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Research Article

Trend and Abrupt Regime Shift of Temperature Extreme in Northeast China, 1957–2015

Patteson Chula Mwagona , Yunlong Yao , Yuanqi Shan , Hongxian Yu , and Yiwen Zhang

College of Wildlife Resources, Northeast Forestry University, No. 26 Hexing Road, Xiangfang District, Harbin 150040, China

Correspondence should be addressed to Yunlong Yao; yaoyunlong@nefu.edu.cn and Hongxian Yu; china.yhx@163.com

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Trend and an abrupt regime shift of temperature extremes were investigated based on diurnal data at 116 meteorological stations in the Northeast China region during 1957–2015. A total of 10 temperature indices divided into two categories: extremely cold and warm indices, were used in this study. The Mann–Kendall (MK) test was employed to evaluate the trend in temperature while changepoint, an R package for changepoint analysis, was used to detect changes in the mean levels of temperature extreme data series. The results of this study reveal that occurrence frequencies of the extreme cold night (TN10p) and extreme warm night (TN90p) have decreased and increased by −1.67 and 1.79 days/decade, respectively. Moreover, variations in temperature extremes have not been uniform with warming trends in minimum temperature being rapidly compared to maximum temperature extremes. The diurnal temperature range (DTR) depicted a remarkable decrease as a result of rapid warming in the minimum temperature. Warming in the region led to a reduction in the number of frost days (FD) and icing days (ID) and an increase in the number of growing season length (GSL) and tropical nights (Tr). Seasonally, TN10p largely decreased in winter and spring, while TNn and TN90p largely increased in winter and summer, respectively. Spatially, most of the stations with a significant warming trend in minimum temperatures were located in the Changbai Mountain, Greater Khingan Range, and Lesser Khingan Range. This implies that the mountainous regions are more sensitive and vulnerable to warming than the plain regions. On the contrary, most stations located in the Songnen Plain, Sanjiang Plain, and Liao River Plain displayed significant positive trend GSL and Tr. These climate extreme trends show that the region is experiencing warming which may have an impact on the hydrological process, ecological process, and agricultural production capacity.

1. Introduction

Changes in temperature extremes have attracted much attention worldwide due to its great potential impact to the human life, economic stability, and ecological systems [1, 2]. For instance, in 2003, extreme summer heat waves claimed about 22,000 lives in different parts of Europe [3], while in Bangladesh, approximately 140,000 flood-related deaths were reported in 1991 [4]. In Nenjiang–Songhuajiang valley and Yangtze River in China, 3000 deaths were reported in the summer of 1998 as a result of extreme flooding [5]. According to the assessment report on risk management and adaptation of climate extremes and disasters in China, an annual economic loss of about 1.07% of the GDP occurred in the twenty-first century as a result of climate extremes [6]. This, therefore, clearly displays the importance of extreme climate change worldwide, nationally, and regionally, from the perspective of global warming.

Recently, many researchers have conducted studies on temperature and precipitation changes from different parts of the globe [7–13]. Despite the challenges of getting high-quality long-term reliable climate data, a notable consistency among the results was revealed from these studies in terms of temperature extremes. These studies revealed that, from the mid of nineteenth century, the mean surface temperature has increased by approximately 0.75°C per year and is anticipated to rise by 1.1–6.4°C in the next 10 decades. Alongside the observed variations in yearly mean temperature, these studies also reported a global positive trend of precipitation of about 1% during the twentieth century.

On the national level, studies show that China has also been affected by climate extremes. You et al. [2], Xu et al. [14], and Xie et al. [12] reported significant warming of temperature by 0.27°C/decade over China, increase in the occurrence of warm nights and warm days, and decrease in the occurrence of cold days and cold nights. The authors further noted a reducing trend of the diurnal temperature range and frost days by −0.18°C/decade and −3.37 days/decade, respectively.

The response of climate extreme in China varies with geographical region characteristics. For example, in the Tibetan plateau and Hengduan Mountains, temperature increase has a remarkable relationship with increase elevation [15, 16]. Warm extremes rised significantly in Northwest China, South China, and Northern China, whereas the frequency of cold extremes reduced remarkably in Northeast China and North China [2, 17]. The implication of these responses sensitivity to climate extremes can be worrying for areas such as Northeast China, which are very sensitive to the impact of human activities due to their geographical position in temperate zones [18].

In Northeast China, changes in rainfall extreme events have already begun to be noticed. For example, Liang et al. [19] noted spatial variability of extreme rainfall in Northeast China as a result of the effect of the East Asian monsoon and topography. Most of the previous studies investigated precipitation changes in Northeast China [18, 19] or the consequences of El Niño-Southern Oscillation to the summer temperature using daily climatic data [20]. However, an inclusive investigation of temperature extremes is still lacking for Northeast China, and therefore, the objectives of this study are (i) to examine the trend and its spatial and seasonal characteristics of temperature extreme and (ii) to investigate the existence of changepoint (abrupt change) and its magnitude in temperature throughout a 58-year hydrometeorological time period from 1957 to 2015.

1.1. Study Area. Northeast China is located at 38°40′–53°34′N; 115°05′–135°02′E, with an area of about $1.24 \times 10^6\,km^2$. Northeast China includes Heilongjiang, Liaoning, and Jilin provinces from north to south, and also it covers the eastern part of Inner Mongolia. The study area is characterized by plains, mountains, and rivers. Among the plains, Songnen Plain, Sanjiang Plain, and Liao River Plain are included which are demarcated by the Changbai Mountains and the Greater Khingan and Lesser Khingan ranges (Figure 1). The region is a typical monsoonal climate region under the influence of East Asian monsoon and a sensitive area of changes in climate [19]. Climate varies from warm to cool temperate in the mid-latitude zones, while in the longitudinal zones, the climate is humid, semihumid, and semiarid. The northeast China region is the agricultural production basin in China with the highest endowment of cropland per capita [21]. In addition to crop farming, the region is also known for livestock keeping, forestry, and manufacturing industry. Large-scale plain reclamation in the Northeast China region became more pronounced under the "food first" agricultural policy and the proportion of crop farm increased significantly. With the current trend of land use change, water extraction coupled with climate change, residents in the regions are worried that the available resources may get depleted in the near future hence affecting agricultural production and the economic growth [22].

