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Changes in daily climate extremes in China and their connection to the large scale atmospheric circulation during 1961–2003

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Abstracts Based on daily maximum and minimum surface air temperature and precipitation records at 303 meteorological stations in China, the spatial and temporal distributions of indices of climate extremes are analyzed during 1961–2003. Twelve indices of extreme temperature and six of extreme precipitation are studied. Temperature extremes have high correlations with the annual mean temperature, which shows a significant warming of 0.27°C/decade, indicating that changes in temperature extremes reflect the consistent warming. Stations in northeastern, northern, northwestern China have larger trend magnitudes, which are accordance with the more rapid mean warming in these regions. Countrywide, the mean trends for cold days and cold nights have decreased by −0.47 and −2.06 days/decade respectively, and warm days and warm nights have increased by 0.62 and 1.75 days/decade, respectively. Over the same period, the number of frost days shows a statistically significant decreasing trend of −3.37 days/decade. The length of the growing season and the number of summer days exhibit significant increasing trends at rates of 3.04 and 1.18 days/decade, respectively. The diurnal temperature range has decreased by −0.18°C/decade. Both the annual extreme lowest and highest temperatures exhibit significant warming trends, the former warming faster than the latter. For precipitation indices, regional annual total precipitation shows an increasing trend and most other precipitation indices are strongly correlated with annual total precipitation. Average wet day precipitation, maximum 1-day and 5-day precipitation, and heavy precipitation days show increasing trends, but only the last is statistically significant. A decreasing trend is found for consecutive dry days. For all precipitation indices, stations in the Yangtze River basin, southeastern and northwestern China have the largest positive trend magnitudes, while stations in the Yellow River basin and in northern China have the largest negative magnitudes. This is inconsistent with changes of water vapor flux calculated from NCEP/NCAR reanalysis. Large scale atmospheric circulation changes derived from NCEP/NCAR reanalysis grids show that a strengthening anticyclonic circulation, increasing geopotential height and rapid warming over the Eurasian continent have contributed to the changes in climate extremes in China.

Keywords Climate extremes · Atmospheric circulation · China

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1 Introduction

In recent decades, changes in climate extremes have attracted much attention in the world because extreme climate events are often more important to natural and human systems than their mean values (Aguilar 2009; Katz and Brown 1992). For example, most societal infrastructure is more sensitive to extreme events. Changes in the distribution of wild plants and animals, climate-induced extinctions, phonological changes, and species' range shifts are being documented at an increasing rate (Easterling et al. 2000). Compared with previous reports, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) makes a much greater effort in analyzing change in climate extremes (IPCC 2007). A warming climate has been shown to exacerbate and trigger certain climate extremes, including extreme high temperatures, decreasing the frequency of extreme low temperatures, and increasing intense precipitation events (Easterling et al. 2000).

Temperature and precipitation extremes have been studied on global, regional and national scales. On the global scale, the most comprehensive analyses on temperature and precipitation extremes (Alexander et al. 2006; Frich et al. 2002) are discussed in the Fourth Assessment Report of IPCC (IPCC 2007). On the regional and national scales, studies include those in Southeast Asia and the South Pacific (Griffiths et al. 2005; Manton et al. 2001), the Caribbean region (Peterson 2002), southern and west Africa (New et al. 2006), South America (Haylock et al. 2006; Vincent et al. 2005), Middle East (Zhang et al. 2005), Central America and northern South America (Aguilar et al. 2005), Central and south Asia (Klein Tank et al. 2006), Asia-Pacific Network region (Choi 2009), the Tibetan Plateau (You et al. 2008), Western central Africa (Aguilar 2009) and North America (Peterson 2008). There is remarkable consistency among the results obtained from these studies in terms of temperature extremes, but less spatial coherence in precipitation extremes. Most of the quoted works are produced after international cooperation fostered by the World Meteorological Organization Joint Expert Team on Climate Change Detection and Indices (ETCCDI), as explained by Peterson and Manton (2008). None of these works have covered the full extent of China, although other authors have studied changes in precipitation and temperature extremes in the country (Zhai and Pan 2003; Zhai et al. 1999, 2005).

Along with the rest of the world, China has experienced significant temperature changes during recent decades. The annual mean surface air temperature has increased significantly, with a rate of 0.22°C/decade, while large regional differences are notable in precipitation trends between 1956 and 2002 (Ding 2005). The daily maximum and minimum air temperatures have increased at rates of 0.13 and 0.32°C/decade from 1955 to 2000, respectively, increases being most pronounced in northeast China and least in the southwest, which is consistent with spatial patterns in mean temperature change (Liu et al. 2005; Wang and Gong 2000). Mean annual precipitation has increased significantly in southwestern, northwestern, and eastern China, but has decreased significantly in central, northern and northeastern parts of the country (Wang and Zhou 2005). Average regional precipitation has increased by 2% but the frequency of precipitation events has decreased by 10% from 1960 to 2000 (Liu et al. 2005). Trends in total precipitation and the frequency of daily precipitation and temperature extremes have also been studied (Zhai and Pan 2003; Zhai et al. 1999, 2005), but uncertainty still exists in the exact patterns of change in such parameters.

The objective of this study is to quantify changes in temperature and precipitation extremes during 1961–2003 throughout China, based on indices generated by the Commission for Climatology (CCl)/Climate Variability and Predictability (CLIVAR)/Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) (http://cccma.seos.uvic.ca/ETCCDI), a widely used approach. The same indices developed by the ETCCDI have been adopted by the IPCC Fourth Assessment Report (AR4). We discuss spatial and temporal variability of changes in these indices. Finally relationships between large scale atmospheric circulation patterns and these changes are discussed.

2 Data and methods

2.1 Data sources

Daily precipitation, maximum temperature and minimum temperature are provided by the National Climate Center, China Meteorological Administration. Calculation of indices is facilitated using the information provided by ETCCDI (see http://cccma.seos.uvic.ca/ETCCDI for available calculated station-level indices) (Peterson and Manton 2008). The density of distribution and the quality of observational data in China meet the World Meteorological Organization's standards at a total of 329 stations in the datasets. Most stations were established in the 1950s but any data before 1961 was excluded. The 303 stations selected (Fig. 1) are not evenly distributed and most of them are located in central and eastern China. Over half of the stations are below 500 m a.s.l. and have mean annual temperature and precipitation above 0°C and 800 mm, respectively. Station coverage is spare at high elevations in

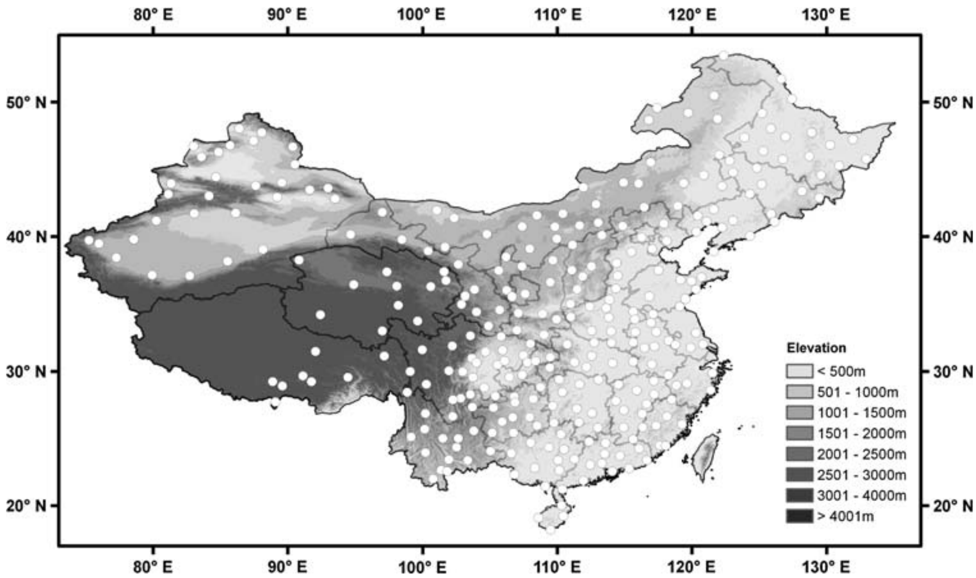

Fig. 1 The distribution of 303 stations used in this study in China

western China and on the Tibetan Plateau, where mean annual temperature are generally below −5°C and precipitation below 200 mm (Fig. 2).

2.2 Data quality and homogeneity

Data quality control and homogeneity assessment were attained using the RClimDex software package (available at the ETCCDI website, http://cccma.seos.uvic.ca/ETCCDI/software.shtml). Precipitation values below 0 mm or days with $T_{max} < T_{min}$ were flagged as erroneous. Additional routines identified potential outliers, which were then manually checked and either validated, corrected or removed. Visual data plots and histograms were also available to aid in this process (Aguilar 2009; Aguilar et al. 2005; New et al. 2006; You et al. 2008). The RHTest software, developed at the Climate Research Branch of Meteorological Service of Canada (available from the ETCCDI website), was applied to assess data homogeneity. It is based on a two-phase regression model applying a linear trend for the parameter in question to identify potential inhomogeneities (Wang 2003; Wang and Swail 2001). Once a possible step change is identified, the metadata would be checked to see if there was any valid explanation. 26 stations with inhomogeneities were removed, leaving a total of 303 stations for use in this study. Not all discontinuities were identified and we acknowledge that some inhomogeneities may remain.

2.3 Definition of extreme indices

We use 12 temperature and 6 precipitation indices (available from http://cccma.seos.uvic.ca/ETCCDI) in this study, many of which are commonly used to validate climate model simulations (Peterson and Manton 2008). Some of the original ETCCDI indices, such as the number of tropical nights and the number of ice days, are not relevant to the whole of China, and were not selected in this case. Although growing season length and frost days would not be relevant to some stations in southern China, and summer days would not be relevant to the highest-altitude stations, we still keep those indices in our study. The number of stations which these indices are not relevant explains the large number of stations with no trend for GSL, FD and SU. Detailed descriptions are provided in Table 1.

