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Trends in Temperature and Precipitation Extremes over Circum-Bohai-Sea Region, China

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Abstract: Trends in temperature and precipitation extremes from 1961 to 2008 have been investigated over Circum-Bohai-Sea region, China using daily temperature and precipitation data of 63 meteorological stations. The results show that at most stations, there is a significant increase in the annual frequency of warm days and warm nights, as well as a significant decrease in the annual frequency of cold days, cold nights, frost days, and annual diurnal temperature range (DTR). Their regional averaged changes are 2.06 d/10yr, 3.95 d/10yr, –1.88 d/10yr, –4.27 d/10yr, –4.21 d/10yr and –0.20℃/10yr, respectively. Seasonal changes display similar patterns to the annual results, but there is a large seasonal difference. A significant warming trend is detected at both annual and seasonal scales, which is more contributed by changes of indices defined by daily minimum temperature than those defined by daily maximum temperature. For precipitation indices, the regional annual extreme precipitation displays a weak decrease in terms of magnitude and frequency, i.e. extreme precipitation days (RD95p), intensity (RINTEN), proportion (RPROP) and maximum consecutive wet days (CWD), but a slight increase in the maximum consecutive dry days (CDD), which are consistent with changes of annual total precipitation (PRCPTOT). Seasonally, PRCPTOT and RD95p both exhibit an increase in spring and a decrease in other seasons with the largest decrease in summer, but generally not significant. In summary, this study shows a pronounced warming tendency at the less rainy period over Circum-Bohai-Sea region, which may affect regional economic development and ecological protection to some extent.

Keywords: temperature; precipitation; climate extreme; trend analysis; Circum-Bohai-Sea region

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1 Introduction

Human and environment often respond to climate and weather extremes rather than just their mean conditions (Yan *et al.*, 2002; Hundecha and Bárdossy, 2005; Nandintsetseg *et al.*, 2007; Aguilar *et al.*, 2009). In the past few years, extreme climate events have drawn more and more attention in the world due to their serious and adverse impacts on society and ecosystems (Karl and Easterling, 1999; Changnon *et al.*, 2000; Easterling *et al.*, 2000; Boroneant *et al.*, 2006). Great efforts have been made to detect the variability and trends of climate extremes (IPCC, 2007). The Fourth Assessment Report of Intergovernmental Panel on Climate Change (IPCC, 2007) noted that the global surface temperature increased by 0.74℃ over the past 100 years (1906–2005); cold days, cold nights and frost days became less frequent while hot days, hot nights and heat waves got more frequent; the frequency of heavy precipitation events increased over most land areas, and since the 1970s, more intense and longer droughts have been observed over wider areas, particularly in the tropics and subtropics. The global analysis by Alexander *et al.* (2006) shows that there are widespread significant changes in temperature extremes associated with warming, and for precipitation extremes, there is a tendency

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toward wetter conditions.

Recently, much attention has been paid to climate extremes at regional or national scales and various indicators, such as percentile-based indices, threshold indices, duration indices and absolute indices, have been widely used to describe their changes (Alexander *et al*., 2006). Generally, most studies have focused on the North Hemisphere, such as North America (Kunkel, 2003; Vincent and Mekis, 2006), Europe (Klein Tank and Können, 2003; Toreti and Desiato, 2008), Asia (Yang *et al*., 2008; Pal and Al-Tabbaa, 2009; Rahimzadeh *et al*., 2009; Zhai *et al*., 2010; Gemmer *et al*., 2011), possibly due to huge economic losses and social effects arising from climate extremes as well as the data availability. The results of many studies indicate that the frequency and intensity of extreme low temperature events decrease significantly; inversely, distinct increases are found in extreme high temperature events but usually those trends are weaker (Nandintsetseg *et al*., 2007; Rusticucci and Renom, 2008; Rahimzadeh *et al*., 2009). In contrast, patterns of precipitation extremes and their changes show a large spatial variability, and therefore, the analysis of the regional extreme precipitation is very important for the assessment of hydrological consequences, such as flooding and droughts (Hundecha and Bárdossy, 2005; Rahimzadeh *et al*., 2009).

In China, a number of studies on temperature and precipitation extremes have been carried out since the 21st century (Zhai and Pan, 2003; Gong *et al*., 2004; Liu *et al*., 2005; Qian and Lin, 2004; 2005; Wang and Zhou, 2005). In general, changes in temperature extremes indicate a dramatic warming trend in most regions of China (Zhai and Pan, 2003). In contrast, there is a great regional difference in trends of precipitation extremes, similar to the pattern of the world (Frich *et al*., 2002; Alexander *et al*., 2006). The annual extreme precipitation has increased in the southeastern, northwestern and eastern China while decreased in the central, northern and northeastern China (Wang and Zhou, 2005) and similar results have also been found by Qian and Lin (2005) and You *et al.* (2011). Nevertheless, uncertainty still exists in the exact patterns of regional changes in climate extremes (You *et al*., 2011). Some studies have examined the annual variability of climate extremes at a regional scale, but usually few indicators have been used and seasonal changes have been rarely documented. In addition, few researches have focused on Circum-Bohai-Sea region. Guo *et al.* (2010) analyzed the spatio-temporal variations of extreme heavy precipitation over Circum-Bohai-Sea region using the indicators of extreme precipitation amount, days and intensity. However, temperature extremes were not noted and few indicators were used to explain the changes of precipitation extremes. Jiang *et al.* (2011) investigated the variability of precipitation extremes over Circum-Bohai-Sea region using eight precipitation indices of total precipitation amount, extreme precipitation days, intensity, proportion, the maximum consecutive wet and dry days, the maximum 1-day and 5-day precipitation, but only summer season was analyzed.

Therefore, this study gives a comprehensive analysis of changes in temperature and precipitation extremes over Circum-Bohai-Sea region on the annual and seasonal timescales, using 12 indicators as well as daily temperature and precipitation data of 63 meteorological stations from 1961 to 2008. The results may contribute to a better insight on the possible impacts of climate change and be helpful to develop appropriate adaptation and mitigation strategies coping with the inverse effects of climate anomalies.

