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Long-term trends in daily temperature extremes over Mongolia

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ABSTRACT

Various indices have been used to investigate recent changes in the annual frequencies of extreme temperature events in Mongolia. A high-quality daily temperature dataset including 53 station records was used to determine trends from 1961 to 2010. The Climdex1.0 software was used to calculate 11 extreme temperature indices for this study. The results showed significant changes in important temperature indices over the study period, especially in the Gobi Mongolia. The analysis showed that an apparent increase in summer days was observed, while an appreciable decrease in frost days was observed. The maximum values of daily maximum temperature (TXx) and daily minimum temperature (TNx) and the minimum values of T_{max} (TXn) and T_{min} (TNn) tended to increase. However, for TXx and TNx, this increasing trend was mainly observed in the Gobi Mongolia, while for TXn and TNn, this increasing trend was observed over the entire country. A significant reduction at a rate of -0.6 d decade^{-1} (-1.0 d decade^{-1}) occurred for cool nights (days), and a significant increase at a rate of 2.8 d decade^{-1} (3.1 d decade^{-1}) occurred for warm nights (days). The reduction of cool nights and cool days occurred over four seasons, while the increase of warm days and warm nights occurred mainly in summer.

Contents

1. Introduction

It is widely known that enhanced atmospheric greenhouse gases contributed to an increase in global mean surface temperature (IPCC, 2007; Alexander et al., 2007). Human activities and the environment are greatly affected by extreme climatic events, such as heat waves, floods and droughts (Moberg and Jones, 2005).

Variations of mean and extreme values of climatic variables as well as the shape of their statistical distribution can be used to characterize climate change. Even though knowledge of climate extremes is required to develop and manage emergency situations, the study of climate change using climate extremes is rather complex. A set of suitable indices describing the extremes of the climate variables can be used for the study of climate change. Mongolia has a highly continental climate with long, dry and very

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cold winters and hot summers. Consequently, four seasons in Mongolia are very distinctive and months within each of them are quite distinctive (Nandintsetseg et al., 2007). It is widely known that Mongolia has the landlocked geography, dispersed and sparse population and harsh temperate climate and due to these conditions Mongolia is very vulnerable to immensely changing weather conditions.

Today, unlike other developing countries, Mongolia has specific concerns related to unique geographical and climatic conditions of Mongolia. Economy and ecosystems in Mongolia are greatly affected by the risk of climate change and/or extreme climatic events such as drought and *dzud* (a Mongolian term for a severe winter). Weather stations data from 1961 to 2001 have been used for climate extreme indices change study since 2003 (Dagvadorj et al., 2009).

A suite of indices through the coordination of the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) working under the joint WMO Commission for Climatology (CCl)/World Climate Research Programme (WCRP) Climate Variability and Predictability (CLIVAR) project (Peterson et al., 2001) have been developed, calculated, and analyzed to rationalize and standardize the expressions for extreme weather events.

The purpose of this study was to investigate changes in temperature extreme events through the long-term trend in the frequency of extreme temperature events in Mongolia using 11 extreme temperature indices.

2. Data and methodology

2.1. Data and quality control

Mongolia is located in the Northern Hemisphere (approximately, 43–52°N and 85–120°N) at an average altitude of 1500 m, surrounded by high mountain ranges that are blocking the wet winds.

The National Agency for Meteorology and Environmental Monitoring (NAMEM) of Mongolia, a governmental agency, operates the meteorological observation network of Mongolia. The Persona-win software has been used for the data quality control. Before the climate data from the meteorological observation network of Mongolia are archived by NAMEN, these data are collected and quality controlled (Namkhajantsan et al., 2006).

Currently, 130 meteorological stations were operated by NAMEM (Battur, 2010). Fifty three meteorological stations, where daily maximum and minimum surface air temperature data between 1961 and 2010 are available from, were selected for this study. These collected data were also quality controlled by a data quality control procedure in the RClimDex package before the extreme indices were calculated by the RClimDex package (Zhang and Yang, 2004). This data quality control procedure is substantially given by Zhang and Yang (2004). It should be noted that an observation was considered as an outlier if it is more than four standard deviations from the mean.

