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ORIGINAL PAPER

The influence of elevation, latitude and Arctic Oscillation on trends in temperature extremes over northeastern China, 1961–2011

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Abstract Trend magnitudes of 14 indices of temperature extremes at 70 stations with elevations, latitude and Arctic Oscillation over northeast China during 1960–2011 are examined. There are no significant correlations between elevation and trend magnitudes with the exception of TXn (Min $T_{\max}$), TNn (Min $T_{\min}$), TR20 (tropical nights) and GSL (growing season length). Analysis of trend magnitudes by topographic type has a strong influence, which overrides that of degree of urbanization. By contrast, most of the temperature indices have stronger correlations with the latitude and Arctic Oscillation index. The correlations between the Arctic Oscillation index and percentile indices, including TX10p (cool days), TX90p (warm days), TN10p (cool nights), TN90p (warm nights), are not the same in different areas. To summarize, analysis of trend magnitudes by topographic type, the latitude and the Arctic Oscillation shows three factors to have a strong influence in this dataset, which overrides that of elevation and degree of urbanization.

1 Introduction

Due to surface climate change associated with global warming might show an elevation signal (Beniston and Rebetez 1996), relationships between climate changes and elevation are receiving increased attention in the recent years. Some studies have suggested that surface air temperatures are increasing more rapidly at higher elevations (Beniston 2003). For example, there is a switch in the gradient of the temperature anomaly with height from cold to warm winters in Switzerland; for warm winters, the higher the elevation, the stronger the positive anomaly; the reverse is true for cold winters (Beniston and Rebetez 1996). The results above are particularly marked over the Alpine region, where lack of snow has severe consequences for the tourist-based economies of mountain communities (Giorgi et al. 1997). Other studies show that enhanced warming with elevation is not universally accepted and some observational studies show contrasting patterns. In South America, lower elevations to the west of the Andes have experienced the greatest warming, while warming at higher elevations to the east is moderate (Vuille et al. 2003). Similarly, trends in extreme indices are consistent with general warming only at low altitudes over South Asia (Revadekar et al. 2012). There is even a decrease in trend magnitude with elevation in South America (Pepin and Seidel 2005). As far as a global analysis of 1084 homogenous stations datasets from the GHCN (Global Historical Climate Network) and CRU (Climate Research Unit) is concerned, there is no systematic relationship between temperature trend magnitude and elevation reported (Pepin and Seidel 2005). At the same time, many studies show that there is a statistically significant warming trend in the Tibet Plateau during the last decades, and that the warming trends in mean temperature are correlated with elevation (Liu and Hou 1998; Liu and Chen 2000), while an enhanced sensitivity of temperature extremes at higher elevations is not apparent in the context of recent warming in this region (You et al. 2008, 2010). On the one hand, the reason is that changes in temperature

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extremes are often disproportionate with changes in mean temperatures in the context of global warming (Easterling et al. 2000). On the other hand, trend magnitudes by topographic type and degree of urbanization have a strong influence in this dataset, which overrides that of elevation (You et al. 2008). In addition, some studies also showed there are significant correlations between the trends of most extreme temperature indices and altitude, i.e., positive correlations between altitude and TNn, negative correlations between altitude and TXx, TX90p, TN90p and GSL over Tibet (Du et al. 2013). It is particularly obvious in autumn that elevation-dependent changes of extreme temperature indices show significant increasing changes with elevation over the Yellow River source region (Hu et al. 2013).

In addition to the elevation, climate changes vary with the difference of latitudes and Arctic Oscillation. It is generally accepted that climate sensitivity increases at higher latitudes as changes in high latitudes are strongly associated with changes in albedo and energy budgets in Arctic summer warming (Chapin et al. 2005). For climate extremes, changes in extremes at lower-latitude stations are often consistent with a warming climate, whereas many stations located at higher latitudes show opposite behavior; this partly reflects a tendency for high-altitude stations in South Asia to also be located at relatively high latitudes (Revadekar et al. 2012). Over Tibet, the relationships between most of extreme temperature indices and geographical locations (such as longitude and latitude) are not significant (Du et al. 2013).

Furthermore, some studies indicate that Arctic Oscillation has a close relationship with northern hemisphere temperature, especially in high-latitude regions where the temperature trends are related to Arctic Oscillation (Thompson and Wallace 1998, 2000; Kerr 1999; Gong et al. 2004a). Across China, there are strong relationships between extreme temperatures and the Arctic Oscillation. In the northern part of eastern China, correlation analysis revealed that winter extreme cold days in the northern part of the study area are significantly impacted by the Arctic Oscillation (Chen et al. 2013). In northern China, the number of winter warm days and warm nights in most areas of northern China is relatively larger during the high Arctic Oscillation phase than those during the low phase, whereas the number of winter cold days and cold nights were higher in the low Arctic Oscillation phase (Ding et al. 2010). In Northwest China, the Arctic Oscillation has little influence on extreme high temperatures in Ningxia Hui Autonomous Region, while it had a significant impact on winter low temperatures (Xue et al. 2012). Therefore, to predict short cycle climate, it is a great significance to study the influence of Arctic Oscillation on temperature over northeast China. In addition, a transition of the Arctic Oscillation relationships to rainfall occurs within the Israeli study area, where it is positively associated with rainfall in the south and negatively to the north (Givati and Rosenfeld 2013). Over Europe, during the second half of the twentieth century, there is a strengthening of the influence of the positive phases of the North Atlantic Oscillation on droughts; in contrast, the negative phases show a weaker influence on droughts during the second half of the twentieth century (Lopez-Moreno and Vicente-Serrano 2008). Over Israel, the North Atlantic Oscillation for the summer and the Arctic Oscillation for the winter are two additional factors governing the interannual variation and the long-term trend of the 850 hPa temperature (Saaroni et al. 2010). The North Atlantic Oscillation may intensify with further increases in atmospheric greenhouse gas concentrations (Kuzmina et al. 2005). Over Iberian Arctic Oscillation (AO), North Atlantic Oscillation (NAO) and Western Mediterranean Oscillation (WeMO) have an important influence on rainfall (Lopez-Bustins et al. 2008). Over Turkish, the NAO is an extremely important mechanism in relating atmospheric causes to the spatial and temporal variations in Turkish lake levels, located mainly in the Marmara and central Anatolia regions, at annual and decadal time periods (Küçük et al. 2009). In the western United States, Shifts in stormtrack position associated with the Northern Annular Mode (NAM) are linked to temperature changes and reduced spring precipitation (McAfee and Russell 2008).

Northeastern China belongs to the east coast at middle–high latitudes in Eurasia. The stations are located from near sea level to nearly 800 m above sea level. This area extends from latitudes 38°40′ to 53°34′ N and from longitudes 118°48′ to 135°07′ E, where climate ranges from warm temperate to cool temperate. Its forested areas also occupy approximately 31% of China's total forested area (Yang et al. 2007; Tan et al. 2007). In a changing global climate, Northeast China is one of the regions where the climate warming becomes obvious in China (Liu et al. 2004; Dong and Wu 2008). The climate is cold and arid in winter and hot and rainy in summer, and snow covers the ground in some areas for about half a year (Zhang et al. 2006). Incidences of low temperature decrease and high temperature damage increase, but the possibility of low temperature losses still exists in some areas under a warming background (Li et al. 2005). The daily minimum temperature rises more strongly than the daily maximum temperature, which markedly narrows the diurnal temperature range (Yang et al. 2007). Due to the increase of accumulated temperature, the growth period is extended and summer cool disasters are less common, which leads to improving conditions for crop growth and northward movement of the agricultural climate zone (Yang et al. 2007). The trend magnitudes in cold/warm nights are larger than those in cold/warm days, and extreme temperature indices strongly correlate with annual mean temperature (Yu and Li 2014). Consecutive dry days have a significant increasing trend (Wang et al. 2013). In the recent years, scholars have found that Arctic Oscillation influences the change of winter air temperature (Pang and Guo 2010; Hu and Liu 2005) and spring extreme temperature (Wang et al. 2007). However, changes in temperature extremes over northeastern China have not been examined in detail. Few previous studies for this study region have examined changes in extremes as a function of observation station elevation, latitude and Arctic Oscillation. This paper has examined trends in a number of indices of temperature extremes over northeast China to determine whether there are significant changes in trends in these indices with altitude, latitude and Arctic Oscillation.

2 Data and methods

Daily minimum and maximum temperature data from 70 stations shown in Fig. 1a, b are used for the analysis. Figure 1b shows that most of the stations distribute high elevations while the distributions of the stations are uniform based on the latitude. Elevations for the ensemble of the stations are ranging from 3.8 to 775 m. Data of poor quality, undesirably low quantity or low spatial coverage will lead to unsatisfactory data analysis and vague results. Several stations are excluded due to frequent missing data and a lack of digitized daily data. Therefore, though 99 stations over northeastern China have longer records, we have selected these 70 stations covering the period of 1960–2011 in order to maximize the number of stations that pass tests for quality and homogeneity. The distribution of the stations is uneven and most of stations are situated in the southern and central northeastern China.

Arctic Oscillation Index (AOI) is defined as the difference in the normalized monthly zonal-mean sea level pressure (SLP) between 35°N and 65°N (Li and Wang 2003). Data from 1960 to 2011 used in this study are acquired from Li's homepage of the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) at http://ljp.lasg.ac.cn. Sea level pressure used in the calculation is from NCEP1 (1948 to present).

14 extreme temperature indices recommended by the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMI) are used. These indices are listed in Table 1 and described more fully at http://etccdi.pacificclimate.org/indices_def.shtml. Data quality checking and extremes analysis are performed by using the RClimDex software maintained by the Climate Research Branch of Environment Canada (http://etccdi.pacificclimate.org/indices_def.shtml). According to the previous study over northeast China, extreme temperature indices are divided into five types (Yu and Li 2014).