The indices were chosen primarily for assessment of the many aspects of a changing global climate which include changes in intensity, frequency and duration of temperature and precipitation events (Alexander et al. 2006). Alexander et al. (2006) divided the indices we have chosen into five different categories: (1) percentile-based indices, such as occurrence of cold nights (TN10), (2) absolute indices represent maximum or minimum values within a season or year, such as maximum daily maximum temperature (TXx) and maximum 1-day precipitation amount (RX1day), (3) threshold indices defined as the number of days on which a temperature or precipitation value falls above or below a fixed threshold, such as the number of frost days (FD), (4) duration indices which define periods of excessive warmth, cold, wetness or dryness (or in the case of growing season length, periods of mildness), such as consecutive dry days (CDD), (5) other indices, such diurnal temperature range (DTR). Most indices have the same name and definition in previous studies (Aguilar 2009; Aguilar et al. 2005; Alexander et al. 2006; Klein Tank et al. 2006; New et al. 2006; You et al. 2008), although their exact definitions may vary slightly.

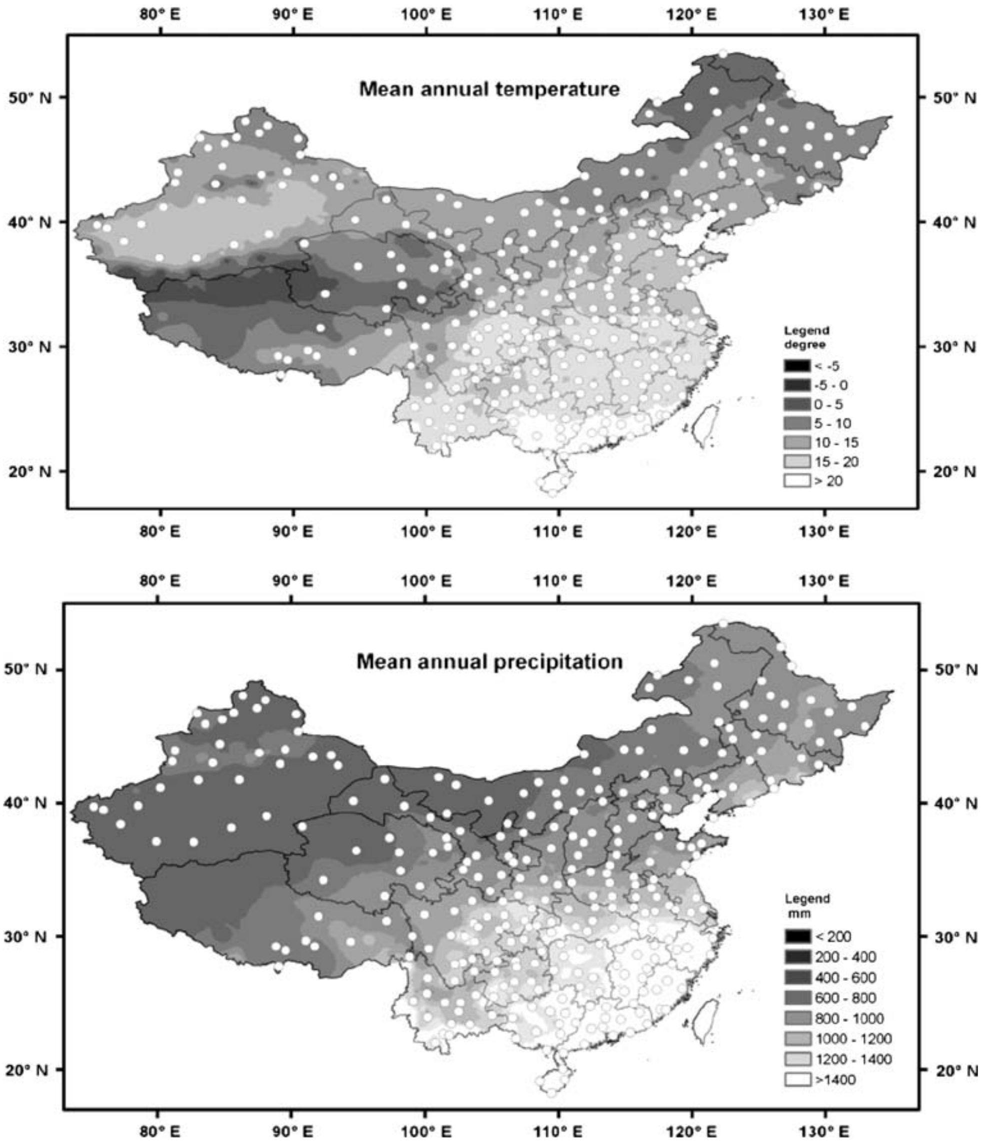

Fig. 2 The mean annual temperature (*top plot*) and precipitation (*bottom plot*) during 1961–2003 in China

2.4 Trend calculation

The Mann–Kendall test for a trend and Sen's slope estimates were used to detect and estimate trends in annual and seasonal temperature series (Kendall 1955; Sen 1968).

A trend is considered to be statistically significant if it is significant at the 5% level.

2.5 Large-scale atmospheric circulation

To quantify changes in large scale atmospheric circulation, monthly mean geopotential height, air temperature, and wind fields at 500 hPa were downloaded from the National Oceanic and Atmospheric Administration—Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES) Climate Diagnostics Center (available from their website at http://www.cdc.noaa.gov/). The dataset covers January 1948 to the present with a spatial resolution of 2.5° × 2.5° and with continuous global coverage (Kalnay et al. 1996; Kistler et al. 2001). We calculate the water vapor flux on the basis of NCEP/NCAR reanalysis data. We derive mean circulation composites in summer and winter for 1961–1982 and 1983–2003 respectively, and subtract the former from the latter (new minus old) to represent the change in circulation between the two periods.

3 Results

3.1 Temperature

3.1.1 Cold extremes (TX10, TN10, TXn, TNn, FD)

Figure 3 show the spatial distribution pattern of the temporal trends in cold extremes for the 303 meteorological stations and Fig. 4 demonstrates the regional annual series

Table 1 Definitions of 12 temperature indices and 6 precipitation indices used in this study, all the indices are calculated by RClimDEX

Index	Descriptive name	Definition	Units
Temperature			
TX10	Cold day frequency	Percentage of days when TX < 10th percentile of 1961–1990	%
TN10	Cold night frequency	Percentage of days when TN < 10th percentile of 1961–1990	%
TX90	Warm day frequency	Percentage of days when TX > 90th percentile of 1961–1990	%
TN90	Warm night frequency	Percentage of days when TN > 90th percentile of 1961–1990	%
DTR	Diurnal temperature range	Annual mean difference between TX and TN	°C
TNn	Coldest night	Annual lowest TN	°C
TNx	Warmest night	Annual highest TN	°C
TXn	Coldest day	Annual lowest TX	°C
TXx	Warmest day	Annual highest TX	°C
FD	Frost days	Annual count when TN < 0°C	days
GSL	Growing season length	Annual count between first span of at least 6 days with TG > 5°C after winter and first span after summer of 6 days with TG < 5°C	days
SU	Summer days	Annual count when TX > 25°C	days
Precipitation			
PRCPTOT	Wet day precipitation	Annual total precipitation from wet days	mm
SDII	Simple daily intensity index	Average precipitation on wet days	mm/day
RX1day	Maximum 1-day precipitation	Annual maximum 1-day precipitation	mm
RX5day	Maximum 5-day precipitation	Annual maximum consecutive 5-day precipitation	mm
R95	Very wet day precipitation	Annual total precipitation when RR > 95th percentile of 1961–1990 daily precipitation	mm
CDD	Consecutive dry days	Maximum number of consecutive dry days	days

TX daily maximum temperature, *TN* daily minimum temperature, *TG* daily mean temperature, *RR* daily precipitation; A wet day is defined when RR >=1 mm and a dry day when RR <1 mm. Indices are included for completeness but are not analyzed further in this paper

for indices in China during 1961–2003. The regional trends in indices of cold extremes are in Table 2. Table 3 shows the number of stations with negative, no trend and positive trends for cold extremes indices. Numbers of stations passing the significant level are also shown in Table 3. Regional averages are calculated as an arithmetic mean of values at all stations in the study.

For cold days (TX10) and cold nights (TN10), about 77 and 97% of stations have decreasing trends, respectively. Stations in northeastern, northwestern, northern China have larger trend magnitudes. The few stations (about 22%) that have increasing trends for cold days (TX10) occur mainly in the Yangtze River basin.

Similarly the temperatures recorded on the coldest days and coldest nights in each year (TXn and TNn) have also increased at approximately 95 and 97% of stations, respectively. Stations situated in northeastern and northwestern China show the largest changes. The number of frost days (FD) has also generally decreased during 1961–2003 with 69% of stations showing a significant decrease at the 0.05 level. Stations with larger trend magnitudes are again distributed in northeastern China and along the lower reaches of Yangtze River. Most regions of southern China have lower trend magnitudes.

In Fig. 4 the temporal variability in regional cold indices is demonstrated. Not all indices show the same pattern. Cold days (TX10) show an increasing trend before the 1970s, irregular variability during the 1980s, and a strong decrease after that, while cold nights (TN10) increase until the late 1960s and then decrease. The regional trends (in percentage of days) for these two indices are −0.47 and −2.06 ($P < 0.05$) days/decade, respectively.

