Dynamic changes in temperature extremes and their association with atmospheric circulation patterns in the Songhua River Basin, China

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A B S T R A C T

Understanding dynamic changes in climate extremes is important in forecasting extreme climate events and reducing their associated impacts. The objectives of this study were to analyze the spatiotemporal variations in temperature extremes and their association with atmospheric circulation, based on daily maximum (TX) and minimum temperatures (TN) collected from 60 meteorological stations in the Songhua River Basin (SRB) and its surroundings from 1960 to 2014. Following the ETCCDI (Expert Team on Climate Change Detection and Indices), eight extreme temperature indices, including three warm indices, three cold indices and two extreme indices, were chosen to quantify temperature extremes. The Mann-Kendall method and linear trend analysis were used to examine the trends, and Pearson correlation analysis was used to analyze the correlation between the temperature extremes and each atmospheric circulation. The results showed that warm indices, including the number of warm nights, warm days, and summer days, and extreme indices, including minimum TN and maximum TX, showed increasing trends in the SRB from 1960 to 2014. On the other hand, cold indices, including the number of cold nights, cold days and frost days, showed decreasing trends; Warm indices and maximum TX showed significant positive correlations with latitude (P < 0.01). The Arctic Oscillation index (AO) displayed significant negative correlations with the cold indices (P < 0.01) and positive correlations with the warm indices. The warm indices and extreme indices had positive correlations with the Northern Hemisphere Subtropical High area and intensity indices, while the reverse relationship was found between the cold indices and Northern Hemisphere Subtropical High. The Asia polar vortex area and intensity indices showed negative correlations with warm indices and extreme indices, while they were positively correlated to cold indices. The multivariate ENSO index (MEI) showed no linear correlation with any of the temperature extremes. These findings will provide useful information in forecasting extreme climate events and taking measures to reduce their associated impacts.

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1. Introduction

Extreme climate events such as heat waves and droughts have become more frequent and more intense globally over the past few decades, resulting in a series of societal, economic and ecological problems (Meehl et al., 2000). Because of these events’ disproportionate impact, understanding climate extremes has become more urgent than tracking changes in mean climate due to climate change (Mutiiwba et al., 2015).

Temperature extremes have received much attention in recent years due to their potential implications for hydrology, infrastructure, public health and ecosystems (Frich et al., 2002; Alexander et al., 2006; Fischer et al., 2011). Alexander et al. (2006) found that > 70% of the Earth’s land area underwent a significant reduction in the number of cold nights and a significant increase in the number of warm days in the last 50 years. Karl et al. (1991) showed that the extreme minimum temperature increased substantially in the United States, Eastern Europe and Russia from 1901 to 1951, while changes in the extreme maximum temperature showed regional differences. The number of extreme high temperature days in Russia had increased significantly (Gruza et al., 1999), and a similar trend had also been noted in Europe, Africa, South America and the Asia-Pacific region (Beniston and Rebetez, 1996; Vincent et al., 2005; New et al., 2006; Choi et al., 2009; Mernild et al., 2014). A number of studies had also focused on temperature extremes in different regions of China, and the results generally showed that extremes related to low temperatures, including the number of...
cold nights, cold days and frost days, had decreased in frequency and intensity, while extremes related to high temperature, including the number of warm nights, warm days and frost-free days, had increased in frequency and intensity. There were regional differences in the changes for all these metrics (Li et al., 2011; Zhou and Ren, 2011; Li et al., 2012a, 2012b; Guan et al., 2015; Yu and Li, 2015). These previous studies have provided key insights for understanding the trend of temperature extremes.

In recent years, some studies have focused on the relationship between dynamic changes in temperature extremes and atmospheric circulation (Kenyon and Hegerl, 2008; Renom et al., 2011). Renom et al. (2011) found that during the period 1946–1975, interannual variability in cold summer nights was associated with the negative phase of the Southern Annular Mode (SAM). On the other hand, the El Nino-Southern Oscillation dominated the interannual variability of warm winter nights in Uruguay. Mutiibwa et al. (2015) identified the correlations between temperature extremes and the PNA (Pacific/North American teleconnection pattern), MEI (Multivariate ENSO Index) and the AO (Arctic Oscillation) in the United States mainland. These correlations also showed regional differences. There was a lagged correlation between extreme temperatures and AO in East Asia (He and Wang, 2016), and the NAO (North Atlantic Oscillation) correlated with frost days and cold days over Europe in both observational studies and simulations (Scaife et al., 2008). Temperature extremes were substantially affected by large-scale circulation patterns, and the relationships between temperature extremes and circulation patterns were different in different climatic conditions (Kenyon and Hegerl, 2008). The above studies show that there are connections between temperature extremes and atmospheric circulation.