Mongolia is geographically divided into four regions: Western Mongolian (WM, high mountain region), Central Mongolian (CM, forest region), Eastern Mongolian (EM, steppe region), and Southern Mongolian (SM, Gobi desert region). The locations of 53 meteorological stations are depicted in Fig. 1.

A regression based homogeneity test of the RHtestsV3 software (Wang and Feng, 2010) was used to detect significant artificial shifts. Quality control of daily temperature was conducted and its homogeneity was also tested before the calculation of temperature extreme indices. These indices were computed for each season (standard seasons) and year and for each station where less than 2% of data were missing. The trends of the seasonal time series of all indices have been analyzed for each station. The magnitude of seasonal trends was estimated using the linear regression method, while its statistical significance was evaluated using the Kendall–Tau test. The method of Kendall's τ statistics was proposed by Dietz and Killeen (1981). A monotone trend based on Kendall's τ was further extended to statistical analysis of seasonal variability (Hirsch et al., 1982). Kendall's statistic S is computed as follows:

$$S=\sum_{i=1}^{n-1}\sum_{k=i+1}^{n}\operatorname{sgn}(x_k-x_i)$$

$$\operatorname{var}(S)=\frac{n(n-1)(2n+5)-\sum_{i=1}^{m}e_i(e_i-1)(2e_i+5)}{18} \quad (1)$$

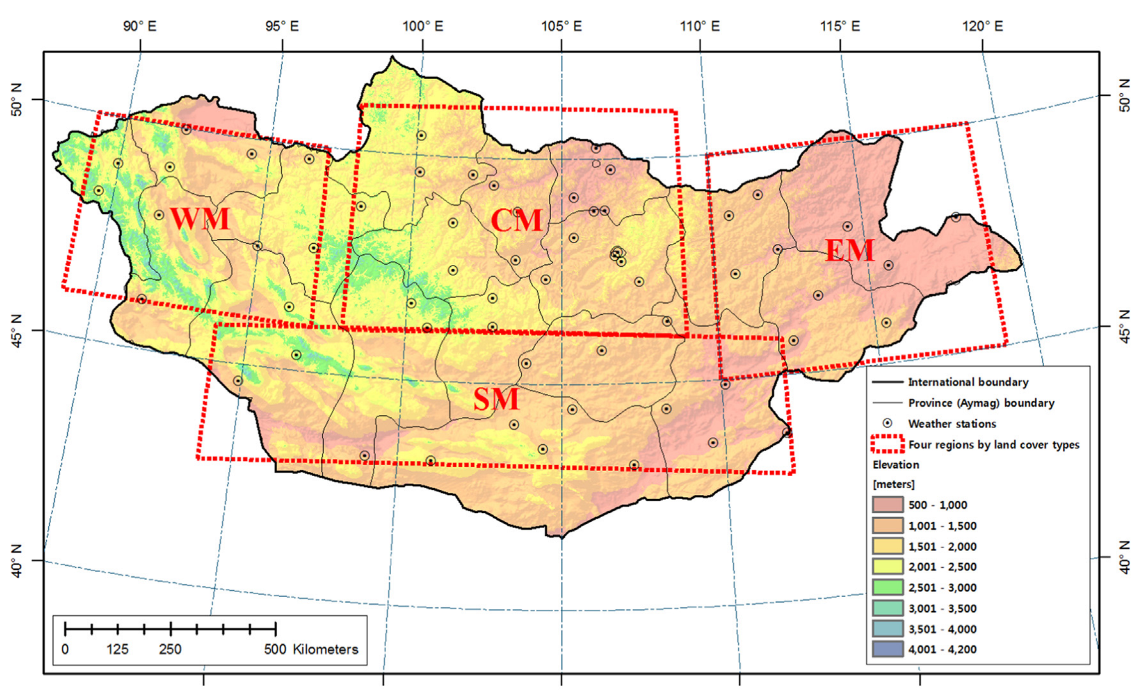

Fig. 1. Map of Mongolia with the locations of the stations.

