of light snow had a significant negative correlation with the summer, autumn, and winter temperatures. The frequencies of the proportion of heavy and moderate snow events had a significant positive correlation with the summer, autumn, and winter temperatures. In addition, the frequency of the proportion of light snow had a significant negative correlation with the summer, autumn, and winter temperatures.

3.4.2.2 Comparison before and after abrupt temperature change

The results showed that no significant differences were observed in the indicators of the amount of rainfall (and frequency) of different intensities before and after the year of the abrupt temperature change. However, significant differences were found in the indicators of the amount of snowfall (and frequency) before and after the abrupt temperature change. The amounts of heavy and moderate snow as well as the frequencies of heavy and moderate snow and the proportions of heavy, moderate, and light snow were significantly different before and after 1987, the year of the abrupt temperature change (Table 5).

4. Discussion

In the context of climatic warming, most scholars believe that SA/PA shows a significant downward trend of various degrees in most parts of the world.(11) The ratio SA/PA showed a significant downward trend in the whole European region from 1961 to 2010,(12) the western United States from 1949 to 2004,(13) New England from 1949 to 2000,(6) the Alps from 1936 to 2011,(14) and the Qinghai–Tibet Plateau from 1961 to 2013.(15) The ratio SA/PA also showed a significant downward trend in Xinjiang and Tianshan in the high latitudes of northwest China.(9,16) So far, an increase of SA/PA has only been observed in Heilongjiang Province in the high latitudes of northeast China, indicating a significant increase in the amount of snow

Table 5
Results of independent sample t-test analysis of rainfall and snowfall patterns.

	Precipitation	Proportion of precipitation		Precipitation frequency	Proportion of precipitation frequency
Rainstorms	☆	☆	Rainstorm frequency	☆	☆
Heavy rain	☆	☆	Heavy rain frequency	☆	☆
Moderate rain	☆	☆	Moderate rain frequency	☆	☆
Light rain	☆	☆	Light rain frequency	☆	☆
Blizzards	★	☆	Blizzard frequency	☆	☆
Heavy snow	★	☆	Heavy snow frequency	★	★
Moderate snow	☆	☆	Moderate snow frequency	★	★
Light snow	☆	☆	Light snow frequency	☆	★

Notes: ★ means that significant differences were found in the indicators before and after the abrupt temperature change ($p < 0.05$). ☆ means no significant difference.

received in this region. When analyzing the global change in SA/PA using ERA-Interim and GPCP data from 1979 to 2017, Tamang *et al.* found that certain areas of Heilongjiang Province displayed a significant increasing trend with a rate of change in SA/PA of about 4%/10a.(11) Hou *et al.* used the Daily Value Data Set of China's Surface Climate Data (V3.0) from 1960 to 2015 and concluded that SA/RA increased significantly in Heilongjiang Province at a rate of 7.60%/10a,(17) which was concentrated in the eastern part of the study area. The results of the present study revealed no significant change in SA/PA time series in Heilongjiang Province in northeast China. However, SA/PA showed a significant upward trend in the eastern part of the study area, which indicates that the high latitudes of northeast China are different from other regions in the world. Comparing the rates of change obtained by Tamang *et al.*,(11) Hou *et al.*,(17) and in this study, the difference is still large and is mainly due to the differences in the spatial resolution of the data. Tamang *et al.* used a data spatial resolution of 2.5°,(11) whereas Hou *et al.* selected data from a total of 27 national reference stations. In this study, 58 stations were selected, giving this study the highest spatial resolution of stations per study area. Therefore, the results presented in the current study are robust. In future studies, why the SA/PA ratio in eastern Heilongjiang Province is different from that of other regions should be analyzed in greater detail.

Changes in the rainfall pattern have also been investigated. Most scholars understand that the amount and frequency of light rain or their proportions have decreased significantly in many areas. For instance, the amount and proportion of frequency of light rain decreased significantly in the Yangtze River basin from 1960 to 2017 and in the Wei River basin from 1981 to 2012.(18,20) The proportion of light rain frequency in highly urbanized areas of the Pearl River Delta decreased significantly from 1973 to 2012.(19) The proportion of light rain frequency in Beijing decreased significantly from 1980 to 2012.(21) The analysis in this study showed that the proportion of the frequency of light rain also decreased in Heilongjiang Province, similarly to other regions. By calculating the regression coefficients between rainfall indicators and temperature, Hu *et al.* found that temperature has a significant positive correlation with the amount (and frequency) of rainstorms and a significant negative correlation with the amount (and frequency) of light rainfall.(18) However, the correlation coefficients between the indicators and temperature were calculated in the present study, and it was found that they were not significantly correlated.