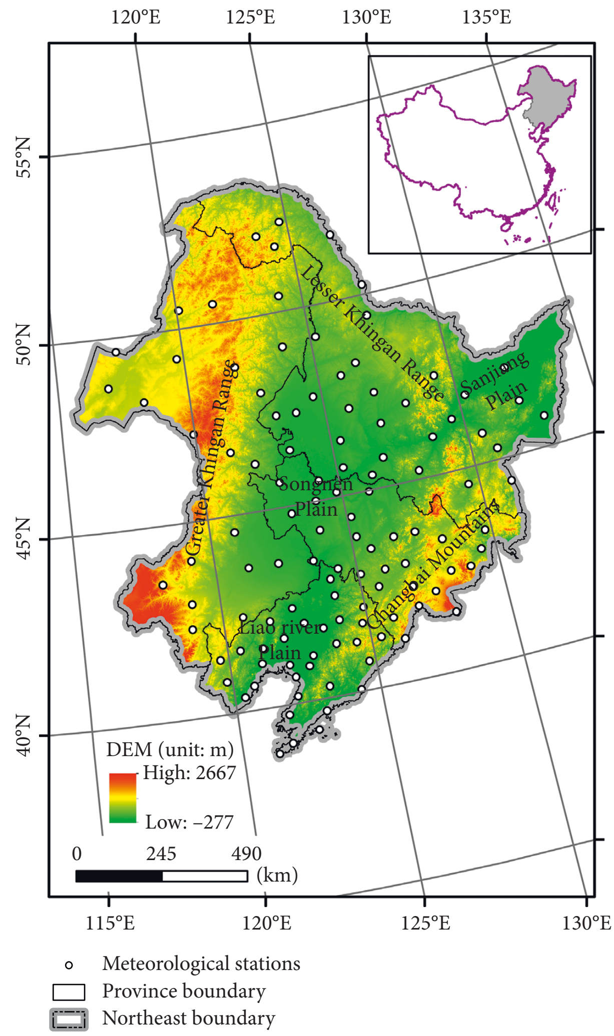

Figure 1: Top at the right corner shaded grey is the location of Northeast China and shaded white is mainland China. The enlarged map at the centre provides the locations of the meteorological stations (dots) in Northeast China.

2. Data and Methods

2.1. Data Source and Quality Control. Just like other parts of the globe, getting a very good climate data in China for the analysis of temperature extreme is very challenging. With exception of Beijing, Shanghai, and other several stations, most stations of China for climatic data observations were established in the 1950s. For the Northeast China region, the time period considered for this study is 58 years (from 1957 to 2015) from 116 meteorological stations located all over Northeast China (Figure 1). The temperature data were obtained from the National Climate Centre of the China Meteorological Administration (http://www.nmic.gov.cn/) and used to extract the extreme indices. According to

Shahid et al. [23], outliers and missing values have a considerable impact on the calculation of indices and trend analyses for temperature extremes. Therefore, data quality assessment was carried out using an RClimDex software package (available at the ETCCDI website, http://cccma.seos.uvic.ca/ETCCDI/software.shtml). Stations with missing data for the time period were filled by the mean values of the nearest stations taking into account the topographical nature and altitude, which had the best correlation with the former data and no missing data during the same period. After the data quality check and homogeneity testing, the 116 meteorological stations were used for the computation of the temperature indices. In order to understand the spatial variations of the temperature extremes, Northeast China was divided into six subgeographical regions, i.e., Songnen Plain, Sanjiang Plain, Liao River Plain, Changbai Mountains, the Greater Khingan Range, and the Lesser Khingan Range. Average variations of temperature extremes were evaluated for each subregion and for Northeast China as a whole. For seasonal variation, December, January, and February were clustered for winter; March, April, and May were clustered for spring; June, July, and August were clustered for summer; and September, October, and November were clustered for autumn.

2.2. Definition of Temperature Indices. Out of the 27 indices for extreme weather and climate events defined by the Expert Team on Climate Change Detection and Indices, a set 10 temperature indices were chosen for this study. This is after excluding the other temperature indices which were found to be highly correlated. The selected indices were further categorized into extremely cold indices and extremely warm indices (Table 1).

2.3. Trend Analysis. The Mann–Kendall (MK) test was employed to evaluate the trend in temperature. The Mann–Kendall (MK) is a nonparametric test which has been commonly applied to determine trends in climatological time series because of the following reasons: (i) it cannot be affected by data outliers; (ii) unlike parametric test, the MK test does not need to satisfy the normal distribution assumption of data; and (iii) MK can be used even when working with censored data or data with missing values [24]. However, the existence of serial dependence in hydrometeorological time series increases the likelihood of rejecting the null hypothesis hence affecting the MK test results. Several ways have been proposed to remove serial correlation from data before the MK test for assessing trends [25, 26]. For this analysis, the Yue and Pilon method proposed by Yue et al. [24] was used. This method first estimates the slope using the Theil–Sen approach (TSA). If the gradient differs from zero; then, it is assumed to be linear and the data are detrended to evaluate the significance of the trend [24].

2.4. Changepoint Analysis. Both natural factors and human activities can have an influence on the hydrometeorological processes leading to abrupt changes. Studies to detect abrupt changes or location of changepoints in hydrometeorological series are very important for examining the stationarity and consistency assumptions [27, 28]. In this paper, changepoint, an R package for changepoint analysis developed by Killick and Eckley [29], was used to detect changes in the mean levels of temperature extreme data series. This method does not require the data to satisfy the normal distribution assumption and can detect multiple changepoints.

3. Results

3.1. Extremely Cold Indices (TN10p, TNn, TXn, FD, and ID). Using the MK test, trends of each index at individual meteorological station were analyzed in order to know the temporal trends for the geographical regions all over Northeast China. Table 2 presents the number of meteorological stations with a positive trend (significant at 95% confidence level), no trend, and negative trend (significant at 95% confidence level), for the indices. It can be inferred from Table 2 that the inclination towards less cold night frequency (TN10p) is dominant with 113 (106 significant) out of 116 stations being a negative trend and only 3 stations showing a positive trend. On the contrary, the minimum value of daily minimum temperature (TNn) showed a positive trend in 112 stations with about 60% of the stations having a significant trend. In terms of the geographical pattern, stations with significant positive trends in TNn were observed mainly in the Changbai Mountains, Lesser Khingan Range, Liao River Plain, and some few stations in the Greater Khingan Range (Figure 2(b)). The minimum value of daily maximum temperature (TXn) also displayed a positive trend with less than 30% of the total stations having a significant trend. The trend for TXn shows fairly well spatial distribution over the study area (Figure 2(c)). Most stations with significant increasing tendencies are concentrated on the northern periphery of the Lesser Khingan Range and some few stations in the Greater Khingan range and Liao River Plain. The few stations which displayed negative trends were located furthest to the northeast of the Greater Khingan Range. Moreover, frost days (FD) depicted a decreasing trend during the 58-year period with 96% of the total stations showing a significant decrease at 95% confidence level. Again the eastern side of Changbai Mountain had some stations with the large trend and other few stations in the northern periphery of the Lesser Khingan Range and in the Greater Khingan range (Figure 2(d)).