2 Materials and Methods

2.1 Study area

Circum-Bohai-Sea region is situated in North China with an area of about 5.2×10^5 km^2 and a population of 2.3×10^8, administratively consisting of Beijing Municipality, Tianjin Municipality, Liaoning Province, Hebei Province and Shandong Province (Fig. 1). It is a very important region for China since it is the political and cultural center of China and also is one of three economic cycles in the eastern China. This region belongs to the warm and semi-humid continental monsoon climate zone. The mean annual precipitation varies from 560 mm to 916 mm with most of the annual precipitation falling in summer (June to August). The mean annual air temperature ranges from 8℃ to 12.5℃. There are three major rivers: the Huanghe River (Yellow River), the Liaohe River and the Haihe River, all entering the Bohai Sea. The Bohai Sea is nearly a closed shallow bay in west Pacific with very weak water exchange ability, greatly affected by both land-based human activities and climate changes. In the past decades, due to large population, rapid social-economic devel-

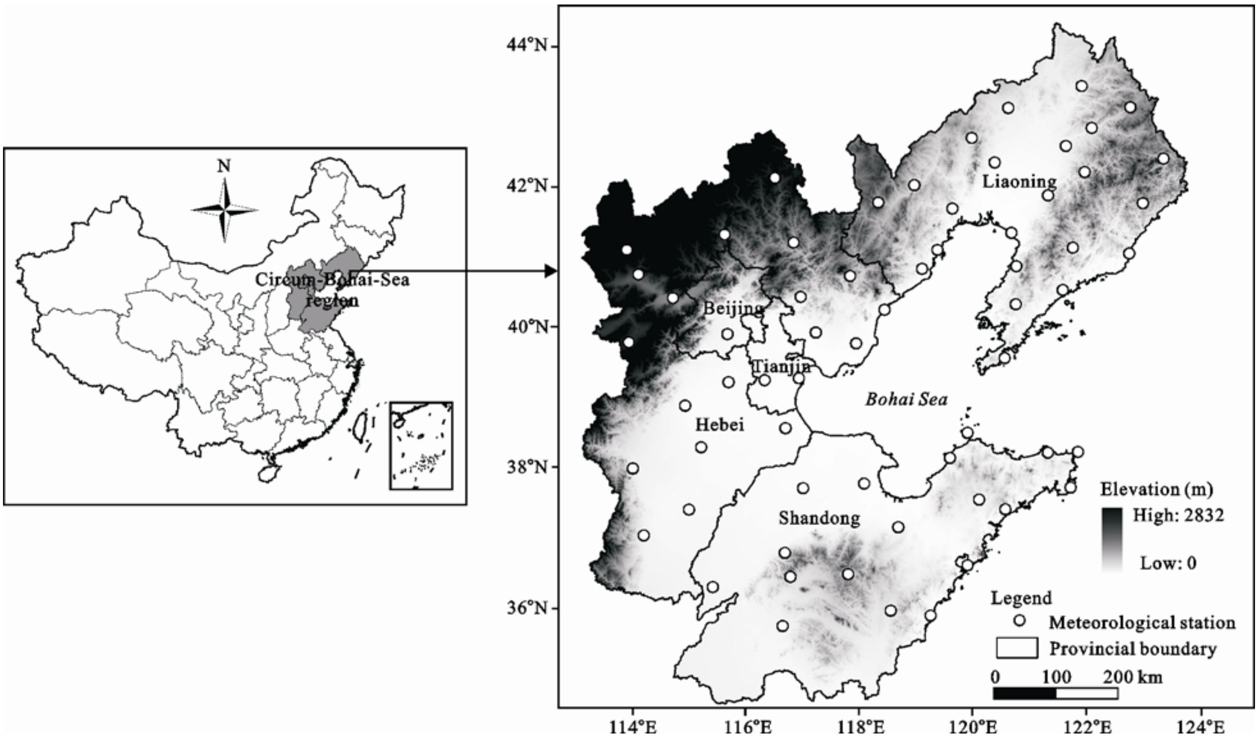


Fig. 1 Location of Circum-Bohai-Sea region in China and distribution of meteorological stations in study area

opment and local climate characteristics, Circum-Bohai-Sea region has being threatened by severe water stress and the Bohai Sea has been the most severely polluted sea area in China. High or low temperature extremes have caused serious effects to agriculture. At present, this region has been one of the most concerned regions in China in terms of the balance between eco-environment protection and social-economic development. Therefore, it is worthwhile investigating trends in climate extremes over this region.

2.2 Data

Daily precipitation, maximum and minimum temperature data of 85 meteorological stations from 1961 to 2008 are available for this study, which are provided by the National Climate Center (NCC), China Meteorological Administration (http://cdc.cma.gov.cn/). In order to minimize the effect of inhomogeneity and the shortness of record length or missing data, 63 meteorological stations are selected in this study.

2.3 Methods

Six temperature indices and six precipitation indices (Table 1) are constructed for each station based on the indicators recommended by the joint Meteorological Organization CCL/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) (http://cccma.seos.uvic.ca/ETCCDI), but there are some differences in definitions of percentile-based indices, which are determined based on percentile thresholds for each station. In detail, warm days (TX95p), warm nights (TN95p), extreme precipitation days (RD95p), intensity (RINTEN) and proportion (RPROP) are calculated based on the 95th percentile while cold days (TX5p) and cold nights (TN5p) are calculated as the number of days below the 5th percentile.

A linear trend analysis has been used to describe changes in a climatological series frequently (Hundecha and Bárdossy, 2005; Rusticucci and Renom, 2008; Rahimzadeh *et al.*, 2009). In this study, the slopes of the linear trends are calculated by the least squares fitting. The non-parametric Mann-Kendall test (MK) (Sneyers, 1990) is used to assess the statistical significance of the trends at the 0.05 level. Four seasons are defined as spring (March–May), summer (June–August), autumn (September–November) and winter (December–February) for climatological 'accounting' purposes.