In China, atmospheric circulation was affected by the East Asian monsoon (EAM), the Subtropical High, tropical cyclones, the polar vortex and other atmospheric systems, due to its continental position (Li et al., 2012a, 2012b). These factors complicated the relationship between temperature extremes and atmospheric circulation. Wei and Lin (2009) found negative phase of AO leads to more frequent cold air outbreaks in China, and vice versa. Fischer et al. (2011) found that abrupt shifts to higher annual mean temperatures could be partly explained by simultaneous changes in the Western Pacific Subtropical High and the East Asian Summer Monsoon (EASM). Tao et al. (2014) identified significant positive correlations between $T_{\text{mean}}$-related indices (warm nights, minimum TN and TNmean) and ENSO in the Poyang Lake Basin, and in northern China, Wei et al. (2004) showed that a good relationship existed between the longitudinal position of the Subtropical High in the western Pacific and summer temperatures. These studies established a linkage between temperature extremes and circulation features at climatic scales in China. However, these studies mainly focus on the influence of one or two patterns of atmospheric circulation at a time; they lack a comprehensive and systematic research project.

In recent years, some new technology and methods were applied to analyze the extreme weather events and its possible reasons (Christidis et al., 2011; Grotjahn et al., 2016). Reanalysis data assimilated multiples available observing systems and provided continuous fields for regions or variables with sparse or no direct observations in research temperature extremes (Zhang et al., 2017). Regional climate models were used to investigate changes of temperature extremes in the future (Kunkel et al., 2010). Optimal fingerprinting analysis and optimal detection methodology were also applied to detect human influences in temperature extremes (Hegerl et al., 2004; Christidis et al., 2011). Some methods, such as Empirical orthogonal functions, Machine learning and Deep Belief Networks had been used to identify the association between extreme temperature events and large scale meteorological patterns (Grotjahn et al., 2016).

The Songhua River Basin (SRB) is located at middle to high latitudes in the far northeastern part of China. It lies along the east coast of Eurasia and at the northern edge of the East Asian monsoon. Thus, the SRB was chosen as a study area because it is one of the most sensitive regions to climate warming in China (Song et al., 2015). The annual climate changes strongly, and the ecological environment is relatively fragile due to the competing influences by the East Asian monsoon, the Subtropical High and the polar vortex. Within the basin, natural hazards such as flash floods and droughts have occurred frequently in recent years, which have caused heavy losses to property and the national economy. For example, the extreme low temperatures in 1957, 1969, 1972 and 1976 resulted in decreases of agricultural output by 20%–30% in the SRB. However, up to date, few studies have focused on the dynamic changes in extreme temperature events in the SRB and the factors that influence them (Sun et al., 2016).

The main objectives of this study were to analyze the spatiotemporal variation in temperature extremes in the SRB and identified relationships between dynamic changes in temperature extremes and largescale atmospheric circulation patterns. To meet these objectives, this study uses the Mann–Kendall non-parametric trend test and Pearson correlation analysis, applied to daily maximum and minimum temperatures collected from 60 meteorological stations in the SRB and its surroundings during the years 1960 to 2014. We further address the following suite of questions: (1) How are temperature extremes changing in the SRB? (2) How does variation in extreme temperature events change with latitude, longitude and altitude? (3) What is the relationship between changes in temperature extremes in the SRB and atmospheric circulation?

2. Data and methodology

2.1. Study area

The SRB is located in the far northeast of China. It has an area of 546,000 km² and stretches latitudinally from 41°42′ N to 51°38′ N and longitudinally from 119°52′ E to 132°31′ E (Fig. 1). The basin is located in the temperate climate zone at the northern margin of the East Asian Monsoon, which causes the annual climate to fluctuate strongly due to the competing influences of the East Asian monsoon, the Subtropical High and the polar vortex. The annual mean temperature is between 3 and 5 °C. Annual precipitation is between 300 and 1200 mm and decreases from southeast to northwest (Li et al., 2014b).

The terrain in the SRB is dominated by plains and hills. The Greater Khingan Mountains are located in the west, and the Changbai Mountains are located in the east (Song et al., 2015). These two ranges contain the headwaters of the Nenjiang and the Second Songhua River, respectively. These two tributaries merge into the Songhua River at the Sanjiang estuary. The primary soil type is Mollisol, and the SRB contains 60% of the Mollisol area in China. The SRB is a main grain-producing region and commodity grain base of China. It is also one of the most sensitive regions to climate warming in China (Song et al., 2015).