Figure 3 shows the annual time series of cold indices. TN10p displayed an irregular pattern of variability before mid-1970s followed by a significant decrease up to the late 1990s (Figure 3(a)). The overall regional trend for the TN10p (in the percentage of days) is −1.67 days/decade, statistically significant at 95% confidence level with a trend that oscillates between −5.50 and 1.5 days/decade. Unlike TN10p, the annual time series for the TNn and TXn displayed an increasing trend from the mid-1970s with an overall regional trend of 0.51($p < 0.05$) and 0.26($p > 0.05$) °C/decade, respectively (Figures 3(b) and 3(c)). On average for all stations in the analyzed region, the trend of FD calculated using the Mann–Kendall (MK) test is −2.04 days/decade ($p < 0.05$), and the overall trend ranges from −5.80∼−0.18 days/decades.

Table 1: Description of the temperature indices used in this paper; all the indices are computed using RClimDEX.

Index	Index description	Definitions	Units
Extremely cold temperature indices			
TN10p	Cold night frequency	Percentage of time when daily minimum temperature <10th percentile	%
TNn	Min Tmin (coldest night)	The minimum value of the daily minimum temperature	°C
TXn	Min Tmax (coldest day)	The minimum value of the daily maximum temperature	°C
DTR	Diurnal temperature range	Mean difference between daily maximum temperature and daily minimum temperature	°C
FD	Frost days	Count of days where daily minimum temperature <0°C	Days
ID	Icing days	Count of days where daily maximum temperature <0°C	Days
Extremely warm temperature indices			
TN90p	Warm night frequency	Percentage of time when daily minimum temperature >90th percentile	%
TNx	Max Tmin (warmest night)	Maximum value of daily minimum temperature	°C
TXx	Max Tmax (warmest day)	Maximum value of daily maximum temperature	°C
Tr	Tropical nights	Count of days where daily minimum temperature >20°C	Days
GSL	Growing season length	Period between when daily mean temperature, >5°C for >5 days and daily mean temperature, < 5°C for >5 days	Days

Table 2: Number of meteorological stations with positive (significant at 95% confidence level), no, and negative (significant at the 95% confidence level) trends for the temperature indices during 1957–2015.

Index	Positive trend	No trend	Negative trend
TN10p	3	0	113(**106**)
TNn	112(**70**)	0	4
TXn	110(**31**)	0	6
DTR	14(**2**)	0	102(**79**)
FD	0	0	116(**111**)
ID	3	0	113(**28**)
TN90p	114(**109**)	0	2(**1**)
TNx	109(**48**)	1	6
TXx	98(**23**)	0	18
Tr	113(**66**)	0	3
GSL	116(**88**)	0	0

Noticeable is that before the end of the 1960s, FD witnessed an increasing trend, followed by slight variability in early 1970s, and then a significant decrease from mid-1970s (Figure 3(d)). Our study further revealed that the number of days where the daily maximum temperature is less than 0°C (icing days (ID)) decreased slightly but not significant by −0.91 days/decade. The relative magnitudes of trends were also compared at individual stations (Table 3). As shown in Table 3, approximately 75.86% of the stations displayed a larger trend in TNn (coldest night) than in TXn (coldest day) suggesting larger warming in nighttime compared to daytime.

For the diurnal temperature range (DTR), more than 65% of the total stations witnessed a significant decreasing trend. The overall regional trend in DTR is −0.16°C/decade significant at the 95% confidence level. A rapid decreased occurred from the mid-1970s to 1998, and thereafter, fluctuated variations were observed (Figure 3(e)). Note that the period of significant decrease in DTR coincides with the period of rapid increase in minimum temperature extremes.

3.2. Extremely Warm Indices (TN90p, TNx, TXx, GSL, and Tr). Unlike the TN10p, 96% of the total stations show a significant increasing trend in warm night frequency (TN90p). Several stations located in the Lesser Khingan Range, Songen Plain, and northwest of the Greater Khingan Range had a larger trend (Figure 4(a)). The regional annual trend series for TN90p (in the percentage of days) is 1.79 days/decade ($p < 0.05$) with fluctuated variations before the mid-1970s followed by a remarkable increase (Figure 5(a)). The maximum value of daily minimum temperature (TNx) also showed an increasing trend for the 58-year period under study. However, less than 50% of the stations have a positive significant trend. Similarly, the temperature for the maximum value of daily maximum temperature (TXx) displayed an increasing and decreasing trend in 98 and 18 stations, respectively, over the study area. The trend for the TXx exhibits some geographical patterns (Figure 4(b)). Most stations with the significant positive trend are observed in northern part of the study area, whereas the central part (Songnen Plain), Changbai Mountain, Greater Khingan Range, and Lesser Khingan Range are dominated by the nonsignificant positive trend. The overall regional trend for TNx and TXx are 0.10($p > 0.05$) and 0.08°C/decade ($p > 0.05$), respectively. It is worth noting that both TNx and TXx show a slight increase from mid-1980s (Figures 5(b) and 5(c)). Compared with TXx, approximately 54.31% of the individual stations showed a larger trend in TNx (Table 3). This further confirms a larger nighttime warming as compared with daytime.

The growing season length (GSL) results showed that all stations in the study area have a positive trend with 76% of the total station being significant. Spatially, stations located in the Songnen Plain, Sanjiang Plain, Liao River Plain, and Greater Khingan Range displayed a significant positive trend (Figure 4(c)). From the regional annual series of the GSL (Figure 5(d)), it is clear that there was a decreasing trend from 1957 to early 1970s followed by slight variations and then remarkable increase from mid-1970s. Taking 116 stations as a whole, the increased trend of GSL is 1.67 days/decade ($p < 0.05$). Similarly, tropical nights (Tr) witnessed increasing tendencies in 113 out of 116 stations with 57% of the stations having a significant trend at 95% confidence level. It is quite interesting that the spatial distribution and annual series of trends for tropical nights almost exhibit