3 Results and Analyses

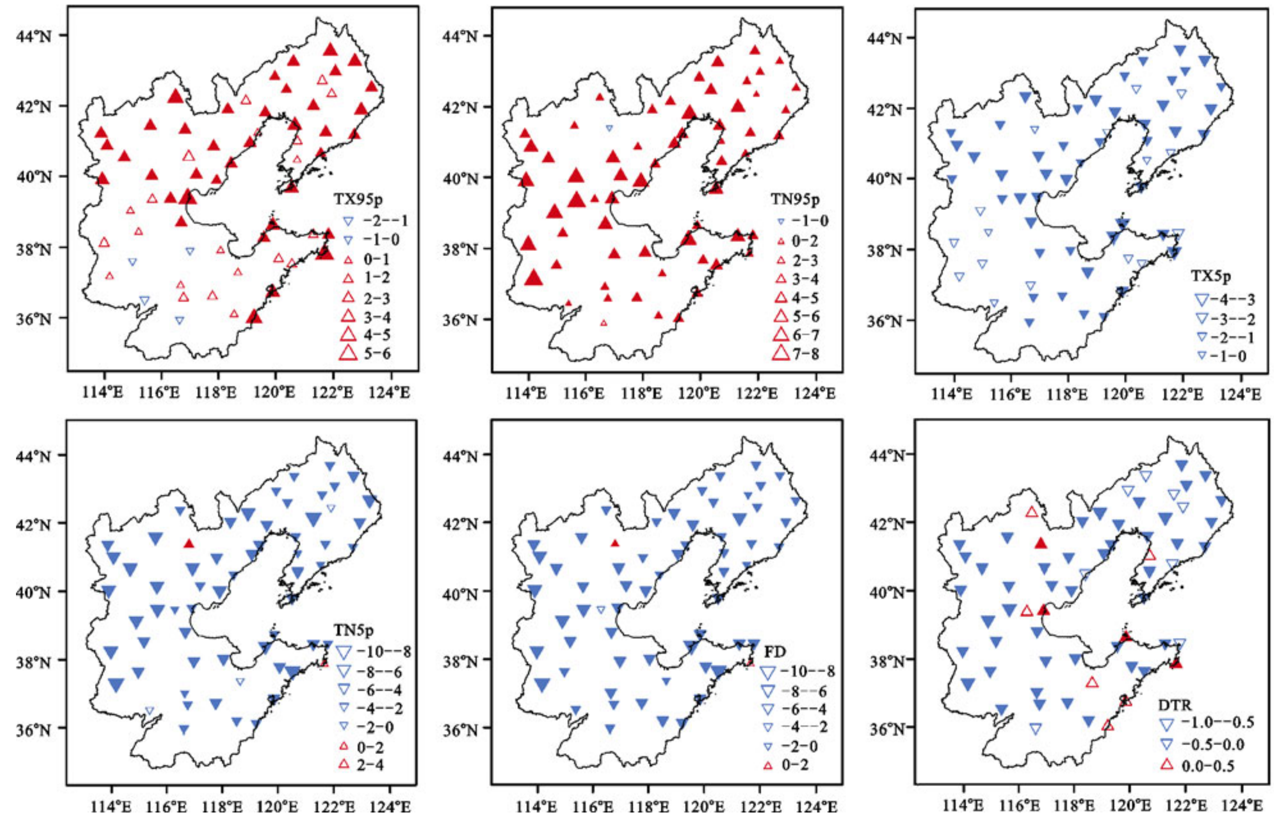
3.1 Changing trends of temperature indices

3.1.1 Annual change

Figure 2 describes the trends and their significances for extreme temperature indices. About 94% of stations display positive trends in warm days (TX95p) and more than half stations (mostly located in coastal regions and the northern part of the study area) are statistically significant at the 0.05 level. However, there are four stations (Nangong, Huimin, Chaoyang and Yanzhou), situated in the southern part, showing a negative trend possibly due to the decrease of maximum temperature in summer, but their changes are not significant. Warm nights

Table 1 Definitions of temperature and precipitation indices

	No.	Index	Definition	Unit
Temperature	1	TX95p	Warm days: number of days with daily maximum temperature (TX) greater than 95th percentile	d
	2	TN95p	Warm nights: number of days with daily minimum temperature (TN) greater than 95th percentile	d
	3	TX5p	Cold days: number of days with TX less than 5th percentile	d
	4	TN5p	Cold nights: number of days with TN less than 5th percentile	d
	5	FD	Frost days: number of days with TN less than 0℃	d
	6	DTR	Diurnal temperature range: difference between TX and TN	℃
Precipitation	1	PRCPTOT	Annual or seasonal total precipitation	mm
	2	RD95p	Number of days with daily precipitation greater than or equal to mean 95th percentile from 1961 to 2008	d
	3	RINTEN	Average intensity of precipitation events greater than or equal to 95th percentile	mm/d
	4	RPROP	Percentage of total precipitation from precipitation events greater than or equal to 95th percentile	%
	5	CDD	Consecutive dry days: maximum number of consecutive days with daily precipitation less than 1 mm	d
	6	CWD	Consecutive wet days: maximum number of consecutive days with daily precipitation greater than or equal to 1 mm	d



Upward and downward triangles indicate positive and negative trends respectively and filled triangles represent significant trends at the 0.05 level, which are the same as following figures

Fig. 2 Decadal trends of extreme temperature indices from 1961 to 2008 in study area

(TN95p) exhibit significant positive trends throughout the study area except for two stations and the central region has larger positive magnitudes. On the contrary, the negative trends are detected across the whole study area for cold days (TX5p) and in appropriately 97% of stations for both cold nights (TN5p) and frost days (FD). However, the number of stations with significant negative trends in cold nights (92%) and frost days (95%) is more than that of cold days (75%). In terms of DTR, 84% of stations show negative trends with more than half of them being significant at the 0.05 level.

Figure 3 shows annual changing trends in regional averaged temperature indices. There is a substantial increase in warm days and warm nights since the end of the 1990s, which coincides with the global warmest period of 1998–2007 on record (http://www.wmo.int/pages/mediacentre/press_releases/pr_805_en.html). Other four temperature indices, i.e. cold days, cold nights, frost days and diurnal temperature range (DTR), exhibit a similar pattern with significant negative changes, which are more significant since the mid-1980s (Fig. 3). Averaged over all the stations, warm days and warm nights increase by 2.06 d/10yr and 3.95 d/10yr respectively while cold days, cold nights, frost days and diurnal temperature range decrease by 1.88 d/10yr, 4.27 d/10yr, 4.21 d/10yr and 0.20℃/10yr respectively. Therefore, warm extremes (warm days, warm nights) become more frequent while cold extremes (cold days, cold nights and frost days) get more scarce. Moreover, the change of indices defined by daily minimum temperature is much greater than those defined by daily maximum temperature, in terms of the number of sta

