Changes in Climatic Factors and Extreme Climate Events in Northeast China during 1961–2010

ZHAO Chun-Yu¹, WANG Ying¹, ZHOU Xiao-Yu¹, CUI Yan¹, LIU Yu-Lian², SHI Da-Ming³, YU Hong-Min², LIU Yu-Ying³

¹Regional Climate Center of Shenyang, Liaoning Meteorological Service, Shenyang 110179, China
²Climate Center of Heilongjiang, Heilongjiang Meteorological Service, Harbin 150000, China
³Climate Center of Jilin, Jilin Meteorological Service, Jilin 132000, China

Abstract

This study focuses on examining the characteristics of climate factors and extreme climate events in Northeast China during 1961–2010 by using daily data from 104 stations, including surface air temperature, precipitation, wind speed, sunshine duration, and snow depth. Results show that annual mean temperature increased at a significant rate of 0.35 ± 0.05°C per decade, most notably in the Lesser Khingan Mountains and in winter. Annual rainfall had no obvious linear trend, while rainy days had a significant decreasing trend. So, the rain intensity increased. High-temperature days had a weak increasing trend, and low-temperature days and cold wave showed significant decreasing trends with rates of −3.9 d per decade and −0.64 times per decade, respectively. Frequency and spatial scope of low-temperature hazard reduced significantly. Warm days and warm nights significantly increased at 1.0 and 2.4 d per decade, while cold days and cold nights decreased significantly at −1.8 and −4.1 d per decade, respectively. The nighttime warming rate was much higher than that for daytime, indicating that nighttime warming had a greater contribution to the overall warming trend than daytime warming. The annual mean wind speed, gale days, and sunshine duration had significant decreasing trends at rates of −0.21 m s⁻¹ per decade, −4.0 d per decade and −43.3 h per decade, respectively. The snow cover onset dates postponed at a rate of 1.2 d per decade, and the snow cover end date advanced at 1.5 d per decade, which leads to shorter snow cover duration by −2.7 d per decade. Meanwhile, the maximum snow depth decreased at −0.52 cm per decade. In addition, the snow cover duration shows a higher correlation with precipitation than with temperature, which suggests that precipitation plays a more important role in maintaining snow cover duration than temperature.

Keywords: climatic factors; extreme climate events; climate change; Northeast China


1 Introduction

The IPCC Fourth Assessment Report (AR4) [IPCC, 2007] showed that global climate had undergone a significant warming change; observations also demonstrated that global mean surface air temperature increased 0.74°C during 1906–2005, and the warming has even accelerated by 0.13°C per decade during the most recent 50 years. In China, the mean temperature increased 1.38°C during 1951–2009 [ECSCNARCC, 2011]; precipitation did not show any significant change trend, but there was a 20–30 years
oscillation. Northeast China, which includes Liaoning, Jilin and Heilongjiang provinces, is an important grain production base of China. Along with global climate change and increasing urbanization in recent years, the regional economic and social development in Northeast China faces multiple challenges. Regional economy has demonstrated high sensitivity to global and regional climate changes. As a result, the increase of extreme weather/climate events has brought great pressure on disaster prevention and mitigation. In order to provide better decision-making services for regional economic development, it is critical to perform detailed analyses on climate variations in Northeast China during the past half century.

2 Data and methodology

The in situ data used in this study include temperature, precipitation, wind speed, sunshine duration, snow and other climatic factors during 1961–2010 at 104 stations selected from 162 stations in Northeast China based on homogeneity test (Fig. 1). The definitions of terminologies used in the text are listed in Table 1 below.

3 Results

3.1 Temperature

3.1.1 Mean temperature

Annual mean temperature had a significant increasing trend at 0.35°C per decade in Northeast China during 1961–2010. The increase rate is higher than the global (0.13°C per decade) [IPCC, 2007] and national rate (0.23°C per decade) [ECSCNARCC, 2011] during the same period. From 1960s to 1980s, temperature was below normal, but it has shown an upward trend since the late 1980s. Mean temperature in the four seasons all showed significant increasing trends, being largest in winter at 0.55°C per decade, followed by spring, autumn and summer. The diurnal temperature range had a significant decreasing trend at {0.29 ± 0.18°C per decade. Geographically, the warming rate showed an increase pattern from south to north, being largest at 0.61–0.64°C per decade on the northern Lesser Khingan Mountains (Fig. 2).

