Theor Appl Climatol (2011) 104:501–509
DOI 10.1007/s00704-010-0369-5

ORIGINAL PAPER

Variability of extreme summer precipitation over Circum-Bohai-Sea region during 1961–2008

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Received: 12 May 2010 / Accepted: 24 October 2010 / Published online: 18 November 2010

Abstract The variability of extreme summer precipitation over Circum-Bohai-Sea region during 1961–2008 was investigated based on the daily precipitation data of 63 meteorological stations using the linear regression method, the non-parametric Mann–Kendall test, and the continuous wavelet transform method. The results showed that there were large spatial differences in the trends of extreme summer precipitation indices. Decreasing trends were found in summer total precipitation, extreme precipitation frequency, intensity and proportion, the maximum consecutive wet days (CWD), and the maximum 1- and 5-day precipitation, and the largest decrease was observed in the central coast area (except CWD), although the trends were not statistically significant at the 5% level at most places. Inversely, the maximum consecutive dry days exhibited non-significant increasing trends. Additionally, the significant 2–4-year periods were detected for eight indices, showing the significant interannual variability of extreme summer precipitation. Overall, the results of this study indicated that in the last 48 years, there was severe water stress over Circum-Bohai-Sea region, especially in the central coast area, which exerted negative effects on economic development and natural ecosystems.

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1 Introduction

Extreme weather and climate events have attracted more attention in the past few years due to their potentially severe and adverse impacts on human life, social economy, and natural ecosystems (Karl and Easterling 1999; Easterling et al. 2000; Changnon et al. 2000; Boroneant et al. 2006; Rusticucci and Renom 2008; Li et al. 2010). Precipitation is among the most relevant climate variables, and its study about climate extremes on a regional scale is particularly meaningful (Santos et al. 2007). Early studies at the end of the twentieth century as summarized in Easterling et al. (2000) showed that heavy precipitation events increased over some regions of the world, such as USA, southeastern China, most regions of Australia, northern Japan, Norway, southwestern South Africa, and southern Canada, while droughts also increased in some regions such as northeastern China, southern Japan, Ethiopia, and Thailand (Easterling et al. 2000). The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report pointed out that 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 (IPCC 2007). The global analysis of precipitation extremes in Alexander et al. (2006) showed that there was a tendency toward wetter conditions concomitant with global warming.

Today, more studies have been carried out at national or regional scales. Because the patterns of extreme precipitation showed large spatial differences, the detection of the variability and trends of the regional extreme precipitation is very important for the assessment of hydrological consequences, such as flooding and droughts (Unkašević et al. 2004; Hundecha and Bárdossy 2005; Rahimzadeh et al. 2009), and it is greatly helpful to develop appropriate adaptation and mitigation strategies coping with the negative effects arising from precipitation extremes (Santos et al. 2007). This study has become one of the main themes of current climate research, especially global change scenarios (Zhang et al. 2008).

Circum-Bohai-Sea region is located in north China with an area of 5.2 × 10^5 km^2 and a population of 2.3 × 10^8, administratively consisting of Beijing city, Tianjin city, 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 eastern China. This region belongs to the warm and semi-humid continental monsoon climate zone. The mean annual precipitation varies from 560 to 916 mm with most of the precipitation falling during summer (June, July, and August). The mean annual air temperature ranges from 8°C to 12.5°C. There are three major rivers: the Yellow River, the Liaohe River, and the Haihe River, all entering Bohai Sea. Bohai Sea is nearly a closed shallow bay in west Pacific with very weak water exchange ability. Hence, Bohai Sea is a typical region of freshwater influence.

In recent years, due to large population, rapid social–economic development, and local climate characteristics, Circum-Bohai-Sea region is one of the places where the shortage of water resource is most severe, and Bohai Sea is the most severely polluted sea area in China. The economy and environment are greatly sensitive to precipitation variability and especially its extremes. Now, 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 the trends in precipitation extremes over this region. This study is aimed at analyzing the variability and detecting the spatial–temporal patterns of extreme summer precipitation over Circum-Bohai-Sea region from 1961 to 2008 based on the daily precipitation data.