where x_k and x_i are sequential data values, m is the number of tied groups, n is the length of the data set, e_i is the size of the ith tied group, sgn(θ) is a sign function extracting the sign of θ. Sgn(θ) can be given as follows:

$$\mathrm{sgn}(\theta) = 1 \quad \theta > 0$$
$$\mathrm{sgn}(\theta) = 0 \quad \theta = 0$$
$$\mathrm{sgn}(\theta) = -1 \quad \theta < 0$$

In order to detect trends within the time series, the slopes of the annual trends and their statistical significances to the climate indices were calculated based on the non-parametric Mann–Kendall test and the least square method. The Mann–Kendall test static Z_c is estimated as follows:

$$z_c = \frac{S-1}{\sqrt{\mathrm{var}(S)}}, \quad S > 0$$
$$z_c = \frac{S-1}{\sqrt{\mathrm{var}(S)}}, \quad S = 0$$
$$z_c = \frac{S-1}{\sqrt{\mathrm{var}(S)}}, \quad S < 0$$

Table 1
Definition of extreme temperature indices used in this study.

Abbreviation name		Description	Unit
Absolute indices			
FD0	Frost days	Year Tn (lowest temperature of the day) < 0 °C	Day
SU25	Summer days	Year Tx (highest temperature of the day) > 25 °C	Day
Extreme value indices			
DTR	Diurnal temperature range	Monthly mean value of difference between TX and TN	°C
TXx	Maximum TX	Monthly maximum value of TX	°C
TNx	Maximum TN	Monthly minimum value of TX	°C
TXn	Minimum TX	Monthly maximum value of TN	°C
TNn	Minimum TN	Monthly minimum value of TN	°C
Relative indices			
TN10p	Cool nights	Percentage of days when TN < 10th percentile	Day
TX10p	Cool days	Percentage of days when TX < 10th percentile	Day
TN90p	Warm nights	Percentage of days when TN > 90th percentile	Day
TX90p	Warm days	Percentage of days when TX > 90th percentile	Day

Table 2
Annual linear trends of the extreme temperature indices in Mongolia form the year 1961 to the year 2010.

Index	Western region	Central region	Eastern region	Gobi region	Whole country
FD0	**−3.7 (−6.2 to −1.5)**	**−4.2 (−6.4 to 0.6)**	**−2.5 (−3.6 to −0.9)**	**−3.7 (−4.4 to −2.3)**	**−0.38 (−0.64 to 0.06)**
SU25	**5.0 (1.2 to 5.4)**	**6.4 (1.4 to 9.0)**	**4.2 (1.5 to 6.4)**	**5.6 (1.7 to 7.0)**	**0.63 (0.12 to 0.90)**
DTR	**−0.1 (−0.3 to 0.1)**	−0.1 (−0.4 to 0.5)	**−0.3 (−2.2 to 0.2)**	**−0.1 (−0.4 to 0.0)**	−0.01 (−0.22 to 0.05)
TXx	**0.8 (0.1 to 0.7)**	**1.0 (0.3 to 1.2)**	0.3 (0.1 to 0.5)	**0.5 (0.2 to 0.7)**	**0.08 (0.01 to 0.12)**
TNx	**0.8 (0.4 to 1.1)**	**0.9 (0.04 to 0.11)**	**0.4 (0.3 to 0.7)**	**0.7 (0.4 to 0.8)**	**0.08 (0.03 to 0.11)**
TXn	0.1 (0.0 to 0.8)	0.0 (−0.8 to 0.8)	0.1 (−0.4 to 0.9)	−0.3 (−0.2 to 0.6)	−0.01 (−0.08 to 0.09)
TNn	0.2 (0.2 to 1.0)	0.1 (−0.7 to 1.0)	0.2 (−0.05 to 0.11)	0.1 (0.0 to 0.8)	0.01 (−0.07 to 0.11)
TN10p	**−1.7 (−0.28 to −0.09)**	**−1.5 (−3.0 to 0.9)**	**−1.4 (−2.9 to 0.4)**	**−1.6 (−2.9 to −1.4)**	**−0.14 (−0.30 to 0.09)**
TX10p	**−1.0 (−0.17 to −0.08)**	**−1.0 (−1.5 to −0.5)**	−0.5 (−1.1 to 0.2)	**−1.0 (−1.3 to −0.5)**	**−0.09 (−0.17 to 0.02)**
TN90p	**2.8 (0.14 to 0.45)**	**2.8 (0.7 to 3.6)**	**1.9 (1.2 to 2.6)**	**3.2 (1.7 to 5.7)**	**0.28 (0.07 to 0.57)**
TX90p	**2.7 (0.9 to 2.9)**	**2.5 (1.2 to 2.7)**	**1.7 (1.1 to 1.9)**	**2.3 (0.9 to 2.7)**	**0.24 (0.09 to 0.29)**

