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Change in mean and extreme temperature at Yingkou station in Northeast China from 1904 to 2017

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Abstract

The understanding of centennial trends of extreme temperature has been impeded due to the lack of early-year observations. In this paper, we collect and digitize the daily temperature data set of Northeast China Yingkou meteorological station since 1904. After quality control and homogenization, we analyze the changes of mean and extreme temperature in the past 114 years. The results show that mean temperature (Tmean), maximum temperature (Tmax), and minimum temperature (Tmin) all have increasing trends during 1904–2017. The increase of Tmin is the most obvious with the rate of 0.34 °C/decade. The most significant warming occurs in spring and winter with the rate of Tmean reaching 0.32 °C/decade and 0.31 °C/decade, respectively. Most of the extreme temperature indices as defined using absolute and relative thresholds of Tmax and Tmin also show significant changes, with cold events witnessing a more significant downward trend. The change is similar to that reported for global land and China for the past six decades. It is also found that the extreme highest temperature (1958) and lowest temperature (1920) records all occurred in the first half of the whole period, and the change of extreme temperature indices before 1950 is different from that of the recent decades, in particular for diurnal temperature range (DTR), which shows an opposite trend in the two time periods.

Keywords Centennial change · Daily data · Temperature · Extreme temperature · Yingkou · Northeast China

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1 Introduction

Global land-surface mean air temperature (Tmean) has increased significantly over the last century, especially in the last five decades (Lawrimore et al. 2011; Jones et al. 2012; IPCC 2013). Globally and regionally, extreme temperature events have also changed significantly over the past 50 years (Zhai and Pan 2003; Gong and Han 2004; Alexander et al. 2006; You et al. 2011). It is also found that the probability of extreme events will increase significantly in the future (Sun et al. 2014; Nangombe et al. 2018). Because of socio-economy and natural systems are more sensitive to changes of extreme events than changes of climate means, the long-term changes of global extreme events attract more attention (Katz and Brown 1992; Easterling 2000; Meehl et al. 2016). Statistics show that annual economic losses caused by extreme weather and climate events are well above US$ 200 billion (in 2010 dollars) (Handmer et al. 2012). Therefore, a better understanding of the long-term change in extreme temperature events will benefit the management of climate-related disasters (Handmer et al. 2012).

Compared with annual or monthly data, which are widely available in global land (Jones and Moberg 2003; Alexander et al. 2006), daily data in digital form for analyzing extreme temperature events seem quite limited at global and regional scales (Alexander et al. 2006; Donat et al. 2013) especially in developing countries including China. The data already digitized are not readily available to the international research community for many portions of the world (Folland et al. 2001). In China, systematical observations on a national scale started in the 1950s (Li et al. 2017), but some stations have daily observations for 100 years even more. It is therefore essential to collect and digitize the earlier time data for use in monitoring and research of extreme climate change (Li et al. 2017).

Collections of the early monthly data in China were first conduced in the 1980s and the 1990s (Wang 1990; Kaiser 1991; Tang and Lin 1992; Lin et al. 1995; Wang et al. 1998). Afterward, some researchers made a lot of efforts to construct and analyze long-term temperature series (e.g., Tang and Ren 2005; Tang et al. 2009; Li et al. 2010; Cao et al. 2013; Li et al. 2017), but most of the works were focused on monthly Tmean at the large urban stations of China. So, it is necessary to collect and analyze the long-term daily observational data at stations of size-varied cities.

In 2017, Hong Kong, Hohhot, Changchun, and Yingkou meteorological stations were approved by the World Meteorological Organization (WMO) as the first batch of centennial meteorological stations of WMO in China. As a centennial meteorological station, Yingkou station is not only observed at the earliest but also the only one with the old site still well preserved. The centennial stations are irreplaceable climate legacy. Therefore, it is important to collect and digitize the daily data of Yingkou station, not only for study of local extreme climate change but also for the construction and maintenance of the WMO centennial meteorological stations.

The International Atmospheric Circulation Reconstructions over the Earth (ACRE) project was initiated in 2008, which aims to promote international cooperation with meteorological organizations to recover, digitize, quality control, and consolidate the global terrestrial and marine instrumental surface data of the last 250 years (Allan et al. 2011, 2016). ACRE China, a regional focus of ACRE, was initiated in 2012 with the main tasks of recovery, imaging, and digitization of historical daily to subdaily climate data from various sources in China and the neighboring countries (Williamson et al. 2018). Under the umbrella of ACRE China, we collected and digitized the historical daily and subdaily data for a couple of stations, including Yingkou station from 1904 to 2017.

The objective of this study is to process and analyze the digitized daily temperature data at Yingkou station, with the objective to understand the long-term change in mean and extreme temperature at the northeastern China city. After the quality control and homogenization, daily temperature data series of centennial are established. We then further analyze mean and extreme temperature events change in the past century.

2 Data and methods

2.1 Station history

The first observation at Yingkou station was on 30 September 1904, and since then, it has been relocated for six times. Detailed information about the station moves is shown in Table 1 and Fig. 1. Meteorological observation in Yingkou was interrupted from 6 September 1945 to 1 March 1949 because of the Civil War. Afterward, the observation was recovered at the same site.

The station, located at No.32 Dongsheng Street, Zhanqian District, has gone through a hundred years (Fig. 2), and it is still completely preserved. Now the official house has been rebuilt as before to become Yingkou Centurial Meteorological Exhibition Hall. On 15 July 2020, it was announced by the World Meteorological Organization (WMO) officer as the first museum dedicated to centurial meteorological stations in the world.

2.2 Data sources

Most of the early data at Yingkou station before 1949 were collected from Japanese records, such as Meteorological Report of Manchuria. Before 5 Aug 1945, Yingkou was under the control of Japanese army. Figure 3 shows the cover (a) and internal contents (b) of Meteorological Report of Manchuria compiled by Japanese. After 1951, the data are from Meteorological Archives of Liaoning Province, China.