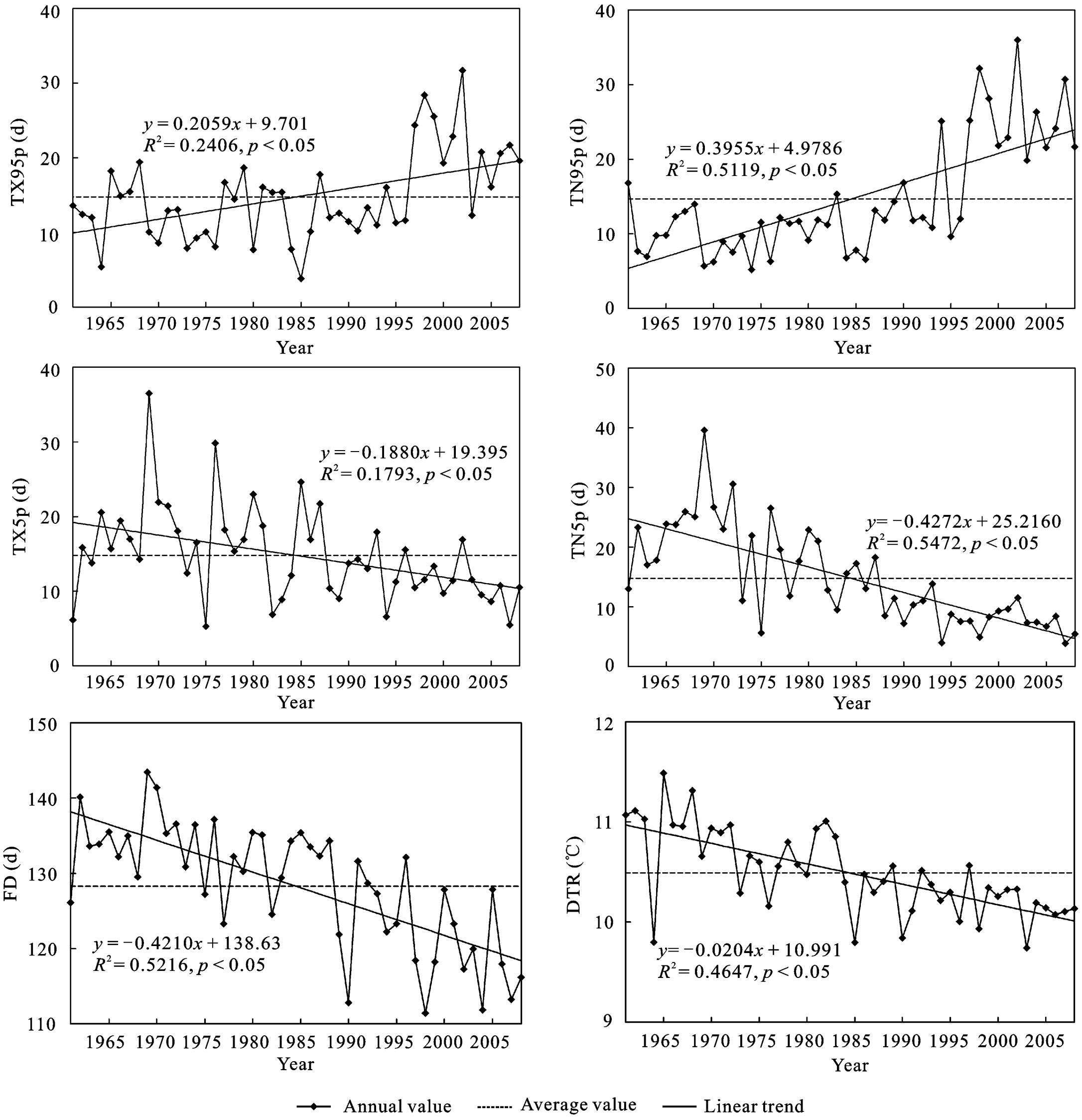


Fig. 3 Annual changing trends of regional averaged temperature indices from 1961 to 2008 in study area

tions displaying significant trends and the regional averaged changes.

3.1.2 Seasonal change

Table 2 presents the results of seasonal changes in four extreme temperature indices. The warming is observed in all seasons and more stations exhibit significant changes for indices defined by daily minimum temperature than those defined by daily maximum temperature, which are similar to the annual results. Figures 4 and 5 display the spatial patterns of seasonal changes in warm nights and cold nights, respectively. For the majority of the stations, warm nights shows increasing trends in all

Table 2 Number of stations with positive or negative trends for temperature and precipitation indices during each season

Index	Spring				Summer				Autumn				Winter			
	+	S+	–	S–	+	S+	–	S–	+	S+	–	S–	+	S+	–	S–
TX95p	56	25	7	1	49	4	14	1	62	31	1	0	56	7	7	0
TN95p	62	57	1	0	58	38	5	0	61	40	2	0	62	45	1	0
TX5p	0	0	63	28	17	1	46	1	9	0	54	4	0	0	63	49
TN5p	2	0	61	58	5	1	58	38	5	0	58	40	1	0	62	54
PRCPTOT	48	1	15	0	3	0	60	8	21	0	42	4	16	0	47	1
RD95p	48	1	15	0	5	0	58	5	20	1	43	5	18	0	45	0

Notes: '+' indicates the positive trend; '–' indicates the negative trend; 'S+' indicates that the positive trend is significant at the 0.05 level; 'S–' indicates that the negative trend is significant at the 0.05 level

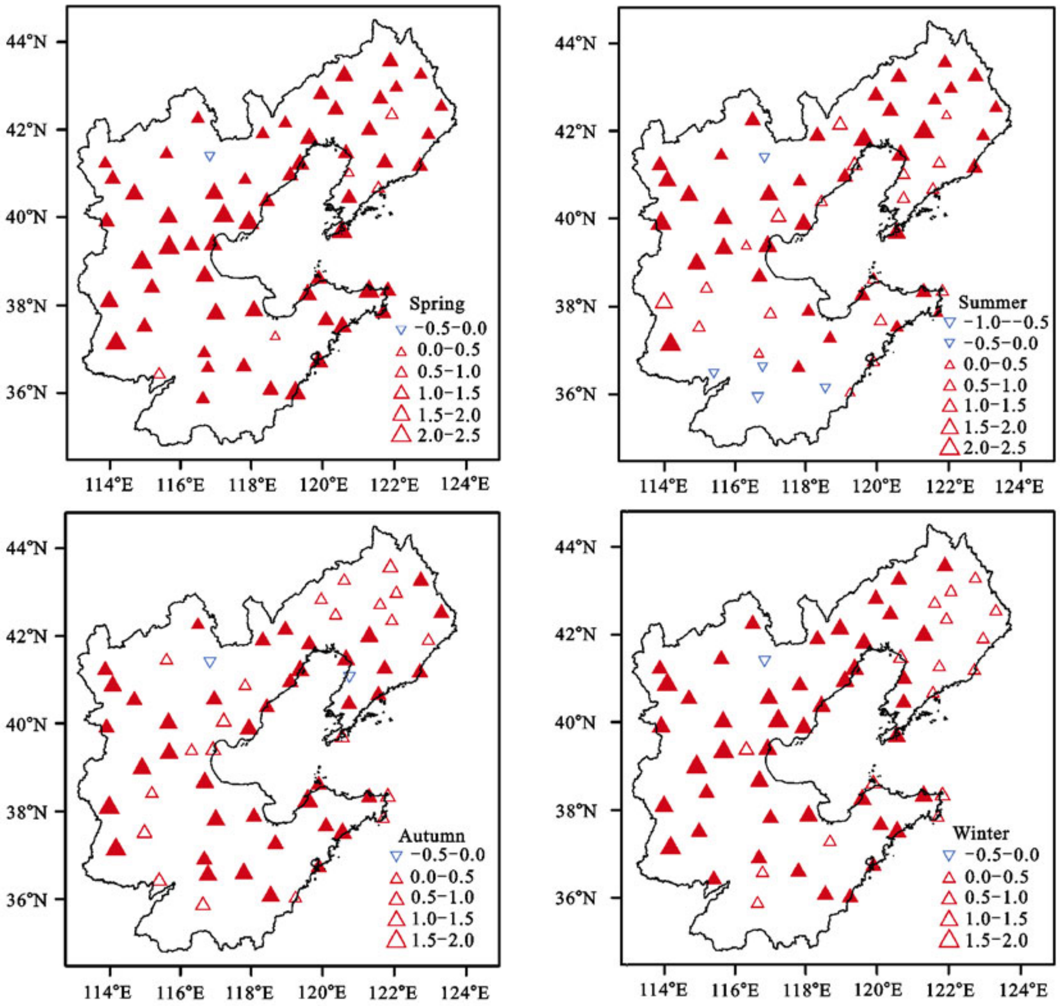


Fig. 4 Seasonal changing trends of warm nights (d/10yr) from 1961 to 2008 in study area