2.2. Data source and quality control

Time series of daily maximum (TX) and minimum temperature (TN) from 73 meteorological stations in the SRB cover the period from 1960 to 2014 were provided by the Meteorological Information Center of the China Meteorological Administration (http://cdc.cma.gov.cn). The climate data have been maintained according to the World Meteorological Organization’s (WMO) standards and China Meteorological Administration’s technical regulations on weather observations (Xu et al., 2006). This dataset has undergone strict quality control procedures (e.g., extreme value and time consistency tests) and has been widely used in studying climatic changes in China (Li et al., 2011; Tao et al., 2014; Guan et al., 2015; Wang et al., 2016). The meteorological stations where the data gap > 30 days would be excluded from this study. When the gap > 30 days, it would be filled by average temperature from two or more nearby stations. Finally, 60 stations were selected during the period from 1960 to 2014. The distribution of these stations is shown in Fig. 1.
Based on previous studies (Shen et al., 2013; Tao et al., 2014; He and Wang, 2016; Sun et al., 2016), multivariate ENSO index (MEI) (Wolter and Timlin, 1993), the Arctic Oscillation index (AO) (Thompson and Wallace, 1998), the Northern Hemisphere Subtropical High area and intensity indices (He and Gong, 2002) and the Asia polar vortex area and intensity indices (Willett, 1949; Davis and Benkovic, 1994) were used to analyze the association between temperature extremes and atmospheric patterns. Monthly mean values for the Arctic Oscillation index, Northern Hemisphere Subtropical High area and intensity indices, Asia polar vortex area and intensity indices were obtained from the China National Climate Center for Climate Systems Consulting Room (http://cmdp.ncc.cma.gov.cn/upload/upload8/hc068). Monthly mean values for the MEI were obtained from the National Oceanic and Atmospheric Administration of the United States (NOAA) (http://www.esrl.noaa.gov/psd/enso/mei/table.html) from 1960 to 2014. These indices meet the corresponding quality control standards and have been used widely in scientific research. Further information about these data can be found on the websites mentioned above and in corresponding articles (Liu, 1986; Li and Fang, 2005; Mutiibwa et al., 2015).

2.3. Definition and selection of extreme indices

The Expert Team on Climate Change Detection and Indices (ETCCDI, http://cccma.seos.uvic.ca/ETCCDI/) has been coordinating an international effort to develop, calculate and analyze a suite of 11 precipitation and 16 temperature indices adopted by the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change in 2006 (Alexander et al., 2006). During the last several years, these indices have been widely used to examine changes in extremes in many regions of the world (Choi et al., 2009; Song et al., 2015; Sun et al., 2016). In this study, eight temperature indices that have been widely used were used to quantify extreme temperature changes (Table 1). Moreover, the temperature indices were divided into 3 different categories: warm indices, including the number of warm days (TX90P), warm nights (TN90P) and summer days (SU); cold indices, including the number of cold days (TX10P), cold nights (TN10P) and frost days (FD); and extreme indices, including minimum TX (TNn) and maximum TX (TXx). Specific methods for calculating these indices can be found on relevant websites (http://etcdci.pacificclimate.org/list_27_indices.shtml) and in research papers (Choi et al., 2009; Mernild et al., 2014; Guan et al., 2015; Alexander et al., 2006).

2.4. Data analysis

The Mann-Kendall test (Kendall, 1948) is a non-parametric test, which is suitable for the data that do not follow a normal distribution, and less sensitive to outliers (Tabari et al., 2011). This method has been widely used to analyze trends in meteorological and hydrological time series (Cannarozzo et al., 2006; Viola et al., 2014; Guan et al., 2015). The Z value is used to judge the direction of the trend, i.e.,

<table>
<thead>
<tr>
<th>Table 1</th>
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<tr>
<td>The definitions of extreme temperature indices which were used in this study.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Index characters</th>
<th>Index</th>
<th>Description name</th>
<th>Definitions</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm indices</td>
<td>TX90P</td>
<td>Warm days</td>
<td>Annual count of days when TX &gt; 90th percentile</td>
<td>Days</td>
</tr>
<tr>
<td></td>
<td>TN90P</td>
<td>Warm nights</td>
<td>Annual count of days when TN &gt; 90th percentile</td>
<td>Days</td>
</tr>
<tr>
<td></td>
<td>SU</td>
<td>Summer days</td>
<td>Annual count of days where TX &gt; 25 °C</td>
<td>Days</td>
</tr>
<tr>
<td>Cold indices</td>
<td>TX10P</td>
<td>Cold days</td>
<td>Annual count of days when TX &lt; 10th percentile</td>
<td>Days</td>
</tr>
<tr>
<td></td>
<td>TN10P</td>
<td>Cold nights</td>
<td>Annual count of days when TN &lt; 10th percentile</td>
<td>Days</td>
</tr>
<tr>
<td></td>
<td>FD</td>
<td>Frost days</td>
<td>Annual count of days where TN &lt; 0 °C</td>
<td>Days</td>
</tr>
<tr>
<td>Extreme indices</td>
<td>TNn</td>
<td>Minimum TN</td>
<td>Annual minimum value of TN</td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>TXx</td>
<td>Maximum TX</td>
<td>Annual maximum value of TX</td>
<td>°C</td>
</tr>
</tbody>
</table>

Note: TX is daily maximum temperature; TN is daily minimum temperature.
when $Z > 0$, the trend is increasing, while the trend is decreasing when $Z < 0$. The greater the absolute value of $Z$, the more significant the trend of the sequence. Absolute values of $Z$ that are $> 1.96$ indicate that the trend is significant at $\alpha = 0.05$ level, $|Z| > 2.58$ indicates a significance of $\alpha = 0.01$, and $|Z| > 3.30$ indicates a significance of $\alpha = 0.001$ (Zhao et al., 2010; Li et al., 2014b).