Table 1 Names, positions, coordinates, heights, and record years of Yingkou meteorological station in different periods

Number	Name	Positions (nowadays)	Latitude, longitude	Height (m)	Time period
1	Japanese 7th Temporary Observatory	Zhongxin Lane, Zhanqian District	40° 40′ N, 122° 14′ E	2.9	30 Sep 1904–31 Oct 1907
2	Yingkou Observatory	East of Yingkou Railway Station	40° 40′ N, 122° 14′ E	2.9	1 Nov 1907–24 Dec 1909
3	Yingkou branch of Guandong Observatory	No.32 Dongsheng Street, Zhanqian District	40° 40′ N, 122° 14′ E	2.4	25 Dec 1909–5 Aug 1945
	Yingkou meteorological station	No.32 Dongsheng Street, Zhanqian District	40° 40′ N, 122° 14′ E	2.4	1 Apr 1949–31 Aug 1955
4	Yingkou meteorological station	Yingkou Machine Tool Factory	40° 40′ N, 122° 12′ E	3.5	1 Sep 1955–31 Dec 1972
5	Yingkou meteorological station	The Meteorological Bureau of Yingkou	40° 40′ N, 122° 16′ E	3.3	1 Jan 1973–31 Dec 2005
6	Yingkou national basic meteorological station	No.19 Bohai Street	40° 40′ N, 122° 10′ E	3.8	1 Jan 2006–now

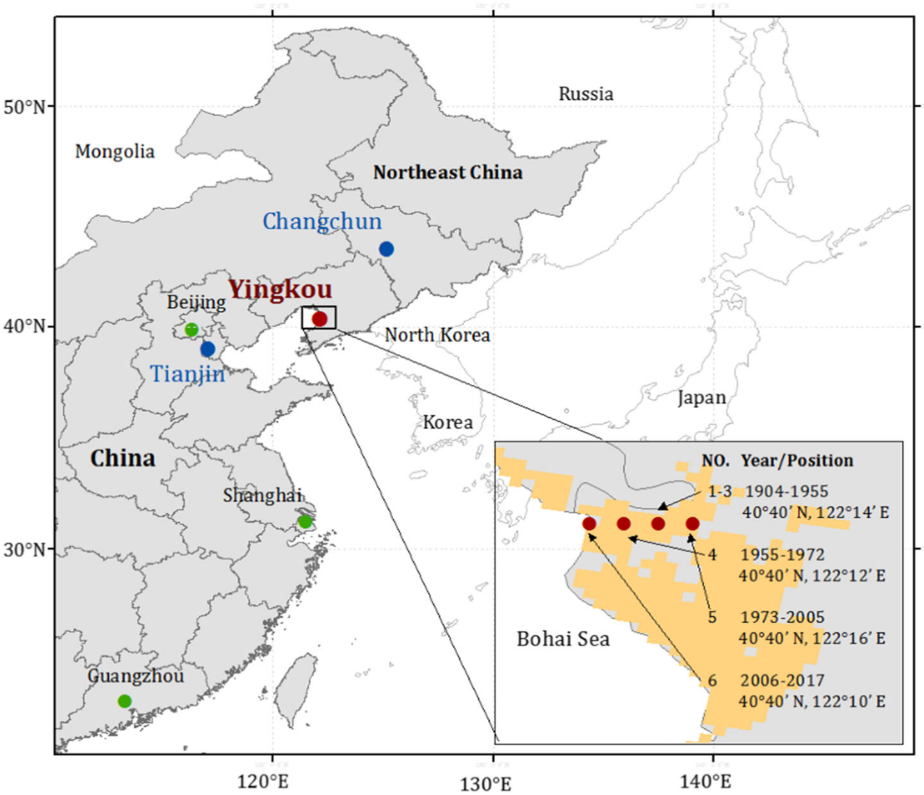


Fig. 1 Change of observational sites for Yingkou meteorological station. Red circles indicate the positions of the observational sites in history, and yellow areas built-up areas (The built-up area data comes from the 2015 land use/cover change (LUCC) data provided by the Resource and Environment Data Cloud Platform of the Chinese Academy of Sciences (http://www.resdc.cn/), Urban land (band 51 in LUCC classification system) and other construction land (band 53) are defined as built-up area data, the resolution is 1 km × 1 km)

The daily observational data were obtained from October 1904 to December 2017. Although the climatological data had already widely collected before 1949, some daily records, such as those of April to November 1937 and May 1942 to April 1950, were still missing. The detailed data sources are shown in Table 2.

2.3 Data processing and statistical methods

2.3.1 Data quality control

The precision of daily temperature data used in this study is 0.1 °C. In order to ensure the reliability of the data, the quality control should be conducted. We conducted the quality control which was mainly based on the module embedded in the software RClimDex (Zhang and Feng 2004). This was performed with the following 4 steps:

(1) Check whether the data are repetitive or not. The results show that there are not any repetitive data.

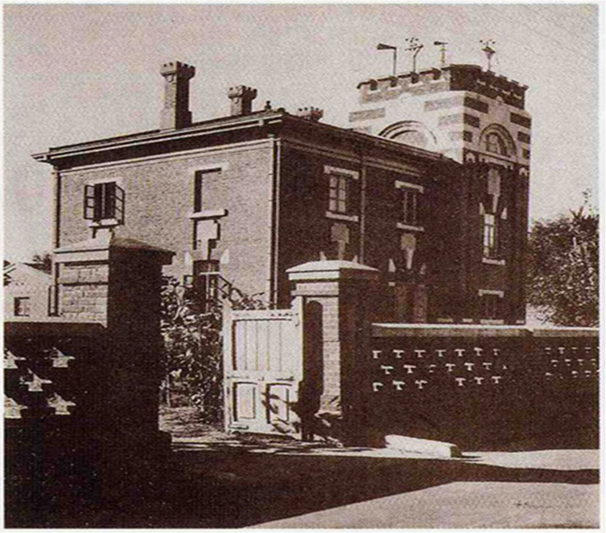
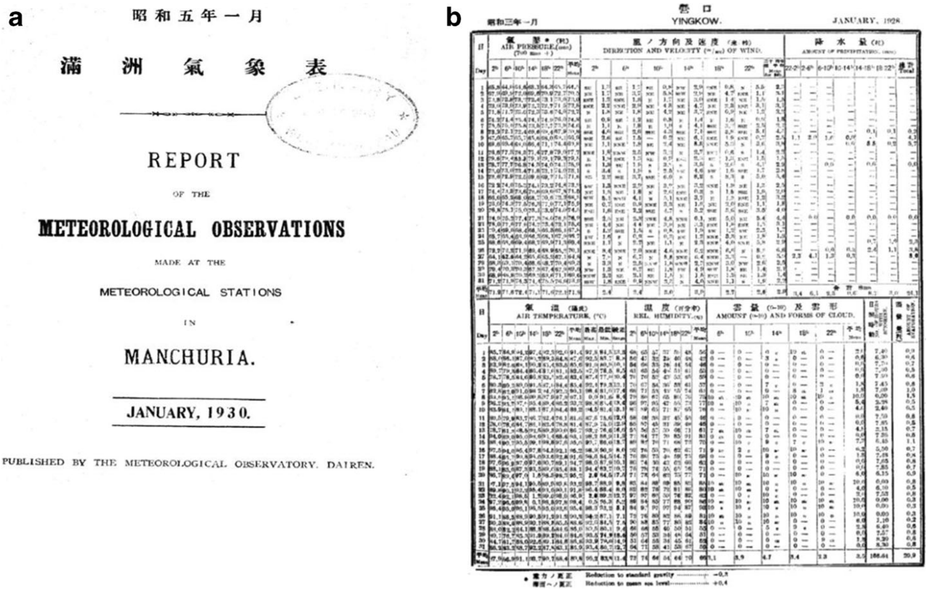