Statistically significant results ($P > 0.05$) shown in bold.
Data given as d decade^{-1} and °C decade^{-1}.

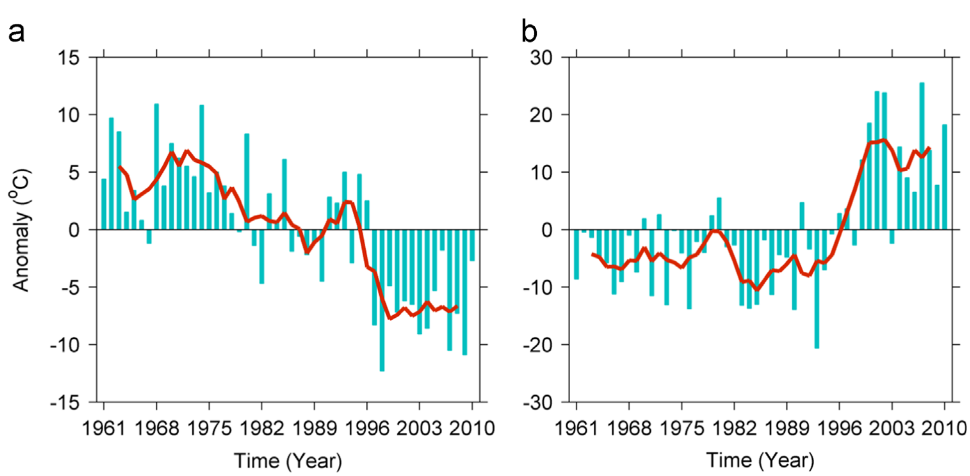

Fig. 2. Anomalies of the country-averaged annual (a) frost days (FD0) and (b) summer days (SU25) over Mongolia from 1961 to 2010. Anomalies are relative to the 1971–2000 mean values. The red curves show 5-years running means.

where Z_c is a standard normal variable. The null hypothesis (H_0) that standard normal variable Z_c is not statistically significant or no significant trend is accepted if $-Z_{1-p/2} \le Z_c \le Z_{1-p/2}$, where $\pm Z_{1-p/2}$ are the standard normal deviates and p is the significance level for the test. Positive Z_c shows increasing trends, while negative values of Z_c indicate decreasing trends (Xu et al., 2005).

2.2. Extreme temperature indices

In this study, we used the RClimdex software (version 1.0) developed by Zhang and Yang (2004). The RClimdex software can calculate the total of 27 indices including temperature and precipitation indices. However, only 11 indices derived from air temperature data were computed for this study (Table 1). The resulting series were analyzed through trends. The non-parametric Mann–Kendall test and the least square method were used to calculate the slopes of the annual trends and their statistical significances to climate indices. These slopes and statistical significances were then used to detect trends within the time series.