The Inverse Distance Weighted interpolation method (IDW) in ArcGIS was used to analyze the spatial distribution of trends in temperature extremes and the spatial distribution of the relationship between the temperature extremes and atmospheric circulation. The Pearson correlation analysis method was used to analyze the correlation between extreme temperature events and atmospheric circulations, and the F value was used to determine the significance level. Seasons were categorized as follows: winter (December to February), spring (March to May), summer (June to August) and fall (September to November).

3. Results and discussion

3.1. Trends of extreme temperature events

3.1.1. Inter-annual variability of extreme temperature events

In the SRB, the warm indices, including the number of warm nights (TX90P), warm days (TN90P) and summer days (SU), and the extreme indices, including minimum TN (TNn) and maximum TX (TXx), showed increasing trends in the SRB during the period from 1960 to 2014 (Fig. 2). On the other hand, cold indices, including the number of cold nights (TX10P), cold days (TN10P) and frost days (FD), showed decreasing trends (Fig. 2). Three warm indices (TX90P, TN90P and SU) showed significant increasing trends ($P < 0.01$) with corresponding rates of change of 2.1, 3.8 and 2.6d/10a, respectively. TX90P showed the most significant increasing trend, with a Mann-Kendall test value of 5.13. On the other hand, the cold indices (TX10P, TN10P and FD) exhibited decreasing trends with corresponding rates of change of $-1.4$, $-4.1$ and $-5.4$d/10a, respectively. The trend in the number of frost days (FD), which yielded a Mann-Kendall test value $Z = -5.81$, showed the most significant decrease, followed by TX10P ($Z = -3.72$), which displayed a trend that was significant at the 0.001 level; TN10P showed a decreasing trend and did not achieve statistical significance. The extreme indices (TXx and TNn) showed increasing trends. TNn increased by 0.7 °C/10a at the 0.001 significance level, while TXx showed an insignificant increasing trend. The warm indices and extreme indices showed increasing trends, while cold indices showed decreasing trends; these results were similar to those recorded in nearby regions in Mongolia (Dashkhuu et al., 2015) and northeastern China (Yu and Li, 2015). The decreasing trends of cold indices were more significant in the SRB than that in the Southwestern China (Li et al., 2012b) and Yangtze River Basin (Guan et al., 2015). The trends of TX90P, TN90P, TX10P, TN10P and TNn in the SRB were more significant than those in the Tibetan Plateau with the highest and largest highland in the world (You et al., 2008).

Anthropogenic forcing and climatic natural variability were considered to the main factors influencing the extreme temperatures (Hegerl et al., 2004). Kiktev et al. (2003) indicated increasing greenhouse gas emissions played an important role in extreme climate simulated by the climate model. Christidis et al. (2011) separated the anthropogenic and natural components by fingerprint analysis. Zhou and Ren (2011) found that urbanization affected the series of extreme temperature indices in the north China by analyzing the trends of

![Fig. 2. Annual variations in temperature extremes in the SRB during the period 1960–2014. Number of asterisks indicates the level of significance; * is 0.05, ** is 0.01, *** is 0.001.](image-url)
3.1.2. Seasonal variations in extreme temperature

Seasonal variations in extreme temperatures were similar to the interannual trend. The warm indices and extreme indices showed increasing trends, while the cold indices showed decreasing trends (Table 2). With the exception of TX10P, the trends in TX90P, SU, TN10P, FD and TXx were significant at the 0.05 level in the fall; observed trends in TN90P and TNN were most significant in summer, and the observed trend in TN10P was most significant in winter.

3.1.3. Spatial distribution of extreme temperature indices

To provide further insights into the spatial variation of temperature extremes, Fig. 3 shows the Mann-Kendall Z-value at different meteorological stations. Warm indices (TX90P, TN90P and SU) and extreme indices (TXx and TNN) showed increasing trends, while cold indices showed decreasing trends at most meteorological stations. The trends in extreme temperatures differed among stations (Fig. 3). The trends in the warm indices (TX90P, TN90P and SU) increased from the south toward the north and west. TN90P was the most significant index, with a mean Z value above 4.5 in the northwest. Cold indices (TX10P, TN10P and FD) showed decreasing trends at most stations, and FD with an average Z value of −4.25 was the most significant index. Changes in TX10P were insignificant; only a few stations showed significant trends. The extreme indices (TXx and TNN) increased in most stations. The trend of TXx increased insignificantly, but the trend of TNN increased significantly in the southeastern part of the SRB.

3.1.4. Variation of extreme temperature events response to latitude, longitude and altitude

The observed variations in temperature extremes were influenced by many factors, and the trends in temperature extremes were different in different regions. Analyzing the correlations between trends in extreme temperatures and latitude, longitude and altitude can further elucidate the relationship between extreme temperature events and latitude, longitude and altitude (Table 3).