On the other hand, both TXn and TNn show decreasing trends before the 1970s and turn to an increasing trend after the 1980s, which show the opposite changes in TX10 and TN10. Regional trends in TXn and TNn are 0.35 and

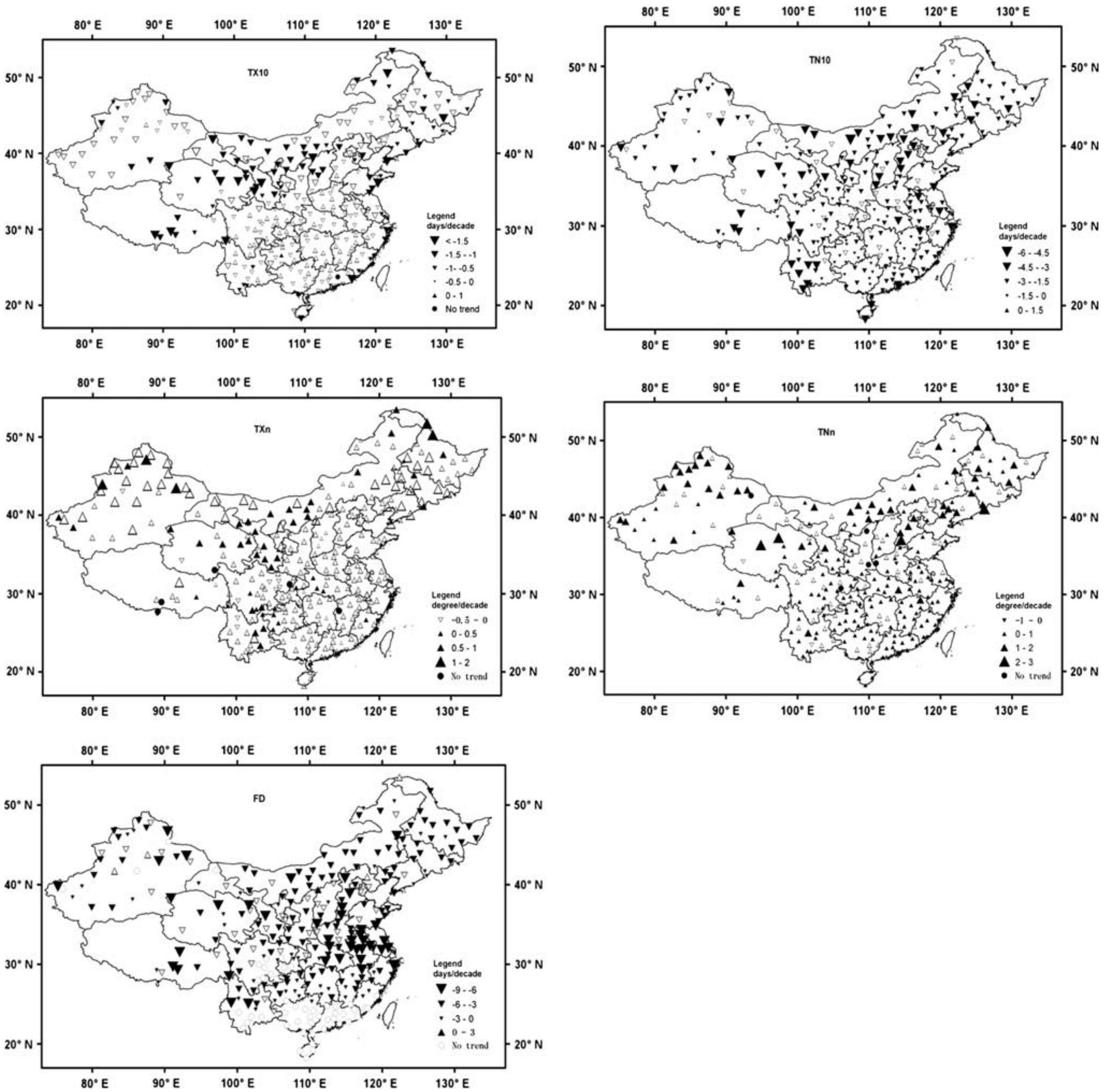

Fig. 3 Spatial patterns of trends per decade during 1961–2003 in China for indices of cold extremes (TX10, TN10, TXn, TNn and FD). Positive/negative trends are shown as *up/down* triangles, and the *filled symbols* represent statistically significant trends (significant at the 0.05 level). The size of the triangles is proportional to the magnitude of the trends

0.63°C/decade at the 0.05 significance level, respectively. The more rapid change for daily minima is consistent in both sets of indices. The regional decline in FD has been relatively consistent with a slight intensification after the mid-1980s. The overall trend is −3.73 days/decade ($P < 0.05$).

Table 4 shows the proportion of stations where trends in indices are of a particular relative magnitude. About 94% of stations show larger trend magnitudes in TN10 than in TX10. This falls to 81% of stations for TNn versus TXn. In most cases, the trend magnitudes of cold extremes are similar to those reported in other regions but are lower than that in the Tibetan Plateau (Table 5).

3.1.2 *Diurnal temperature range*

Many of the above changes may be, at least in part, a result of differential changes in daily maximum and minimum

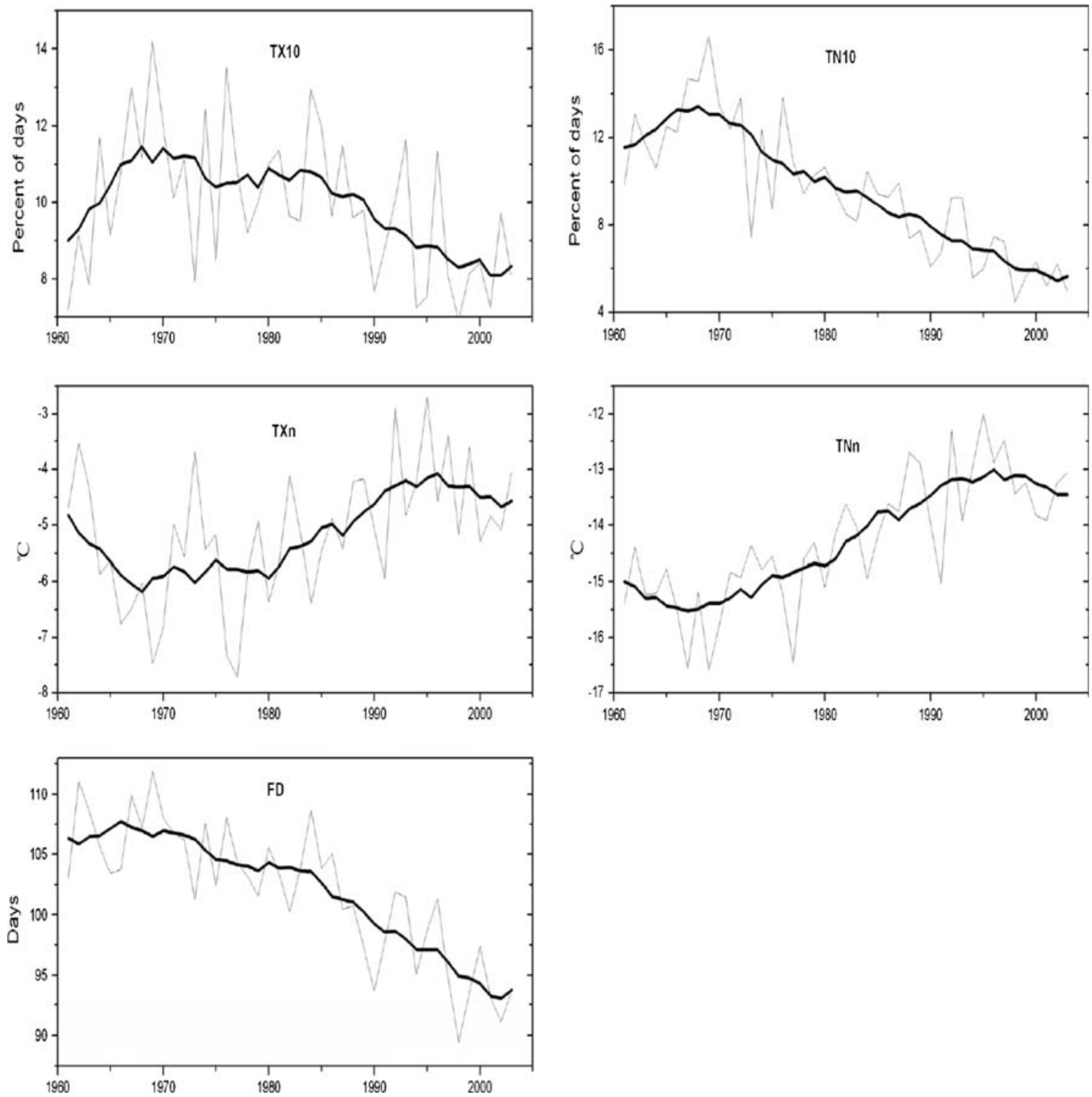

Fig. 4 Regional annual series for indices of cold extremes. The smoother line is the 9-year smoothing average

temperatures, resulting in a narrowing of the diurnal temperature range (DTR) (Easterling et al. 1997). Numerous previous studies in China (Ding 2005; Liu et al. 2004) have shown that minimum temperatures are increasing more rapidly than maximum temperatures. However since 1980 the increases in minimum and maximum temperatures are more comparable, which has muted recent DTR trends (Vose et al. 2005).

In our data, about 80% of stations show a decreasing trend in DTR in China (Table 3). Trend magnitudes tend to decrease from northeastern to southern China (Fig. 5), consistent with more rapid change in northern China (Wang and Gong 2000). The regional trend in DTR is −0.18°C/decade with significant at the 0.05 level, which drastically declines before the mid-1980s and keep fluctuated variations after that (Fig. 6). The rate of decline of DTR for China found in this study is greater than that found for other regions (Table 5).

3.1.3 Warm extremes (TX90, TN90, TXx, TNx, GSL, SU)

Changes in warm extremes during 1961−2003 are shown in a similar way in Fig. 7. Figure 8 demonstrates the regional annual series for indices of warm extremes. The regional trends and number of stations with negative (significant at the 0.05 level), no trend and positive (significant at the 0.05 level) trends are listed in Tables 2 and 3.