2 Data and methods

Daily precipitation data for the period of 1961–2008 were available for 85 meteorological stations, which were obtained from the National Climate Center of China, China Meteorological Administration. Data quality control was performed to remove mistakes from the observation data set, such as missing values and daily precipitation amounts less than 0 mm. The homogeneity of the precipitation data series for each station was assessed by the double-mass curve method (Su et al. 2006), which was frequently used in hydrometeorological practice to test the homogeneity of precipitation and runoff records (WMO 1983). In order to minimize the effect of inhomogeneity, the shortness of record length and missing data, 63 meteorological stations were selected for this study (Fig. 1).

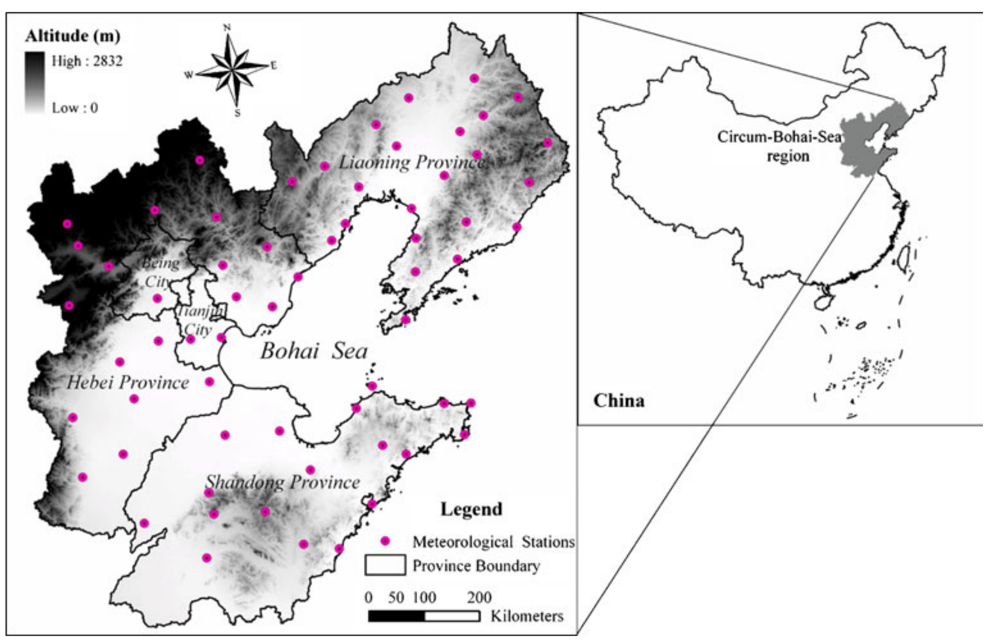

Fig. 1 Location map of Circum-Bohai-Sea region and 63 meteorological stations

Eight indices of precipitation extremes (Table 1) were constructed based on the indicators recommended by the joint Meteorological Organization CCL/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (http://cccma.seos.uvic.ca/ETCCDI). First, the extreme precipitation thresholds for each station were determined according to the 1961–2008 mean 95th percentiles of daily precipitation. These thresholds were greatly different from those defined basing on pre-defined arbitrary threshold methods, which were only applicable to a specific region or area (Bartolini et al. 2008). Then, the extreme precipitation indices of extreme precipitation frequency (RD95p), intensity (RINTEN), and proportion (RPROP) in summer were calculated based on these precipitation thresholds. Additionally, indices of summer total precipitation (PRCPSM), the maximum consecutive dry days (CDD), the maximum consecutive wet days (CWD), the maximum 1-day precipitation (Rx1day), and the maximum 5-day precipitation (Rx5day) were calculated in this study. PRCPSM was the summer total precipitation, which was used to depict the summer precipitation conditions over the study area. CDD and CWD were calculated as the maximum number of consecutive days in summer with daily precipitation less than 1 mm and more than or equal to 1 mm, respectively. Rx1day and Rx5day were respectively the monthly maximum 1-day precipitation and the monthly maximum consecutive 5-day precipitation in summer.