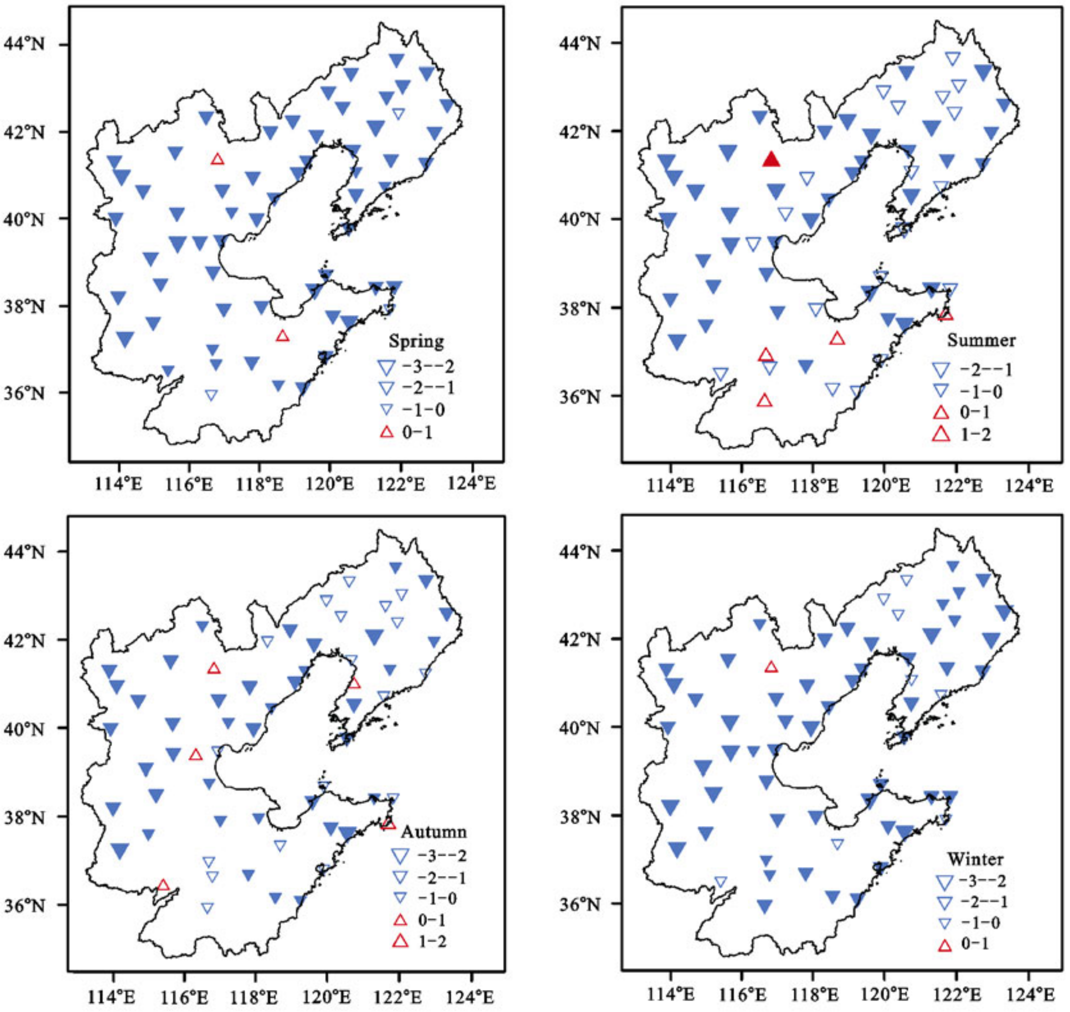


Fig. 5 Seasonal changing trends of cold nights (d/10yr) from 1961 to 2008 in study area

seasons with more than half of these increases being significant. The largest regional averaged increase in warm nights is observed in spring, which is 1.31 d/10yr, and the least is found in autumn with a small increase of 0.76 d/10yr. Inversely, cold nights shows significant decreasing trends at most stations in all seasons and it displays a greater decrease in winter (1.41 d/10yr) than in summer (0.74 d/10yr).

3.2 Changing trends of precipitation indices

3.2.1 Annual change

Annual total precipitation (PRCPTOT) shows negative trends at 94% of stations but most stations are not statistically significant (Fig. 6). The larger or significant decrease is observed mainly in coastal regions, implying that these regions might be undergoing higher water stress. Similar to PRCPTOT, extreme precipitation indices of RD95p, RINTEN and RPROP also display insignificant decreasing trends at the majority of stations. In terms of CDD and CWD, there are about three-fourths of stations showing increasing trends and decreasing trends respectively, but also not significant. Generally, most stations have decreasing trends in all precipitation indices except for CDD, and these stations are distributed widely across the whole study area.

Figure 7 presents annual changing trends in regional averaged precipitation indices. From 1961 to 2008, a slight decrease in PRCPTOT, RD95p, RINTEN, RPROP and CWD while a weak increase in CDD are observed. The annual contribution of extreme precipitation events to the total precipitation, i.e. RPROP, is more than 70% averaged over all the stations during the past 48 years, suggesting that PRCPTOT is well correlated with precipitation extremes. In other words, ex-