Fig. 2 Former office of Yingkou meteorological station at No.32 Dongsheng Street, Zhanqian District (Reproduced by courtesy of "Meteorological observation network in Imperial Japan" by Prof. Haruhiko Yamamoto)

(2) Check the climatological limit value of the daily data. According to the climatological characteristics of Yingkou, a city located in temperate monsoon climate region, if the daily temperature values which fall outside of the range (− 60–60 °C), they are regarded as unreasonable values.



昭和五年一月

滿洲氣象表

REPORT
OF THE
METEOROLOGICAL OBSERVATIONS
MADE AT THE
METEOROLOGICAL STATIONS
IN
MANCHURIA.

JANUARY, 1930.

PUBLISHED BY THE METEOROLOGICAL OBSERVATORY, DAIREN.

營口
YINGKOW.
昭和三年一月
JANUARY, 1928.

Fig. 3 The cover (**a**) and internal contents (**b**) of Meteorological Report of Manchuria (Reproduced by courtesy of ACRE China)

Table 2 The detailed data sources of Yingkou meteorological station from October 1904 to December 2017

Number	Time period	Data source	Archive unit
1	Oct–Dec 1904, 1905, 1910	Meteorological Table of Yingkou	Chinese Meteorological Archives
2	1906, 1908–1909, 1913, Jan–Mar 1923, 1924	Meteorology of Manchuria	Japanese Meteorological Agency Archives
3	1907, 1911–1912, 1914, 1916–1922	Meteorological Report for Manchuria	National library of Japan
4	1925–1932	Meteorology of Manchuria	Pro. Guoyu Ren, ACRE
5	1915, Apr–Dec 1923, 1933–1936, May 1941	Meteorology of Manchuria	Chinese Meteorological Archives
6	Jan–Mar and Dec 1937, 1938–1939, Jan–Oct 1940	Meteorological Monthly Table of Manchuria	Chinese Meteorological Archives
7	Nov–Dec 1940, Jan–Apr and Jun–Dec 1941, Jan–Apr 1942	Meteorological Simple Table of Manchuria	Chinese Meteorological Archives
8	May 1950–1951	Monthly Report of Meteorological Records	File office of Yingkou Meteorological Bureau
9	1951–2017	Monthly Report of Information ground Meteorological Observation Records	Liaoning Meteorological Archives

(3) Check whether the data are internal consistency or not. If daily minimum temperature is larger than maximum, for example, they should be regarded as unreasonable values.

(4) Check the climate extreme value of the daily data. The maximum range of Tmax is defined as three standard deviations (std) of the reference period (1961–1990) mean Tmax value. The daily Tmax records which are found falling outside of this range should be regarded as unreasonable values. The daily Tmin records are checked similarly. After manual verification, reasonable values are retained.

Finally, there are 17 temperature values (nine Tmax values and eight Tmin values) which are registered as the unreasonable values after checking. The missing and unreasonable values in this study are both considered as the missing data. All the missing data of Tmax account for 7.49% of the total and Tmin account for 7.48%. Most of them appear between May 1942 and April 1950.

2.3.2 Data homogenization

Non-climatic factors of station like the relocation and change in observational times and instruments can induce the inhomogeneity of data series (Wang et al. 2004; Cao et al. 2013). The inhomogeneity may make the estimates of change trend of extreme climate indices unreliable. In this study, we use the RHtestsV5 software (Wang 2008a, b; Wang and Feng 2013) which is based on the penalized maximum F (PMF) test to detect and adjust inhomogeneity of the monthly and daily temperature data without a reference series. After checking, two monthly break-points (February 1912 of the monthly Tmin series and October 1952 of the monthly Tmax series), and two daily break-points (30 November 1910 of the daily Tmin series and 4 November 1952 of the daily Tmax series), are identified at the confidence level 95%. After comparing with the detailed relocation information (Table 1), two break-points corresponding to 25 December 1909 of the daily Tmin series and 1 September 1955 of the daily

Tmax series are respectively considered as inhomogeneous points. The break-point of 25 December 1909 is then adjusted in the daily Tmin series and the break-point of 1 September 1955 is adjusted in the daily Tmax series. The monthly temperature time series is calculated by using the homogenized daily time series.

2.3.3 Trend estimation

Because of the simplicity and intelligibility, ordinary least square (OLS) is widely used in computing trend. But, it is based on the assumption that the data obey the Gaussian distribution (Zhang et al. 2000). When the data do not obey the Gaussian distribution, OLS is not suitable for the calculation. Shapiro-Wilk normality test (Royston 1982) was used to test if the extreme temperature indices obey the Gaussian distribution. The results showed that most of indices do not. Therefore, a modified Theil-Sen estimator (Sen 1968; Jassby and Cloern 2017) is used to calculate the linear trend of extreme temperature indices in this study, which could decrease the effect of lag-1 auto-correlation by means of an iterative pre-whitening process (Zhang et al. 2000; Wang and Swail 2001), and the Mann-Kendall test (Mann 1945; Kendall 1955) is used to test the significance of the trend. The linear trends of temperature (Tmean, Tmax, and Tmin) are still estimated by using OLS, and the significance of the trends is examined by using the 2-tailed simple t test method. A trend is considered statistically significant if it is significant at the 95% ($p < 0.05$) confidence level.

In order to avoid the inhomogeneity induced by changes in observational times, we calculate the arithmetic mean of Tmax and Tmin as Tmean (Tang and Ren 2005). Monthly mean values are calculated by averaging daily values and seasonal or annual mean values calculated by averaging monthly values. If a daily value is missing, the monthly value is regarded as missing. If a monthly mean value is missing, the seasonal or annual mean value is taken as missing. The time period of 1961–1990 is considered as the climate reference period. Climatic seasons are used, with last December, January, and February as winter; March, April, and May as spring; June, July, and August as summer; and September, October, and November as autumn.