In this study, the slopes of the linear trends were calculated by the least squares fitting. The non-parametric Mann–Kendall test was used to test the statistical significance of all the trends at the 5% level. Inverse distance weighted method was used for spatial interpolation to calculate slopes or significance levels between known pixels.

The continuous wavelet transform (CWT; Torrence and Compo 1998) was used to detect the periodicity of the time series of extreme precipitation indices, which has been widely applied to analyze the variability of precipitation time series (Partal and Küçük 2006; Hartmann et al. 2008; Kayano and Sansígolo 2009). The Morlet wavelet was chosen for the time–frequency analyses because it could provide a good balance between time and frequency localization. The wavelet function at each scale was normalized to have unit energy, and thus, the wavelet transform at each scale could be comparable with each other and also could be contrasted to the transform of other time series. Detailed information of CWT application and algorithms could be seen in Torrence and Compo (1998).

3 Results and discussions

3.1 Trend analysis

3.1.1 Summer total precipitation

The trends in summer total precipitation (PRCPSM) showed great spatial variations, as seen in Fig. 2a. Negative trends were found in most of the study area, which were the largest in the central coast area. Positive trends were detected only in the northeast most regions. The trends of PRCPSM were not statistically significant at most places except the coastal areas of Tianjin city and Hebei province. Figure 3a showed the regional averaged changes of PRCPSM. We saw that the regional averaged summer total precipitation exhibited decreasing trends, which decreased by 17.5 mm/decade from 1961 to 2008.

Because few studies on precipitation extremes were focused on Circum-Bohai-Sea region, the results of this study were compared with several other studies in northern China or North China Plain which covered Circum-Bohai-Sea region. During summer, the precipitation amount decreased in northern China (Gemmer et al. 2004; Zhai et al. 2005) and North China Plain (Liu et al. 2005), and therefore, the dominant downward trends in PRCPSM over Circum-Bohai-Sea region were similar to northern China and North China Plain.

3.1.2 RD95p

Seen from Fig. 2a, b, changes of RD95p in summer showed a similar spatial distribution to those of PRCPSM, i.e., most

Table 1 Definitions of extreme summer precipitation indices

No.	Index	Definition	Unit
1	PRCPSM	Summer total precipitation	mm
2	RD95p	Number of days with daily precipitation greater than or equal to the 1961–2008 mean 95th percentile	days
3	RINTEN	Average intensity of precipitation events greater than or equal to the 95th percentile	mm/day
4	RPROP	Percentage of summer total precipitation from events greater than or equal to the 95th percentile	%
5	CDD	Consecutive dry days: maximum number of consecutive days with daily precipitation <1 mm	days
6	CWD	Consecutive wet days: maximum number of consecutive days with daily precipitation ≥1 mm	days
7	Rx1day	Max 1-day precipitation: monthly maximum 1 day precipitation	mm
8	Rx5day	Max 5-day precipitation: monthly maximum consecutive 5 days precipitation	mm