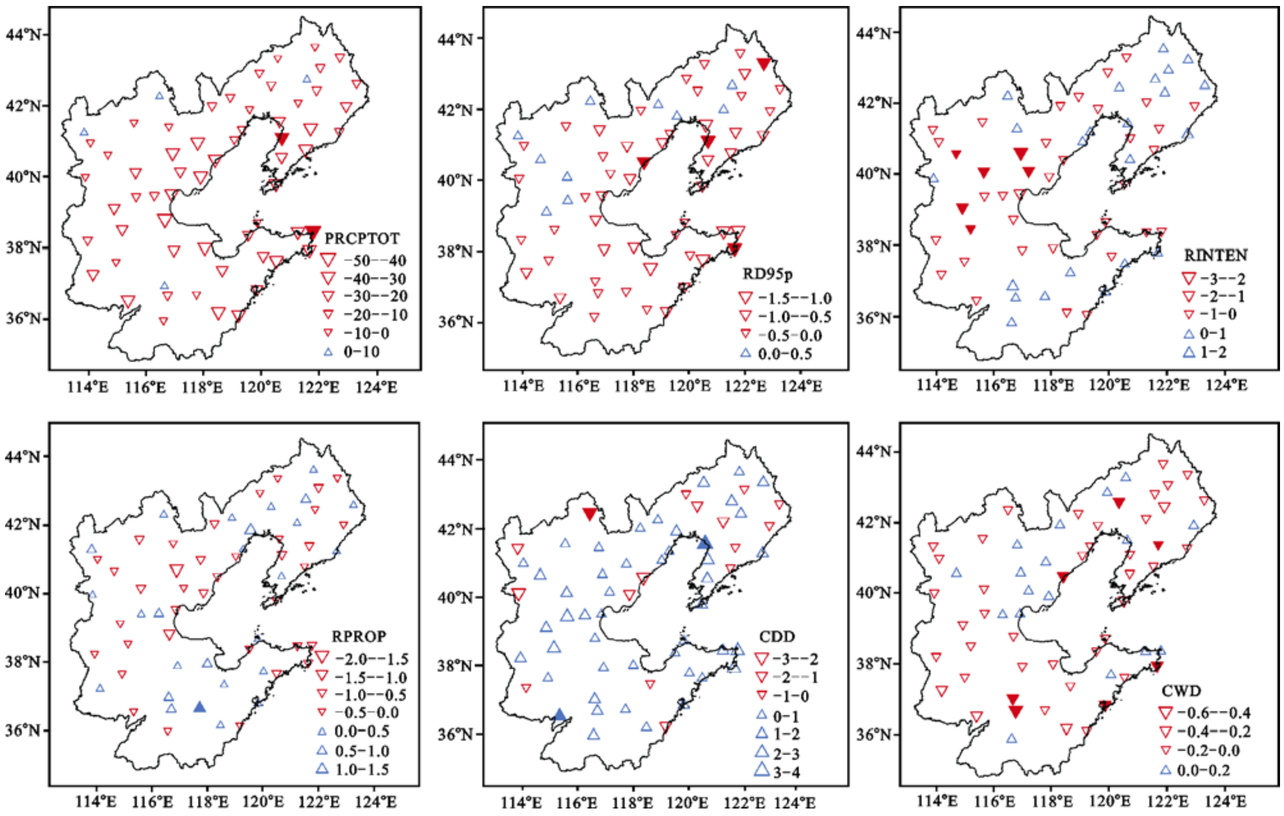


Fig. 6 Decadal trends of extreme precipitation indices from 1961 to 2008 in study area

treme precipitation events are the largest contributor for PRCPTOT. Therefore, an excess or a deficiency of precipitation mainly depends on the occurrence of extreme precipitation events, which affect water resources situation over Circum-Bohai-Sea region.

3.2.2 Seasonal change

Seasonally, two precipitation indices, i.e. seasonal total precipitation and RD95p, are analyzed. A similar pattern is found for them. For the majority of stations, increasing trends in spring but decreasing trends in other seasons are detected (Table 2 and Figs. 8 and 9); however, these trends are generally insignificant for all seasons. The relatively larger change during the year is observed in summer and coastal regions have larger decreasing magnitudes, similar to the annual results. This seasonal difference is also found in regional averaged changes, i.e. a weak increase occurs in spring but a slight decrease in other seasons. In addition, the larger decreases for seasonal total precipitation and RD95p also appear in summer. Because more than 80% of annual precipitation falls in summer, and changes in summer total precipitation and RD95p have influences on annual total precipitation, consequently, on water resources over the study area.

4 Discussion

Either at the annual or seasonal scales, a pronounced warming trend over Circum-Bohai-Sea region is presented by variations of warm extremes (warm days, warm nights), cold extremes (cold days, cold nights and frost days) and diurnal temperature range, which are consistent with previous studies over China (Zhai and Pan, 2003; Zhang *et al.*, 2008) and the northern China (Ma *et al.*, 2003) as well as other regions in the world (Alexander *et al.*, 2006; IPCC, 2007; Brown *et al.*, 2008). All of six temperature indices indicate large seasonal differences. For example, winter has the most widespread significant change in cold days and cold nights, which are similar to the seasonal results of China (Qian and Lin, 2004; Zhang *et al.*, 2008). Greater changes are found in indices defined by daily minimum temperature than those defined by daily maximum temperature at annual and seasonal scales and a similar