2.4 Extreme temperature indices

Seven out of 27 temperature-related extreme indices recommended by the Expert Team for Climate Change Detection Indices (ETCCDI) (Zhang and Feng 2004; Alexander et al. 2006) are used in this study. They are four percentile-based indices including cold nights (TN10p), cold days (TX10p), warm nights (TN90p), and warm days (TX90p), and three absolute-threshold value-based indices including frost days (FD), summer days (SU), and diurnal temperature range (DTR). Definitions of the seven extreme indices are showed in Table 3.

3 Results

3.1 Changes in mean and extreme values of temperature

The anomalies of annual mean Tmean, Tmax, and Tmin at Yingkou station from 1904 to 2017 are shown in Fig. 4. Tmean, Tmax, and Tmin all show upward trends in the past 114 years. Tmin has an increasing trend of 0.34 °C/decade, and Tmax registers an increase of 0.18 °C/

Table 3 Trends of extreme temperature indices of Yingkou meteorological station from 1904 to 2017

Indicator name	ID	Definition	Trend	Unit
Cold nights	TN10p	Days when Tmin < 10th percentile	− 2.17*	days/decade
Cold days	TX10p	Days when Tmax < 10th percentile	− 1.18*	days/decade
Warm nights	TN90p	Days when Tmin > 90th percentile	1.62*	days/decade
Warm days	TX90p	Days when Tmax > 90th percentile	0.92*	days/decade
Frost days	FD	Annual count when Tmin < 0 °C	− 2.53*	days/decade
Summer days	SU	Annual count when Tmax > 25 °C	2.53*	days/decade
Diurnal temperature range	DTR	Monthly mean difference between Tmax and Tmin	− 0.16*	°C/decade

Note: * denotes the trend is statistically significant at the 0.05 confidence level

decade, which is about a half of Tmin trend. Tmean increases at a rate of 0.26 °C/decade. The increasing trend of Tmin is much larger than Tmax, indicating that the significant annual mean warming mainly occurs at night. Figure 4 also shows that, in the early time before 1940, the increasing trend of Tmax is larger than Tmin and Tmean, but after 1980, the warming of Tmin is becoming more and more significant.

There is an abrupt warming around 1987 for the last five to six decades in northern China, which has been widely reported (e.g., Ren et al. 2005; Cao et al. 2016). Therefore, we divide the whole period into two subperiods of 1904–1987 and 1988–2017 to discuss the temperature trends. The trend of Tmax is 0.15 °C/decade during 1904–1987, but − 0.08 °C/decade during 1988–2017. It means that, after 1987, Tmax is decreasing (not significant) despite the annual mean Tmean and Tmin are still experiencing a significant increase. The trends of Tmin are 0.28 °C/decade and 0.22 °C/decade during 1904–1987 and 1988–2017, respectively. It is obvious that the value of the Tmin trend is also smaller during the last three decades than those of 1904–1987 and 1904–2017 (0.34 °C/decade).

The decadal variations of annual temperature are showed in Fig. 5. The variations are relatively synchronized. The annual mean Tmean is 9.14 °C, and it shows a relatively stable upward trend in the early time, but it rises less significantly after the 1990s and stabilizes at a high plateau. The lowest decadal average occurs in 1904–1909 (7.72 °C) and the highest in the 2000s (10.39 °C). The annual mean Tmax is 13.71 °C and before the 1990s, it generally

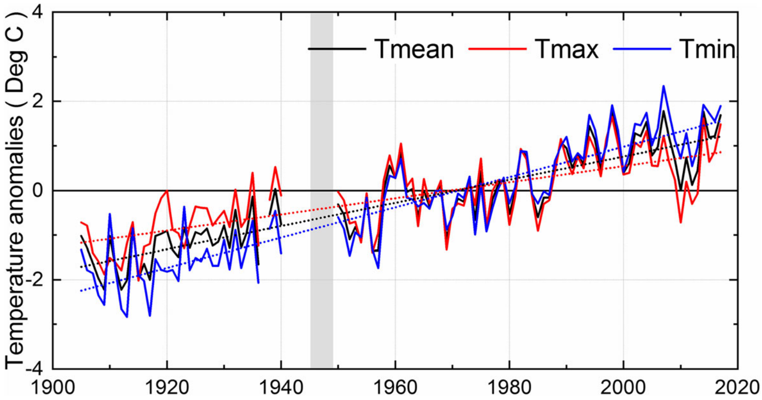


Fig. 4 The anomalies of temperature at Yingkou meteorological station from 1904 to 2017. The black solid line indicates Tmean, the red solid line indicates Tmax, and the blue solid line indicates Tmin. The dashed lines indicate the trend of Tmean, Tmax, and Tmin, respectively. The gray shadow is the period when observation was interrupted

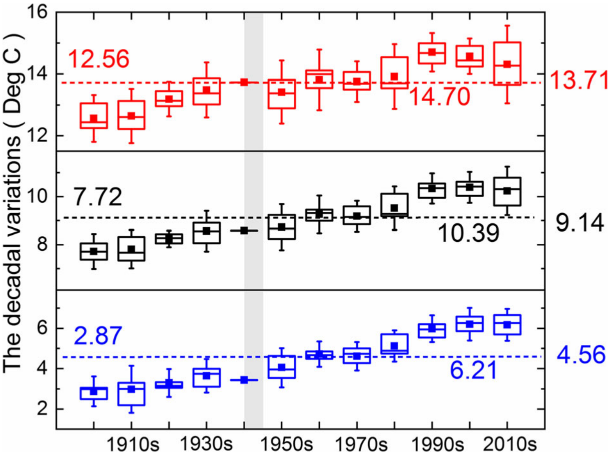


Fig. 5 The decadal variations of temperature at Yingkou meteorological station from 1904 to 2017. The black boxplots indicate Tmean, the red boxplots indicate Tmax, the blue boxplots indicate Tmin, and the dashed lines indicate the average values of temperature. The gray shadow is the period when observation was interrupted. In every boxplot, the block indicates the average value, the horizontal line indicates the median value, box upper and lower lines indicate 75% and 25% value, respectively, and the black bar indicates the standard deviation bar. And the values in the left are the average values from 1904 to 2017

increases, but after that, it begins to decrease. The lowest decadal average of Tmax occurs in 1904–1909 (12.56 °C) and the highest in the 1990s (14.70 °C). The mean Tmin is 4.56 °C. The variation in Tmin is similar to that of Tmean, with the lowest decadal average occurring also in 1904–1909 (2.87 °C) and the highest in the 2000s (6.21 °C).