Data preprocessing has been considered to be an important part of the present study (Aguilar et al. 2005). Data quality control plays a pivotal role in the indices' calculation and their trends. A series of methods in data quality control are attained by the National Meteorological Information Center of China Meteorological Administration to correct the errors (Li and Xiong 2004; Wang 2004). Simple data quality control of the indices in this study is performed using the software RClimDex V1.1 (developed by Zhang and Yang (2004) at the Climate Research Branch of Meteorological Service of Canada) whose software and documentation are available online for downloading (http://etccdi.pacificclimate.org/indices_def.shtml). The program can identify all missing or unreasonable values. A well-considered preprocessing is crucial for a meaningful analysis in order that extremes are not discarded with an overenthusiastic or a purely automated data cleansing. Exploratory Data Analysis (EDA) is used to explore some extreme outliers and gives an idea of potential inhomogeneities and missing values in the datasets for each station individually. Time series plots for maximum and minimum temperatures have also been examined with our visual sense. Some quality checks are also used for station datasets, on account of some potential sources of error with the daily data, for example, decimal point is out of place and maximum temperature is less than minimum temperature of the day. We also try our best to cross-check the suspected/doubtful data and to confirm erroneous values, with the help of parallel datasets. In addition, data plots and histograms are also consulted to reveal outliers visually as well as a variety of problems that cause changes in the seasonal cycle or variance of the data (Aguilar et al. 2005; New et al. 2006).

The RHtest software, which uses a two-phase regression model to check for multiple step-change points that could exits in a time series, is employed to assess data homogeneity (Wang 2003; Wang and Zhou 2005). When a step change is regarded as the annual series, it can also be checked against the station metadata in the original records. Due to homogeneity testing being quite complex and requires detailed station history, some discontinuities are not identified and some inhomogeneities may still remain (You et al. 2008). Then, temperature indices from the daily data are calculated by using RClimDex.

Trends per year have been computed for each index of temperature extreme (1960–2011) using ordinary least squares regression and deriving the slope of the linear fit. The statistical significance of the trends (significant at $p < 0.05$) is assessed by a t test after taking temporal autocorrelation into account (Santer et al. 2000). In addition, relationships between temperature index and elevation

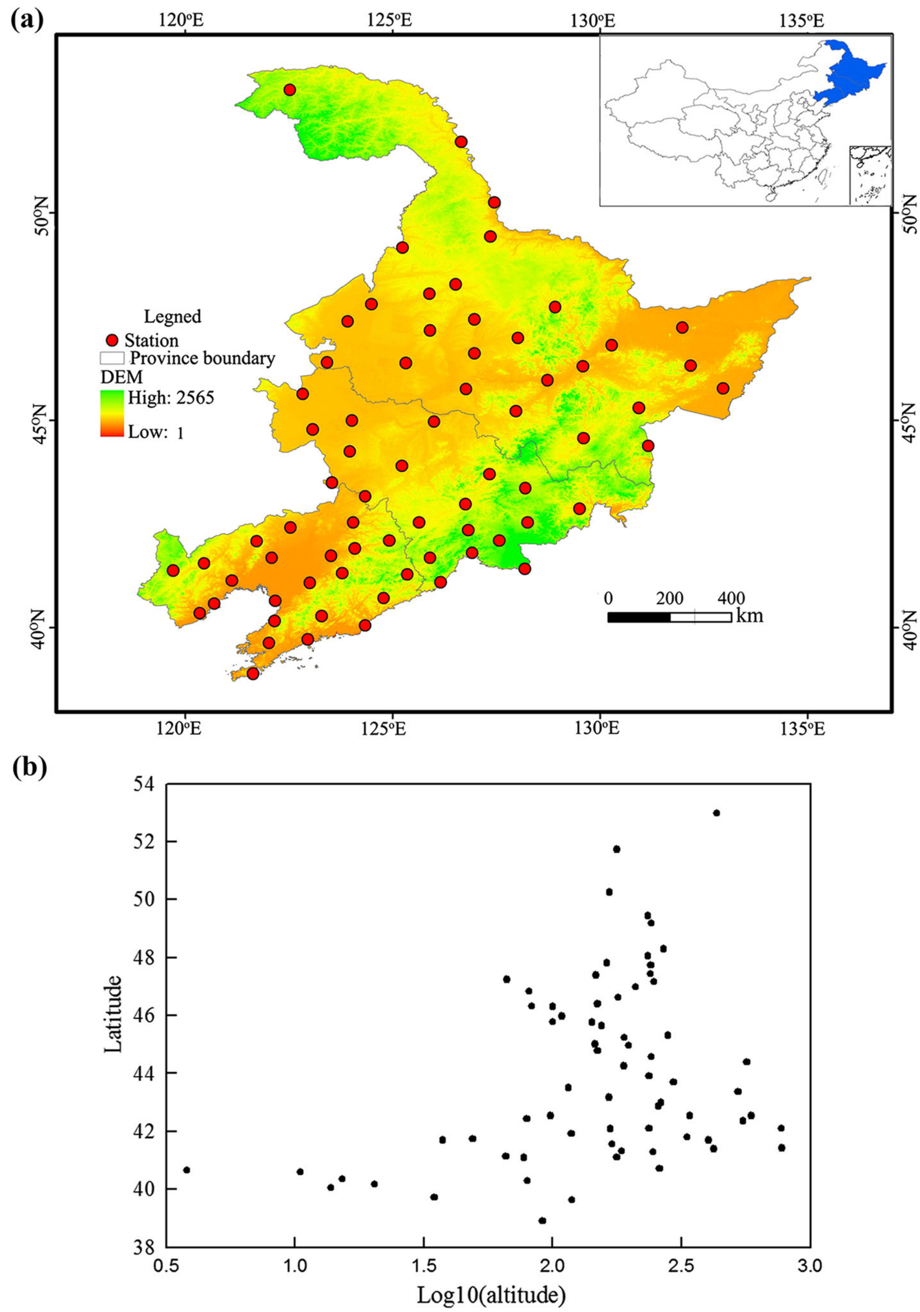

Fig. 1 **a** Location of the stations used in the study *shade* represent elevation (m) and **b** latitude versus log (base 10) of elevation (m) for the stations used in the study

as well as latitude and Arctic Oscillation, along with the correlation coefficients for the relationships, and the slope of temperature index with elevation/latitude and their statistical significance are also ordinary least squares regression and a *t* test.

The topographical index is calculated by centering a grid on each station and calculating the elevation difference between the station and the eight surrounding cells. Each of the 71 stations are divided into topographic types which were summit, flat, intermountain and valley (Li et al. 2011; Wang et al. 2013), according to topographic index derived from SRTM digital elevation data (available from http://srtm.csi.cgiar.org). Additionally, the aforementioned stations are classified as urban (>30,000 population) or rural (<30,000 population).

3 Results

3.1 Number of stations with negative, insignificant, and positive trends

Table 2 shows the number of stations with significant trends (either negative or positive), insignificant trend, and

Table 1 Definitions of temperature indices used in this study

ID	Index name	Index name	Units
Absolute indices			
TXn	Min T_{max}	Monthly minimum value of daily maximum temperature	°C
TXx	Max T_{max}	Monthly maximum value of daily maximum temperature	°C
TNn	Min T_{min}	Monthly minimum value of daily minimum temperature	°C
TNx	Max T_{min}	Monthly maximum value of daily minimum temperature	°C
Percentile indices			
TX10p	Cool days	Percentage of days when TX <10th percentile	Days
TX90p	Warm days	Percentage of days when TX >90th percentile	Days
TN10p	Cool nights	Percentage of days when TN <10th percentile	Days
TN90p	Warm nights	Percentage of days when TN >90th percentile	Days
Threshold indices			
FD0	Frost days	Annual count when TN (daily minimum) <0 °C	Days
ID0	Ice days	Annual count when TX (daily maximum) <0 °C	Days
SU25	Summer days	Annual count when TX (daily maximum) >25 °C	Days
TR20	Tropical nights	Annual count when TN (daily minimum) >20 °C	Days
Duration indices			
GSL	Growing season length	Annual count between first span of at least 6 days with TG >5 °C and the first occurrence after 1st July of at least six consecutive days with TG <5 °C	Days
Other indices			
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C

Table 2 Number of stations with significant negative, insignificant, and significant positive trends for the annual indices of temperature extremes over northeast China during 1960–2011, significant at the 0.05 level

Index	No. of data series	Positive trend		Negative trend		Stationary trend
		SS[a]	Non-SS	SS[a]	Non-SS	
TXn	70	41	29	0	0	0
TXx	70	7	48	0	8	7
TNn	70	49	20	0	0	1
TNx	70	31	32	0	5	2
TX10p	70	0	0	60	10	0
TX90p	70	49	21	0	0	0
TN10p	70	0	0	67	3	0
TN90p	70	68	2	0	0	0
FD0	70	1	0	68	1	0
ID0	70	0	0	23	46	1
SU25	70	49	18	0	1	2
TR20	70	35	30	0	1	4
GSL	70	51	18	0	0	1
DTR	70	2	1	60	7	0

[a] *SS* statistical significance: $a = 0.05$

stationary trends of extreme temperature indices. Cold nights (TN10p) and cold days (TX10p) show significant decreasing trends at 67 and 60 stations, respectively. They both have no significant increasing trends. At the same time, significant increases are 68 stations for warm nights and 49 stations for warm days. No stations show statistically significant decreases for the two indices. Fewer cold nights/days and more warm nights/days reflect the general