3.1.2 Extreme temperature

High-temperature days with daily maximum temperature >35°C had a weak increasing trend in Northeast China during 1961–2010, which is consistent with the results for the great North China during a similar period [Zhai and Pai, 2003]. Low-temperature days with daily minimum temperature ≤–25°C had a significant decreasing trend of {3.9 d per decade. Areas with annual low-temperature days more than 40 d were located in the north of 45°N in the 1960s (Fig. 3), and the boundary had gradually moved northward since the 1970s. In the 1990s, the boundary was near 47°N, but it moved southward slightly in the 2000s.

3.1.3 Warm days, warm nights, cold days, and cold nights

The regional mean annual warm days had a weak increasing trend (1.0 d per decade) during 1961–2010. Most regions had an increasing trend except for central Liaoning and central and western Jilin, with strong increase of 2.1–4.0 d per decade in northern Heilongjiang and southern Liaoning (Fig. 4a). Warm nights had a significant increasing trend of 2.4 d per decade, and the highest (4.1–5.7 d per decade) was found in...
Table 1  Definition of terminologies

<table>
<thead>
<tr>
<th>Element</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainy day</td>
<td>Daily precipitation ≥ 0.1 mm</td>
</tr>
<tr>
<td>Rainfall intensity</td>
<td>The ratio of rainfall amount and rainy days</td>
</tr>
<tr>
<td>Light rain</td>
<td>0.1 mm ≤ daily rainfall ≤ 9.9 mm</td>
</tr>
<tr>
<td>Moderate rain</td>
<td>10.0 mm ≤ daily rainfall ≤ 24.9 mm</td>
</tr>
<tr>
<td>Heavy rain</td>
<td>25.0 mm ≤ daily rainfall ≤ 49.9 mm</td>
</tr>
<tr>
<td>Rainstorm</td>
<td>Daily rainfall ≥ 50.0 mm</td>
</tr>
<tr>
<td>Very light snowfall</td>
<td>Daily snowfall ≤ 0.1 mm</td>
</tr>
<tr>
<td>Light snowfall</td>
<td>0.1 mm ≤ daily snowfall ≤ 2.4 mm</td>
</tr>
<tr>
<td>Moderate snowfall</td>
<td>2.5 mm ≤ daily snowfall ≤ 4.9 mm</td>
</tr>
<tr>
<td>Heavy snowfall</td>
<td>5.0 mm ≤ daily snowfall ≤ 9.9 mm</td>
</tr>
<tr>
<td>Snowstorm</td>
<td>Daily snowfall ≥ 10.0 mm</td>
</tr>
<tr>
<td>Warm day</td>
<td>Daily maximum temperature higher than the 95th percentile during 1971–2010</td>
</tr>
<tr>
<td>Warm night</td>
<td>Daily minimum temperature higher than the 95th percentile during 1971–2010</td>
</tr>
<tr>
<td>Cold day</td>
<td>Daily maximum temperature lower than the 5th percentile during 1971–2010</td>
</tr>
<tr>
<td>Cold night</td>
<td>Daily minimum temperature lower than the 5th percentile during 1971–2010</td>
</tr>
<tr>
<td>Cold wave</td>
<td>Days when daily minimum temperature lower than 4°C and daily minimum (or daily mean) temperature decreases more than 8°C within 24 h, or 10°C within 48 h, or 12°C within 72 h</td>
</tr>
</tbody>
</table>

Seasons: winter (last December to February), spring (March to May), summer (June to August), and autumn (September to November)

Figure 2  Spatial distribution of linear trends in annual mean temperature in Northeast China during 1961–2010 (+ denotes the trend significant at 95% confidence level)

southwestern Heilongjiang (Fig. 4b).

A significant decreasing trend of −1.8 d per decade for cold days was seen during 1961–2010. The decreasing trend was most distinguished (−4.3 to −3.0 d per decade) in eastern and northern Heilongjiang, eastern Jilin, most parts of Liaoning (Fig. 5a). Cold nights also had a significant decreasing trend (−4.1 d per decade for regional mean) at most stations (96%) (Fig. 5b).