For warm days (TX90) and warm nights (TN90), 83 and 94% of stations respectively show increasing trends. Stations in northeastern and western China and some southern

Table 2 Trends per decade (with 95% confidence intervals in parentheses) for regional indices of temperature and precipitation extremes

Index	Units	1961–2003
Temperature		
TX10	days/decade	−0.47 (−1.00 to 0.01)
TN10	days/decade	**−2.06** (−2.53 to−1.60)
TX90	days/decade	0.62 (−0.07 to 1.26)
TN90	days/decade	**1.75** (1.06 to 2.40)
DTR	°C/decade	**−0.18** (−0.25 to −0.12)
TNn	°C/decade	**0.63** (0.47 — 0.83)
TNx	°C/decade	**0.21** (0.14 to 0.29)
TXn	°C/decade	**0.35** (0.11 to 0.64)
TXx	°C/decade	0.07 (−0.06 to 0.18)
FD	days/decade	**−3.73** (−4.66 to −2.90)
GSL	days/decade	**3.04** (1.45 to 4.33)
SU	days/decade	1.18 (−0.25 to 2.42)
Precipitation		
PRCPTOT	mm/decade	3.21 (−4.98 to 12.48)
SDII	mm/decade	0.06 (−0.02 to 0.14)
RX1day	mm/decade	1.37 (−0.18 to 2.67)
RX5day	mm/decade	1.90 (−0.43 to 4.40)
R95	mm/decade	**4.06** (0.45 to 8.78)
CDD	days/decade	−1.22 (−3.17 to 0.51)

Values for trends significant at the 5% level (*t* test) are set bold face

Table 3 Number of stations with positive (significant at the 0.05 level), non-trend, and negative (significant at the 0.05 level) trends for the annual temperature and precipitation indices during 1961–2003

Index	Positive	Non-trend	Negative
Temperature			
TX10	67 (1)	2	234 (93)
TN10	10 (1)	0	293 (259)
TX90	252 (118)	0	51 (2)
TN90	286 (236)	0	17 (5)
DTR	52 (5)	9	242 (187)
TNn	293 (215)	5	5 (2)
TNx	244 (131)	25	34 (3)
TXn	288 (54)	5	10 (0)
TXx	157 (37)	42	104 (10)
FD	5 (1)	51	247 (210)
GSL	174 (71)	117	12 (0)
SU	229 (51)	43	31 (5)
Precipitation			
PRCPTOT	170 (21)	0	133 (9)
SDII	174 (18)	41	88 (2)
RX1day	176 (11)	1	126 (2)
RX5day	160 (10)	2	141 (6)
R95	152 (16)	43	108 (2)
CDD	103 (4)	50	150 (14)

provinces (such as Guangdong province) have larger trend magnitudes. The 17% of stations with decreasing trends for warm days (TX90) mainly occur in the Yangtze River basin. Stations in the middle of China have lower trend magnitudes for warm nights (TN90). The temperatures of the warmest days and warmest nights in each year (TXx and TNx) have also show increases, but the spatial patterning is less consistent than for other indices, particularly for TXx. About 52% of stations, mainly in western China, show increases in TXx but 34% of stations, mostly in the east of China show decreases. Around 81% of stations show an increase in TNx, with the largest changes in northwestern China.

For growing season length (GSL), about 57% of stations have positive trends, with stations in northern China having larger trend magnitudes. About 42.5% of stations, mainly in southern China, have no trend or a decrease. Finally, for summer days (SU), around 76% of stations show increasing trends, with again northern stations having larger trend magnitudes. Some stations in the southern province in China show decreasing trends. Therefore these spatial patterns of warm indices are broadly similar to the other studies (Table 5).

Most of the increase in warm extremes is focused after 1980 for both TX90 and TN90. The regional trends for these two indices are 0.62 ($P > 0.05$) and 1.75 ($P < 0.05$) days/decade, respectively. TXx has a slight decreasing trend before the mid-1980s but increases rapidly after that, while TNx has been continually increasing. The regional trends for these two indices are equivalent to 0.07 ($P > 0.05$) and 0.21 ($P < 0.05$) °C/decade. Finally,

Table 4 Number and proportion of individual stations where the trend in one index is of greater magnitude than trend in a second

Index	Comparison	Number	Proportion
TX90 > TX10	Abs	219	0.72
TN10 > TN90	Abs	181	0.60
TXn > TXx	Rel	242	0.80
TNn > TNx	Rel	281	0.93
TNx > TXx	Rel	193	0.64
TNn > TXn	Rel	246	0.81
FD > SU	Abs	210	0.69
FD > GSL	Abs	195	0.64
TN90 > TX90	Abs	253	0.83
TN10 > TX90	Abs	265	0.87
TN10 > TX10	Abs	284	0.94
TN90 > TX10	Abs	270	0.89

abs indicates that the absolute magnitudes of trends are compared, *rel* indicates that the signs of trends are retained during comparison

Table 5 Trends of temperature and precipitation extremes from this study and other works

Index	This study	Global	Eastern and central Tibetan Plateau	Middle east	China	Central and south Asia	Southern and west Africa	Central and northern south America	Western central Africa
Temperature									
TN10	**−2.06**	**−1.26**	**−2.38**	**−1.3**	−3.0	**−5.70**	**−1.63**	**−2.4**	**−1.71**
TX10	−0.47	**−0.62**	**−0.85**	−0.4	−0.5	**−2.60**	**−1.00**	**−2.2**	**−1.22**
TN90	**1.75**	**1.58**	**2.54**	**1.2**	3.0	**6.86**	**2.35**	**1.7**	**3.24**
TX90	0.62	**0.89**	**1.26**	**0.66**	–	**4.72**	**2.24**	**2.5**	**2.87**
DTR	**−0.18**	**−0.08**	**−0.20**	**−0.12**	–	**−0.12**	−0.01	**0.1**	0
TNn	**0.63**	**0.71**	**0.69**	**0.28**	–	**0.73**	**0.27**	**0.3**	**0.23**
TNx	**0.21**	**0.30**	**0.25**	**0.23**	–	–	**0.19**	**0.2**	**0.21**
TXn	**0.35**	0.37	**0.30**	0.2	–	–	**0.18**	**0.3**	**0.13**
TXx	0.07	**0.21**	**0.28**	0.07	–	**0.17**	**0.16**	**0.3**	**0.25**
FD	**−3.73**	–	**−4.32**	−0.6	−2.4	–	–	–	–
GSL	**3.04**	–	**4.25**	–	–	–	–	–	–
SU	1.18	–	–	1.0	–	–	**5.05**	–	–
Precipitation									
PRCPTOT	3.21	**10.59**	6.66	−0.3	–	6.87	−0.05	8.7	**−31.13**
SDII	0.06	0.05	0.03	−0.006	–		**0.08**	**0.3**	0.06
RX1day	1.37	**0.85**	0.27	0	–	1.02	0.05	**2.6**	−0.87
RX5day	1.90	0.55	−0.08	0	–	1.26	0.33	3.5	−1.54
R95	**4.06**	**4.07**	1.28	-0.3	–	**6.46**	0.02	**18.1**	−12.19
CDD	−1.22	−0.55	**−4.64**	**−5.0**	–		**3.57**	0.4	−0.06

Data sources and time period: Global (Alexander et al. 2006) during 1951–2003, Eastern and central Tibetan Plateau (You et al. 2008) during 1961–2005, Middle east (Zhang et al. 2005) during 1950–2003, Temperature extremes in China (Zhai and Pan 2003) during 1951–1999 and precipitation extremes in China (Zhai et al. 2005) during 1950–2000, Central and south Asia (Klein Tank et al. 2006) during 1961–2000, Southern and west Africa (New et al. 2006) during 1961–2000, Central America and northern south America (Aguilar et al. 2005) during 1961–2003, Western central Africa (Aguilar 2009) during 1955–2006

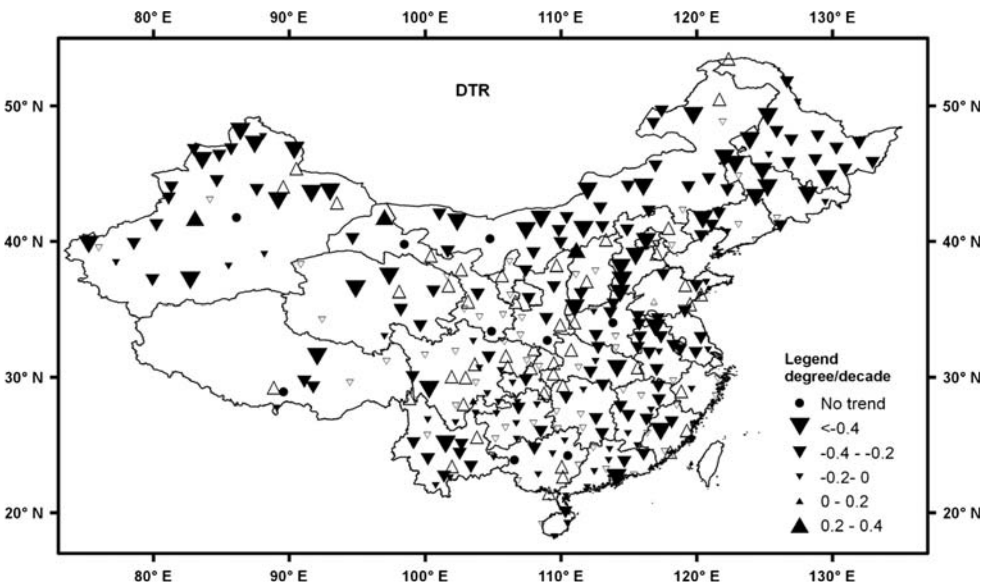

Fig. 5 Same as Fig. 3 but for DTR

regional trends for GSL and SU are 3.04 ($P < 0.05$) and 1.18 ($P > 0.05$) days/decade, respectively. GSL shows a gradual increase during the period of 1961–2003, while SU shows little change until after 1990.