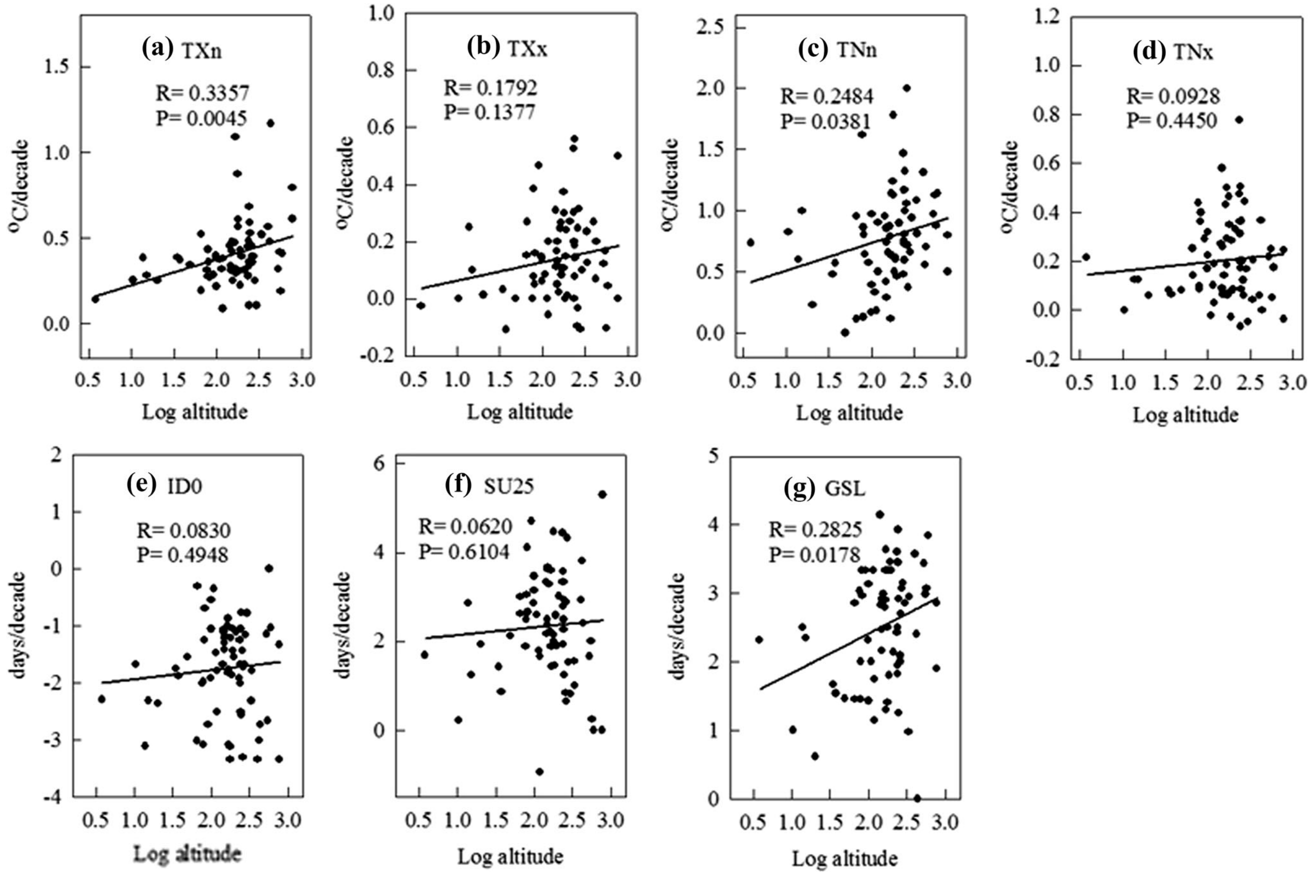

Fig. 2 Trend magnitudes of temperature extremes versus elevation over northeast China. *R* stands for correlation coefficients for the relationships and *P* for statistical significance. All abbreviations are as same as interpreted in Table 1

warming trend in mean temperatures over northern China over the past 52 years. Diurnal temperature range (DTR) shows a significant decrease at 60 stations and increase at 2 stations. Significant increasing trends of annual lowest minimum temperature (TNn), annual lowest maximum temperature (TXn), annual highest minimum temperature (TNx) and annual highest maximum temperature (TXx) are 49, 41, 31 and 7 stations, respectively. For the rest indices, cold indices of 23 stations show statistically significant decreases in ice days (ID0) and 68 stations show statistically significant decreases for frost day frequency (FD0). Warm indices of 51 stations show statistically significant increases in growing season length (GSL), 35 stations show statistically significant increases in tropical nights (TR20) and 49 stations show statistically significant increases for summer days (SU25).

In addition, changes in minimum of daily minimum and maximum temperature (TNn, TXn, and FD0) generally have higher trend magnitudes than that in maximum of daily minimum and maximum temperature (TNx, TXx, SU25). The reason above is that winter temperatures are increasing more quickly than are summer temperatures (IPPC, 2007). This makes physical sense in that the amount of water vapor content in the air in winter is frequently less than that of in summer, which will enhance any fractional change in greenhouse gas radiative forcing (Aguilar et al. 2009).

3.2 Changes in extreme temperature indices versus elevation

Figures 2 and 3 present relationships between elevation and the station trends in extreme temperature indices. The correlation coefficients for the relationships and their statistical significance are also shown in Figs. 2 and 3. A function of log10 (altitude) is applied to reduce the large range in station altitudes over northeastern China. There is a positive correlation between elevation and the trend magnitudes of TNn, TNx, TXn, TXx, ID0, SU25 and GSL, and the correlation coefficients are strong for TXn (0.34, $p < 0.01$), TNn (0.25, $p < 0.05$) and GSL (0.28, $p < 0.05$) (Fig. 2). For trends in TXn, TNn and GSL, the variability at the highest stations contributes to the observed positive slope. Figure 3 shows negative relationships between elevation and the trend magnitudes of TX10p, TX90p, TN10p, TN90p, FD0, TR20 and DTR. The only strong relationship

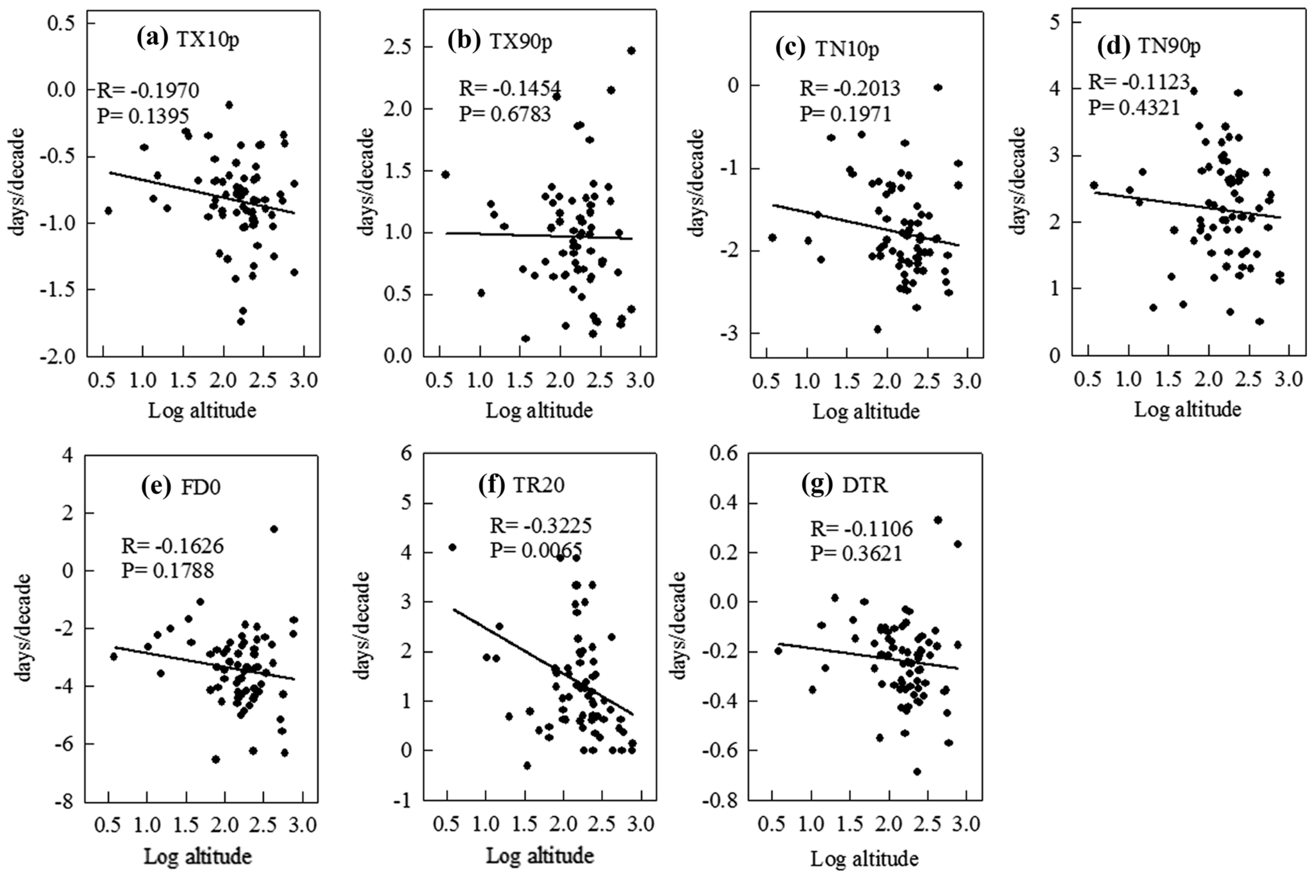

Fig. 3 Trend magnitudes of temperature extremes versus elevation over northeast China. *R* stands for correlation coefficients for the relationships and *P* for statistical significance. All abbreviations are as same as interpreted in Table 1

is for TR20 (−0.32, $p < 0.01$). In addition, with the elevation elevating at average 100 m, the ranges of TXn, TXx, TNn, TNx ID0, SU25 and GSL increase by 0.15 °C/decade, 0.06 °C/decade, 0.23 °C/decade, 0.04 °C/decade, 0.16 day/decade, 0.17 day/decade and 0.58 day/decade, respectively. The ranges of TX10p, TX90p, TN10p, TN90p, FD0, TR20 and DTR decrease by −0.13 day/decade, −0.02 day/decade, −0.21 day/decade, −0.16 day/decade, −0.48 day/decade, −0.92 day/decade and −0.04 °C/decade, respectively (Table 3). Changes with elevation of the cold extremes (TN10, TX10, TXn and TNn) are larger than those of the warm extremes (TN90, TX90, TXx and TNx). Changes with elevation of night extremes (TNn, TN10, TN90) appear to be larger than those of day extremes (TXn, TX90, TX10), but not those of TNx and TXx.