For the annual extreme maximum (TXx) and minimum (TNn) temperature (Fig. 6), the highest TXx appeared on 20 July 1958 (35.3 °C) and the lowest TNn appeared on 10 February 1920 (− 31.0 °C). TXx reveals an increasing trend at a rate of 0.17 °C/decade, but it fails to pass the significance test. TNn significantly increases at a rate of 0.57 °C/decade.

In order to compare the early and current change, we divide the whole time series into three periods (1904–1940, 1950–2017, and 1904–2017) respectively to analyze the annual, seasonal, and monthly characteristics of temperature. The trends of annual temperature are shown in

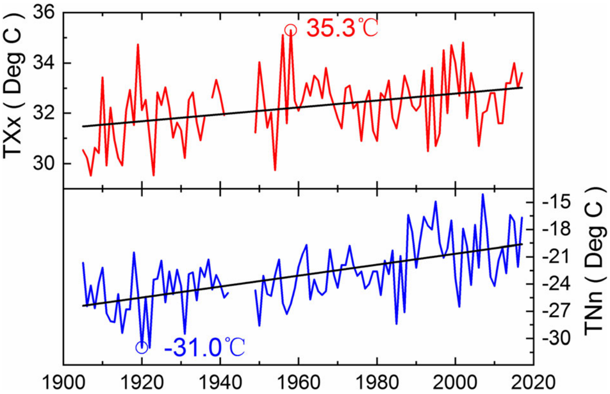


Fig. 6 The change of extreme temperature at Yingkou meteorological station from 1904 to 2017. Red line indicates the extreme maximum temperature, blue line indicates the extreme minimum temperature, and black lines indicates linear trends

Fig. 7. Tmean exhibits relatively stable upward trends in the three periods without a clear difference. Tmax rises most significantly at a rate of 0.39 °C/decade during 1904–1940, but Tmin rises most significantly at a rate of 0.39 °C/decade during 1950–2017. It indicates that the significant warming of Tmax mainly occurs in the early time and Tmin increase dominantly appears after the 1950s. The change of TXx is special because it increases much more significantly in the early than current time, with a significant upward trend of 0.79 °C/decade during 1904–1940 and a weak positive trend of 0.03 °C/decade during 1950–2017. However, the changes of TNn during the different periods are similar to those of Tmin except for a larger magnitude of trend than that of the latter.

The seasonal changes of temperature are shown in Fig. 8. Tmean in four seasons shows an obvious increasing trend. Spring and winter warming is more obvious, reaching 0.32 °C/decade and 0.31 °C/decade, respectively. The seasonal mean positive trend of Tmean is the most significant during 1904–1940 than during 1950–2017 and 1904–2017 in all seasons except for winter. Seasonal mean Tmax generally increases like Tmean, with the trend in the early time also the most significant except for winter. Seasonal mean Tmin in four seasons all shows a significant increasing trend and the largest increase is in spring and winter. Therefore, the seasonal mean Tmean, Tmax, and Tmin all show an increasing trend. The upward trend of Tmin during 1904–2017 in each season is more obvious than that of Tmean and Tmax. Spring and winter experience the most obvious warming. In the early time, however, the upward trend of Tmax is more obvious than those of Tmean and Tmin.

It is clear that the changes in the period 1950–2017 are similar to that of the period 1904–2017, but the changes in the period 1904–1940 are quite different. From 1904 to 1940, the increase of Tmean, Tmax, and Tmin in autumn is statistically significant, and the smallest increase is in winter which is completely opposite to the rapid winter warming during period 1950–2017. Even the autumn trend of Tmax from 1904 to 1940 can reach 0.52°C/decade. This shows that the early temperature change is very different from the recent decades.

The trends of monthly temperature for different periods are shown in Fig. 9. From 1904 to 1940, Tmean, Tmax, and Tmin all show a non-significant decreasing trend in January. TXx presents a decreasing trend in the six months in summer and autumn during 1904–2017. Except for August and October of 1904–1940, TNn in all months show a warming trend. February experiences the most obvious warming, especially for Tmin during 1904–2017 which reaches a rate of 0.56 °C/decade. The changes in the period 1950–2017 are very similar to the whole period, but the changes in the period 1904–1940 are unique.

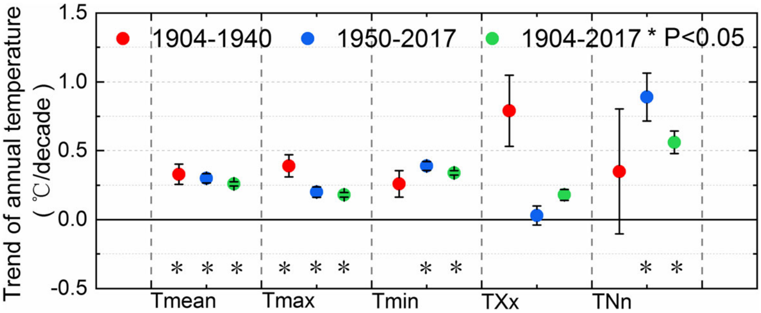


Fig. 7 The annual change trends of temperature at Yingkou meteorological station from 1904 to 2017. Red symbols: 1904–1940; blue symbols: 1950–2017; green symbols: 1904–2017; black bars: standard deviation bars; *: statistically significant at the 0.05 confidence level

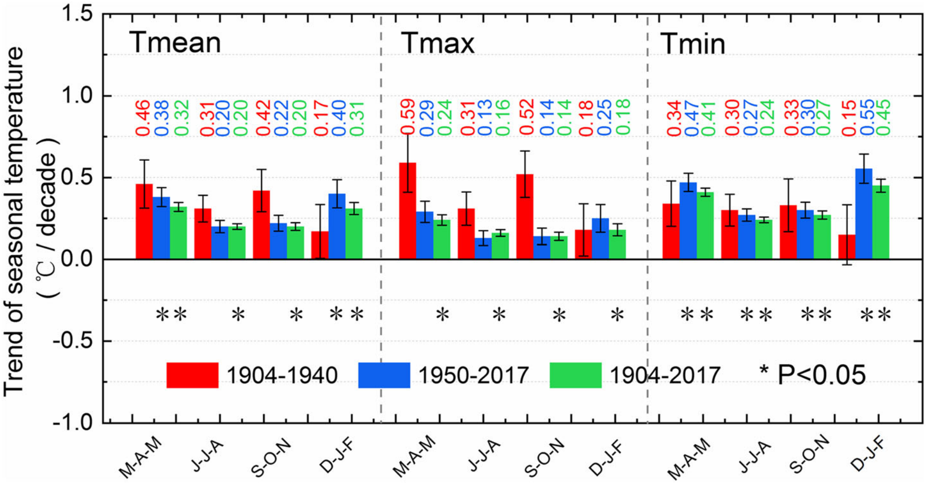


Fig. 8 The seasonal change trends of temperature at Yingkou meteorological station from 1904 to 2017. Red columns: 1904–1940; blue columns: 1950–2017; green columns: 1904–2017; black bars: standard deviation bars; *: statistically significant at the 0.05 confidence level