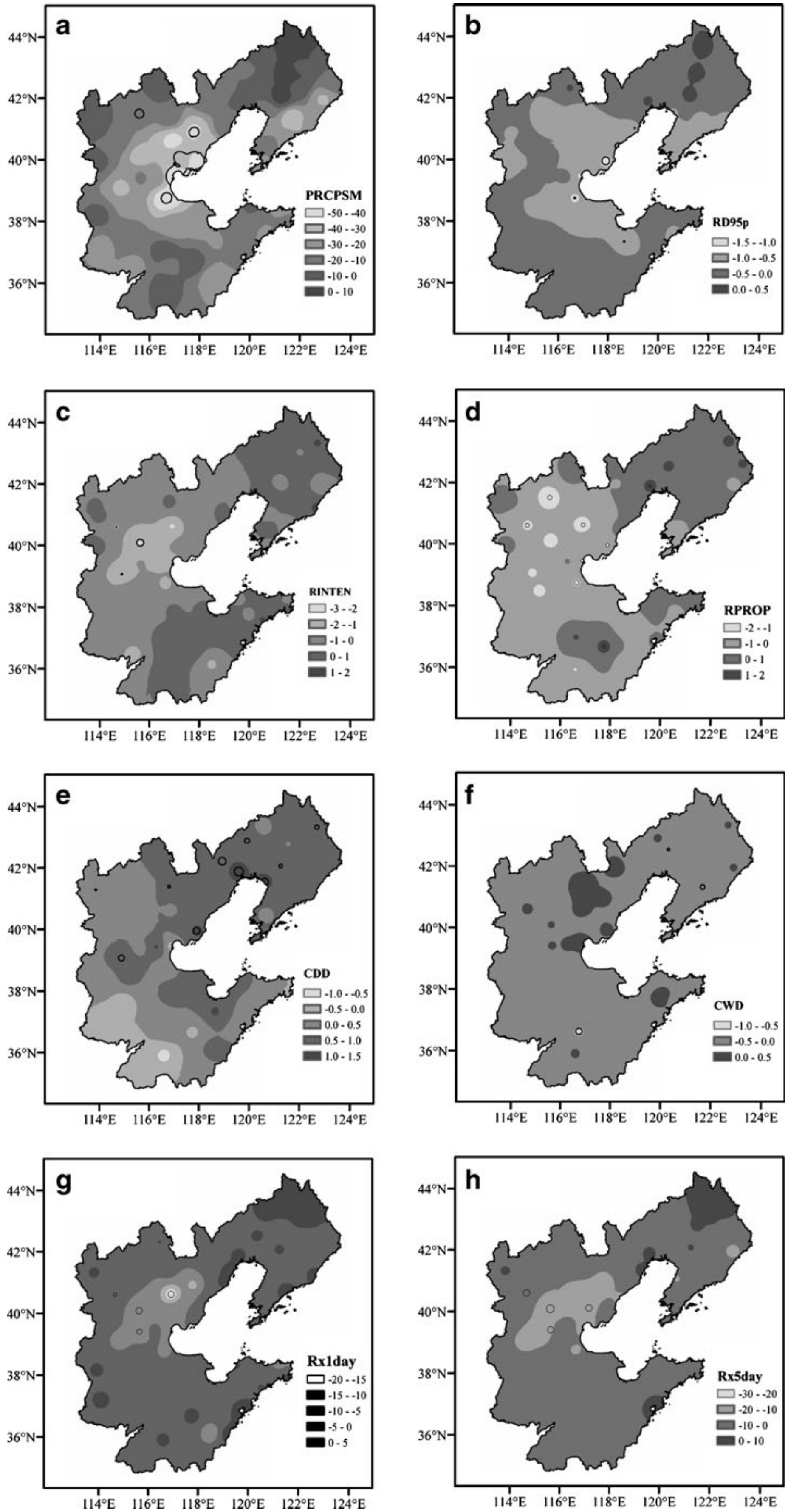

Fig. 2 Decadal trends in extreme summer precipitation indices of **a** PRCPSM (millimeters per decade), **b** RD95p (days per decade), **c** RINTEN (millimeters per decade), **d** RPROP (percent per decade), **e** CDD (days per decade), **f** CWD (days per decade), **g** Rx1day (millimeters per decade), and **h** Rx5day (millimeters per decade) during 1961–2008. *Black lines* enclosed regions where trends were significant at the 5% level