3.1.4 Cold wave

The number of cold waves decreased significantly (−0.64 times per decade) in Northeast China during 1961–2010 (Fig. 6). Decreasing trends are found in most areas of Northeast China, and 65% stations have significant trends at 95% confidence level (Fig. 7).

3.1.5 Cold hazard

During 1961–2010, a wide range of cold hazards
Figure 4  Spatial distribution of linear trends in warm days (a), and warm nights (b) in Northeast China during 1961–2010 (+ denotes the trend significant at 95% confidence level)

Figure 5  Spatial distribution of linear trends in cold days (a), and cold nights (b) in Northeast China during 1961–2010 (+ denotes the trend significant at 95% confidence level)

Figure 6  Variations of the number of cold waves in Northeast China during 1961–2010

happened mainly in the mid-1960s and 1970s. At more than 90% stations, cold hazards were observed in 1969, 1972 and 1976. The most serious cold hazard happened in 1976 with 98% stations affected. In the 1980s and 1990s, cold hazards with wide range occurred occasionally, only 50%–70% stations recorded cold hazards in 1981, 1983, 1986, 1987 and 1992. Since the end of the 1990s, large scale cold hazards have scarcely occurred (Fig. 8).

The number of cold hazards had a large decadal variation in Northeast China (Fig. 9). In the 1960s, cold hazards occurred most frequently (7–9 times per decade) in northern and western Heilongjiang, whereas
3.2 Precipitation

3.2.1 Rainfall amount

Regional mean annual rainfall had no significant linear trend during 1961–2010, but it had large decadal variations. From the mid-1960s to the early 1980s, and from the late 1990s to the 2000s, it was below normal; in the early and mid-1960s, and from the mid-1980s to the mid-1990s, it was above normal (Fig. 10). It decreased significantly in southeastern Liaoning, and showed a weak increase trend in most parts of Heilongjiang and in eastern and central Jilin (Fig. 11a). This is consistent with decrease in the southeastern area and with increase in the northern part of Northeast China [Ren et al., 2005]. Seasonally, rainfall showed a significant increasing trend at 9.3% and 5.4% per decade in winter and spring, respectively; in contrast, it had a weak decreasing trend at −1.6% and −3.3% per decade in summer and autumn, respectively.

3.2.2 Rainy days

The annual rainy days had a significant decreasing trend (−2.4 d per decade) in Northeast China during 1961–2010. This is consistent with previous studies [Sun et al., 2007; Wang and Zhai, 2008]. Geographically, the decreasing trends were most notable in eastern and southern Liaoning, northeastern and central parts of Heilongjiang (−10.7 to −6.0 d per decade) (Fig. 11b). The rainy days in spring and winter had an insignificant increasing trend at 0.4 and 0.2 d per decade, respectively, while it had a significant decreasing trend of −1.9 and −1.2 d per decade in summer and autumn, respectively.

3.2.3 Rain intensity

Annual rain intensity had a very weak increasing trend during 1961–2010. Geographically, the largest increase was found in southeastern Liaoning with 0.6–0.7 mm d$^{-1}$ per decade (Fig. 12). The rain intensity in the four seasons had a weak increasing trend, only in summer and winter significant (0.3 and 0.1 mm d$^{-1}$ per decade, respectively).
Figure 9 Spatial distribution of the number of cold hazards in Northeast China during 1961–2010 (unit: times per decade)

Figure 10 Variation of annual rainfall percentage anomalies in Northeast China during 1961–2010

3.2.4 Extreme precipitation

The regional mean annual light-rain days had a significant decreasing trend (~2.3 d per decade), most notably in summer and autumn and geographically in Liaoning, followed by Heilongjiang and Jilin (Table 2).

There is no obvious linear trend in moderate-rain days, heavy-rain days and rainstorm days (Fig. 13). This indicates that the decrease of overall rainy days is mainly contributed by the decrease of light-rain days.

The regional mean snowfall days had a significant decreasing trend (~2.8 d per decade) during 1961–2010 (Fig. 14). This was mainly contributed by the decreasing of very-light-snowfall and light-snowfall days,
Figure 11 Spatial distribution of linear trends in (a) annual rainfall, and (b) annual rainy days in Northeast China during 1961-2010 (+ denotes the trend significant at 95% confidence level)

Geographically, the most distinguished decrease of very-light-snowfall days was in Heilongjiang, followed by Jilin. The decrease rate of very-light-snowfall days in Liaoning was smaller than that in the other two provinces. The largest decrease trend of annual snowfall days was found in Jilin province, followed by Heilongjiang province (Table 3).