Table 4 again shows comparative trends at individual sites. Compared with TX90, about 83% of stations have greater trend magnitudes in TN90, and approximately 64% of stations have greater trend magnitudes in TNx than in

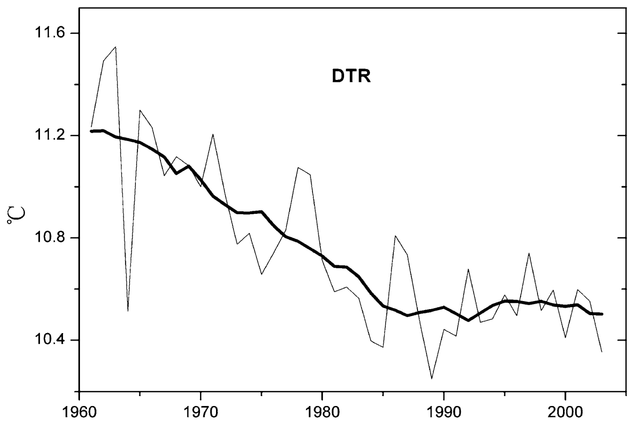

Fig. 6 Same as Fig. 4 but for DTR

TXx. This again reinforces the enhanced nighttime warming in comparison with daytime.

3.1.4 Comparison of warm and cold extremes

We also compare the relative magnitudes of trends in warm versus cold indices, and some results are shown in Table 4. For TX90 versus TX10, 72% of stations have larger trend magnitudes in TX90, and the regional trend in TX90 (0.62 days/decade) is slightly more than 1.3 times that of TX10 (−0.47 days/decade). For TN90 versus TN10, the regional trend in TN10 (−2.06 days/decade) is of greater magnitude than that of TN90 (1.75 days/decade), about 60% of stations having higher trend magnitudes in TN10 than in TN90. This means that during the day there is a tendency towards increased inter-diurnal variability. For TXx and TXn, however, the regional trend in TXn (0.35°C/decade) is much higher than in TXx (0.07°C/decade), and roughly 80% of stations show larger trends in TXn. TXn (which occurs in winter) warms faster than TXx (which occurs in winter) due to the rapid warming in winter, suggesting decreased daytime inter-diurnal variability when extremes are examined, in contradiction with the daytime percentile analysis. The regional trend in TNn (0.63°C/decade) is more than three times than that of TNx (0.21°C/decade) in agreement with the percentile analysis. At individual stations, about 93% of stations have greater trend magnitudes in TNn compared with TNx. In addition, changes in extremes based on daily minimum temperature (TN10 and TN90) are generally larger than changes in extremes based on daily maximum temperature (TX10 and TX90), and changes in minimum of daily minimum and maximum temperature (TNn and TXn) generally have higher trend magnitudes than that in maximum of daily minimum and maximum temperature (TNx and TXx).

In most cases, both cold and warm extremes have high correlations with the mean annual temperature, with correlation coefficients higher than 0.5 ($P < 0.05$), indicating that changes in temperature extremes can reflect general warming in China.

3.2 Precipitation (PRCPTOT, SDII, RX1day, RX5day, R95, CDD)

The spatial distributions of trends and the regional annual series of precipitation indices are shown in Figs. 9 and 10. As was the case for temperature, the regional trends for precipitation indices are listed in Table 2. Compared with the other studies, the precipitation indices have large variations (Table 5).

In a majority of cases, most precipitation indices suggest that both the amount and the intensity of precipitation are increasing. For example, 56% of stations have increasing trends in annual total precipitation (PRCPTOT), mostly occurring in the southeastern, southwestern and northwestern China. The 44% of stations with decreasing trends are situated in northeastern and middle China. For SDII, RX1day, RX5day and R95, the proportion of stations with positive trends for these indices is 57, 58, 53 and 44%, respectively, and the proportion of stations with negative trends for these indices is 29, 42, 47 and 23%, respectively. Thus, there is a tendency towards positive trends dominating, consistent with the intensification of the hydrological cycle in China. Stations in southern and northwestern China have larger trend magnitudes while stations in northern and northeastern China have lower trend magnitudes, which is accordance with the spatial distribution of PRCPTOT trends. Changes in CDD further reinforce this pattern, with only 34% of stations having an increasing trend (mostly in southern China) and 50% of stations (mainly in northern China) having decreasing trends in CDD.

For China as a whole, the trend in PRCPTOT is weak and non-significant, and shows an increase (3.21 mm/decade) consistent with other precipitation indices. Most of the change occurred during the late 1980s and 1990s. Four other regional indices also show increasing trends: average wet days precipitation (SDII), maximum 1-day precipitation (RX1day), maximum 5-day precipitation (RX5day) and total precipitation on extreme wet days (R95), although only R95 shows a statistically significant increasing trend (4.06 mm/decade).

The number of consecutive dry days (CDD) has decreased, and the correlations between CDD and other indices are quite weak. The regional trend for CDD is −1.22 days/decade. Compared with other studies, the precipitation indices have large variations (Table 5). Comparing the behavior of different precipitation indices (Table 6C), PRCPTOT has strong correlations with most other indices, indicating that annual total precipitation is well correlated with precipitation extreme.

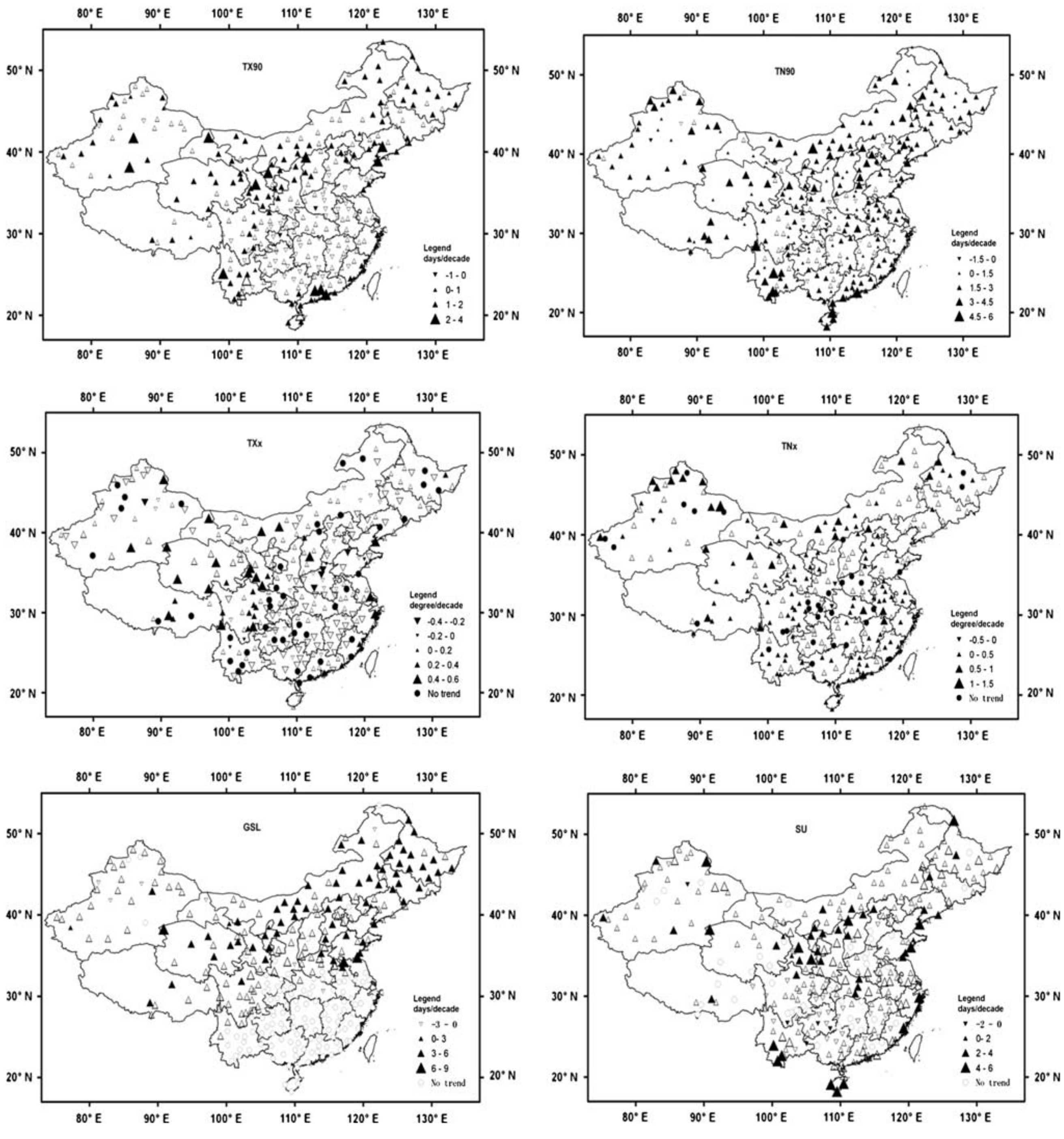

Fig. 7 Same as Fig. 3 but for warm extremes (TX90, TN90, TXx, TNx, GSL and SU)

3.3 Changes in large scale atmospheric circulation (wind field, geopotential height, water vapor flux, air temperature)

To investigate the role of circulation change in the trends discussed above, we created circulation composite maps from NCEP/NCAR reanalysis (see Sect. 2.5) in summer and winter for the two halves of the data period (1961–1982 and 1983–2003), and subtract one from the other. The selected region has the domain of 0°–70°N and 40°−170°E.

Figure 11 shows the mean difference of wind vectors and geopotential height at 500 hPa between 1983–2003 and 1961–1982 in summer (June, July, August, top plot) and winter (December, January, February, bottom plot). Enhanced anticyclonic circulation has developed over the Eurasian continent, centered on Mongolia and Lake Baikal.