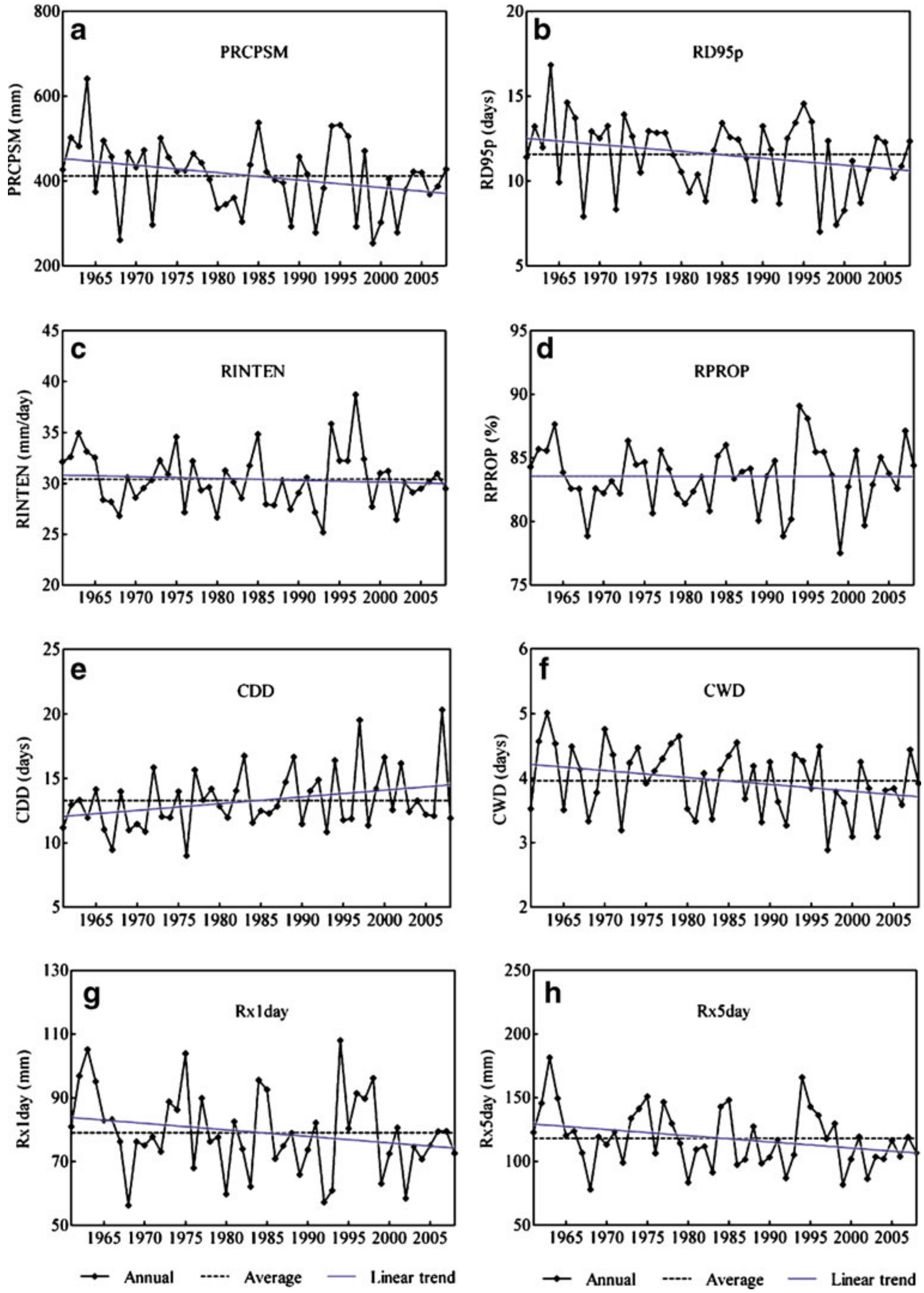

Fig. 3 Time series of regional averaged indices for **a** PRCPSM, **b** RD95p, **c** RINTEN, **d** RPROP, **e** CDD, **f** CWD, **g** Rx1day, and **h** Rx5day during 1961–2008

places showed negative trends and the largest decrease was found at the central coastal part while only the northeastern part showed positive trends; furthermore, no significant trends were noticed at most places. The downward trends in RD95p over Circum-Bohai-Sea region were consistent with the decrease of rain days during summer in northern China (Gemmer et al. 2004; Zhai et al. 2005; Wang and Zhou 2005) and North China Plain (Liu et al. 2005), and furthermore, they were also similar to the annual trends in northern China (Qian and Lin 2005; Wang and Zhou 2005; Zhai et al. 2005; You et al. 2010).