Latitudinal gradients influence the distribution of energy over the earth’s surface. According to the IPCC’s 3rd assessment report, warming at high latitudes was more evident in the northern hemisphere and especially in the Arctic (Houghton et al., 2001; Serreze et al., 2000; Zhang, 2005). In the SRB, the warm indices (TX90P, TN90P and SU) and TXx showed significant positive correlations with latitude (P < 0.01). This result indicated that the changes in the number of warm nights, warm days, summer days and maximum TX would be more significant at higher latitudes (Table 3). However, TN10P, FD and TNN showed no significant correlation with latitude (P > 0.05), whereas FD and TNN showed negative correlations with latitude, indicating that frost days and minimum TN would decrease with increasing latitude.

Li et al. (2012a, 2012b) found that the warming trend became more significant with increasing latitude in the Hengduan Mountains. Guan et al. (2015) found that cold indices (the number of ice days, cold day frequency, frost days and cold spell duration index) decreased with increasing latitude in the Yangtze River Basin. Tang et al. (2005) found that trends toward higher temperatures were more prominent at higher latitudes in China. Some simulation studies (Manabe and Stouffer, 1994; Rind et al., 1998) also indicated that climate warming would be more pronounced in polar regions under global warming. In the SRB, the correlation between temperature extremes trend and latitude was consistent with the above results. The SRB covers a range of latitudes of approximately 9.3°, and its topography is dominated by plains and hills. The zonal distribution of solar energy and water vapor is less disturbed by external sources of energy, so the correlation between changes in extreme temperature events and latitude is stronger than that in other research regions. However, the physical mechanisms responsible for the higher degrees of correlation between trends in temperature extremes and altitude should be further investigated.

Longitude influences the transport of water and energy from the coast to inland areas, thereby affects regional climate change. In the northeastern United States, climate change was more significant in coastal areas than that farther inland (Brown et al., 2010), and a similar phenomenon was noted by Keim and Rock (2002). In the Yangtze River Basin, cold indices showed positive correlation with longitudes at the regions with longitudes < 112°, while correlation between the cold indices and longitude were reversed where the longitude was > 112° (Guan et al., 2015).

As shown in Table 3, the correlations between all the temperature indices and altitude were insignificant (P > 0.05), indicating that longitudinal transport of water and energy was uncorrelated with changes in temperature extremes which might occur due to the geographical location of the SRB in which the basin terrain is enclosed. The Changbai Mountains block energy and water vapor from the east; and the distribution of energy and water vapor were primarily controlled by the Southeast Asian Monsoon in the SRB. Furthermore, human activity may also be one of the factors that drove the observed changes in extreme temperatures (Kiktev et al., 2003).

Altitude determines the vertical distribution of energy and water, which might affect regional temperature change. Some studies had suggested that surface air temperatures increased more rapidly at higher altitude (Beniston and Rebetez, 1996; Giorgi et al., 1997). For example, Liu et al. (2009) found that warming was more significant at higher altitudes, especially during winter and spring in the Tibetan Plateau and its surroundings. Li et al. (2012a, 2012b) also found that temperature warming was more significant at higher altitude in southwest China. Similar conclusions were also obtained in the Alps, the Rocky Mountains and the Yangtze River Basin (Giorgi et al., 1997; Fyfe and Flato, 1999; Guan et al., 2015).

As shown in Table 3, except for TX10P, the correlations between all extreme temperature indices and altitude were insignificant. The lack of significance might be due to the terrain of the SRB, which is dominated by plains and hills that cover 56.5% of the basin area. That is, topographic relief was not sufficient to affect the extreme temperature indices. Therefore, altitude cannot compete with the effects of altitude on trends in temperature extremes.

Table 2

<table>
<thead>
<tr>
<th>Season</th>
<th>Warm indices</th>
<th>Cold indices</th>
<th>Extreme indices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TX90P</td>
<td>TN90P, SU</td>
<td>TXx, TNN</td>
</tr>
<tr>
<td>Spring</td>
<td>0.36</td>
<td>-0.89</td>
<td>1.06</td>
</tr>
<tr>
<td>Summer</td>
<td>2.24*</td>
<td>-2.18*</td>
<td>2.93**</td>
</tr>
<tr>
<td>Fall</td>
<td>2.84***</td>
<td>-1.76</td>
<td>2.93**</td>
</tr>
<tr>
<td>Winter</td>
<td>/</td>
<td>-3.70***</td>
<td>2.15*</td>
</tr>
</tbody>
</table>

Note: / means statistically insignificant; * is 0.05 confidence level, ** is 0.01 confidence level, *** is 0.001 confidence level; Bold is through significance level of α = 0.05; winter range was from 1960 to 2013.
3.2. Correlation between temperature extremes and atmospheric circulation

3.2.1. Correlation between temperature extremes and MEI

The El Nino-Southern Oscillation (ENSO) has been the most active atmospheric circulation patterns in recent years and has had a profound impact on global climate change (Harris et al., 2014).