Table 4 exhibits the average trend magnitude of extreme temperature indices in categorized elevation bands and the number of stations in each band. For TXn, TXx, TX10p, TX90p and SU25, the largest positive mean trend magnitudes emerge at the high-elevation category, which indicates enhanced warming over high-elevation stations because of extremes in maximum temperature. For TNx, TN10p, TN90p, FD0 and TR20, the largest negative mean trend magnitudes also appear at the high-elevation category. Diurnal temperature range (DTR) also increase over

Table 3 Changes in index trends with altitude and latitude over northeast China

Index	Altitude	Latitude
TXn	$y = 0.1514x + 0.0719$	$y = 0.0226x - 0.5931$
TXx	$y = 0.0645x - 0.002$	$y = 0.0163x - 0.5822$
TNn	$y = 0.2264x + 0.2844$	$y = -0.0081x + 1.1339$
TNx	$y = 0.0367x + 0.1224$	$y = 0.0259x - 0.9387$
TX10p	$y = -0.1327x - 0.5461$	$y = -0.0398x + 0.9092$
TX90p	$y = -0.0195x + 1.0049$	$y = 0.038x - 0.6236$
TN10p	$y = -0.2135x - 1.3269$	$y = -0.0139x - 1.2207$
TN90p	$y = -0.1647x + 2.5323$	$y = 0.0647x - 0.6701$
FD0	$y = -0.4764x - 2.3838$	$y = -0.0396x - 1.6716$
ID0	$y = 0.1589x - 2.0958$	$y = 0.1118x - 6.6772$
SU25	$y = 0.1741x + 1.9664$	$y = 0.1564x - 4.5477$
TR20	$y = -0.9202x + 3.3911$	$y = -0.0588x + 3.9852$
GSL	$y = 0.5768x + 1.2592$	$y = 0.0589x - 0.0823$
DTR	$y = -0.0429x - 0.1448$	$y = -0.0062x + 0.0341$

Table 4 Mean trend magnitudes of temperature extremes in categorized elevation ranks over northeast China

Altitude (m)	<100	100–200	200–300	300–400	400–500	500–600	>600
No. of stations	17	25	17	0.52	3	4	2
TXn	0.32	0.41	0.38	0.18	**0.74**	0.33	0.25
TXx	0.12	0.12	0.18	**0.95**	0.18	0.06	0.65
TNn	0.61	0.72	0.95	0.12	0.86	**1.03**	0.10
TNx	0.18	0.20	0.26	−0.86	0.14	0.17	**−1.04**
TX10p	−0.71	−0.87	−0.88	0.76	−1.07	−0.59	**1.42**
TX90p	1.04	0.91	0.92	−1.8	**1.59**	0.56	−1.08
TN10p	−1.59	−1.79	−2.04	1.67	−1.25	**−2.30**	1.16
TN90p	2.19	2.32	2.24	**−2.93**	1.40	2.34	−1.95
FD0	−3.13	−3.49	−3.73	−2.05	−1.45	**−5.33**	−2.33
ID0	−1.99	−1.55	−1.61	1.29	**−3.02**	−1.21	2.65
SU25	2.34	2.44	2.50	0.81	**3.05**	0.98	0.07
TR20	1.79	1.70	1.08	1.96	1.03	0.36	**2.38**
GSL	2.13	2.65	2.67	−0.19	1.99	**3.34**	0.03
DTR	−0.18	−0.25	−0.30	**0.52**	0.01	−0.44	0.25

The elevation band with maximum magnitude for each index is highlighted in bold. Units are days or degrees per decade

the high-elevation category as a result of the higher rate of warming through maximum temperature. In Table 4, we see that each temperature index shows a different fluctuation in trend with elevation.

So understanding the physical mechanisms that drive elevation-dependent warming is essential to explain the regional differences. Albedo, clouds, aerosols, water vapor and radiative fluxes have been linked to elevation-dependent warming (Pepin et al. 2015). Take TXn for example, there is again an increase in the variability of the trend magnitudes as elevation increases, and the slope of the regression is significant at the 5% level. We also see that the trends are small, below 150 m elevation, and the variability at the high-elevation stations contributes to the observed positive slope. The rate of snowline retreat may increase with temperatures rising because the elevation dependency of snow cover duration is nonlinear (Hantel et al. 2000). This will cause significant increases in the surface absorption of incoming solar radiation around the retreating snowline, initially causing enhanced warming at that elevation (Barnett et al. 2008). When the snowline migrates upslope, this effect will extend to increasingly higher elevations (Pepin et al. 2015). The daily temperature without snow cover is higher than one with snow cover (Scherrer et al. 2012). In addition, TXn mainly reflects temperature change in winter. Recently, winter snow has a decreasing trend (Zhao et al. 2009). Due to reduction in snow cover in high elevation, change in the surface albedo of the region will increase the surface air temperature, thereby acting as a positive feedback mechanism (Meehl 1994). Furthermore, low cloud cover in winter has a decreasing trend over northeastern China (Liu et al. 2013). The decreases of low cloud cover will increase the amount of solar radiation that reaches the earth's surface, which increases surface temperature.

3.3 Changes in extreme temperature indices versus latitude

The positive correlations between latitude and the station trends in extreme temperature indices are shown in Fig. 4 and negative ones in Fig. 5, along with the correlation coefficients for the relationships and their statistical significance. The relationship between TNX and latitude is statistically significant at $p < 0.0001$, $r = 0.48$ (Fig. 4c). As is shown in Fig. 4f, g, the slopes of the regression for ID0 and SU25 show a increase with latitude and are statistically significant ($r > 0.40$, $p < 0.001$). For TXn and TXx (Fig. 4a, b), the slops of the regression line show increase trends with latitude and are significant at the 0.01 level. For TX90p and TN90p (Fig. 4d, e), the slops of the regression line show increase trends with latitude and are significant at the 0.05 level. The slope of the regression for GSL is negligible and shows an increase with latitude ($r = 0.21$, $p = 0.08$, $n = 70$). As far as the negative correlations are concerned, the only strong relationship is for TX10p (-0.41, $p < 0.001$) (Fig. 5b). The correlations are not perfect for TNn ($r = -0.07$, $p = 0.59$), TN10p ($r = -0.09$, $p = 0.54$), FD0 ($r = -0.10$, $p = 0.42$), TR20 ($r = -0.15$, $p = 0.21$) and DTR ($r = -0.12$, $p = 0.34$) (Fig. 5). This reflects that the influence of latitude on these indices is very weak and negligible. In addition, with the

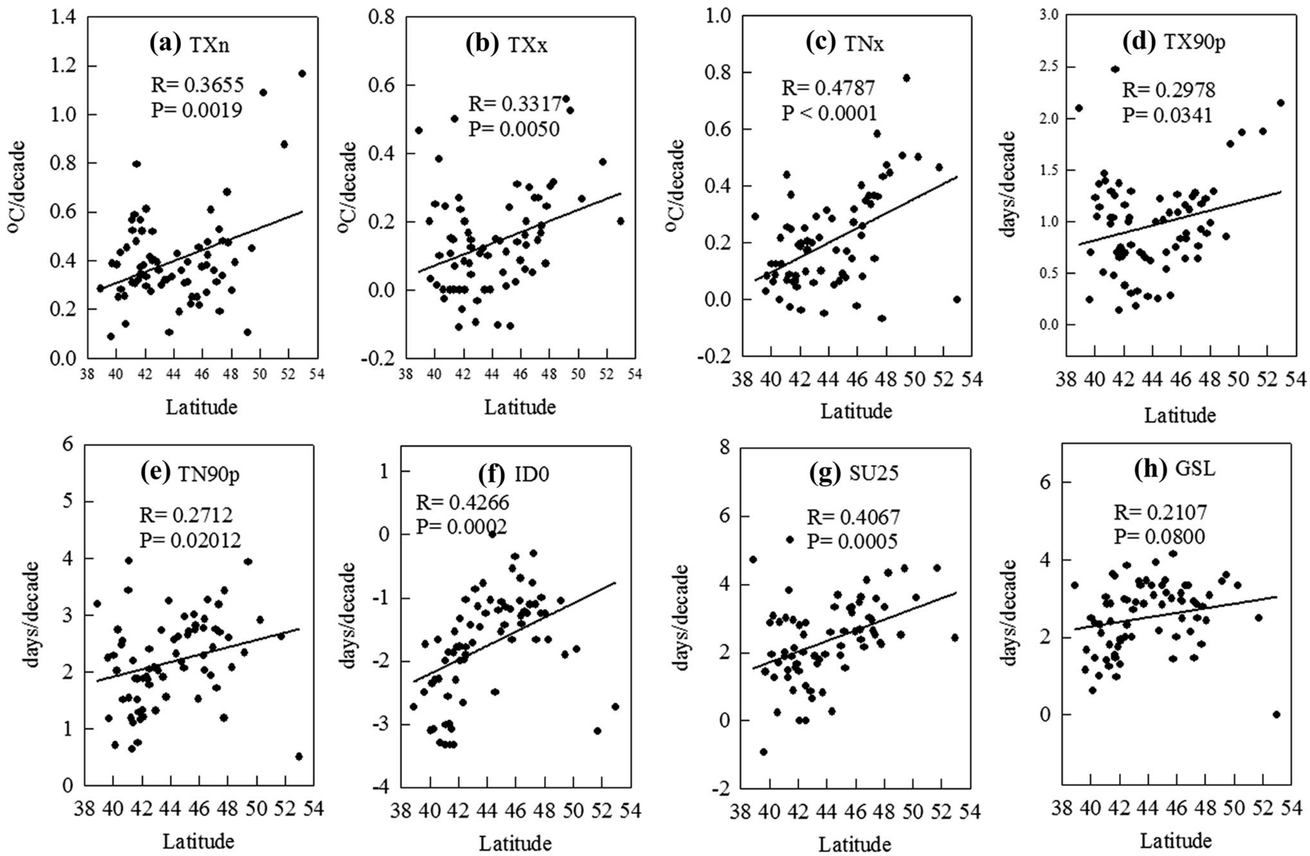

Fig. 4 Trend magnitudes of temperature extremes versus latitude over northeast China. *R* stands for correlation coefficients for the relationships and *P* for statistical significance. All abbreviations are as same as interpreted in Table 1

altitude elevating at average 1° N, the ranges of TXn, TXx, TNx, TX90p, TN90p, ID0, SU25 and GSL increase by 0.02 °C/decade, 0.02 °C/decade, 0.03 °C/decade, 0.04 day/decade, 0.06 day/decade, 0.11 day/decade, 0.16 day/decade and 0.06 day/decade, respectively. However, the ranges of TNn, TX10p, TN10p, FD0, TR20 and DTR decrease by −0.01 °C/decade, −0.04 day/decade, −0.01 day/decade, −0.04 day/decade, 0.06 day/decade and −0.01 °C/decade, respectively (Table 3).