3.2 Changes in extreme temperature indices

The changes of the seven extreme temperature indices at Yingkou station from 1904 to 2017 are shown in Table 3 and Fig. 10. In the past hundred years, TN10p and TX10p show an obvious decreasing trend (Fig. 10a and b) at rates of 2.17 days/decade and 1.18 days/decade, respectively. TN90p shows a significant increasing trend at 1.62 days/decade (Fig. 10c). The change of TX90p is not as obvious as TN90p with an increasing trend at 0.92 days/decade (Fig. 10d). The upward trend of TN10p is greater than TN90p, and TN90p has a greater positive trend than TX90p, indicating that the warming at night is more significant than that in the day.

FD decreases at a trend of 2.53 days/decade, with a small change before 1940 and a significant downward trend afterward, especially after 1990 (Fig. 10e). SU shows an increasing trend for the whole period with the rate of 2.53 days/decade (Fig. 10f). For DTR, it decreases significantly at a rate of 0.16 °C/decade for the whole period (Fig. 10g).

The trends of extreme temperature indices for different periods (1904–1940, 1950–2017, and 1904–2017) are shown in Fig. 11. TN10p presents relatively stable downward trends in

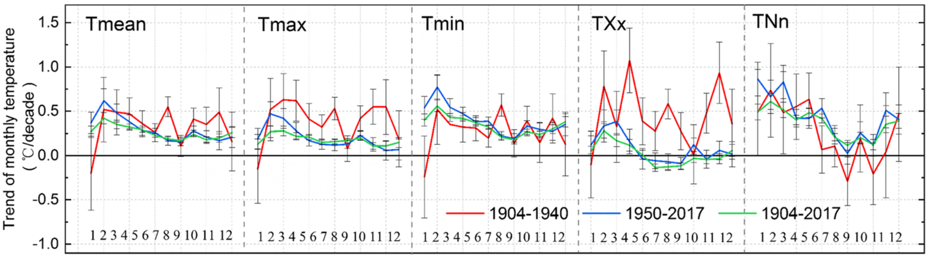


Fig. 9 The change trends of monthly temperature at Yingkou meteorological station from 1904 to 2017. Red lines: 1904–1940; blue lines: 1950–2017; green lines: 1904–2017; black bars: standard deviation bars

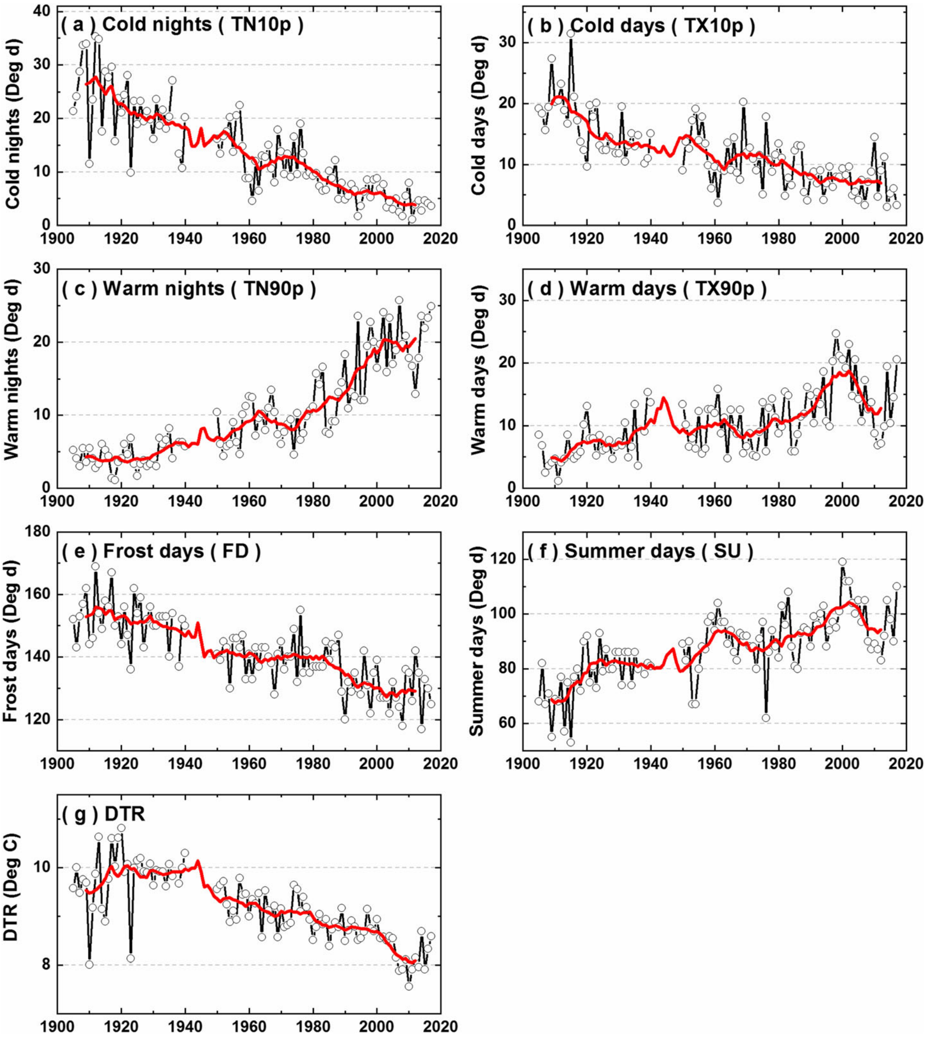


Fig. 10 Change in extreme temperature indices at Yingkou meteorological station from 1904 to 2017, including (**a**) cold nights, (**b**) cold days, (**c**) warm nights, (**d**) warm days, (**e**) frost days, (**f**) summer days, and (**g**) DTR. Red lines indicate 11-year moving average

the three periods with that of 1904–1940 more significant. TX10p has a downward trend, but the changing rate is larger than that of TN10p during 1904–1940. TN90p presents upward trends, especially during 1950–2017 and 1904–2017. TX90p has upward trends for the three periods, with the most significant rise (1.63 days/decade) occurring during 1904–1940.