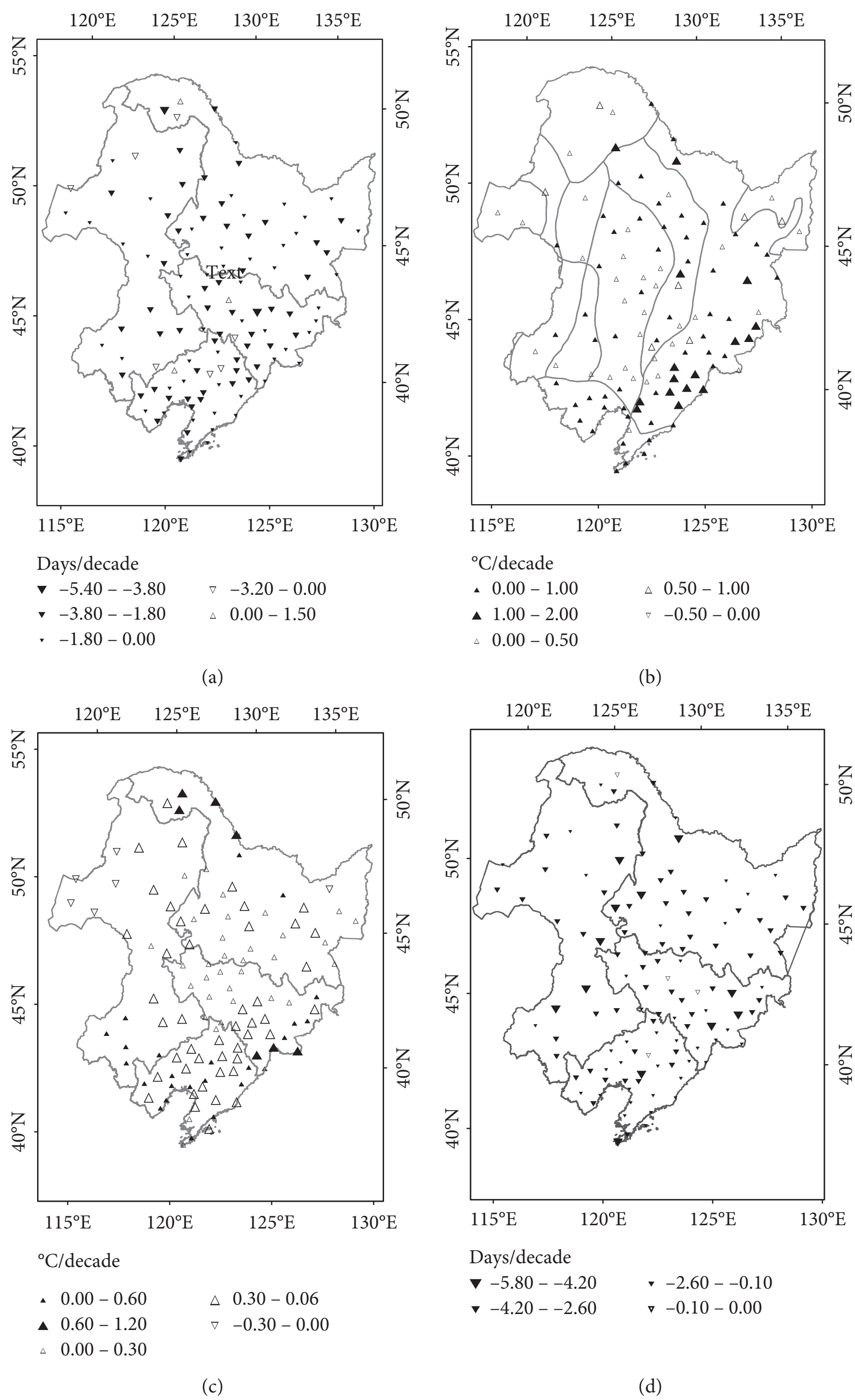

Figure 2: Spatial distributions of trends per decade for the period of 1957–2015 in Northeast China for extremely cold temperature indices (TN10p (a), TNn (b), TXn (c), and FD (d)). The up and down triangles represent positive and negative trend, respectively. Filled triangles indicate that the trend is significant at 95% confidence level, and vice versa. The size of the triangle is proportional to the magnitude of the trends.

a pattern similar to that of GSL. Most of the stations located in the Songnen Plain have positive trends which are significant and the overall regional trend for Tr is 0.96 days/decades ($p < 0.05$).

3.3. Comparison of Linear Trend for Cold and Warm Temperature Extremes. Relative magnitudes of linear trends in cold versus warm indices were also compared in this study. From Table 3, approximately 98.27% of stations have a larger