When averaged over the study area, RD95p showed downward trends with the decrease of 0.4 days/decade (Fig. 3b), which possibly contributed to the decline in summer total precipitation. Because the annual total precipitation mainly occurred during summer, negative trends in PRCPSM and RD95p could cause water stress in most regions of the study area, especially Beijing city, Tianjin city, and Eastern Hebei province (Fig. 2a, b), because these areas have been undergoing serious water shortage and water pollution.

3.1.3 RINTEN and RPROP

RINTEN showed negative trends in the middle part of Circum-Bohai-Sea region with the largest decrease noticed mainly in Beijing and Tianjin city (Fig. 2c), which was similar to PRCPSM and RD95p. Positive trends were found mainly in the south and northeast parts. Therefore, in the south part and the northeast part except the northeast most regions, an increase in RINTEN was not able to compensate the loss of summer total precipitation due to a great decrease in RD95p. In other words, the decrease in summer total precipitation in these areas was the result of fewer extreme precipitation events. Figure 2c indicated no significant trends in RINTEN, which was also true for its regional average change (Fig. 3c). From 1961 to 2008, the regional averaged RINTEN decreased by 0.2 mm/decade.

RPROP was the proportion of summer total precipitation from events greater than or equal to the 95th percentile. Figure 2d showed no significant trend in RPROP, but negative trends were detected at most places. In addition, the northeast part and some regions of Shandong province showed positive trends (Fig. 2d). The regional averaged RPROP was 83.6%, indicating that the extreme summer precipitation events greater than or equal to the 95th percentile was the most important contributor to summer total precipitation. Figure 3d showed no change in the regional averaged RPROP, implying that summer total precipitation varied as changes in extreme summer precipitation. In other words, changes in extreme summer precipitation determined the variability of summer total precipitation.

3.1.4 CDD and CWD

The trends of CDD and CWD in summer were shown in Fig. 2e, f, respectively. Figure 2e indicated that CDD had no significant trends at most places except some small regions that exhibited significant increasing trends. Also that, the increase was found in most of the study area, and only the southwest part showed decreasing trends. Figure 2f displayed decreasing trends of CWD at most places and exhibited increasing trends mainly in small regions of the middle part. However, the increase or decrease of CWD in summer was all not statistically significant. These results were also found in the earlier studies in northern China (Qian and Lin 2005).

Figure 3e, f showed the trends of regional averaged indices of CDD and CWD in summer, respectively. CDD indicated an increase but CWD showed a decrease, which also implied water stress over Circum-Bohai-Sea region, although their trends were not significant. For the past 48 years, CDD increased by 0.5 days/decade and CWD decreased by 0.1 days/decade.

3.1.5 Rx1day and Rx5day

Rx1day and Rx5day indicated that whether there were changes in the amount of summer precipitation received in the day with the highest precipitation and received in the consecutive 5 days with the highest precipitation, respectively. These indices gave an indication of the trends in summer total precipitation usually coming from extreme weather occurrences (Pal and Al-Tabbaa 2009). Figure 2g, h showed that the trends and their spatial distribution of Rx1day were almost similar to those of Rx5day. These two indices had decreasing trends in most areas, and the largest decrease was found in the middle-east part. Additionally, increasing trends were noticed in the northeast most regions. When averaged over the study area, Rx1day and Rx5day all exhibited downward trends (Fig. 3g, h), which decreased by 2.0 and 4.8 mm/decade, respectively. Qian and Lin (2005) detected a decrease in the greatest 5-day total precipitation during summer in northern China, and therefore, the downward trends in Rx5day over the study area were consistent with northern China.

Generally, changes in Rx1day and Rx5day had similar patterns of temporal trends and spatial differences as those of PRCPSM and RD95p, implying that except the northeast part, most places, especially Beijing city, Tianjin city, and Northeastern Hebei province, were undergoing serious water stress, which had adverse effects on agriculture and water supply of megacities such as Beijing city.

3.2 Wavelet analysis

Figure 4 illustrated wavelet analysis results from the time series of eight extreme summer precipitation indices. Seen from Fig. 4a–h, the significant 2–4-year periods at the 5% level were predominant, which were observed from the wavelet power spectrum (WPS) and the global wavelet spectrum (GWS). Furthermore, the WPS and GWS between PRCPSM and RD95p, between RINTEN and RPROP, and between Rx1day and Rx5day showed the similar patterns, respectively.