FD has a gradual downward trend in all of the three periods. Although SU shows upward trends in the all three periods, the changing rate during 1904–1940 witnesses the largest and most significant increase (4.88 days/decade). DTR shows the opposite trends in the early period and the recent period, with a significant increasing trend at 0.13 °C/decade during 1904–1940, and a similarly significant decreasing trend at 0.20 °C/decade during 1950–2017.

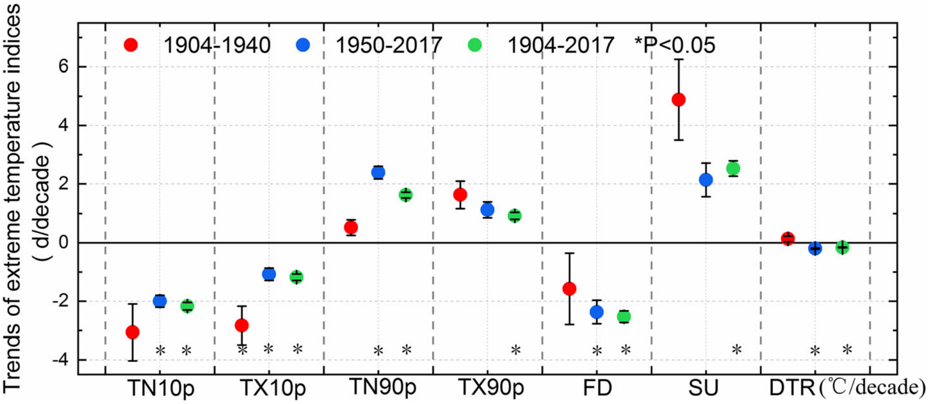


Fig. 11 The change trends of annual mean extreme temperature indices at Yingkou meteorological station from 1904 to 2017. Red symbols: 1904–1940; blue symbols: 1950–2017; green symbols: 1904–2017; black bars: standard deviation bars; *: statistically significant at the 0.05 confidence level

3.3 Comparison with other stations in China

In China, a few of other stations also have daily observations for 100 years or longer time. Among these, the daily temperature data at Changchun (Yu et al. 2020) and Tianjin (Guo et al. 2011) stations of Northern China (Fig. 1) have been analyzed for extreme temperature change. We compared the analysis results of this paper to those from the two stations (Table 4).

The start years of observations are little different, ranging from 1904 to 1910, but the difference caused by the varied periods is very small, and it would not significantly affect the estimates of the long-term trends. In the past 110 years or so, Tmin all show a significant increasing trend with the rates ranging from 0.28 °C/decade to 0.36 °C/decade. The trend of Tmin is moderate at Yingkou station, and the largest at Chengchun station. Among the three meteorological stations, however, the changes of Tmax are quite different or even opposite. Tmax at Yingkou and Changchun stations both experience obvious warming, but the rate at Yingkou station is 0.18 °C/decade which is twice as that of Changchun station. The trend of Tmax at Tianjin station is unique in that it is opposite to the others with a rate of − 0.02 °C/decade. The reason for the negative trend is unclear, but it is may be due to different methods used to homogenize the data.

The decrease of TN10p and TX10p at Yingkou station is larger and more significant than at Changchun station, indicating that Yingkou is experiencing more obvious warming. Yingkou and Changchun stations generally show less change in TN90p, with the increasing trend at the two stations of 1.62 days/decade and 1.71 days/decade, respectively. TX90p and SU are quite different, however, with TX90p showing a significant increasing trend at Yingkou station, but a decrease at the rate of 0.09 days/decade at Changchun station. The increasing trend of SU at Yingkou station is 2.53 days/decade, which is much bigger than the rate of 0.33 days/decade at Changchun station. DTR shows a significant decrease at both stations with little difference in between.

Guo et al. (2011) used a set of different extreme temperature indices. Only FD can be compared with those from Yingkou and Changchun stations. Among the three stations, the changes of FD all experience a significant decreasing trends with the rates ranging from − 2.33 days/decade to − 3.60 days/decade.

Table 4 Trends of temperature and extreme temperature indices in centennial stations

Stations	Period	Tmax (°C/ decade)	Tmin (°C/ decade)	TN10p (days/decade)	TX10p (days/decade)	TN90p (days/decade)	TX90p (days/decade)	FD (days/decade)	SU (days/decade)	DTR (°C/ decade)
Yingkou	1904–2017	0.18*	0.34*	− 2.17*	− 1.18*	1.62*	0.92*	− 2.53*	2.53*	− 0.16*
Changchun	1909–2018	0.09*	0.36*	− 1.42*	− 0.46*	1.71*	− 0.09	− 2.33*	0.33*	− 0.27*
Tianjin	1910–2009	− 0.02	0.28*	–	–	–	–	− 3.60*	–	–

Note: *denotes that the trend is statistically significant at the 0.05 confidence level. The results of Changchun from the paper of Xiujing Yu, and the results of Tianjin from the paper of Jun Guo

Therefore, the trends of mean temperature and extreme temperature indices at Yingkou, Changchun, and Tianjin stations for the 100 years and plus have similarities and differences. The reasons for the differences need further research, but it may be due to the missed data or the methods of homogenization. It may also be related to the real spatial pattern of climate change in Northern China.

4 Discussion

It is of importance to construct the long-term homogeneous daily temperature data series for the research of extreme climate change. Based on a new collection of early-year observational data, we establish a homogeneous daily temperature series at Yingkou station, Northeast China, from 1904 to 2017, and make a preliminary analysis of the long-term change in mean temperature and a few of extreme temperature indices at the station.

Global average annual mean surface temperature has increased by about 1.0 °C over the last 115 years from 1901 to 2016 according to the IPCC assessment report (IPCC 2013), Sun et al. (2019), and Climate Science Special Report 2017 of USA. Compared to this trend, the warming trend (0.26 °C/decade) at Yingkou station is much stronger. Tang and Ren (2005), and the following updates based on their method, showed a 0.08–0.10 °C/decade upward increase of annual Tmean during the last 100 years plus for China, much smaller than that of Yingkou station; Cao et al. (2013) calculated the average warming trend in the eastern and central China over the last hundred years (1909–2010) based on a homogenized temperature dataset from 16 stations, which shows an annual mean warming rate of 0.15 °C/decade, almost doubling the value as reported in Tang and Ren (2005), but still smaller than the estimated warming trend for Yingkou. The extreme temperature indices exhibit similar changes with those of Tmean at Yingkou station.