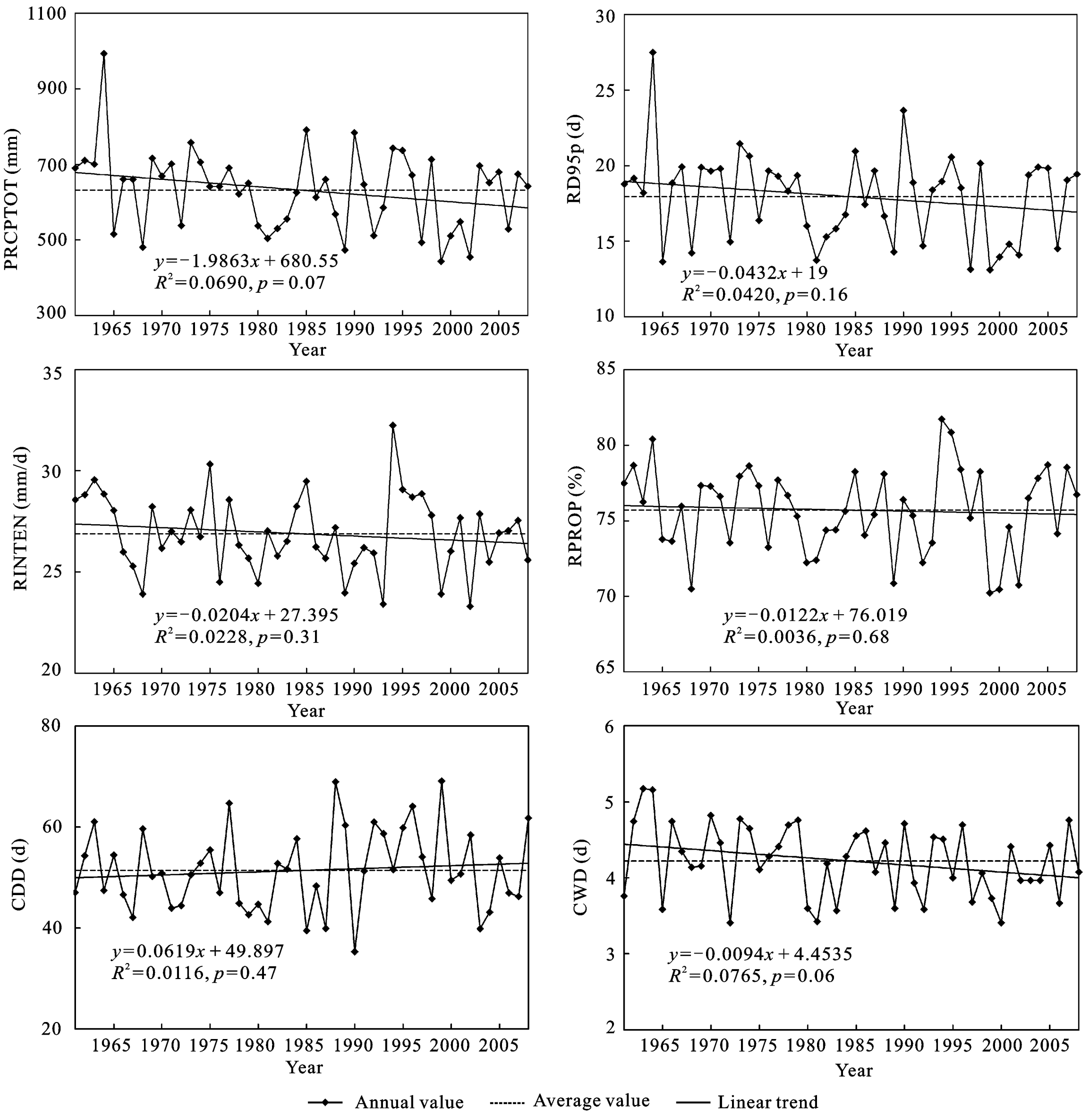


Fig. 7 Annual changing trends in regional averaged precipitation indices from 1961 to 2008 in study area

result is also detected in the global studies (Alexander *et al.*, 2006; Brown *et al.*, 2008) and some studies over China (Zhang *et al.*, 2008) and the northern China (Ma *et al.*, 2003). However, there are some differences between our findings and other studies (Table 3). For example, the annual decreasing rate of cold extremes and diurnal temperature range as well as the annual increasing rate of warm extremes over the study area are higher than those of the China's averages (Zhai and Pan, 2003), but lower than those of the northern China (Qian and Lin, 2004).

Annual precipitation indices show both positive and negative trends with most stations being not significant, similar to earlier conclusions of Qian and Lin (2005) and You *et al.* (2011). A negative trend is observed in more than three-fourths of stations for the annual extreme precipitation days (RD95p), which agrees with previous results of Qian and Lin (2005), Wang and Zhou (2005), Zhai *et al.* (2005), You *et al.* (2011) and Guo *et al.* (2010). Averaged over all the stations, a weak decrease in all precipitation indices except for CDD are strongly correlated with changes in PRCPTOT, which result in relatively infrequent rain stages for the study area. Seasonally, PRCPTOT and RD95p display a similar pattern, for instance, only increase in spring and decrease in other seasons with the largest decrease in summer, but both not significant. This result is consistent with the conclusions drawn by Zhai *et al.* (2005).

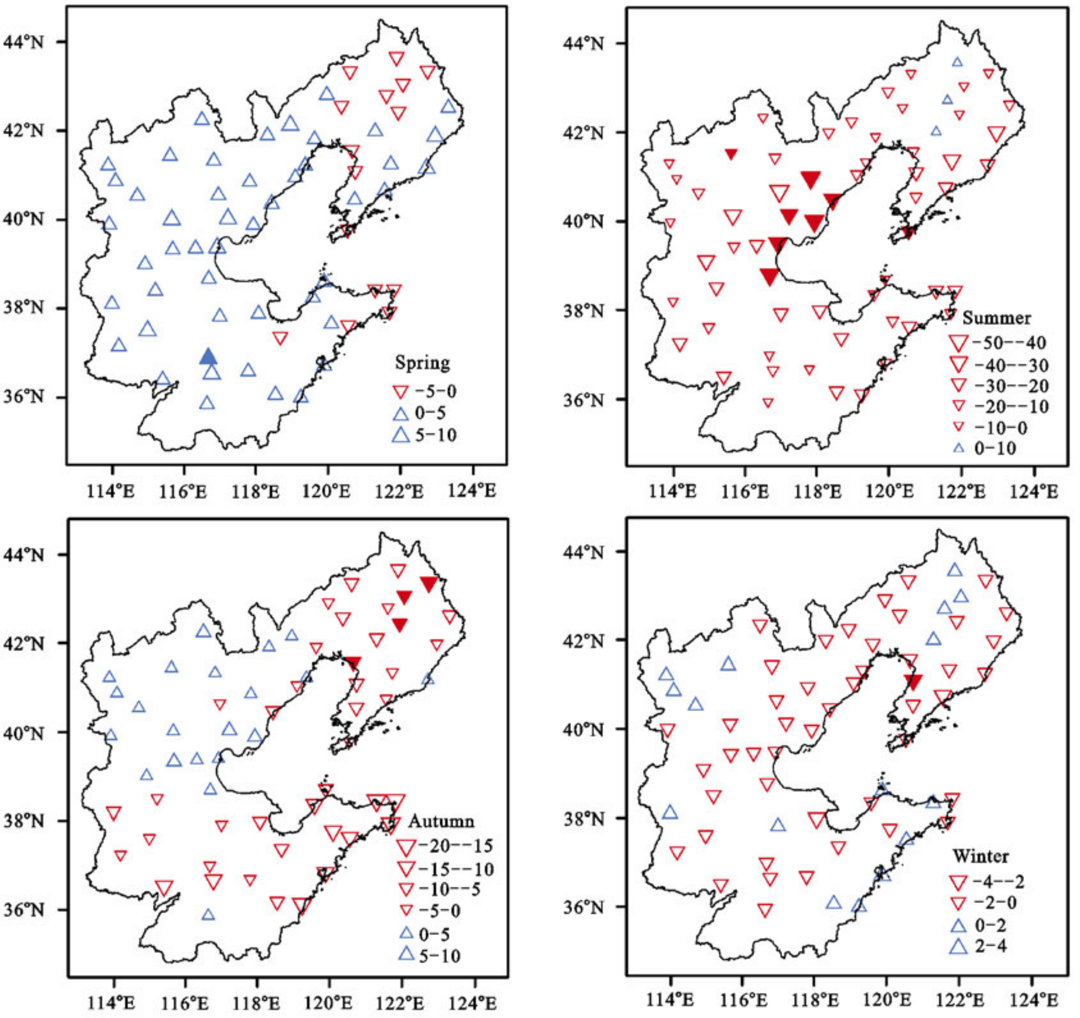


Fig. 8 Seasonal changing trends of PRCPTOT (mm/10yr) from 1961 to 2008 in study area