The 11 extreme temperature indices used in this study are summarized in Table 1. More detail information of their definitions can be found by Alexander et al. (2006). FD0 and SU25 respectively represent the annual counts of frost days (daily minimum temperatures ≤0 °C) and summer days (daily maximum temperature ≥25.0 °C). TXx, TNx, TXn, and TNn are the annual highest maximum temperature, highest minimum temperature, lowest maximum temperature, and lowest minimum temperature recorded every year, respectively. TN10p is an index measuring the percentage of time with daily minimum temperatures lower than the 10th percentile of minimum temperatures calculated for each calendar day (with reference to the climatological norm) using a running 5-day window. This is a measure of the percentage of unseasonably low-temperature nights (cool nights) in a year. Similarly, TX10p is an index showing the percentage of unseasonably low-temperature days (cool days). TN90p and TX90p are indices corresponding to the percentage of unseasonably high-temperature nights (warm nights) and days (warm days) in a year, respectively. The percentile-based temperature indices that include exceedance rates of temperature smaller than the 10th percentile or larger than 90th percentile, as well as heat wave or cold spell related indices. Unlike absolute indices such as FD0 and SU25, relative indices may be most appropriate to assess changes in synoptic situations favorable for extreme temperatures (Zwiers et al., 2011).

3. Results

3.1. Trends in absolute extreme temperature indices

Table 2 shows the linear trends in extreme temperature indices for Mongolia. Linear trends have been used to analyze climate variability in Western, Central, Eastern, and Gobi regions of Mongolia for 50 years. This analysis revealed mainly positive trends in SU25, TXx, TNx, TX90p, and TN90p indices and negative trends in FD0, TX10p, and TN10p indices.

Fig. 2 displays the anomalies of time series curves of absolute indices (FD0 and SU25) in the entire country. Frost days (FD0) underwent a slight decrease from the year 1970 to the year 1987 and a rapid decline from the year 1993 to the year 2000 (Fig. 2a). Summer days (SU25) show negative anomalies, especially prior to 1995. A rapid increase from 1996 to 2002 can be observed (Fig. 2b). As shown in Fig. 3, frost days significantly declined across the whole country, and the decreasing trends for most of the stations were less than −2 d decade^{-1}. Summer days at most stations in Mongolia showed an increasing trend (Fig. 3b) and the most apparent increasing trends, greater than 8 d decade^{-1}.

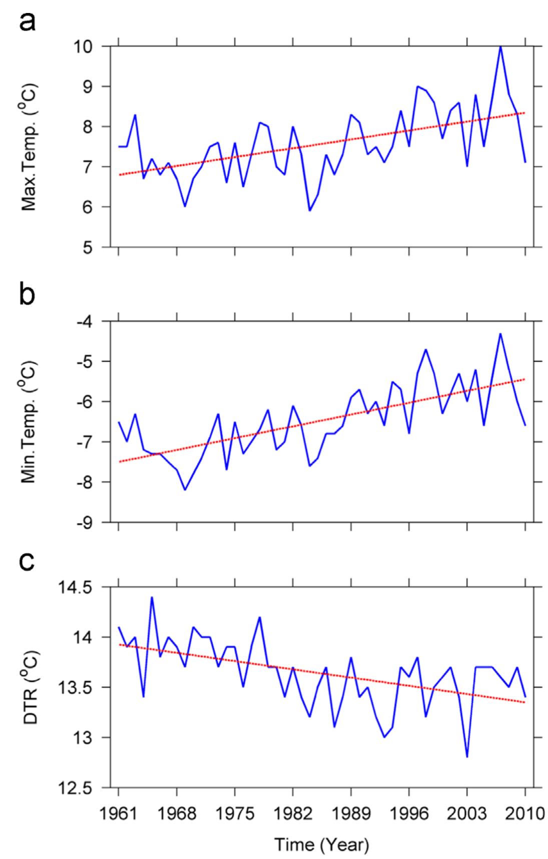

Fig. 4. Country-averaged annual mean (a) maximum temperature, (b) minimum temperature, and (c) diurnal temperature range (DTR) over Mongolia for the period 1961–2010. The red dotted lines show linear trends.