3.3 Snow

The regional mean snow cover onset dates postponed at 1.2 d per decade during 1961–2010. It postponed at 4.1–5.1 d per decade in southwestern and northeastern Heilongjiang province, while it advanced at 4.0–7.1 d per decade in western Liaoning province (Fig. 15a).

The regional mean snow ending date advanced at the rate of 1.5 d per decade during 1961–2010. It advanced at 6.0–6.9 d per decade in southeastern Liaoning, while it postponed very weak at some stations (Fig. 15b).

Table 2 Linear trend in annual light-rain days for different region and in seasonal light-rain days for different season in Northeast China during 1961-2010 (unit: d per decade)

<table>
<thead>
<tr>
<th>Annual light-rain days in different region</th>
<th>Linear trend</th>
<th>Seasonal light-rain days for Northeast China</th>
<th>Linear trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast China</td>
<td>−2.3*</td>
<td>Spring</td>
<td>0.3</td>
</tr>
<tr>
<td>Heilongjiang</td>
<td>−2.5*</td>
<td>Summer</td>
<td>−1.7*</td>
</tr>
<tr>
<td>Jilin</td>
<td>−0.9</td>
<td>Autumn</td>
<td>−1.2*</td>
</tr>
<tr>
<td>Liaoning</td>
<td>−3.0*</td>
<td>Annual</td>
<td>−2.3*</td>
</tr>
</tbody>
</table>

Note: * denotes the trend significant at 95% confidence level.
Regional mean snow cover duration decreased at \(-2.7\) d per decade during 1961–2010. The most distinguished decrease (\(-7.7\) to \(-4.0\) d per decade) took place in the southern parts of central Liaoning and southeastern Liaoning, northern and southeastern Jilin, northern and southern Heilongjiang (Fig. 16a). Meanwhile, it increased slightly (0.1–6.2 d per decade) in the southern parts of the Liaohé River Plain.

Regional mean maximum snow depth decreased at \(-0.5\) cm per decade during 1961–2010. It decreased at \(-3.4\) to \(-2.0\) cm per decade in southwestern Heilongjiang and eastern Liaoning, while it had a slight increase (0.1–2.0 cm per decade) in northern Liaoning, southern Liaohé River Plain, central and northwestern Jilin (Fig. 16b).

The snow cover onset dates had a significant cor-

Table 3 Linear trends in annual snowfall days at different regions (unit: d per decade)

<table>
<thead>
<tr>
<th>Region</th>
<th>Very-light-snowfall</th>
<th>Light snowfall</th>
<th>Moderate snowfall</th>
<th>Heavy snowfall</th>
<th>Snowstorm</th>
<th>All snowfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast</td>
<td>(-2.6^*)</td>
<td>(-0.3)</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>(-2.8^*)</td>
</tr>
<tr>
<td>Heilongjiang</td>
<td>(-3.4^*)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.0</td>
<td>(-2.9^*)</td>
</tr>
<tr>
<td>Jilin</td>
<td>(-3.1^*)</td>
<td>(-0.7)</td>
<td>(-0.1)</td>
<td>(-0.1)</td>
<td>(-0.1)</td>
<td>(-4.0^*)</td>
</tr>
<tr>
<td>Liaoning</td>
<td>(-1.3^*)</td>
<td>(-0.5)</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
<td>(-1.7^*)</td>
</tr>
</tbody>
</table>

Note: \(^*\) denotes the trend significant at 95% confidence level
relation with temperature ($r=0.49$) and precipitation ($r=-0.42$) in October. This indicates that increase in temperature in October resulted in the delay of snow cover onset, while the increase in precipitation pushed snow cover onset ahead.

The snow cover end dates had no correlation with precipitation but a significant correlation ($r=-0.34$) with temperature in February. This indicates that lower temperature in February usually postponed the snow cover end dates.

The snow cover durations had no significant correlation with temperature, but a significant correlation with precipitation ($r=0.61$) in the same period. This indicates that precipitation plays a primary role in determining the snow cover duration, while temperature is not a critic factor on it.