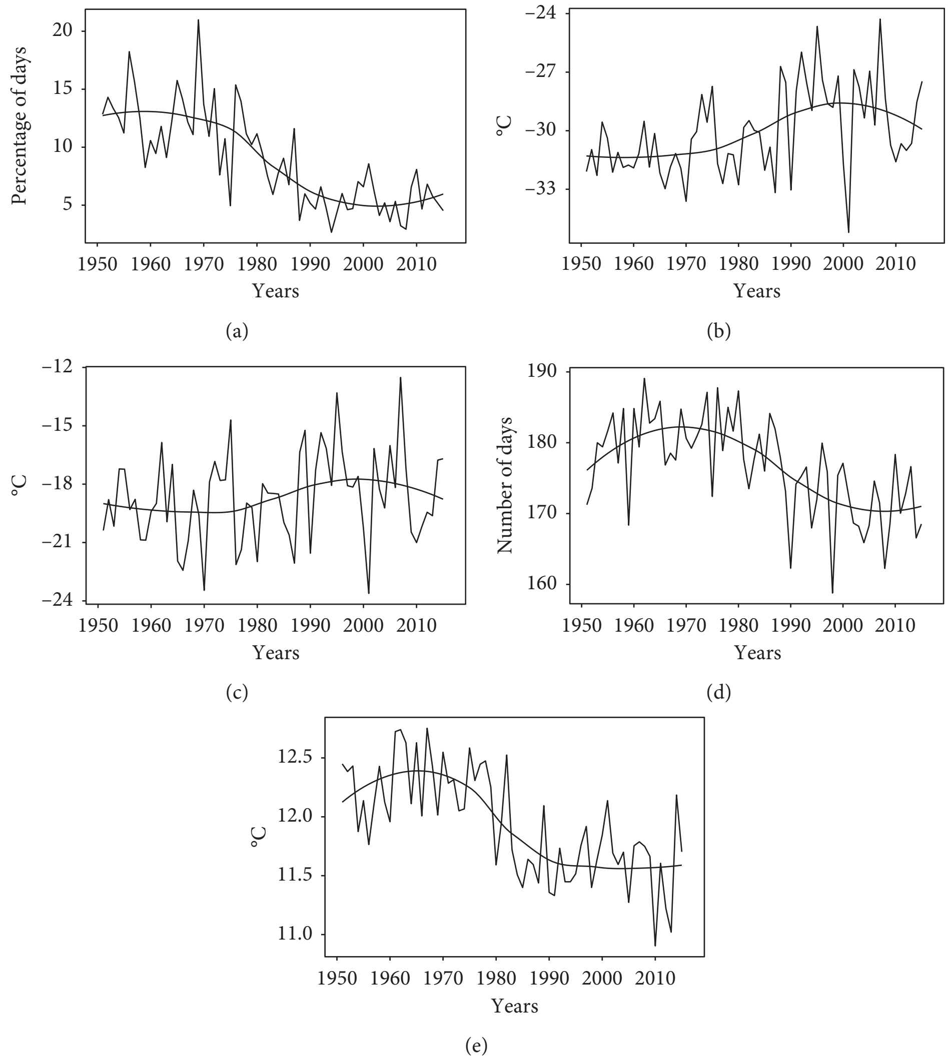

Figure 3: Presentation of regional time series for extremely cold temperature indices. (a) Cold night frequency (TN10p). (b) Annual minimum value of daily minimum temperature (TNn). (c) Annual minimum value of daily maximum temperature (TXn). (d) Frost days (FD). (e) Diurnal temperature range (DTR). The heavy bold solid black line is an annual smoothing mean.

Table 3: Number and percentage of stations where the linear trend of one index is of greater magnitude than that of the other.

Index	Number of stations	Percentage
Tn90p > Tn10p	114	98.27
TNn > TNx	110	94.83
TXn > TXx	103	88.79
TNn > TXn	88	75.86
TNx > TXx	63	54.31
GSL > FD	116	100
GSL > ID	116	100

trend in TN90p compared to TN10p. Moreover, the overall regional trend of TN90p (1.79 days/decade) is relatively larger than that of TN10p (−1.67 days/decade). This implies that the occurrence frequency of warm night is much higher than that of cold night. For the TNn and TNx, the overall regional trend of TNn in all stations as a whole of 0.51°C/decade is five times more than that of TNx (0.10°C/decade). In addition, roughly 94.83% of the stations have a larger trend in TNn than that in TNx. Similarly, for TXn and TXx, the overall regional of TXn (0.26°C/decade) is remarkably higher than that of TXx (0.08°C/decade). Moreover, 103 stations have a larger trend in TXn compared to that in TXx. Based on the trend of magnitude, the minimum index TXn which occurs in winter warms faster than the maximum index TXx implying declined daytime interdiurnal variability when extremes are assessed. From the results, it is also clear that the rate of change in a maximum of daily minimum and maximum temperatures (TNx and TXx) has a lower trend than that in a minimum of daily minimum and maximum temperatures (TNn and TXn).

3.4. Seasonal Variation of Temperature Extremes. The seasonal variation of temperature extremes is shown in Table 4. It is quite clear that the greatest contribution to the decrease in cold night frequency (TN10p) comes from winter and

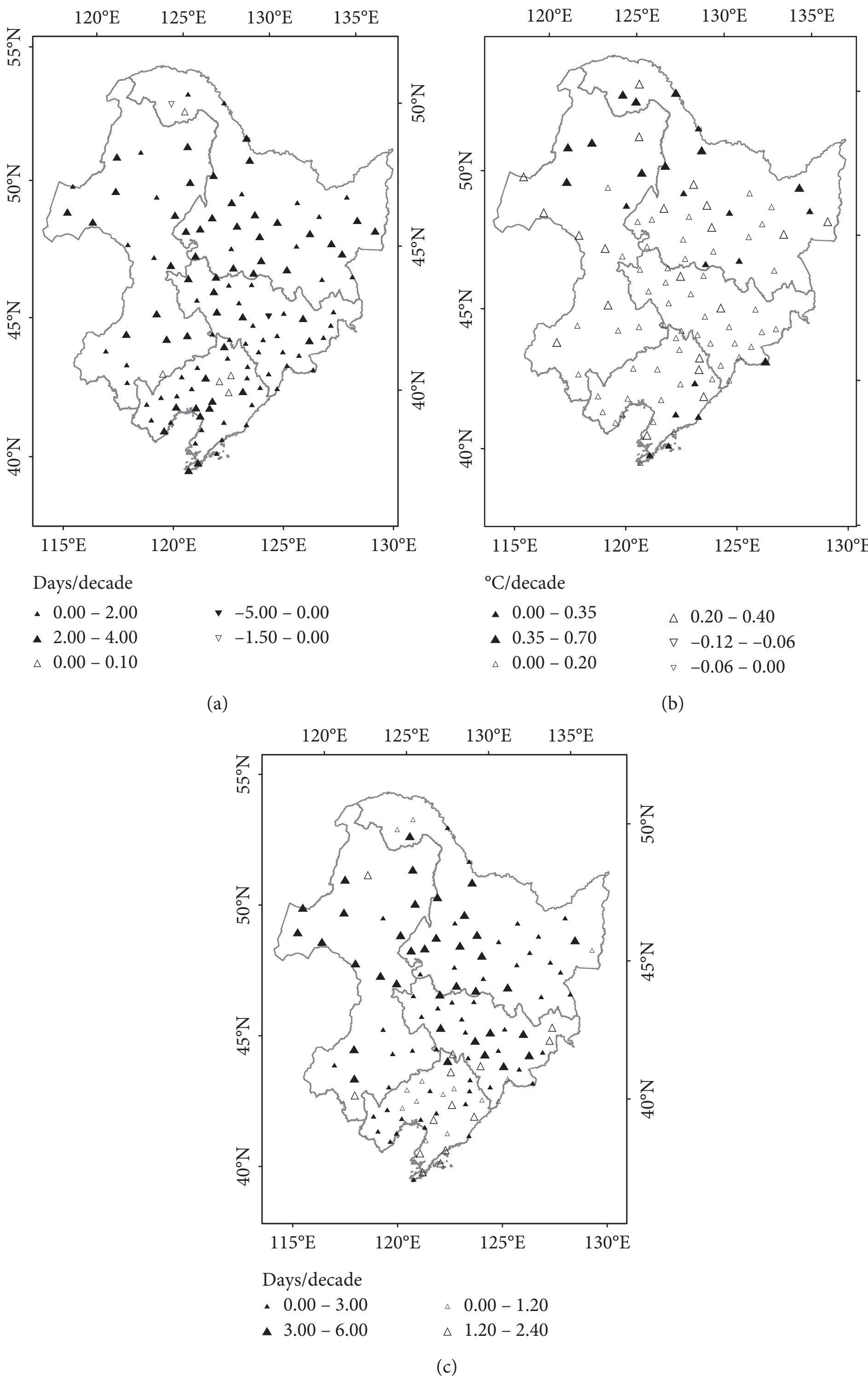

Figure 4: Spatial distributions of trends per decade for the period of 1957–2015 in Northeast China for extremely warm temperature indices (TN90p (a), TXx (b), and GSL (c)). The up and down triangles represent positive and negative trends, respectively. The filled triangles indicate that the trend is significant at 95% confidence level, and vice versa. The size of the triangle is equivalent to the magnitude of the trends.