Table 5 presents mean trends per decade of extreme temperature in categorized latitude ranks over northeast China during 1960–2013. The range of 6 out of 14 indices is the smallest in 38°N, while 7 out of 14 indices have the largest range in 52°N. By contrast, TXn and TX90P have the largest range in 38°N, and smallest in 50°N. 4 out of 14 indices have the smallest range in 50°N. ID0 have the largest range in 38°N and in 52°N. DTR attains a maximum value in 40°N have minimum values in 48°N. With latitude increase, ID0, TXn and TX90p exhibit a decrease–increase–decrease tendency, while all the other extreme temperature indices display increase–decrease–increase trends. Overall, most indices have larger ranges in the relatively high latitude and smaller in the relatively low latitude.

In a word, changes with latitude of the cold extremes (TN10, TX10 and TNn) increase while those of the warm extremes (TN90, TX90, TXx and TNx) decrease. The increasing trends of annual and seasonal mean temperature are more obvious at the higher latitude over northeastern China (He et al. 2013), and both cold and warm extremes have high correlations with the mean annual temperature (Yu and Li 2014). This will result in the more obvious trends at high-latitude regions. In addition, the distribution of snow cover over northeastern China is mainly located at low-latitude regions (Zhang 2010). The amount of solar radiation reaching the earth's surface at high-latitude regions is more than at low-latitude regions, which slightly increases surface temperature at high-latitude regions with global warming.

Table 5 Mean trends per decade of extreme temperature in categorized latitude ranks over northeast China.

3.4 Changes in extreme temperature indices versus Arctic Oscillation

The Arctic Oscillation (AO) is characterized by pressure anomalies of one sign in the Arctic and with the opposite

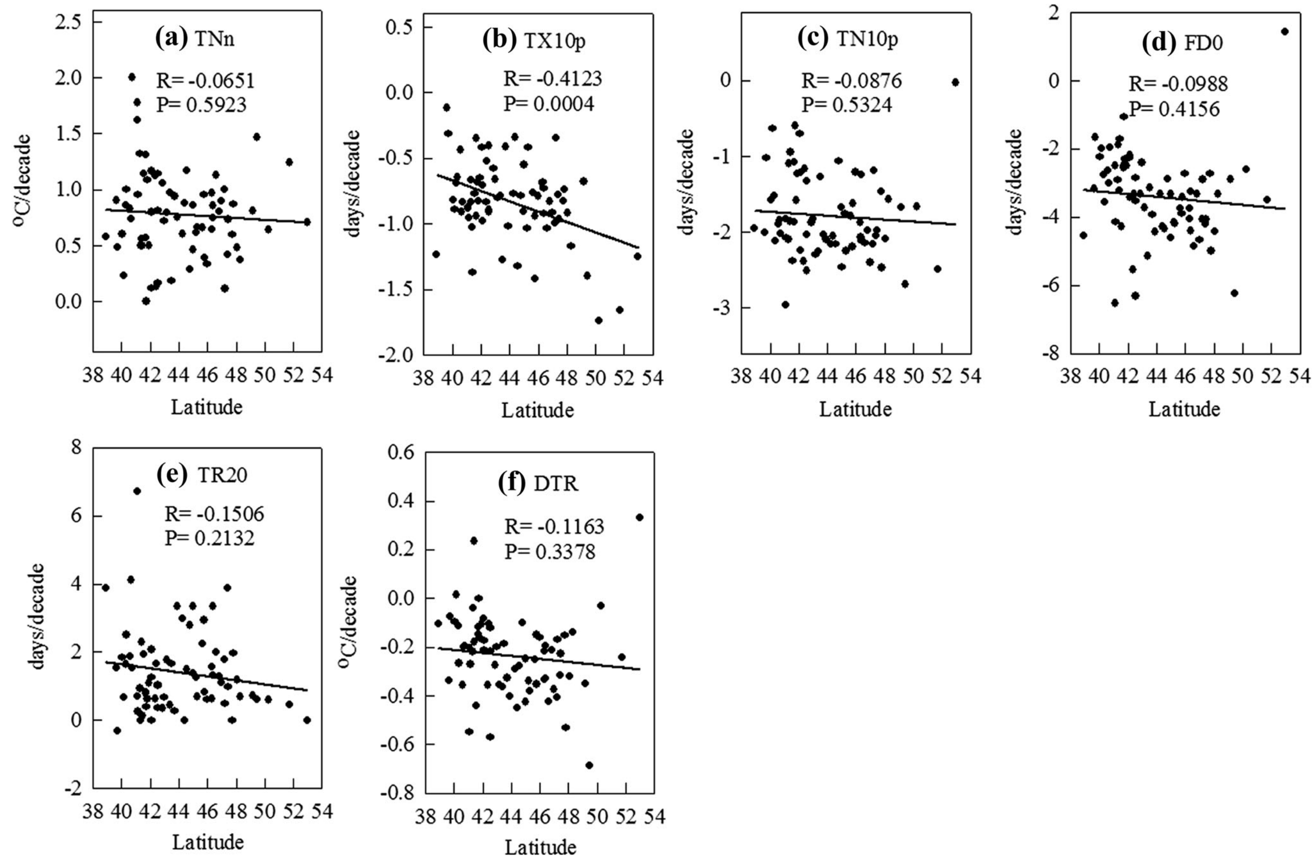

Fig. 5 Trend magnitudes of temperature extremes versus latitude over northeast China. *R* stands for correlation coefficients for the relationships and *P* for statistical significance. All abbreviations are as same as interpreted in Table 1

Table 5 Mean trends per decade of extreme temperature in categorized latitude ranks over northeast China

Latitude	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
Number	1	2	7	13	10	5	5	7	7	7	2	2	1	1	1
TXn	1.17	0.98	0.36	0.40	0.31	0.27	0.38	0.43	0.43	0.43	0.34	0.42	0.09	0.39	0.28
TXx	0.20	0.32	0.33	0.16	0.06	0.08	0.10	−0.02	0.07	0.15	0.20	0.25	0.20	0.03	0.47
TNn	0.71	0.94	0.74	0.79	0.56	0.72	0.60	0.91	0.89	0.99	0.55	1.30	0.90	0.48	0.58
TNx	0.00	0.48	0.51	0.23	0.13	0.17	0.16	0.15	0.15	0.12	0.07	0.12	0.03	0.08	0.29
TX10p	−1.25	−1.7	−0.95	−0.82	−0.86	−0.71	−0.77	−0.67	−0.80	−0.85	−0.79	−0.83	−0.12	−0.31	−1.23
TX90p	2.12	1.86	1.12	0.95	0.81	0.66	0.84	0.56	0.93	1.22	1.20	1.31	0.24	0.70	2.09
TN10p	−0.03	−2.08	−2.07	−1.93	−1.72	−1.97	−1.62	−1.90	−1.70	−1.70	−1.08	−1.80	−2.01	−1.02	−1.95
TN90p	0.5	2.77	2.89	2.46	2.34	2.29	1.67	1.93	1.81	1.95	1.36	1.90	2.24	1.18	3.20
FD0	1.43	−3.05	−4.32	−3.87	−3.59	−4.12	−2.90	−3.91	−3.09	−2.62	−2.38	−2.10	−3.18	−1.67	−4.55
ID0	−2.73	−2.47	−1.38	−1.20	−1.12	−1.20	−1.84	−2.06	−2.30	−2.54	−2.72	−3.20	−2.50	−1.74	−2.73
SU25	2.41	4.03	3.27	2.93	2.34	1.76	1.75	1.35	2.05	2.00	2.50	2.87	−0.93	1.43	4.71
TR20	0.00	0.52	1.43	1.69	1.37	1.49	1.21	0.91	1.45	1.66	1.16	1.69	1.54	−0.31	3.88
GSL	0.00	2.92	2.95	2.80	2.92	2.93	2.25	2.62	2.25	1.82	1.04	2.30	1.14	1.67	3.33
DTR	0.33	−0.14	−0.37	−0.30	−0.26	−0.31	−0.17	−0.31	−0.19	−0.16	−0.05	−0.15	−0.34	−0.07	−0.11

anomalies centered about latitudes of 37–45°N (Givati and Rosenfeld 2013). It modulates the circulation pattern over the middle and high latitudes, thereby regulating the frequency and intensity of significant weather events (Thompson and Wallace 1998, 2001). During the recent decades a trend toward lower pressure over the poles, higher pressure in the