### 3.4 Wind speed and sunshine duration

The annual mean wind speed had a significant decreasing trend at $-0.2$ m s$^{-1}$ per decade during 1961–2010, and the largest decrease ($-0.52$ to $-0.40$ m s$^{-1}$ per decade) was found in northeastern Heilongjiang, central Jilin, western and southern Liaoning. The mean wind speed in the four seasons had a significant decreasing trend, with the largest in spring ($-0.30$ m s$^{-1}$ per decade), followed by autumn and winter (both $-0.21$ m s$^{-1}$ per decade), and summer ($-0.15$ m s$^{-1}$ per decade).
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Regional mean gale days had a significant decreasing trend (~4.0 d per decade), and 75% stations were significant at the 95% confidence level (Fig. 17a). This is consistent with the decreasing trend in days with wind speed $\geq 8.0$ m $s^{-1}$ at ~2 d per decade during 1975–2005 at most stations, and even ~4 d per decade at some stations [Wang and song, 2008]. The gale days were above normal before the mid-1980s, while below normal after late 1980s.

Regional mean annual sunshine duration had a significant decreasing trend at ~43.3 h per decade during 1961–2010, which is larger than the significant decreasing trend for China in the past 50 years [Ren et al., 2005]. Geographically, the largest decrease was found in northern Jilin (~159.2 to ~120.0 h per decade), while significant increasing are found in northeastern Heilongjiang and southern Jilin (Fig. 17b). The sunshine duration in the four seasons had a significant decreasing trend, most in spring (~16.1 h per decade), followed by summer (~11.3 h per decade), winter (~9.0 h per decade) and autumn (~6.4 h per decade).

**Figure 17** Spatial distribution of linear trends in (a) annual gale days, and (b) annual sunshine duration in Northeast China during 1961–2010 (+ denotes the trend significant at 95% confidence level)

4 Conclusions and discussion

(1) Annual mean temperature had a significant increasing trend at 0.35°C per decade in Northeast China during 1961–2010, which was higher than the global and the national rate during the same period. The increase was most distinguished in winter and in Lesser Khingan Mountains of Heilongjiang. High-temperature days (daily maximum temperature $\geq 35^\circ$C) had a weak increasing trend, while low-temperature days (daily minimum temperature $\leq -25^\circ$C) had a significant decreasing trend (~3.9 d per decade). The boundary of annual low-temperature days over 40 d moved about 2° latitudes northward. The increasing rates of warm nights (2.4 d per decade) and cold nights (4.1 d per decade) were over twice as those of warm days (1.0 d per decade) and cold days (1.8 d per decade), respectively. This indicates that the increase of air temperature during nighttime is much larger than that during daytime. The frequency of cold wave and cold hazard reduced significantly. The temperature increase in Northeast China was in the context of global warming, meanwhile, it was also affected by local industrialization and urbanization. Studies showed that urbanization could contribute to the increase of annual mean temperature by 0.06°C per decade and urban heat island effect can explain 15% of it [Zhang et al., 2010]. Further study on the effect of urbanization using surface meteorological observations is needed.
(2) Annual precipitation in Northeast China did not show any linear trend but had decadal variations. Rainy days decreased at −2.4 d per decade, which was dominated by the decrease of light-rain days. There was no obvious trend in moderate-, heavy-rain days and rainstorm days. Snowfall days decreased significantly, which was dominated by the decrease of very-light-snowfall days.

(3) Snow cover onset dates postponed at 1.2 d per decade in Northeast China, while snow cover end date advanced at 1.5 d per decade. Accordingly, snow cover duration shortened at 2.7 d per decade. Maximum snow depth decreased at −0.52 cm per decade. High temperature in October delays the snow cover onset dates, and high temperature in February advances the snow cover end dates. More precipitation during the snow cover duration usually extends the snow cover duration.

(4) The annual mean wind speed and gale days had significant decreasing trends at −0.21 m s⁻¹ per decade and −4.0 d per decade, respectively. Sunshine duration had a significant decreasing trend at −43.3 h per decade. The decrease of mean wind speed might be associated with fast urbanization, and decrease of continental cold highs and cyclones. Generally speaking, the decrease of sunshine duration is associated with the increasing aerosols due to anthropogenic emissions [Ren et al., 2005].

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