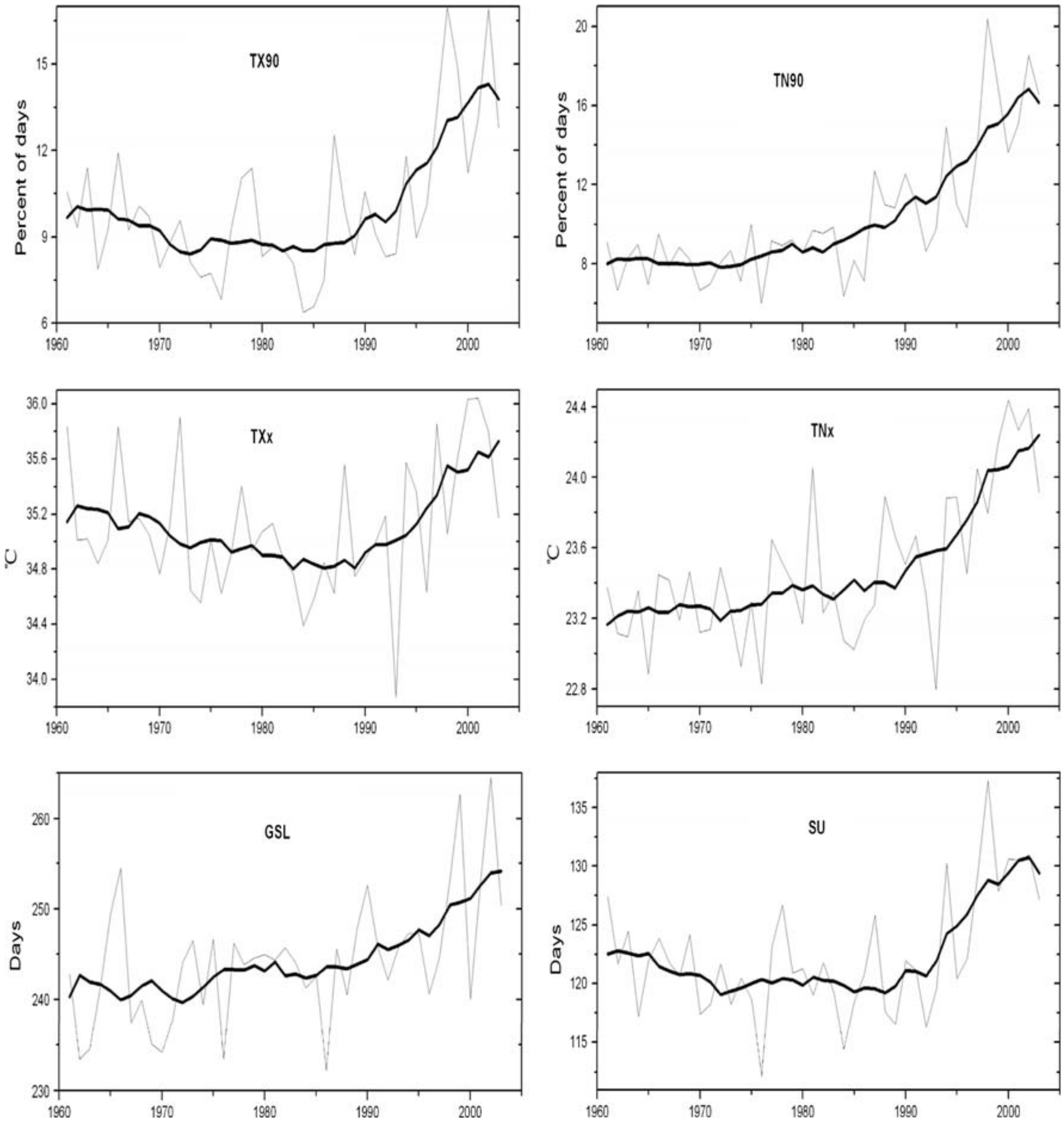

Fig. 8 Same as Fig. 4 but for warm indices

This is also shown on the geopotential height composite, the largest differences (approximately 27 gpm) occurring near Lake Baikal (Fig. 11 top plot). An anomalous anticyclonic circulation has also developed in the western Pacific near 25°N and 150°E (Wang and Zhou 2005), and enhanced cyclonic activity over eastern Europe (focused near 40°N and 40°E). The enhanced high pressure pattern over the Eurasian continent, suggests a weaker eastern Asian summer monsoon during 1983–2003 as compared to 1961–1982. The northeasterly wind in northern and eastern China has strengthened, and in turn weakened the northern and eastern extent of the westerly jet stream and any southwesterly flow from the ocean. This may explain the decreasing trend in precipitation in northern and eastern China, because of the difficulty that the monsoon would have in penetrating into that region (Xu 2006). Thus in summer, the increasing northeasterly wind tendency over central and eastern China is weakening the southwesterly summer monsoon, limiting its northward extension, and causing a longer East Asian rainy season in the Yangtze River basin but a shorter rainy season in northern China. This would explain why the annual mean precipitation and extreme precipitation events have consistently decreased in northern China but increased in the middle and lower reaches of the Yangtze River and in southern China (Wang and Zhou 2005; Zhang et al. 2008). The increased geopotential height over Mongolia is consistent with rapid warming (Fig. 12 top plot). This flow pattern will tend to

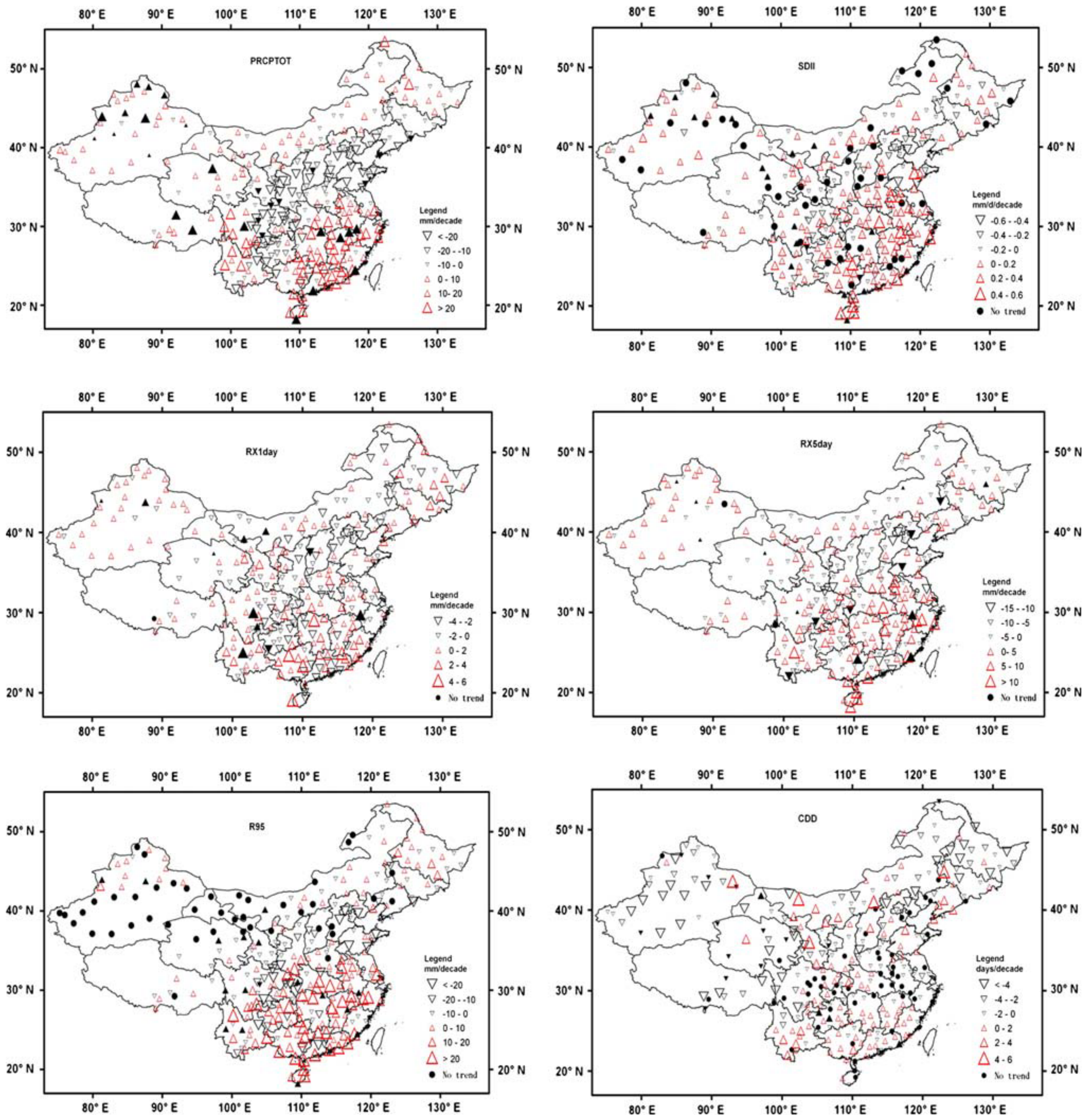

Fig. 9 Same as Fig. 3 but for precipitation indices (PRCPTOT, SDII, RX1day, RX5day, R95 and CDD)

prevent any northward transportation of water vapor flux, and moisture will stay longer in the Yangtze River basin as a result, increasing precipitation there (Zhang et al. 2008). Changes in mean water vapor flux and temperature at 500 hPa are shown in Fig. 12 (top plot) and strangely most of China has shown a decrease. This does not fit in well with the above scenario of change.