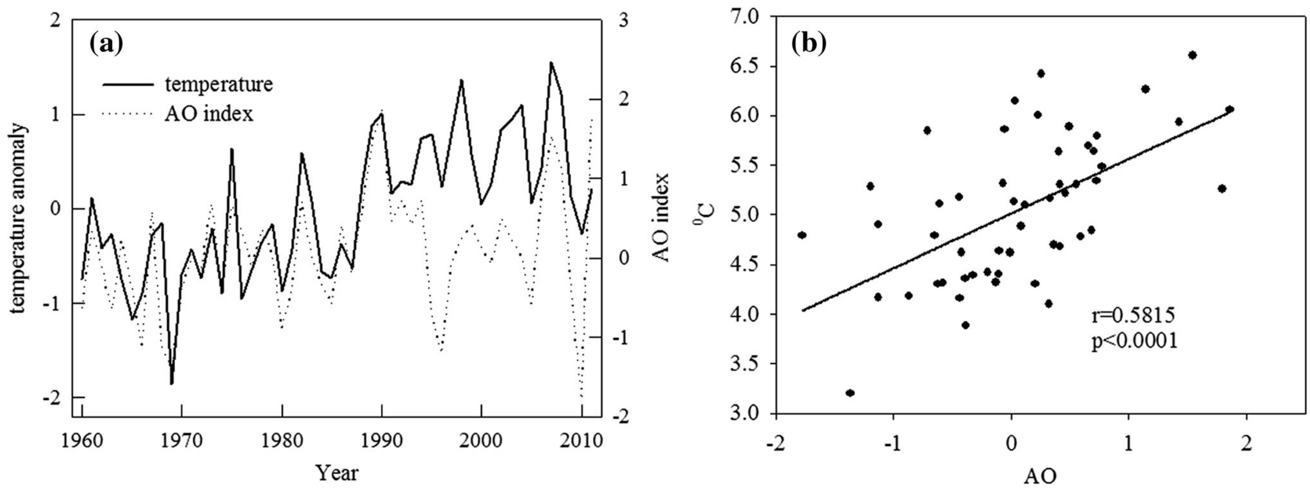

Fig. 6 **a** Interannual changes of annual mean temperature anomaly (*solid line*) and AO index (*dashed line*) over northeast China; **b** correlation between AO index and annual mean temperature over northeast China

Table 6 Correlation between AO index and g temperature indexes over northeast China

AO index	TXn	TXx	TNn	TNx	TX10p	TX90p	TN10p	TN90p	FD0	ID0	SU25	TR20	GSL	DTR
Annual	0.27	0.01	0.32*	0.18	−0.62**	0.44**	−0.47**	0.39**	−0.44**	0.56**	0.15	0.23	0.50**	0.03

* Significant at the 0.05 level

** Significant at the 0.01 level

mid-latitudes, and stronger sub-polar westerlies indicated a more persistent positive phase of the AO (Thompson and Wallace 2000). Due to sea level pressure increasing over the subtropics and mid-latitudes, and decreasing over high latitudes, there is a poleward expansion and weakening of the Hadley Circulation and a poleward shift of the storm tracks of several degrees latitude with a consequent increase in cyclonic circulation patterns over the high-latitude Arctic and Antarctic regions (IPCC 2007). Thus, there is a projected increasing trend of the Arctic Oscillation (AO). Givati and Rosenfeld (2013) tested the significance of the observed upward trend in the AO over 60 years for each month and found it to be significant from January to March. The PNU-CGCM can predict that the positive-phase AO is associated with an anomalous southwesterly flow over western North Asia, which brings relatively warm air from the mid-latitude Asian region and with an anomalous easterly and southeasterly flow over northern East Asia, which brings relatively warm air from the western North Pacific and mid-East Asia regions (Sun and Ahn 2015). In China, the correlation between temperature and AO is mainly positive except some stations in southeast of the Tibetan plateau, especially in northern Xinjiang, northeastern China, north China, Shandong Province where it is significant (Gong and Wang 2003).

Figure 6a presents interannual changes of spring temperature anomaly (solid line) and Arctic Oscillation index (dashed line) over northeast China during 1960–2011. Figure 6b shows relationships between Arctic Oscillation and the annual mean temperature, along with the correlation coefficients for the relationships and their statistical significance. We can see from Fig. 6a, b, the change trend in the annual mean temperature is consistent with Arctic Oscillation; the correlation coefficient is 0.58 and the confidence coefficient is more than 99.9%. When Arctic Oscillation index increases, cold advection over the Asia is weak. So the temperature advection is mainly zonal. The aforementioned phenomena lead to increased temperature over northeast China. However, when Arctic Oscillation index decreases, cold advection over the Asia is strong and heat exchange strengthens from south to north, causing the temperature decreasing over northeast China.

Table 6 exhibits relationships between the temperature indices and Arctic Oscillation. The Arctic Oscillation index has high correlation with TX10p, TX90p, TN10p, TN90p, TNn, FD0, ID0 and GSL, with correlation coefficients over 0.32 ($p \geq 0.05$), indicating that changes in the Arctic Oscillation index can predict general warming over northeastern China. Comparing the behavior of these indices, TX90p has the strongest correlations with mean temperature, and their coefficient is −0.62. Correlations are not perfect for the rest indices because the influences of Arctic Oscillation on them are obviously seasonal.

Figure 7 further indicates that Arctic Oscillation is more obvious in the daytime than that in the nighttime, and the confidence coefficient of them is more than 99.9%. Figure 8 shows the spatial distribution of the correlation coefficient between the Arctic Oscillation index and

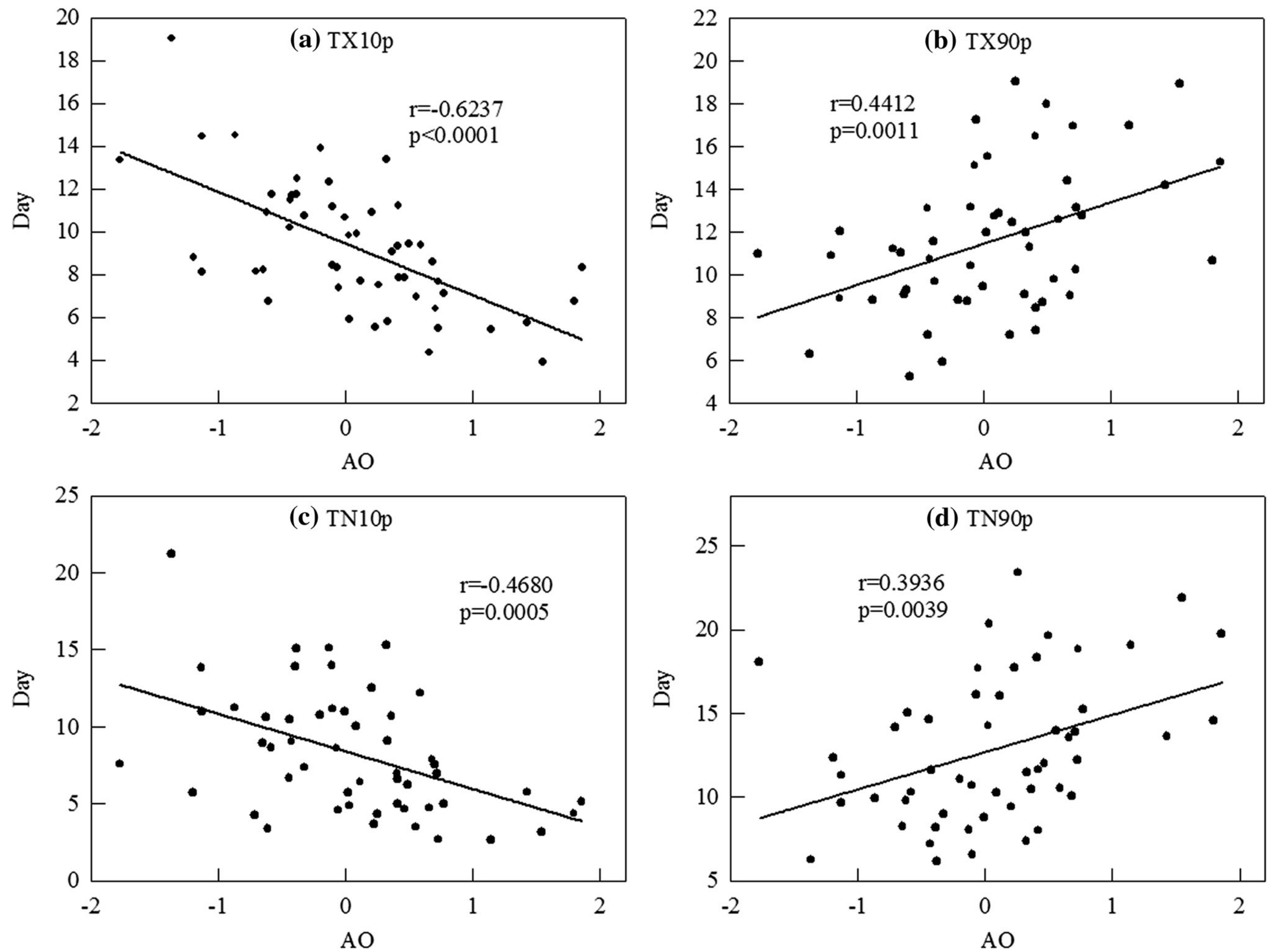

Fig. 7 Correlation between AO index and temperature indices over northeast China

percentile indices (TX10p, TX90p, TN10p and TN90p). Negative correlations between the Arctic Oscillation index and cold day/night are shown at each station. The correlations are not the same in different areas, with higher value in the middle and the north of northeast China for TX10p and the south of northeast China for TN10p. Compared with TN10p, TX10p has higher correlation. TX90p and TN90p present positive correlation with the Arctic Oscillation index. The correlations are also not the same in different areas. For TX90p, the stations in the south of northeast China have stronger correlation. However, for TN90p, the stations in the middle and the north of northeast China have better correlation.