Correlations between temperature extremes and ENSO have been identified by some previous studies. The number of temperature extremes in most regions of the United States decreased during El Nino and increased during La Nina (Higgins et al., 2002). There were weak correlations between Tmax-related indices (TXMean, TX90P, TXx and TX10P) and the Global-SST ENSO index, while the correlations between Tmin-related indices (TNMean, TNx, TNn and TN90P) and Global-SST ENSO index were positive and significant in Poyang Lake Basin (Tao et al., 2014). The occurrence of extreme temperature events strongly correlated with ENSO evolution approximately 1976 in Uruguay (Renom et al., 2011). ENSO affected extreme temperature events throughout the world, especially around the Pacific Rim and throughout North America (Kenyon and Hegerl, 2008).

However, some studies failed to establish the correlation between temperature extremes and ENSO. Leathers et al. (2008) found that there was no significant correlation between temperature extremes and ENSO, showing that ENSO could not clearly explain changes in temperature extreme events. In addition, Barros et al. (2002) showed that ENSO had a considerable impact on precipitation, but had a relatively modest impact on surface temperatures in southeastern South America, and Nicholls et al. (2005) concluded that an observed decrease in the number of cool days and cold nights in east Asia and the west Pacific had a weak relationship with El Nino; and warm nights and hot days showed strongly increasing trends, which did not match trends in ENSO.

As shown in Table 4, the correlations between MEI and all extreme temperature indices were insignificant, consistent with the findings of Leathers et al. (2008), Barros et al. (2002), Kenyon and Hegerl (2008) and Nicholls et al. (2005). The effects of ENSO on extreme temperature events differed by region (Nicholls et al., 2005; Kenyon and Hegerl, 2008; Mutiibwa et al., 2015). Mutiibwa et al. (2015) also found that the correlations between extreme temperature events and MEI were
insignificant in the northeastern United States, where was similar to the SRB for they are both in the eastern part of mainland and at middle to high latitudes. Some large regional (Nicholls et al., 2005) and global studies (Muller et al., 2005; Kenyon and Hegerl, 2008; Davey et al., 2014) also suggested weak correlations between temperature extremes and ENSO in northeastern China.

3.2.2. Correlation between temperature extremes and AO

The Arctic Oscillation (AO) is a dominant mode of climate variability over the extratropic of the Northern Hemisphere (Thompson and Wallace, 1998). It is also an important signal of climate change and has a profound impact on surface temperatures in the Northern Hemisphere (Thompson and Wallace, 2000; Alexander et al., 2006; He et al., 2017).

Table 4 shows significant negative correlations between the cold indices (TN10P, TX10P and FD) and AO (P < 0.01), positive significant correlations between TNn and AO (P < 0.01), and insignificant positive correlations between the warm indices (TN90P, TX90P and SU) and AO in the SRB. These results indicated that cold days, cold nights and frost days would decreased with increasing AO, while reverse trend was observed for minimum TN.

The impact of AO on the seasonal temperature extremes could be further illustrated by the correlation between temperature extremes and AO during different seasons (Fig. 4 and Table 5). Fig. 4 shows the spatial distribution of the most significant correlations between temperature extremes and AO in different seasons. Significant negative correlations occurred between both TX10P and TN10P and AO in winter over most of the SRB. The correlation between FD and AO in spring was similar to the relationship between winter TX10P/TN10P and AO. Correlations were stronger in the plains and weaker in mountainous regions. Positive correlations existed between TNn and AO in the fall. These correlations were higher in the western region of the SRB and lower in the east, and they were insignificant in some parts of the east.

Table 4

<table>
<thead>
<tr>
<th>Atmosphere ocean circulation</th>
<th>Warm indices</th>
<th>Cold indices</th>
<th>Extreme indices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TX90P</td>
<td>TN90P</td>
<td>SU</td>
</tr>
<tr>
<td>MEI</td>
<td>0.19</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>AO</td>
<td>0.14</td>
<td>0.11</td>
<td>0.07</td>
</tr>
<tr>
<td>Northern Hemisphere Subtropical High area index</td>
<td>0.07</td>
<td>0.43</td>
<td>0.24</td>
</tr>
<tr>
<td>Northern Hemisphere Subtropical High intensity index</td>
<td>0.06</td>
<td>0.45</td>
<td>0.23</td>
</tr>
<tr>
<td>Asia polar vortex area index</td>
<td>0.43</td>
<td>0.60</td>
<td>0.51</td>
</tr>
<tr>
<td>Asia polar vortex intensity index</td>
<td>0.24</td>
<td>0.53</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Note: * is 0.05 confidence level, ** is 0.01 confidence level; + is positive correlation, – is negative correlation.

Fig. 4. Spatial distributions of the most significant correlations between temperature extremes and the Arctic Oscillation area index in different seasons. Hatching shows areas where the correlation was insignificant.
and Wallace, 2001; Jeong and Ho, 2005; Park et al., 2010). He and Thompson extremes and AO in different regions of the world (Thompson and Wallace, 2001; Jeong and Ho, 2005; Park et al., 2010). He and Wang (2016) identified a significant negative correlation between the frequencies of cold days and cold nights in January and the Arctic Oscillation in October–December (AO-OND). Park et al. (2010) found that AO affected heavy snowfalls by strong cold surges in Korea during the winter of 2009–2010. A significant negative correlation between the frequency of extreme low temperature events in winter and AO was identified in Beijing (Xu and Ma, 2011), and similar findings had also been reported from other regions in China (Gong et al., 2004; Li and Fang, 2005; Suo et al., 2008). The conclusions in this study were consistent with those of previous studies.