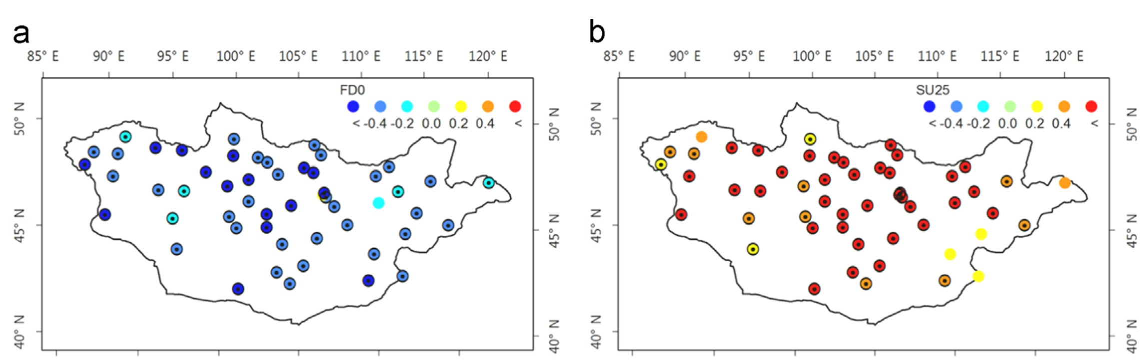

Fig. 3. Linear trends distribution in d decade^{-1} of (a) frost days (FD0) and (b) summer days (SU25) in Mongolia. The symbols (⊙) indicate significant at the 95% confidence level.

3.2. Trends in extreme value indices

Fig. 4 shows the time series of annual mean maximum and minimum temperatures and DTR in Mongolia for the study period. Both annual mean maximum and minimum temperatures showed increasing trends. Overall decrease in a linear trend of DTR was observed for the entire country. This decreasing trend may be explained by considering the asymmetry of maximum and minimum temperature variations. DTR was linearly reduced by 0.4 °C in the country during the study period.

The areal averages of anomalies for annual maximum and minimum values of daily maximum temperatures (referred to as TXx and TXn respectively) are displayed in Fig. 5. Neither series shows a significant trend, though values are higher near the end of series. The long-term changes in the annual maximum (TNx) and minimum (TNn) values of daily minimum temperatures (Fig. 5a and c) are similar to those of TXx and TXn (Fig. 5b and d), but the trends of TNx and TNn are stronger than those of TXx and TXn. TXn and TNn have increased significantly since the year 1981, while TXx and TNx have increased rapidly since the year 1995. Significant upward trends in TXx and TNx occurred in Central Mongolia, while TXx underwent an obvious downward trend in the Gobi region. TXn and TNx increased significantly across the whole country, but TNx increased more strongly (Table 2).

3.3. Trends in relative extreme temperatures

A high degree of spatial coherence and widespread change was also evident in percentile-based temperature indices. The station-by-station estimated trends for the annual number of cool/warm nights and cool/warm days analyzed through TN10p/TN90p and TX10p/TX90p (daily minimum or maximum temperatures below its 10th percentile and above its 90th percentile) are displayed in Fig. 6. The percentile-based temperature indices are presented in d decade^{-1}. About 85% of the stations have statistically significant (5% level) decreases in cool nights (TN10p) and increases in warm nights (TN90p). The daytime trends for individual stations in cool days (TX10p) and warm days (TX90p) have the same signs as their nighttime counterparts, showing decreasing and increasing trends at approximately 92% of the stations. Spatial characteristics of trends of the relative extreme temperature indices are displayed in Fig. 6. Cool days significantly declined in Gobi Mongolia, and the areas with increasing trends were mainly in Eastern Mongolia (Fig. 6a).

Considering Mongolia as a whole, the annual number of warm nights and days (TN90p and TX90p) averaged from all 53 stations has significantly increased by 10 days and 12 days (Fig. 7c and d). Conversely, the annual number of cool nights and days (TN10p and TX10p) has decreased at the significant rates of –3.0 day. Cool days (nights) primarily showed positive anomalies before the year 1990, followed by a rapid decline (Fig. 7a and b). Warm days (nights) showed negative anomalies for most years before 1990, with a negative anomaly occurring in only 1 year during the last 15 years (Fig. 7c and d). More significant changes occurred for cool (warm) nights than for cool (warm) days.