In winter, both an enhanced anticyclonic circulation centered on Mongolia (focused near 45°N and 110°E) and an anomalous cyclonic circulation near 60°N and 55°E have developed over the Eurasian continent. This is also shown on the geopotential height composite (Fig. 11 bottom plot). The differences between anticyclonic circulation and cyclonic circulation enhanced over the Eurasian continent have been strengthened, suggesting an enhanced westerly during 1983–2003 as compared to 1961–1982. The southwesterly wind in northern Mongolia has been strengthened, which in turn weakens the southern extent of

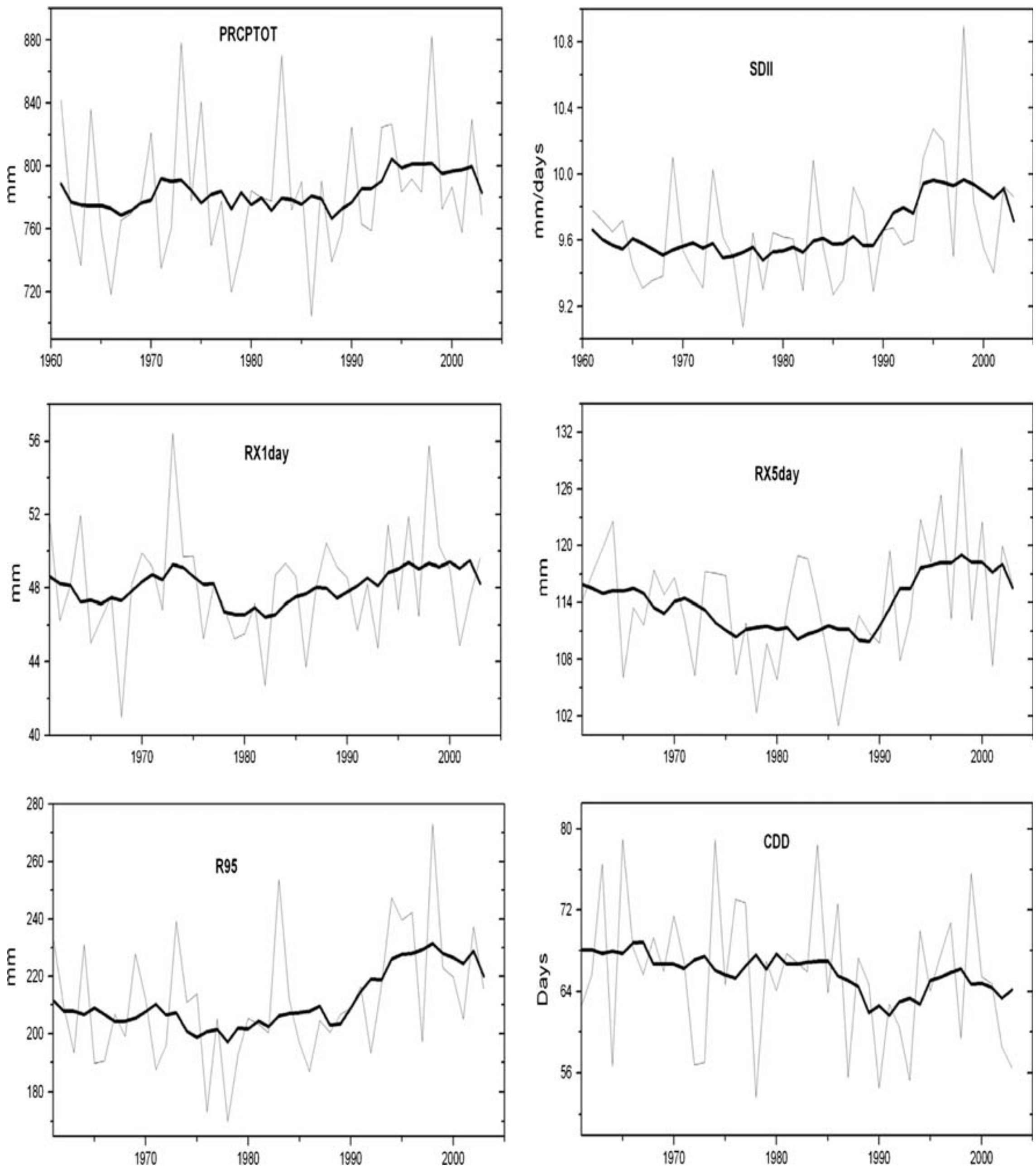

Fig. 10 Same as Fig. 4 but for precipitation indices

winter monsoon, limited its southward extension and decreased incursions of colder air. This would explain why the cold temperature extremes events have consistently decreased in northern China, which is consistent with rapid warming in the region in winter (Fig. 12 bottom plot).

4 Discussion and conclusions

We have examined the spatial and temporal distribution of trends in climate extremes for 303 stations in China over the period 1961–2003. We selected 12 indices of extreme temperature and six of extreme precipitation developed by the joint CC1/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices. All the temperature-based indices show patterns consistent with a general warming trend (the annual mean temperature has warmed by 0.27°C/decade) and these changes are consistent with previous studies in other parts of the world (Alexander et al. 2006; Brown 2008; Frich et al. 2002).

For the majority of stations, significant increases in warm nights/days and significant decreases in cold nights/

Table 6 Correlation coefficients of temperature (A for cold extremes and B for warm extremes) and precipitation indices (C) during 1961–2003 in China

	Tmean	TX10	TN10	TXn	TNn	FD
(A)						
T_{mean}	1					
TX10	−0.71**	1				
TN10	−0.88**	0.66**	1			
TXn	0.55**	−0.63**	−0.53**	1		
TNn	0.66**	−0.42**	−0.69**	0.68**	1	
FD	−0.95**	0.62**	0.89**	−0.44**	−0.69**	1

	Tmean	TX90	TN90	TXx	TNx	GSL	SU
(B)							
T_{mean}	1						
TX90	0.74**	1					
TN90	0.92**	0.84**	1				
TXx	0.38*	0.57**	0.39	1			
TNx	0.78**	0.70**	0.82**	0.63**	1		
GSL	0.61**	0.44**	0.62**	0.17	0.44**	1	
SU	0.71**	0.85**	0.78**	0.50**	0.64**	0.31*	1

	PRCPTOT	SDII	RX1day	RX5day	R95	CDD
(C)						
PRCPTOT	1					
SDII	0.61**	1				
RX1day	0.50**	0.63**	1			
RX5day	0.56**	0.61**	0.85**	1		
R95	0.81**	0.86**	0.78**		1	
CDD	−0.36*	−0.23	−0.10	−0.03	−0.23	1

The mean annual temperature (T_{mean}) is on the basis of Wang and Gong (2000)

** Significant at the 0.01 level, * significant at the 0.05 level

days are observed during 1961–2003. Moreover, the trend magnitudes in cold/warm nights are larger than those in cold/warm days. Thus trends in minimum temperature extremes are more rapid than trends in maximum temperature extremes, consistent with a long-term decrease in DTR. However, the decline in DTR has been small since 1990 because daily maxima and minima increased at a similar pace during the 1990s (Liu et al. 2004).

Cold extremes, which predominantly occur in winter, appear to be warming faster than warm extremes (Aguilar 2009), and winter temperatures are warming more quickly than summer temperatures (IPCC 2007). This makes physical sense in that the amount of water vapor in the air in winter is frequently less than in summer so any fractional change in greenhouse gas radiative forcing will be enhanced (Aguilar 2009). The warming climate has caused the number of frost days to decrease significantly while the growing season length and number of summer days have increased significantly. The annual extreme lowest temperature (TNn) shows the largest trend magnitude of all annual extremes.

There are variations within China in the strength of the temperature changes discussed above. Although there is much small-scale variability, stations in the north-east, north and north-west of China tend to have larger trend magnitudes and stations in the south the smallest trend magnitudes. This is in accordance with other studies which show the most pronounced warming in northeastern China (Liu et al. 2004), and studies using NCEP/NCAR reanalysis data have also confirmed this.

Compared with other regions in the world (Alexander et al. 2006; IPCC 2007), patterns in China are broadly similar, but there are some differences. Table 5 lists trend magnitudes for similar indices for eight other studies. Time periods differ slightly but broadly cover the second half of the twentieth century. While changes in warm/cold nights are broadly similar to other regions, the changes in warm/cold days are much less significant. This is true both for frequencies and for annual extremes. The decrease in DTR is stronger in China than reported in all other regions (apart from the Tibetan plateau study—which is a subset of this dataset anyway). This may well be associated with rapid urbanization, increased aerosol loading and/or other land-use change. China has experienced rapid urbanization and dramatic economic growth since the 1970s, and many studies have shown this to have had a strong effect on regional climate (Hua et al. 2008; Jones et al. 2008; Ren et al. 2008; Zhou et al. 2004). However the extent to which urbanization accounts for surface warming in China is a matter for debate. On the other hand, urban-related warming over China is quantified as about 0.1°C/decade over the period 1951–2004 (Jones et al. 2008). Other authors found strong effects of urbanization in large cities with urban warming being as much as 0.16°C/decade for subsets of stations (Ren et al. 2008). After any urban warming bias in a regional average temperature anomaly series was corrected, the rate of increase of annual mean temperature for China was brought down from 0.29°C/decade to 0.18°C/decade (Ren et al. 2008). These case studies indicate the importance of paying attention to urban warming when examining long-term mean temperatures series in China. The effect to which this influences extremes, in a preferential way (perhaps minima more than maxima, and thus DTR), needs further study. We have not made any assessments for urbanization bias in this paper and further work is required to address this issue.