To further explore the mechanism behind the relationships between Arctic Oscillation and trends in temperature extremes, TXn is selected to analyze the influence of Arctic Oscillation on extreme temperature on the interdecadal scale. TXn mainly reflects temperature change in winter. So we choose the winter Arctic Oscillation index. Accumulated anomaly series of TXn index and winter Arctic Oscillation index have a good corresponding relationship over northeast China (Fig. 9a, b). The phases of TXn index and winter Arctic Oscillation index are also same (Fig. 10a, b). Wu and Wang (2002) consider that winter Arctic Oscillation shows possible effects on winter Siberian high (SH), and further influences the East Asian winter monsoon (EAWM). Air temperature from near the surface to the middle troposphere is affected in the southeastern Siberia and the East Asian. He and He (2003) found that air temperature in North China is affected by Siberian high and East Asian Trough. At the ground surface, when the winter AO index is in a negative (positive) phase, both of winter Siberian high and East Asian winter monsoon are strengthened (weakened), and northeast China undergoes a successive cold (warm) winter. In the middle troposphere, when the winter Arctic Oscillation is in its negative (positive) phase, the East Asia trough and the ridge west and north of Baikal Lake are strengthened (weakened), the circulation develops

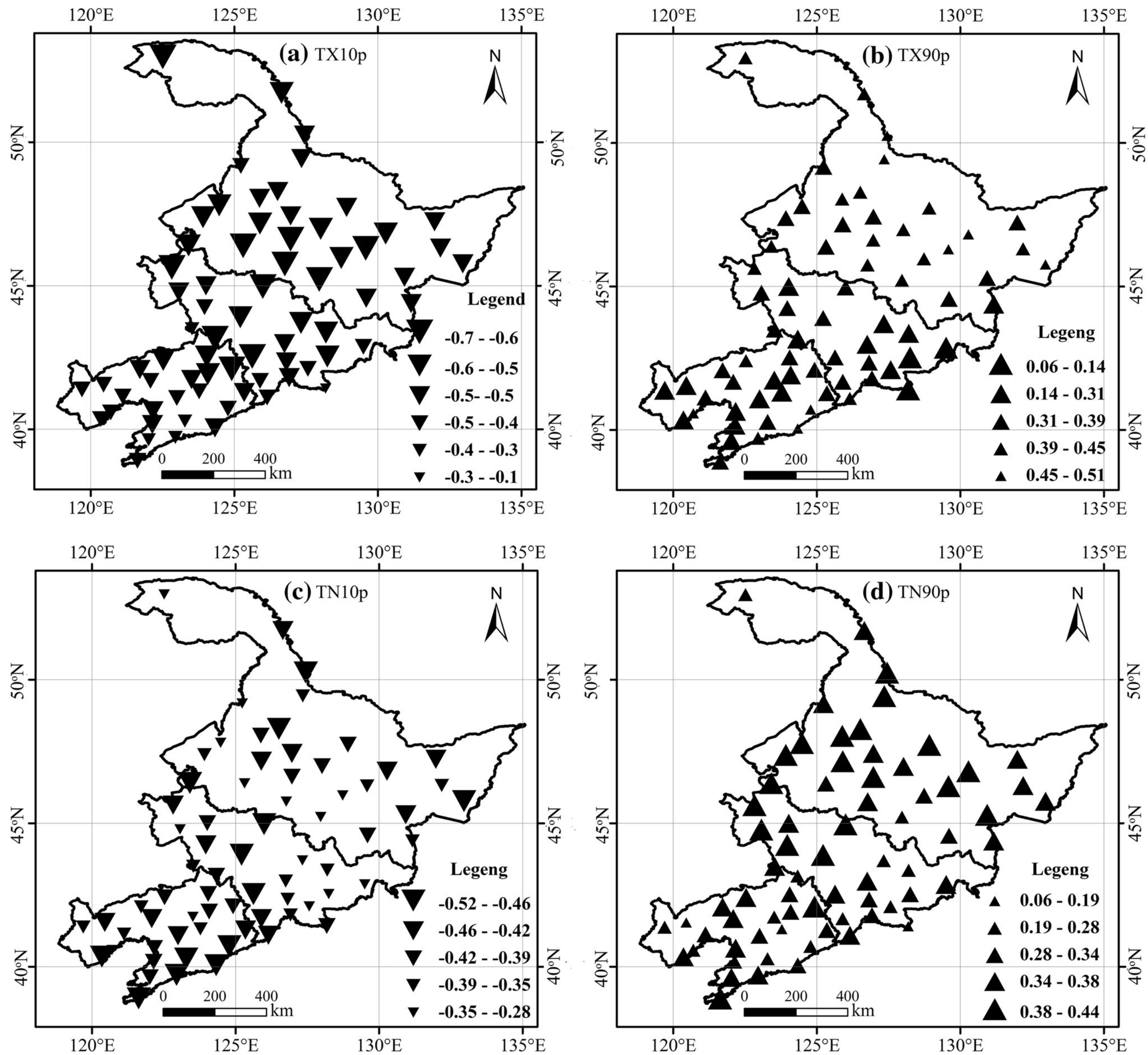

Fig. 8 Spatial distribution of correlation between AO index and temperature indices over northeast China

meridionally (zonally), the northerly wind is strengthened (weakened), and northeast China undergoes successive cold (warm) winter.

4 Discussion

A majority of studies suggest that warming is more rapid at higher elevations, but there are a number of studies showing either no relationship or a more complex situation (Pepin et al. 2015). There are no significant correlations between elevation and trend magnitude of temperature extremes with the exception of TXn, TNn, TR20 and GSL. Winter temperature indices, including TXn and TNn, show positively significant relationships with elevation. GSL which reflects mean temperature also displays significant gradient at high elevations. As minimum temperature indices, TR20 has negatively significant relationship with elevation. For 10 out of 14 indices, the correlation coefficients are again insignificant. In most cases, therefore, the correlations between elevation and the trend magnitudes are negligible. Temperature extremes display obvious warming with elevation in southwestern China (Li et al. 2012). As winter temperature indices, only TNn shows significant gradient at high elevations. Summer temperature indices, including TXx and TNx, show positively significant relationships with elevation. The warm extremes (TX90p, TN90p) increase significantly with

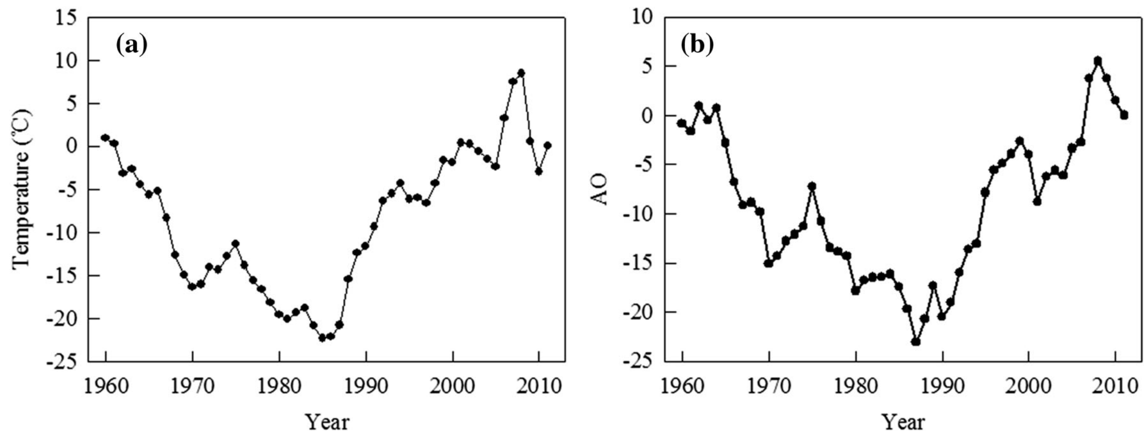

Fig. 9 Accumulated anomaly series of TXn index (**a**) over northeast China and winter AO index (**b**)

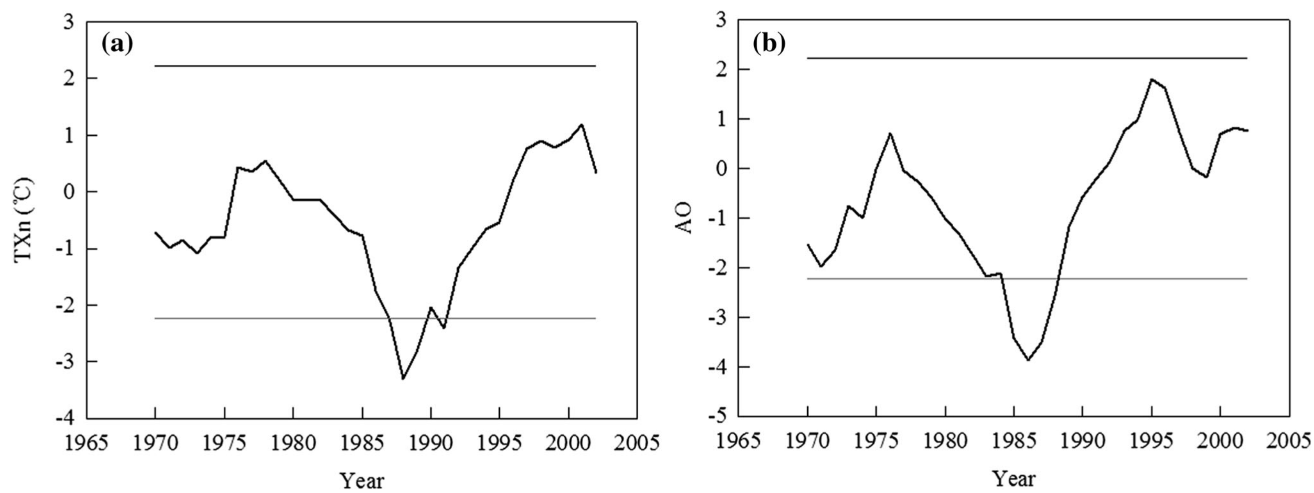

Fig. 10 The running *t*-statistical curve of winter temperature index (**a**) over northeast China and winter AO index (**b**)

elevation while the cold extremes (TX10p, TN10p) decrease significant with elevation. In the eastern and central Tibetan Plateau, there are no significant correlations between elevation and trend magnitude of temperature extremes (You et al. 2008). However, there are limitations in analyzing change of extreme temperature with elevation in China except the aforementioned regions. In northwestern and northeastern China, few reports are associated with the extreme temperature trend in relation to elevation. In addition, some studies pay more attention to mean temperature in the plateau. In the Qinghai-Xizang Plateau grassland, an enhanced temperature change trend is found in higher elevation than in lower elevation for autumn nights and winter temperatures, while the temperature change trends for other seasons are more evident in lower elevation areas (Tao et al. 2013). At the same time, a significant altitudinal amplification trend in mean temperature is also found in the Loess Plateau and Yunnan-Guizhou Plateau (Wang et al. 2014). It's worth noting that, although recent climatic warming over the Tibet Plateau is correlated with elevation (Liu and Hou 1998; Liu and Chen 2000) and warming in high elevation regions appears much more rapid than in low elevations (Yao et al. 2000; Tian et al. 2006; Kang et al. 2007), extreme temperature fails to substantiate this relationship. The mechanism may be that changes in temperature extremes can be disproportionate in comparison to the changes in mean temperature associated with climate change (You et al. 2008).