spring. The occurrence of TN10p has decreased at −2.24 and −2.01 days/decade in winter and spring, respectively, for Northeast China as a whole, which is about two times more than that in summer (−1.23 days/decade). Unlike the TN10p, the occurrence of warm night frequency (TN90p) shows a remarkable increase in summer at an average of 2.14 days/decade. For the minimum value of daily minimum temperature (TNn), the greatest average increase is

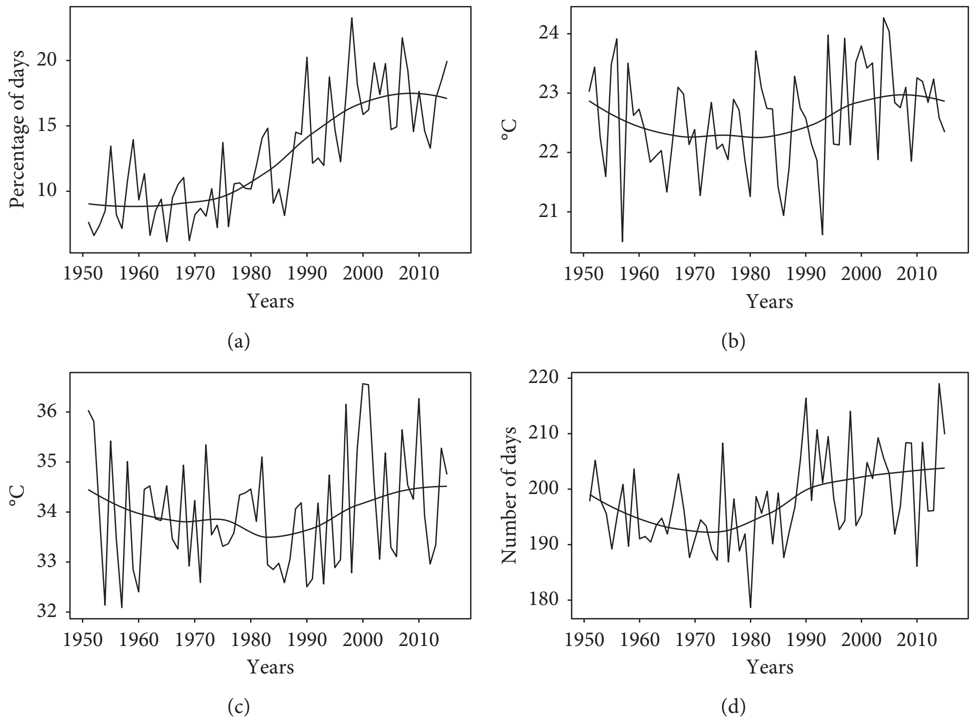

Figure 5: Presentation of regional time series for extremely warm temperature indices. (a) Warm night frequency (TN90p). (b) Annual maximum value of daily minimum temperature (TNx). (c) Annual maximum value of daily maximum temperature (TXx). (d) Growing season length (GSL). The heavy bold solid black line is the annual smoothing mean.

Table 4: Seasonal mean variations of temperature extreme indices over Northeast China.

		Songnen Plain	Sanjiang Plain	Liao River Plain	Changbai Mountains	The Greater Khingan Range	The Lesser Khingan Range	Northeast China
TN10p	Winter	-1.76^{***}	-1.37^{**}	-2.38^{***}	-2.84^{***}	-1.28^{ns}	-1.73^{ns}	-2.24^{***}
	Spring	-1.68^{***}	-1.94^{***}	-2.37^{***}	-2.55^{***}	-1.62^{***}	-1.86^{***}	-2.01^{***}
	Summer	-1.28^{***}	-1.49^{***}	-0.99^{**}	-1.16^{***}	-1.65^{***}	-1.55^{***}	-1.23^{***}
	Autumn	-1.25^{***}	-0.95^{*}	-1.75^{***}	-1.17^{***}	-1.18^{**}	-0.60^{ns}	-1.21^{***}
TNn	Winter	0.37^{ns}	0.41^{*}	0.60^{***}	0.55^{***}	0.50^{***}	0.61^{***}	0.48^{***}
	Spring	0.32^{ns}	0.33^{ns}	0.63^{***}	0.40^{***}	0.30^{ns}	0.48^{***}	0.40^{***}
	Summer	0.19^{ns}	0.31^{*}	0.20^{ns}	0.17^{ns}	0.45^{**}	0.19^{ns}	0.20^{**}
	Autumn	0.20^{ns}	0.33^{*}	0.35^{*}	0.24^{ns}	0.40^{**}	-0.06^{ns}	0.18^{*}
TXn	Winter	0.23^{ns}	0.26^{ns}	0.41^{**}	0.27^{ns}	0.54^{***}	0.82^{***}	0.24^{*}
	Spring	0.20^{ns}	0.25^{ns}	0.28^{**}	0.19^{ns}	0.09^{ns}	0.45^{***}	0.22^{*}
	Summer	0.14^{ns}	0.08^{ns}	0.07^{ns}	0.11^{ns}	0.24^{**}	0.03^{ns}	0.10^{ns}
	Autumn	0.14^{ns}	0.27^{ns}	0.12^{ns}	0.08^{ns}	0.28^{ns}	0.17^{ns}	0.07^{ns}
TN90p	Winter	1.98^{***}	1.24^{**}	2.05^{***}	1.21^{***}	1.61^{ns}	0.83^{ns}	1.50^{***}
	Spring	2.87^{***}	2.31^{***}	2.24^{***}	1.59^{***}	2.18^{***}	1.60^{***}	1.83^{***}
	Summer	2.40^{***}	2.35^{***}	1.34^{**}	1.84^{***}	2.10^{***}	2.16^{***}	2.14^{***}
	Autumn	1.51^{***}	1.23^{***}	1.32^{***}	0.99^{***}	2.15^{***}	0.81^{ns}	1.28^{***}
TNx	Winter	0.40^{***}	0.36^{*}	0.45^{***}	0.32^{**}	0.37^{*}	0.045^{**}	0.030^{**}
	Spring	0.49^{***}	0.45^{***}	0.41^{***}	0.34^{***}	0.50^{***}	0.032^{**}	0.040^{***}
	Summer	0.19^{***}	0.21^{**}	0.10^{ns}	0.09^{ns}	0.41^{***}	0.011^{ns}	0.013^{*}
	Autumn	0.35^{***}	0.33^{***}	0.22^{**}	0.23^{***}	0.43^{***}	0.008^{ns}	0.024^{***}
TXx	Winter	-0.01^{ns}	0.02^{ns}	0.17^{ns}	0.10^{ns}	0.08^{ns}	0.004^{ns}	0.003^{ns}
	Spring	0.24^{*}	0.19^{ns}	0.23^{*}	0.24^{*}	0.38^{ns}	0.008^{ns}	0.023^{*}
	Summer	0.22^{*}	0.06^{ns}	0.01^{ns}	-0.01^{ns}	0.18^{ns}	0.026^{ns}	0.001^{*}
	Autumn	0.14^{ns}	0.24^{*}	0.12^{ns}	0.10^{ns}	0.24^{ns}	0.028^{ns}	0.011^{ns}