Compared with changes in temperature extremes, the trends in precipitation indices are more ambiguous. For China as a whole, most indices show a wetting, with regional annual total precipitation increasing. The other precipitation indices, including average wet day precipitation, maximum

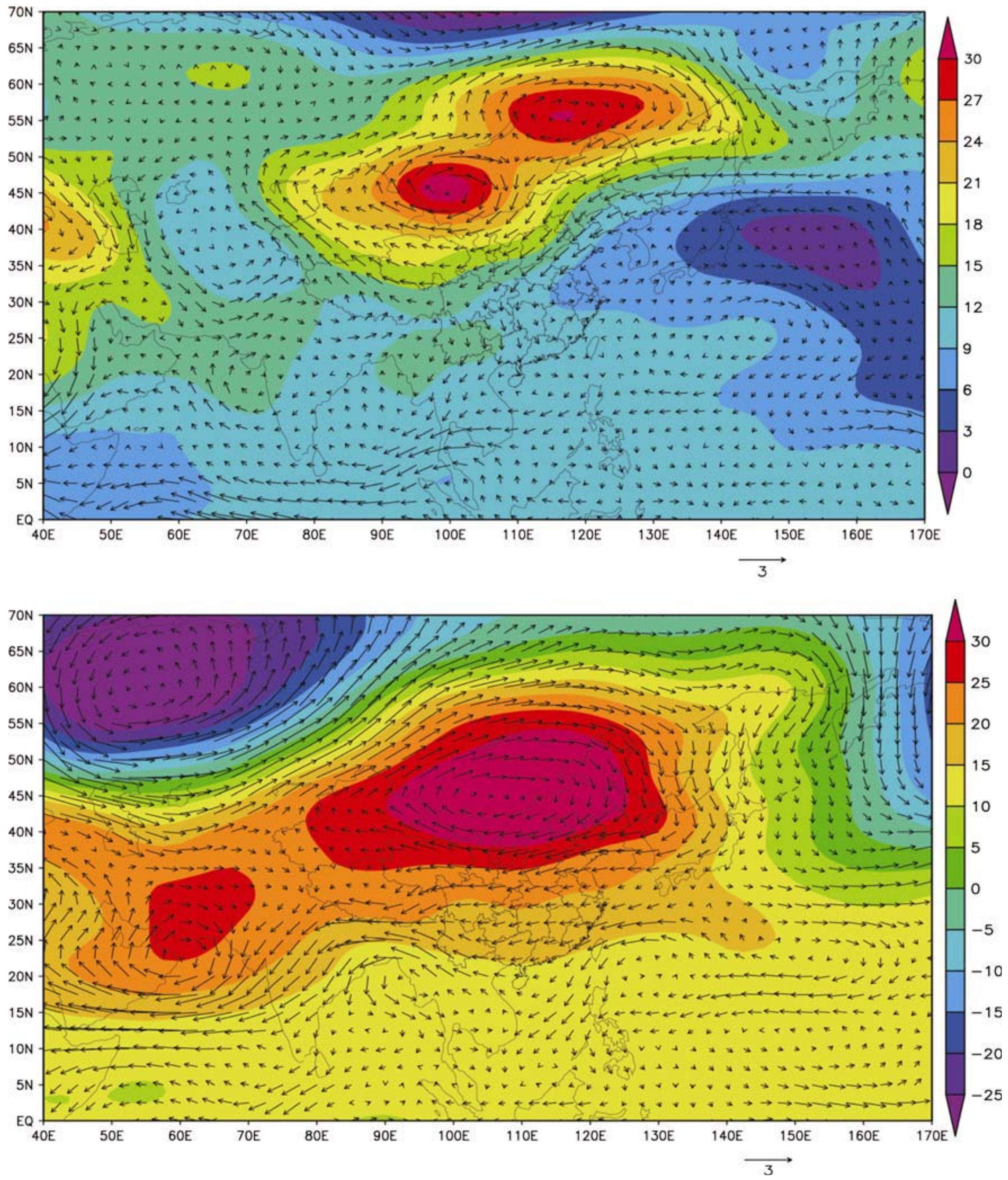

Fig. 11 Difference of wind speed and geopotential height at 500 hPa in summer (*top plot*) and winter (*bottom plot*) between 1983–2003 and 1961–1982

1-day precipitation, maximum 5-day precipitation and heavy precipitation days, are positively correlated with annual total precipitation, and exhibit a regional increasing trend during 1961–2003. Consecutive dry days are negatively correlated with annual total precipitation and show a decrease.

Within China there are large differences with general drying in the north and wetting in the south (the latter dominates the regional signal). For annual total precipitation, most of the declining trends occur in the Yellow River basin and in northern China Stations in southern China tend to have the larger positive trend magnitudes for all precipitation indices based on intensity. Unusually though, the strongest negative trends in consecutive dry days are in northern China, because values of CDD are typically higher in the drier climates of northern and western China.

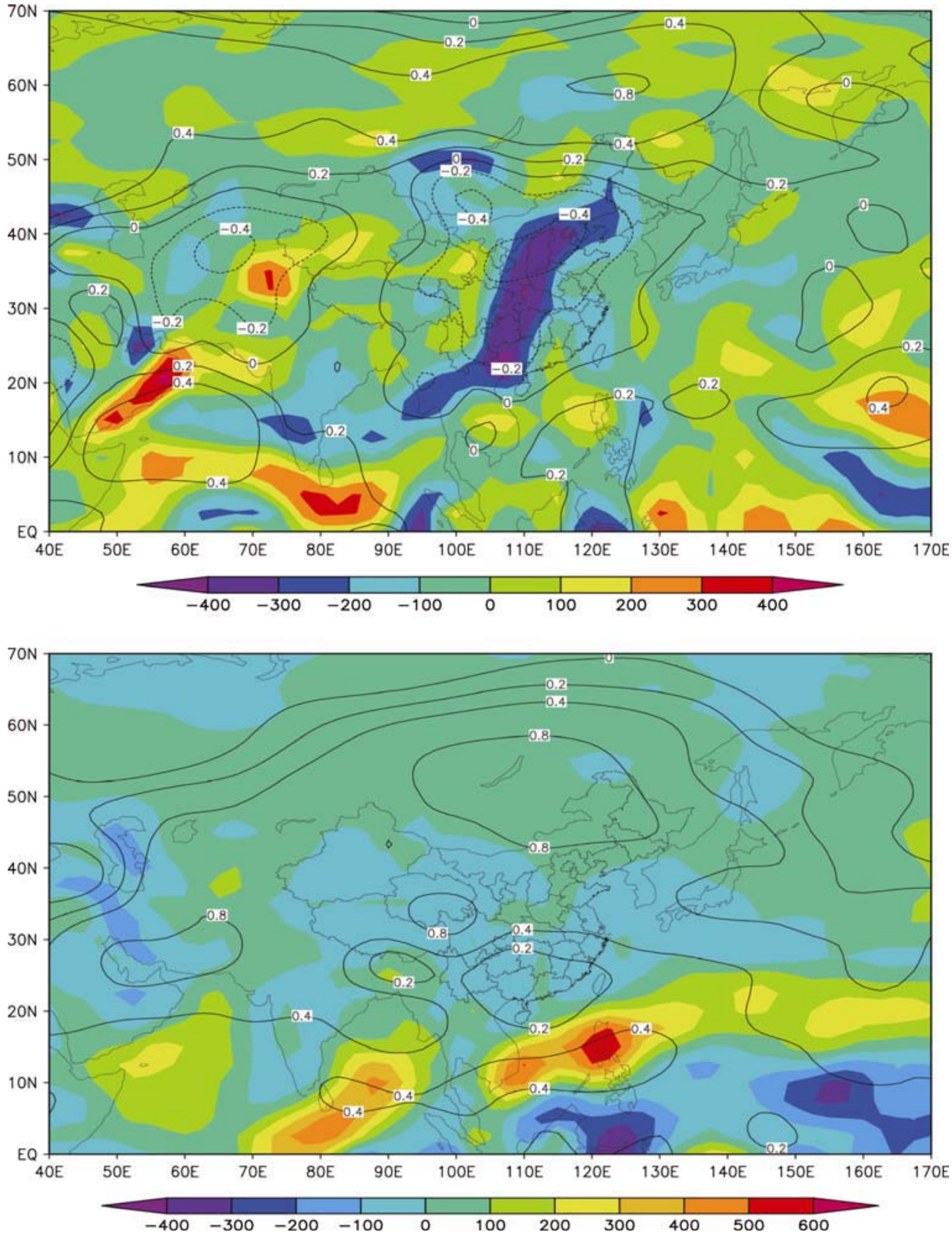

Fig. 12 Difference of water vapor flux and air temperature at 500 hPa in summer (*top plot*) and winter (*bottom plot*) between 1983–2003 and 1961–1982

This means that precipitation may become more frequent in northern regions, even though it is not becoming heavier.

Precipitation in China mostly occurs during the summer monsoon and since the 1970s, the Asian monsoon circulation is thought to have weakened (Wang 2001). This tends to produce heavier precipitation in southern China but less moisture transport to regions further north. Warmer waters in the Western Pacific and South China Sea tend to enhance the subtropical high that stalls the summer rain belt for long periods over southern China (Xu 2006). Thus the decline of the Asian monsoonal circulation strength has contributed to severe rainfall anomalies over recent decades, including floods in southern China, and droughts in the north (Ding 2005; Gong and Wang 2000; Xu 2006). Increasing geopotential height over Mongolia and northern China, the South China Sea and west Pacific regions has also prevented the northward propagation of the vapor flux, increasing summer precipitation in the middle and lower Yangtze River basin (Wang and Zhou 2005; Zhang et al. 2008). In winter, the southwesterly wind in northern Mongolia has strengthened, which in turn weakens the southern extent of the winter monsoon, limiting its southward extension. This would explain why the cold temperature extremes events have greatly decreased in northern China,

The reasons for such a decline in monsoon strength are widely debated. They may relate to increased air pollution, especially sulfate aerosols, over south-central China. Several model simulations suggest that anthropogenic air pollution may have contributed to the decline of the East Asian summer monsoon (Xu 2006). However it is also know that climate warming would increase atmospheric moisture advection from the oceans because evapotranspiration would increase preferentially over the ocean, altering the distribution of precipitation (IPCC 2007). Thus many models disagree about the impacts of greenhouse warming on rainfall changes in China (Gong and Wang 2000).

We have not assessed the reasons for the changes we observed in this study but plan to do so in subsequent work. In particular assessment of changes in extremes in climate model simulations (as well as observations) is required to see how anthropogenic emissions are expected to influence extremes. We should also look at relationships between changes in temperature extremes and attendant changes in precipitation extremes, since any enhancement of the hydrological cycle under warmer temperatures should mean that the two types of extreme are not necessarily independent.

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