In detail, the GWS of PRCPSM and RD95p all showed significant interannual variances (2 to 3 years) with a 2.5-year peak (Fig. 4a, b), which was due to significant variances in this scale observed from their WPS in the end of 1960s and 1990s. The WPS and GWS of RINTEN and RPROP all showed a significant 3-year period, which was observed in the 1990s (Fig. 4c, d). For CDD, a significant 2.5-year period was found around 1975, and significant 2- to 3-year periods with 3-year peak were detected around 1995 (Fig. 4e). The GWS of CWD

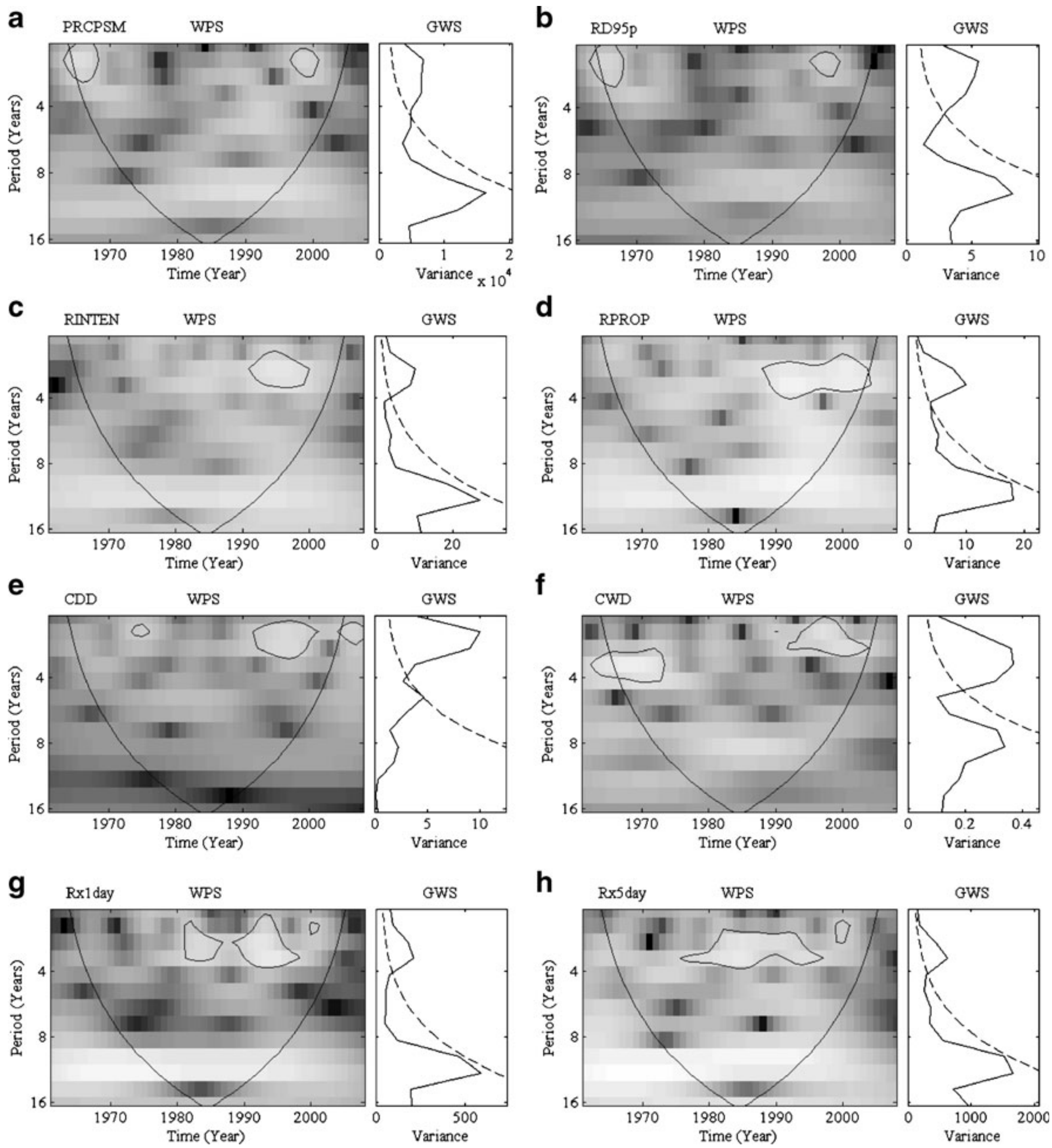

Fig. 4 The wavelet power spectrum (*WPS*; *left graph*) and the global wavelet spectrum (*GWS*; *right graph*) for the time series of **a** PRCPSM, **b** RD95p, **c** RINTEN, **d** RPROP, **e** CDD, **f** CWD, **g** Rx1day, and **h** Rx5day. The *closed contours* of WPS encompassed significant variances at the 5% level and the region where the edge effects were important was under the *U-shaped curve*. The *dashed curve* of GWS was the significance at the 5% level assuming a red-noise spectrum

showed the major significant 3- to 4-year periods and the secondary significant 2- to 3-year periods (Fig. 4f), which were noticed around 1970 and in the 1990s, respectively. The WPS and GWS of Rx1day and Rx5day exhibited the major significant 3- to 4-year periods, which were indentified in 1980s and 1990s, and a secondary significant 3-year period, which was found around 2000 (Fig. 4g, h). In general, the results of wavelet analysis showed significant periods and interannual variability of extreme summer precipitation. However, the periods were relatively small, possibly due to the shorter study period. We expected to find more abundant period characteristics with longer time series of precipitation data in the future.

4 Conclusions

This study analyzed the variability of extreme summer precipitation over Circum-Bohai-Sea region during 1961–2008 based on the daily precipitation data of selected 63 meteorological stations. The linear regression method and the non-parametric Mann–Kendall test were used to detect the trends and their significances at the 5% level for eight indices, including PRCPSM, RD95p, RINTEN, RPROP, CDD, CWD, Rx1day, and Rx5day. The CWT method was used to examine the periodicity of these indices.