Few studies have addressed the change in the snowfall pattern. By dividing the snowfall into blizzards as well as heavy, moderate, light, and trace snow (<0.1 mm), Zhou *et al.* concluded that the proportions of the frequency (and amount) of blizzards, heavy snow, moderate snow, and light snow increased significantly in northeast China from 1961 to 2017, whereas the proportion of light snow amount decreased significantly.(23) In addition, the proportions of the frequency of heavy, moderate, and light snow increased significantly, whereas the proportion of the amount of light snow decreased significantly in Liaoning Province, located in the northeast of China. Furthermore, the proportions of blizzards as well as the amounts (and frequencies) of heavy and moderate snow increased significantly, whereas the proportion of the amount (and frequency) of light snow decreased significantly in the northern Xinjiang region. In this study, we found that the proportions of the amount (and frequency) of heavy snow and moderate snow increased significantly, whereas the frequency of the proportion of light snow declined significantly. The difference in the results in northeast China may be related to the fact that trace snowfall was not calculated in this study, which is similar to the results obtained in northwest China. In addition, in the studies listed above, only changes in time series were calculated, whereas we also calculated the characteristics of the spatial variation of the snowfall pattern. We found that the characteristics of the regional variation of the snowfall pattern were significant, especially in the eastern part of the study area.

The pattern of the frequency of snowfall at different intensities showed significant regional characteristics in Heilongjiang Province from 1961 to 2016. The amounts and frequencies of blizzards and heavy snow increased in the mideast part of the study area, whereas the amount, frequency, and proportion of light snow decreased in this part. The amount, frequency, and proportion of moderate snow increased in the western part of the study area. The results showed that snowfall is directly related to the sources of water vapor and atmospheric circulation. We analyzed the relationship with temperature but not from the perspective of water vapor sources and atmospheric circulation; thus, a more comprehensive analysis is required as the next step.

5. Conclusions

The precipitation pattern is an indicator of climate change. It has important implications for agricultural disaster reduction and sustainable regional economic development. Under the background of climatic warming, research on the change in the pattern of precipitation frequency is limited. Meanwhile, a comparison of the sensitivity differences between rainfall and snowfall to climatic warming is lacking. In this study, Heilongjiang Province was selected as the study area. We analyzed the changes in the structure of the precipitation amount and precipitation frequency from 1961 to 2016, clarified the sensitivity differences between rainfall and snowfall to climatic warming, and proposed that the frequency and proportion of snowfall are the most sensitive indicators to temperature changes. The conclusions of this study provide a basis for climate modeling and prediction and a reference for the correct assessment of the impact of climatic warming on regional climate change.

(1) Under the backdrop of climatic warming, the annual amount of snowfall received has increased significantly in Heilongjiang Province with a rate of change of 5.34 mm/10a. The annual amounts of precipitation and rainfall did not show a significant increasing trend. No significant change was observed in RA/PA, SA/PA, and SA/RA. In other words, no significant change was shown in the pattern of the amount of precipitation received. No significant change was observed in the frequencies of total precipitation, rainfall, and snowfall, nor in the RF/PF, SF/PF, and SF/RF ratios in Heilongjiang Province from 1961 to 2016, suggesting that there was no change in the pattern of precipitation frequency.

(2) The amount of rain from rainstorms as well as heavy, moderate, and light rain showed no significant change in Heilongjiang Province from 1961 to 2016. The proportions of rainfall amounts also showed no significant change. No significant change was observed in the frequency of rainstorms nor heavy, moderate, and light rain in Heilongjiang Province from 1961 to 2016. Also, no significant change was observed in the frequency proportion. Thus, no change was found in the rainfall pattern at different rainfall intensities.

(3) The amounts and frequencies of heavy and moderate snow increased significantly in Heilongjiang Province from 1961 to 2016, with rates of change of 0.94, 0.14, 0.56, and 0.17times/10a for the heavy snow amount, heavy snow frequency, moderate snow amount, and moderate snow frequency, respectively. No change was observed in the amount or frequency of blizzards and light snow in the study area. The proportion of the frequency and amount of heavy snow increased significantly, whereas that of the amount of light snow and its frequency decreased significantly. The change trends were 0.84, 0.46, −0.89, and −1.15%/10a for the proportions of heavy snow amount, heavy snow frequency, light snow amount, and light snow frequency, respectively. The proportion of the frequency of moderate snow increased significantly with a rate of change of 0.54%/10a. Hence, the amount and frequency patterns of snowfall at different intensities changed significantly.

(4) Changes in the patterns of the snowfall amount and frequency mainly occurred in the eastern part of Heilongjiang Province from 1961 to 2016. The results showed that the proportion of the frequency of blizzards and the amount (and frequency) of heavy snow increased significantly, whereas the proportion of the amount (and frequency) of light snow decreased significantly.

(5) The analysis revealed that the amount and frequency of rainfall are not sensitive to changes in temperature, whereas the amount and frequency of snowfall are related to temperature. The frequency and proportion of snowfall are sensitive to changes in temperature. An increase in temperature will change the pattern of snowfall frequency. An increase in temperature will result in increases in the proportions of the frequency of heavy and moderate snow and a decrease in the proportion of the frequency of light snow. Thus, a significant correlation was observed between temperature and snowfall pattern. The amount and frequency of light snow had a significant negative correlation with temperature.

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