Compared with other regions in the world, there are some differences. Take South Asia as example, extreme temperature trends at lower-altitude stations are consistent with a warming climate whereas stations at higher altitudes often show mixed trends (Revadekar et al. 2012). In mountain environments, growing evidence shows that the rate of warming is amplified with elevation (Pepin et al. 2015). As far as minimum temperature and maximum temperature are concerned, observational studies show that Europe (particularly western Europe), and parts of Asia displaying the strongest high-altitude warming during the period of record; the signal appears to be more closely

Table 7 Number of stations in differing topographical and urban/rural classes in categorized elevation ranks over northeast China

Altitude (m)	<100	100–200	200–300	300–400	400–500	500–600	>600
Summit station	6	8	6	1	0	1	0
Intermountain station	2	7	8	0	1	1	1
Valley station	0	0	2	1	1	1	0
Flat station	9	10	3	0	1	1	1
Urban station	11	15	11	2	0	2	1
Rural station	6	10	6	0	3	2	1

Units are days or degrees per decade

Table 8 Mean trend magnitudes of temperature extremes in differing topographical and urban/rural classes in categorized elevation ranks over northeast China

Altitude (m)	Summit station	Intermountain station	Valley station	Flat station	Urban station	Rural station
Number	21	20	4	25	42	28
TXn	0.36	0.45	**0.54**	0.37	0.37	**0.44**
TXx	0.11	0.15	**0.16**	0.15	0.12	**0.17**
TNn	0.72	**0.98**	0.79	0.66	0.73	**0.84**
TNx	**0.24**	0.17	0.14	0.20	0.20	**0.21**
TX10p	−0.76	**−0.90**	−0.83	−0.84	**−0.83**	−0.82
TX90p	0.85	**1.07**	1.03	0.97	0.95	**0.99**
TN10p	**−1.92**	−1.84	−1.44	−1.69	−1.78	**−1.79**
TN90p	**2.50**	1.86	1.68	2.24	**2.22**	2.11
FD0	**−3.88**	−3.28	−2.40	−3.30	**−3.44**	−3.39
ID0	−1.40	**−2.22**	−1.57	−1.70	−1.70	**−1.82**
SU25	2.20	**2.49**	1.89	2.42	2.30	**2.41**
TR20	**1.91**	0.85	0.45	1.55	**1.47**	1.28
GSL	**2.69**	2.49	1.62	2.52	**2.56**	2.45
DTR	**−0.28**	−0.22	−0.15	−0.23	−0.23	**−0.25**

The elevation band with maximum magnitude for each index is highlighted in bold. Units are days or degrees per decade

related to increases in daily minimum temperature than changes in the daily maximum (Diaz and Bradley 1997). In the western United States, the trend in minimum average temperature increases with elevation, while the trends in the mean maximum temperature increase with height only in the Colorado Rockies (Diaz and Eischeid 2007). In Nepal, seasonal and annual maximum temperature trends show high rates of warming in the high-elevation regions (Middle Mountains and Himalaya), while low warming or even cooling trends are found in the low-elevation regions (southern regions) (Shrestha et al. 1999). This is attributed to the sensitivity of mountainous regions to climate changes.

To further investigate whether topography and the degree of urbanization influence the results obtained, stations are classified for both parameters. Each of the 71 stations are divided into topographic types which were summit, flat, intermountain and valley (Li et al. 2011; Wang et al. 2013), according to topographic index derived from SRTM digital elevation data (available from http://srtm.cgiar.org). A topographical index is calculated by centering a grid on each station and calculating the elevation difference between the station and the eight surrounding cells. The sum of these elevation differences is consistent with our topographic index. Additionally, the aforementioned stations are classified as urban (>30,000 population) or rural (<30,000 population). Table 7 shows the number of stations in each category for each elevation band. For most parameters, topography influences the mean trend magnitudes whereas urbanization is weak (Table 8). 5/14 of index trends are significantly steeper for urban stations when compared to their rural counterparts. For summit station, 1/2 of index magnitudes are significantly higher than those of the rest topographical index. 5/14 of index trends in Intermountain station are higher those of summit stations, valley stations and flat stations. This reflects that local influences are fundamental importance in this dataset instead of simple effect of elevation.

Some scholars considered that topography influenced trend magnitudes with summit sites show weaker increases than other sites (Pepin and Seidel 2005), and that locally the urbanization and land use change impact on surface warming is not negligible (Kalnay and Cai 2003). As far as most temperature indices over northeast China are concerned, topography influences the mean trend magnitudes of these indices whereas urbanization is weak. Further study manifests that most of temperature index have stronger correlation with the latitude, and most indices have larger ranges in the relatively high latitude and smaller in the relatively low latitude over northeast China. This reflects that latitude is integral part to impact on extreme temperature over northeast China. As far as temperature is concerned, many scholars also study the influence of Arctic Oscillation and come to significative conclusions. Wang et al. (2007) considered that there is a closely positive correlation between the spring temperature over northeast China and the spring Arctic Oscillation index on yearly time scale, and that Arctic Oscillation index and extreme temperature indices have the same period and abrupt change date. Pang and Guo (2010) believed that significant differences existing in Arctic Oscillation related atmospheric circulation anomaly during different periods may be the reason for the interdecadal variation of the relationship between Arctic Oscillation and surface air temperature in Northeast China. Hu and Liu (2005) found that when the winter Arctic Oscillation index is in a low (high)phase,the winter air temperature in northeast China undergoes a successive cold(warm) winter. The study also indicates Arctic Oscillation index has high correlations with TX10p (cool days), TX90p (warm days), TN10p (cool nights), TN90p (warm nights), TNn (coldest night), FD0 (Frost days), ID0 (Ice days) and GSL (Growing season Length), indicating that changes in the Arctic Oscillations index can predict general warming over northeastern China.

To summarize, elevation has no effect on temperature changes and the other factors (topographic type, the latitude and the Arctic Oscillation) do have. The mechanisms for this contrast are that albedo, clouds, aerosols, water vapor and radiative fluxes have been linked to elevation-dependent warming. The rate of snowline retreat may increase with temperatures rising because the elevation dependency of snow cover duration is nonlinear. The distribution of snow cover over northeastern China is mainly located at low-latitude regions. The amount of solar radiation reaching the earth's surface at high-latitude regions is more than at low-latitude regions, which slightly increases surface temperature at high-latitude regions with global warming. The phases of temperature index and winter Arctic Oscillation index are also same. At the ground surface, when the winter AO index is in a negative (positive) phase, northeast China undergoes successive cold (warm) winter. In addition, ENSO event (Liu and Wang 2001), the northern hemisphere temperature (Lu et al. 2009), the polar vortex (Lu et al. 2009), atmospheric total ozone (Gong et al. 2004b) and the East Asian of winter monsoon background (Liu et al. 2014) also impact on temperature, while the influences of them on extreme temperature need to further study in future.

5 Conclusions

Based on the above analysis, some conclusions can be drawn as follows.

1. Overall there are no significant correlations between elevation and trend magnitude of temperature extremes with the exception of TXn (coldest day), TNn (coldest night), TR20 (tropical nights) and GSL (growing season length) over northeastern China during 1960–2011. This reflects that the influence of elevation on extreme temperature is not apparent in the context of recent warming in this region. There is a positive correlation between elevation and the trend magnitudes of TNn, TNx, TXn, TXx, ID0, SU25 and GSL, and the correlation coefficients are strong for TXn (0.34, $p < 0.01$), TNn (0.25, $p < 0.05$) and GSL (0.28, $p < 0.05$). Negative relationships between elevation and the trend magnitudes of TX10p, TX90p, TN10p, TN90p, FD0, TR20 and DTR are found. The only strong relationship is for TR20 (−0.32, $p < 0.01$).
2. 8 out of 14 temperature indices have stronger correlation with the latitude. For temperature indices of TNX, ID0, SU25, TXn, TXx, TX90p and TN90p, the slops of the regression line show increase trends with latitude and are significant. The slope of the regression for GSL is negligible and shows an increase with latitude. As far as the negative correlations are concerned, the only strong relationship is for TX10p. The correlations are not perfect for TNn, TN10p, FD0, TR20 and DTR. Overall, most indices have larger ranges in the relatively high latitude and smaller in the relatively low latitude.
3. The Arctic Oscillation index has high correlations with TX10p, TX90p, TN10p, TN90p, TNn, FD0, ID0 and GSL, indicating that changes in the Arctic Oscillation index can predict general warming over northeastern China. The correlations between the Arctic Oscillation index and percentile indices, including TX10p (cool days), TX90p (warm days), TN10p (cool nights), TN90p (warm nights), are not the same in different areas.

4. For most parameters, topography influences the mean trend magnitudes whereas urbanization is weak. 5/14 of index trends are significantly steeper for urban stations when compared to their rural counterparts. For summit station, 1/2 of index magnitudes are significantly higher than those of the rest topographical index. 5/14 of index trends in Intermountain station are higher those of summit station, valley station and flat station.

To summarize, analysis of trend magnitudes by topographic type, the latitude and the Arctic Oscillation shows three factors to have a strong influence in this dataset, which overrides that of elevation and degree of urbanization.

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