The results showed that changes of eight indices were found having great spatial differences and the largest change was noticed in the central coast area for all indices except CDD and CWD. In most regions, decreasing trends were observed in PRCPSM, RD95p, RINTEN, RPROP, CWD, Rx1day, and Rx5day except CDD that exhibited increasing trends, although these trends were not statistically significant. Furthermore, the trends in eight indices were also detected in their responding time series of regional average changes. When averaged over the study area, PRCPSM, RD95p, RINTEN, CWD, Rx1day, and Rx5day decreased by 17.5 mm/decade, 0.4 days/decade, 0.2 mm/decade, 0.1 days/decade, 2.0 mm/decade, and 4.8 mm/decade, respectively, and CDD increased by 0.5 days/decade while RPROP had no change. Generally, the dominant trends in extreme precipitation indices over Circum-Bohai-Sea region were consistent with the earlier studies in northern China (Gemmer et al. 2004; Zhai et al. 2005; Wang and Zhou 2005; Qian and Lin 2005) and North China Plain (Liu et al. 2005). Additionally, the wavelet analysis revealed that the significant 2–4-year periods at the 5% level were predominant for eight indices, which indicated the interannual variability of extreme summer precipitation.

Overall, this study gave knowledge about the variability of extreme summer precipitation over Circum-Bohai-Sea region during 1961–2008. The temporal trends and their spatial characteristics of eight indices suggested that the study area, especially the central coast area, was undergoing severe water stress in the last 48 years, which was greatly unfavorable for economic development, ecological protection, and restoration. The results of this study might be helpful to assess the precipitation and water resource situations over this region and hence to make the reasonable mitigation and adaption strategies to cope with changes in precipitation extremes.

Acknowledgments This study is financially supported by the National Natural Science Foundation of China (No. 40901028). The authors kindly thank the National Climate Center of the China Meteorological Administration for providing the data for this study. We are very grateful to the anonymous reviewers for their helpful comments and suggestions and Miss Jianxiu Qiu for her help in modifying English.

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