One of the major reasons for the much larger increase of temperature at Yingkou station may have been related to the urbanization effect. The regional average annual Tmean increase would be also significantly affected by urbanization process, as evidenced for the last decades in many studies (e.g., Ren et al. 2008; Yang et al. 2011, 2017; Wen et al. 2019). However, Yingkou is a large city with urban population more than 1.2 million in 2016, and the urbanization contribution to the observed warming trend would be larger than that of the regional average. The city was established in the 1860s when British occupied the harbor, developed afterward under the occupation of Russian (1900–1904) and Japanese (1895–1900 and 1904–1945), and rapidly urbanized in the last four decades after reform and opening up of the country in 1978. The observational sites of the station during 1904–2017 have been located in urban areas or suburban areas (Fig. 1), and the observational period is almost consistent with the stage of development of the urban areas. Obviously, this issue needs to be further investigated in the future.

Compared to the analysis results of the extreme temperature indices obtained by Zhou and Ren (2011) for China from 1961 to 2008, the percentile-based indices (TN10p, TX10p, TN90p, and TX90p) have the similar changes, but the values of the trends are much smaller at Yingkou stations from 1904 to 2017. The absolute indices (FD, SU, and DTR) of Yingkou station have similar trends. DTR decreases at − 0.16 °C/decade at Yingkou station from 1904 to 2017 and − 0.15 °C/decade in China on a whole from 1961 to 2008.

Interestingly, the change of DTR at Yingkou station from 1904 to 2017 is also similar to the results as reported by Sun et al. (2019) for global land average for period 1901–2014. They found that DTR had a significant downward trend during the whole period with the decline rate of − 0.036 °C/decade, but the decrease was caused dominantly by the highly significant decline from 1951 to 2014 (− 0.054 °C/decade), while the period from 1901 to 1950 actually underwent an increasing trend. DTR at Yingkou station shows a much more rapid decrease from 1950 to 2017 (− 0.20 °C/decade) and from 1904 to 2017 (− 0.16 °C/decade), and also a significant increasing trend at 0.13 °C/decade from 1904 to 1940.

Sun et al. (2019) noted that the northern hemisphere land decrease of DTR was closely related to the change of precipitation, indicating that the increase of cloud cover and precipitation may be one of the reasons for the decrease of DTR. The increase of DTR in the first half of the twentieth century may also be caused by the decline of volcanic activities and atmospheric aerosol compared to the later twentieth century. In addition to the large-scale factors, urbanization would be a major local driver of the large DTR decrease observed at Yingkou station, in particular in the last decades. The urbanization effect on daily temperature is characterized by the more rapid increase of Tmin than that of Tmax (Ren and Zhou 2014; Yang et al. 2017), mainly due to the asymmetric warming related to the urban heat island and urban aerosols effect.

Tang and Ren (2005) found that there are two warming periods from the 1930s to the 1940s, and from mid-1980s on, in China, based on a dataset of the most complete and continuous records. Yan et al. (2020) showed that the warming period of 1930s–1940s may not be obvious if the homogenization of data was made, because quite a few stations relocated around 1950 may have disturbed the trends of the data series. The homogenized data series thus will show a larger trend of temperature over the last 100 years plus. Our work supports this claim in some extents. If the break-point 1 September 1955 is not adjusted for inhomogeneity in the daily Tmax series, there is an obvious warming period during the 1930s–1940s, which is somehow different from the results of this paper. This confirms that, in case of a single station or fewer stations, whether or not to make homogenization of the data is indeed important for detecting the decadal to multi-decadal variation and long-term trend of mean and extreme temperature.

One issue with the daily temperature data series at Yingkou station is that they are not continuous, with most of the records for period 1941–1949 missed due to the wars. Interpolation is usually used to fill the missing records of annual or monthly data series (Steurer 1985; Yu et al. 2012; Cao et al. 2013). There are few researches about the interpolation method for the daily series, especially for early time periods with few reference data. In this study, we do not interpolate the missing data. This may pose an impact on the estimate of long-term trends. However, the impact would be minor because the missing records are mainly located near the middle, rather than in the two ends, of the data series.

Finally, there is a need to further rescue and digitize the early observational records, and to extend the data series to earlier years, at the current stations including Yingkou station (Allan et al. 2011, 2016). A site called Niuzhuang, about 50 km north of Yingkou station, was observed from February 1880, and the digitized daily data from March 1890 to May 1932 are available. The data could be fit together to form a longer daily data series for Yingkou station. It would be also important to rescue the missed records during the WWII. At the old location of Yingkou station (site 3 in Fig. 1), a large number of broken but not rotten meteorological observational reports were dug up on 5 May 2019. The partially ruined reports might have been burned and buried by the retreated Japanese in August, 1945. It is possible to rescue and obtain some data to fill the gap of data during the 1940s.

5 Conclusions

Based on the daily temperature data, long-term changes in mean and extreme temperature at Yingkou station, Northeast China, are analyzed. The main conclusions are as follows.

1. Tmean, Tmax, and Tmin all have significant increasing trends during 1904–2017. The annual mean Tmean, Tmax, and Tmin increase at rates of 0.26 °C/decade, 0.18 °C/decade, and 0.34 °C/decade, respectively. TXx and TNn significantly increase at rates of 0.18 °C/decade and 0.56 °C/decade, respectively.

2. Significant warming as indicated by Tmean, Tmax, and Tmin is found in each season. The largest warming occurs in spring and winter at the rates of 0.32 °C/decade and 0.31 °C/decade respectively for Tmean. February registers the largest warming among all the months.
3. TN10p and TX10p show significant decreasing trends at 2.17 days/decade and 1.18 days/decade, respectively, and TN90p and TX90p all significantly increase at 1.62 days/decade and 0.92 days/decade, respectively. FD decreases at the rate of 2.53 days/decade, and SU witnesses a significant increasing trend. DTR shows a highly significant decrease at a rate of 0.16 °C/decade for the whole time period.
4. Although there are good similarities of the mean and extreme temperature changes between 1950–2017 and 1904–2017, the temperature trends during 1904–1940 bear a substantial difference from those of the whole time periods. This is caused by the more rapid increase in Tmax than Tmin during 1904–1940, and in Tmin than in Tmax during 1950–2017.
5. The 110-year changes of the extreme temperature indices at Yingkou station have similarities and differences with Changchun and Tianjin stations. It is among the stations with the largest increase of Tmax, and the downward trend of FD at Yingkou station falls in the middle level of the three stations.

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