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; ns = not significant.

0.48°C/decade in winter, which is twice the mean increase in summer (0.20°C/decade) and autumn (0.18°C/decade). In the four seasons, the variation of temperature extremes had different subregional features (Table 4). In winter and spring, the occurrence of TN10p decreased remarkably in the Changbai Mountains. For TN90p, the increase was relatively higher in summer in Songnen Plain and Sanjiang Plain. Interestingly, in winter and spring, TNn depicted significant relative higher increases in the mountain regions (Table 4).

3.5. Changepoint Analysis. In the present study, the changepoint analysis indicates changepoints for some of the climate extreme indices analyzed (Table 5). For extremely cold indices, the cold night frequency (TN10p) shows a clear changepoint at around 1984 at 95% confidence level. Before the changepoint, the mean TN10p was 12.28% (1957–1984) and changed to 5.83% thereafter (1984–2015) (Figure 6(a)). In 1990, warm night frequency (TN90p) displayed significant abrupt change. However, unlike TN10p, TN90p displayed a positive shift (Figure 6(d)). Prior to the changepoint, the mean TN90p was 9.65% (1954–1990) and changed to 16.40% thereafter (1990–2015). For the annual minimum value of daily minimum temperature (TNn), about 74% of the total station showed a positive shift in the study area. The changing point was detected in 1990 with an average mean temperature of −31.11°C before 1990 and −28.75°C thereafter (Figure 6(b)). The results further indicate that a changing point occurred in both numbers of FD and GSL around 1990, with a mean number of days decreasing and increasing from 180.45 to 194.22 days before 1991 and 171.28 and 202.07 days thereafter, respectively (Figures 6(c) and 6(e)).

4. Discussion

According to the Fifth Intergovernmental Panel on Climate Change (IPCC) technical report, climate extremes such as increasing in the number of heavy rainfall events, increasing in warm night frequency, and decreasing of cold are catalyzed by global warming [30]. Mid-latitude zones such as Northeast China, an agricultural region in China, are very sensitive to climate change due to geographical location, humid, and semiarid climatic characteristics and influence of human activities [18]. This study analyzed the spatial and temporal trend characteristics and abrupt change of temperature extremes in order to get a clear comprehension of the interaction between climate change and the regional climate variability.

4.1. Spatial and Seasonal Variation of Temperature Extremes. Our results showed decreasing and increasing trends in the occurrence of cold night frequency (TN10p) and warm night frequency (TN90p), respectively. This means that most meteorological stations in the Northeast China region have recorded more warm night and fewer cold nights during the period of 1957–2015. Moreover, our study revealed that the increasing trends of TNn (coldest night) (0.51°C/decade) and TNx (warmest night) (0.10°C/decade) were larger than those of TXn (coldest days) (0.26°C/decade) and TXx (warmest night) (0.08°C/decade), respectively. This suggests faster warming of air temperature in nighttime compared to that in daytime. Consequently, the diurnal temperature range (DTR), which is a measure of temperature variability, depicted a remarkable decrease in Northeast China with a rate of −0.16°C/decade, significant at the 0.05 level. The rate of decrease of DTR is remarkably higher than that at the global scale (−0.08°C/decade) [31] during 1951–2003 and Southern and West Africa (−0.01) [32] during 1961–2000, Middle East (−0.12) [33] during 1950–2003 and slightly lower than that in Eastern and Central Tibetan Plateau (−0.20) during 1961–2005 and China (−0.18) [2] during 1961–2003. The observed differences may be explained by the fact that Northeast China is a humid and semiarid region characterized by unique mountains, plains, and rivers hence very sensitive to climate warming. Associating with the increased warming of temperature in the Northeast China region is the significant increase in both growing season length and tropical nights and subsequent reduction in frost days.

In assessing the seasonal contribution, the occurrence of cold night frequency (TN10p) largely decreased in winter and spring, while for the warm night frequency (TN90p), it largely increased in summer. Moreover, the minimum value of daily minimum temperature (TNn) largely increased in winter which conforms with previous studies [34]. According to You et al. [2], winter temperatures are warming more rapidly compared to summer temperatures probable because of less water vapor in the air in winter than that in summer. Spatially, most of the stations with a significant warming trend in minimum temperatures were observed in the Changbai Mountains, Lesser Khingan Range, and few stations in the Greater Khingan Range. Stations located in Songnen Plain and Sanjiang Plain and a few on the northern part of the Greater Khangan Range recorded nonsignificant positive trends. This shows that the mountain regions in Northeast China are becoming warmer faster than the lowland plain regions.

4.2. Temporal Variation of Temperature Extremes. For the temporal variation, minimum temperature extremes show a regular pattern characterized by no obvious change before the periods of the mid-1970s and after 1998 (Figures 3(b) and 3(c)). A notable increasing trend in the minima started in the mid-1970s in accordance with previous studies in China [2, 35]. However, the maximum temperature extremes reveal slight increases from the mid-1980s which is ten years later compared to the minimum temperature extremes. It should be noted that changes on land surface as a result of urbanization and increases in aerosols which may play a crucial role in warming the surface air temperature have not been ruled out for the above observations. According to Feng et al. [36] and Dai et al. [37], surface albedo, latent heat flux and cloud cover are major drivers of maximum temperature extremes. Kaiser [38] reported a significant decrease of cloud cover in Northeast China as from 1950, and on the contrary, a remarkable decrease in surface albedo was noticed in the 1960s to mid-1980s [39]. Therefore, since the period of decrease in surface albedo happened together with a decrease in cloud cover [35], probably the slight increase in minimum temperature extremes in Northeast China was as the result of increases in aerosols and changes on the land surface. Model simulations indicate that land use change derived by urban development can lead to an increase of the area experiencing extreme temperatures but mainly affect the nighttime (minima) temperatures [40]. However, we should be careful

Table 5: Analysis results of changing points of the climate extreme indices in Northeast China.