5 Conclusions

Changing trends in temperature and precipitation extremes over Circum-Bohai-Sea region have been investigated based on daily temperature and precipitation data of 63 meteorological stations from 1961 to 2008. The results show that at most stations, significant increases are detected in the annual frequency of warm days and warm nights while significant decreases in the annual frequency of cold days, cold nights, frost days, and annual diurnal temperature range, suggesting a dramatic warming trend in the study area. Their regional averaged changes are 2.06 d/10yr, 3.95 d/10yr, –1.88 d/10yr, –4.27 d/10yr, –4.21 d/10yr and –0.20℃/10yr, respectively. Similar to the annual results, changes of six temperature indices in all seasons also show a warming trend with large seasonal variations. Winter has the most widespread significant change in cold days and cold nights while autumn and spring respectively in warm days and warm nights. Either at annual or seasonal scales, greater changes are found in indices defined by daily minimum temperature than those defined by daily maximum temperature.

At the annual scale, most stations show a weak decrease in precipitation extremes in terms of magnitude and frequency, i.e. RD95p, RINTEN, RPROP and CWD, but a slight increase in CDD in accordance with regional averaged trends, which are closely associated with changes in PRCPTOT. Seasonally, PRCPTOT and RD95p both exhibit an increase in spring and a decrease in other seasons with the largest decrease in summer, but generally insignificant.

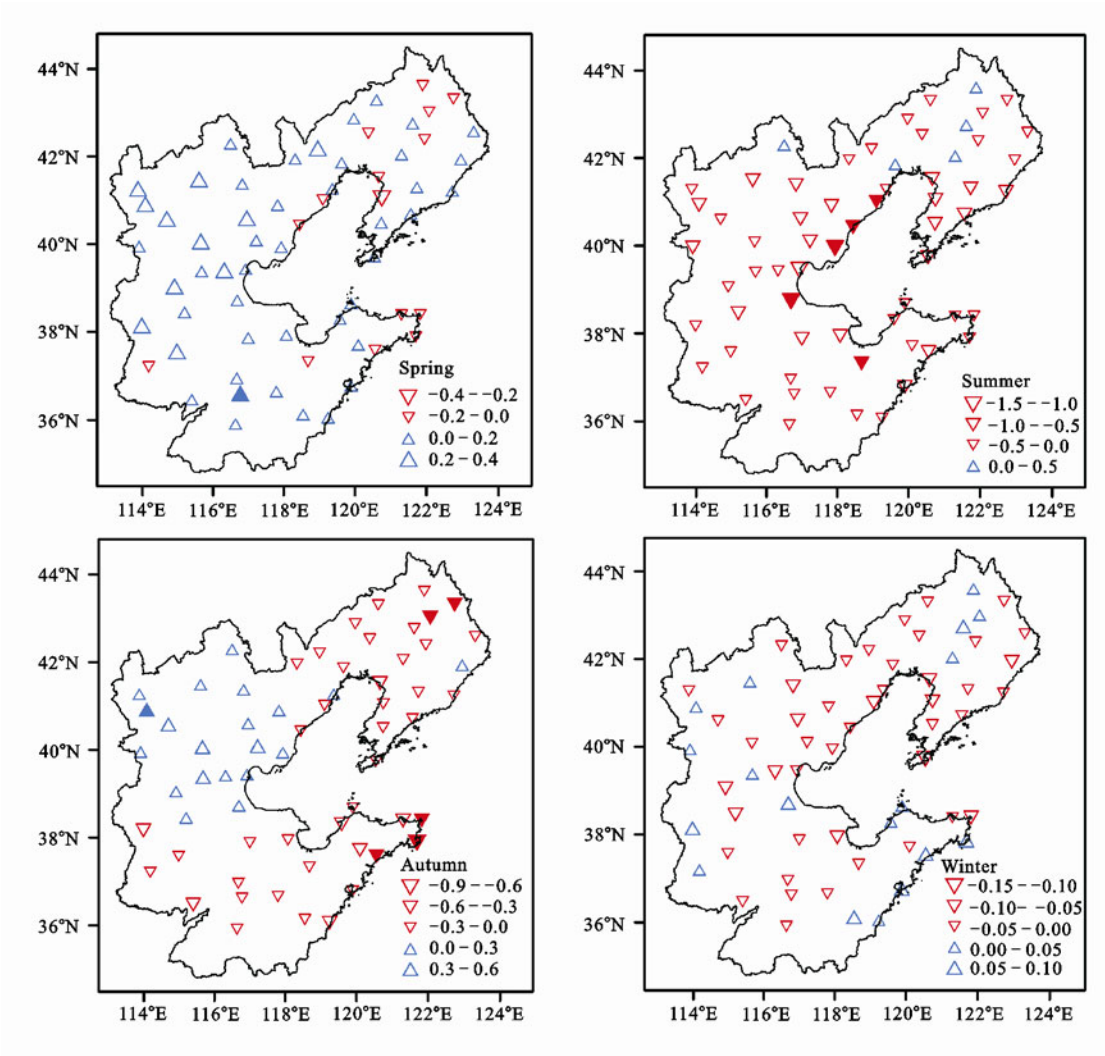


Fig. 9 Seasonal changing trends of RD95p (d/10yr) from 1961 to 2008 in study area

Table 3 Trends of temperature extremes in this study and other studies

	Warm days (d/10yr)	Warm nights (d/10yr)	Cold days (d/10yr)	Cold nights (d/10yr)	Frost days (d/10yr)	Diurnal temperature range (℃/10yr)
This study	2.06	3.95	–1.88	–4.27	–4.21	0.20
China [a]	–	3.00	–0.50	–3.00	–2.40	–
China [b]	0.62	1.75	–0.47	–2.06	–3.73	0.18
Northern China [c]	–	6.83	–3.23	–7.07	–	–

Notes: a (Zhai and Pan, 2003) represents the period from 1951 to 1999; b (You *et al*., 2011) represents the period from 1961 to 2003; c (Qian and Lin, 2004) represents the period from 1961 to 2000

Overall, this study illustrates the variability of temperature and precipitation extremes over Circum-Bohai-Sea region from 1961 to 2008. The results show a warming tendency at the stages of relatively less rainfall for the last 48 years in the study area, which could have impacts on economic development and natural ecosystems. The warming can extend the growing season and increase grain production. However, the study area has being suffered from serious water stress. Hence, under the infrequent rainfall conditions, global warming might aggravate droughts and adversely affect agricultural development, ecological protection and construction. In the future, crop structure adjustment may be a good way for drought resistance and grain yield increase.

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