The AO fluctuation creates an atmospheric pressure seesaw in the northern polar and middle latitudes, which alternates between positive and negative phases (Thompson and Wallace, 2000). This type of variation generally resembles the zonal cycle, which is enhanced during the winter half-year and weakens during the summer half-year. As a result, AO shows significant negative correlations with those indices that mainly occurs in the winter half-year (TN10P, TX10P, FD and TNn) and insignificant correlation with the indices that mainly occurs in the summer half-year (TN90P, TX90P, SU and TXx).

AO anomalies significantly impacted the Siberian High and thereby impacted the East Asian Winter Monsoon, leading winter temperature anomalies over East Asia (Gong et al., 2001; Gong and Wang, 2003; Li et al., 2014a; He and Wang, 2016; He et al., 2017). Previous studies demonstrated that when AO was in its negative phase, the Siberian High and the sea level pressure gradients in the East Asian and Pacific areas increased, the East Asian winter monsoon intensity also increased, and then, cold air outbreak became more frequent, temperatures in northeast China decreased and colder winters tended to occur (Gong et al., 2001; Gong et al., 2004; Huan et al., 2007; Park et al., 2010; He et al., 2017). However, when AO was in its positive phase, the Siberian High and the sea level pressure gradients in the East Asian and Pacific areas decreased, the East Asian winter monsoon intensity also decreased, and then, temperatures in northeast China increased, warmer winters tended to occur (Gong et al., 2001; Huan et al., 2007; He et al., 2017).

3.2.3. Correlation between temperature extremes and Northern Hemisphere Subtropical High

The Subtropical High is an important atmospheric circulation system that links tropical and extratropical circulations. The Subtropical High swings from north to south with changes in the seasons and is one of the key weather and climate systems in East Asia. Anomalies in intensity and position of the Subtropical High affect climate variability in China (He and Gong, 2002). Since the SRB was located in the middle to high latitudes and at the western flank of the northwestern Pacific Subtropical High, climate change in the SRB was sensitive to the strength and location of the Subtropical High.

As is shown in Table 4, there are positive correlations between the warm and extreme indices and the Subtropical High, while negative correlations exist between the cold indices and the Subtropical High area and intensity index during 1960 to 2014. TN90P showed a significant positive correlation with the Subtropical High area and intensity index (P < 0.01), while the TN10P and FD showed significant negative correlations with the Subtropical High area and intensity index (P < 0.01), which indicated that TN90P would increase rapidly while TN10P and FD would decrease with increases in Subtropical High area and intensity.

The impact of the Subtropical High on seasonal temperature extremes could be further illustrated by the correlations between temperature extremes and the Subtropical High in different seasons (Table 5 and Fig. 5). Fig. 5 shows the spatial distribution of the most significant correlations between temperature extremes and the Subtropical High area index in different seasons. There were significant negative correlations between winter TN10P, fall FD and the Subtropical High area index, while a significant positive correlation existed between summer TN90P, winter TN and the Subtropical High area index in most parts of the SRB. The correlation between TN90P and the Subtropical High area index decreased from northwest to southeast. However, the correlation between TNn and the Subtropical High area index decreased from southeast to northwest.

There was a good relationship between the longitudinal position of the Subtropical High and summer temperature in northern China (Wei et al., 2004). Sun et al. (2016) also found Subtropical High showed positive correlations with warm extremes (SU and TX90), and significant negative correlations with cold extremes (TX10, TN10 and FD). Subtropical High strongly influenced warm/cold extremes and contributed significantly to climate changes in the Loess Plateau. Variation in sea level pressures associated with the Subtropical High could result in anomalies of tropical western Pacific westerly (Li et al., 2010), and further resulted in variations in the Southeast Asian Monsoon (Sun and Ying, 1999). The anomalous longitudinal position of the Subtropical High was closely associated with changes of long wave pattern of the westerlies, which influenced temperatures in the northern part of China (Li et al., 2010).

3.2.4. Correlation between temperature extremes and Asia polar vortex

The polar vortex is a large-scale cyclonic circulation system, and its center is located over the North Pole. It reflects transport direction of different air masses, especially the flow of cold air masses around the pole, which is closely related to the climate variability of China and East Asia (Davis and Benkovic, 1994). The polar vortex is a symbol of large-scale cold air, and most powerful in winter, has closely association with the winter temperatures in China.