Climate indices	Trend test		Turning points				
	Trend rate	Significant level	Shift year	Mean before shift	Mean after shift	Number of stations with a positive shift	Number of stations with a negative shift
TN10p	−1.67 d/10 yr	0.05	1984*	12.28%	5.83%	27	89
TN90p	1.79 d/10 yr	0.05	1990*	9.65%	16.40%	98	18
TNn	0.51°C/10 yr	0.05	1990*	−31.11°C	−28.75°C	86	30
FD	−2.04 d/10 yr	0.05	1990*	180.45 days	171.28 days	25	91
GSL	1.67 d/10 yr	0.05	1990*	194.22 days	202.07 days	98	18

* $p < 0.05$.

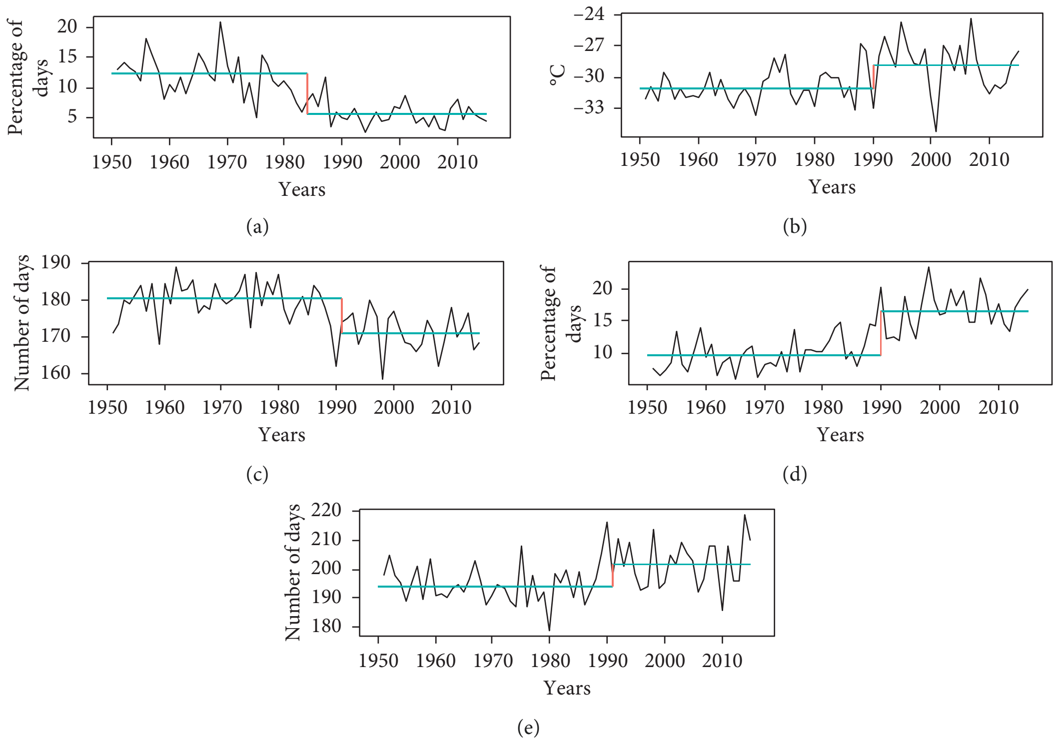

Figure 6: Annual changes of extreme temperature indices in Northeast China. (a) Cold night frequency (TN10p). (b) Annual minimum value of daily minimum temperature (TNn). (c) Frost days (FD). (d) Warm night frequency (TN90p). (e) Growing season length (GSL). The blue line indicates the mean value before and after the changepoint, while red indicates the magnitude of change.

in agreeing with this explanation since Gong et al. [41] also linked the changes in extreme low and high temperature to Northern, North Pacific, and Southern Oscillations in China. It is also quite clear that the minimum temperature extremes increased rapidly compared to maximum temperature extremes between the period of the mid-1970s and mid-1980s.

4.3. Implication of Temperature Extremes on Agriculture in Northeast China. Being an agricultural region, changes in temperature extremes could mean a lot in Northeast China. The decrease of cold extremes over Northeast China can reduce agricultural lose and damages caused by low temperatures. Moreover, warming in Northeast China could imply an increase in the potential agricultural area hence increase in production. Liu et al. [42] reported that warming enabled hybrid cereals to be planted in Heilongjiang Province in Northeast China which was formally too cold for growing maize before warming. Unlike in South China and lower reaches of the Yangtze where multiple cropping in a year has been possible, in Northwest and Northeast areas of China, cropping systems have been only once per year [43]. However, according to different researchers, multiple cropping systems will be shifting towards areas where initial single cropping was the only option (e.g., Northeast China) due to current warming and increase in GSL [43–46]. The discrete subgeographical regional variations of temperature extremes denote different climate responses to the warming scenarios in different parts of Northeast China. For that reason, proper actions should be taken in order to deal with the changes in climate extremes and their impact.

5. Conclusions

In this study, trend characteristics, their spatial distribution, and changepoint analysis of temperature extremes for 116 stations in Northeast China over the period of 1957–2015 were analyzed using a set of extreme climate indices. We conclude that the occurrence frequencies of cold events (cold night frequency (TN0p)) and extremely warm events (warm night frequency (TN90p)) have decreased and increased, respectively. Therefore, the region is experiencing more warm night and fewer cold nights. Moreover, variations in temperature extremes have not been uniform with warming trends in daily minimum temperature being faster compared to daily maximum temperature extremes. The diurnal temperature range (DTR) depicted a remarkable decrease in Northeast China as a result of rapid warming in the minimum. Warming in Northeast China led to a reduction in a number of frost days (FD) and icing days (ID). Note, however, that the number of warm days, i.e., GSL and Tr increased at a rate of 1.67 and 0.96 days/decades, respectively. Spatially, most of the stations with a significant warming trend in minimum temperatures were located in the Changbai Mountain, Greater Khingan Range, and Lesser Khingan Range. This implies that the mountainous regions of Northeast China are warming faster than the lowland plain regions. On the contrary, most stations located in Songnen Plain, Sanjiang Plain, and Liao River Plain displayed the significant positive trend in GSL and Tr. This could have a positive impact on crop production in the region.

Data Availability

All the data used in the manuscripts are available by contacting the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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