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Some similar studies addressed the correlations between temperature extremes and AO in different regions of the world (Thompson and Wallace, 2001; Jeong and Ho, 2005; Park et al., 2010). He and Wang (2016) identified a significant negative correlation between the frequencies of cold days and cold nights in January and the Arctic Oscillation in October–December (AO-OND). Park et al. (2010) found that AO affected heavy snowfalls by strong cold surges in Korea during the winter of 2009–2010. A significant negative correlation between the frequency of extreme low temperature events in winter and AO was identified in Beijing (Xu and Ma, 2011), and similar findings had also been reported from other regions in China (Gong et al., 2004; Li and Fang, 2005; Suo et al., 2008). The conclusions in this study were consistent with those of previous studies.

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As shown in Table 4, there were negative correlations between warm indices and the Asia polar vortex, indicated that the frequency of warm days, warm nights and summer days would decreases with
Fig. 5. Spatial distributions of the most significant correlations between temperature extremes and the Northern Hemisphere Subtropical High area index in different seasons. Hatching shows areas where the correlation is insignificant.

Fig. 6. Spatial distributions of the most significant correlations between temperature extremes and the polar vortex area index in different seasons. Hatching shows areas where the correlation is insignificant.
increases in the Asia polar vortex area and intensity. Additionally, there were also negative correlations between the extreme indices and the Asia polar vortex, indicating that the minimum TN and maximum TX decreased with increases of the Asia polar vortex area and intensity. There were positive correlations between the cold indices and the Asia polar vortex area and intensity, illustrating that the frequency of cold days, cold nights and frost days increased in step with the Asia polar vortex area and intensity. The Asia polar vortex area and intensity indices showed highly significant correlations with TN90P, TN10P, FD and TNN (P < 0.01).

The impact of the Asia polar vortex on seasonal temperature extremes could be further illustrated by the correlations between temperature extremes and the Asia polar vortex in different seasons (Table 5 and Fig. 6). Fig. 6 shows the spatial distribution of correlation between temperature extremes and the Asia polar vortex area index in different seasons. A significant positive correlation existed between winter TN10P, fall FD and the Asia polar vortex area index, while a significant negative correlation existed between summer TN90P and the Asia polar vortex area index in most parts of the SRB. The strength of this correlation decreased from northwest to southeast. The correlation between TNN and the Asia polar vortex area index was significant in summer, while it was insignificant in winter. This result indicated that the Asia polar vortex significantly affected summer minimum TN, and insignificant affected the winter minimum TN, which was opposite to the previous understanding (Davis and Benkovic, 1994).

Li and Liu (1986) calculated the monthly polar vortex area index from 1951 to 1985 and noted that there was a negative correlation between winter temperature and the polar vortex area index in China, while Liu (1986) also noted that there was a negative correlation between the temperature and the polar vortex intensity index at the same time in China. Zhang et al. (2014) reported a positive correlation between cold days, cold nights and the polar vortex area index, and a negative correlation between warm days, warm nights and the polar vortex area index, which consistent with the findings of this study. When the arctic vortex was active at the North Pole, summer temperatures in northeastern China increased, while when the vortex was active in Eurasia, summer temperatures in northeastern China decreased (Meteorological Observatory of Jilin Province and Meteorological Observatory of Jilin City, 1981). When the arctic vortex expanded, the frequency of cold nights would decrease in most parts of northern China (Zhang et al., 2014). When the northern circumpolar vortex contracted, winter temperatures increased in most region of China (Gu and Yang, 2006).

4. Conclusions

This study presented the spatiotemporal variation of temperature extremes in the SRB and their relationship with several atmospheric circulation patterns. Warm indices, including warm nights, warm days and summer days, and extreme indices, including minimum TN and maximum TX, showed increasing trends in the SRB from 1960 to 2014. Cold indices, including cold nights, cold days and frost days, showed a decreasing trend in the same period. The trends of warm nights (Z = 5.13) and frost days (Z = −5.81) were the most significant. These findings were consistent with many regional previous studies, and some trends of extreme indices in SRB were stronger than that in Yangtze River Basin, Southwestern China and even either Tibetan Plateau. The results indicate that the SRB might be at risk of increased extreme high temperature events, and much attention should be paid to this higher risk of extreme events.

Warm indices and maximum TX showed significant positive correlations with latitude (P < 0.01), which indicated that the number of warm nights, warm days, summer days and maximum TX would be more significant at higher latitudes. It had confirmed the fact that the higher latitude stronger warming trend.

There were significant correlations between extreme temperature events and atmospheric circulation. The Arctic Oscillation (AO) index displayed significant negative correlations with the cold indices (P < 0.01) and positive correlations with the warm indices. Northern Hemisphere Subtropical High area and intensity indices showed positive correlations with the warm indices and extreme indices, while reverse relationship between the cold indices and Northern Hemisphere Subtropical High. The Asia polar vortex area and intensity indices showed negative correlations with warm indices and extreme indices, while they were positive correlated to cold indices. The multivariate ENSO index (MEI) showed no linear correlation with any of the temperature extremes. These findings will provide useful information in researching mechanism of temperature extremes, forecasting extreme climate events and taking measures to reduce their associated impacts.

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References