As shown in Fig. 6b, for cool nights (TN10p), more significant decrease was observed in the country with most areas registering downward trends (approximately 1 d decade^{-1}). Especially, an even larger decrease was observed in Western Mongolia and some parts of central Mongolia (greater than 2 d decade^{-1}). For warm days (TX90p), increasing trends higher than 2 d decade^{-1} were

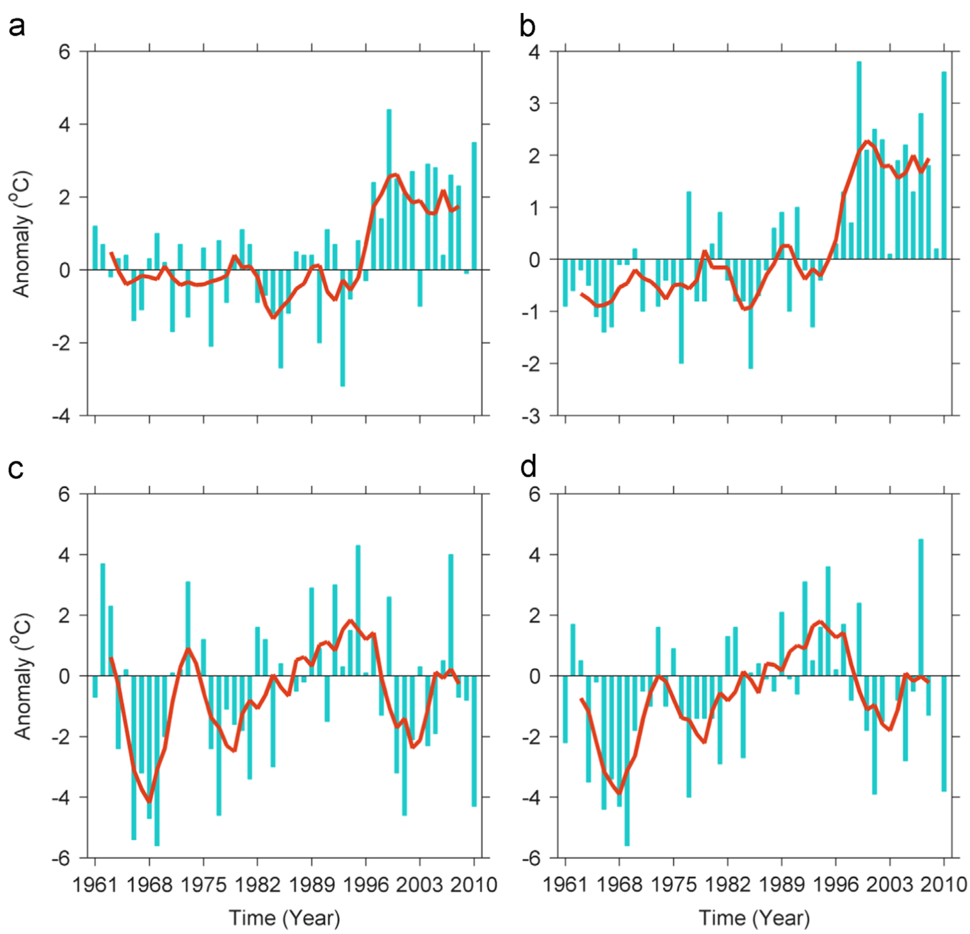

Fig. 5. Anomalies of the country-averaged annual (a) maximum T_{max} (TXx), (b) maximum T_{min} (TNx), (c) minimum T_{max} (TXn), and (d) minimum T_{min} (TNn) in Mongolia, from 1961–2010. The anomalies are relative to the mean values of 1971–2000. The red curves show 5-year running means.

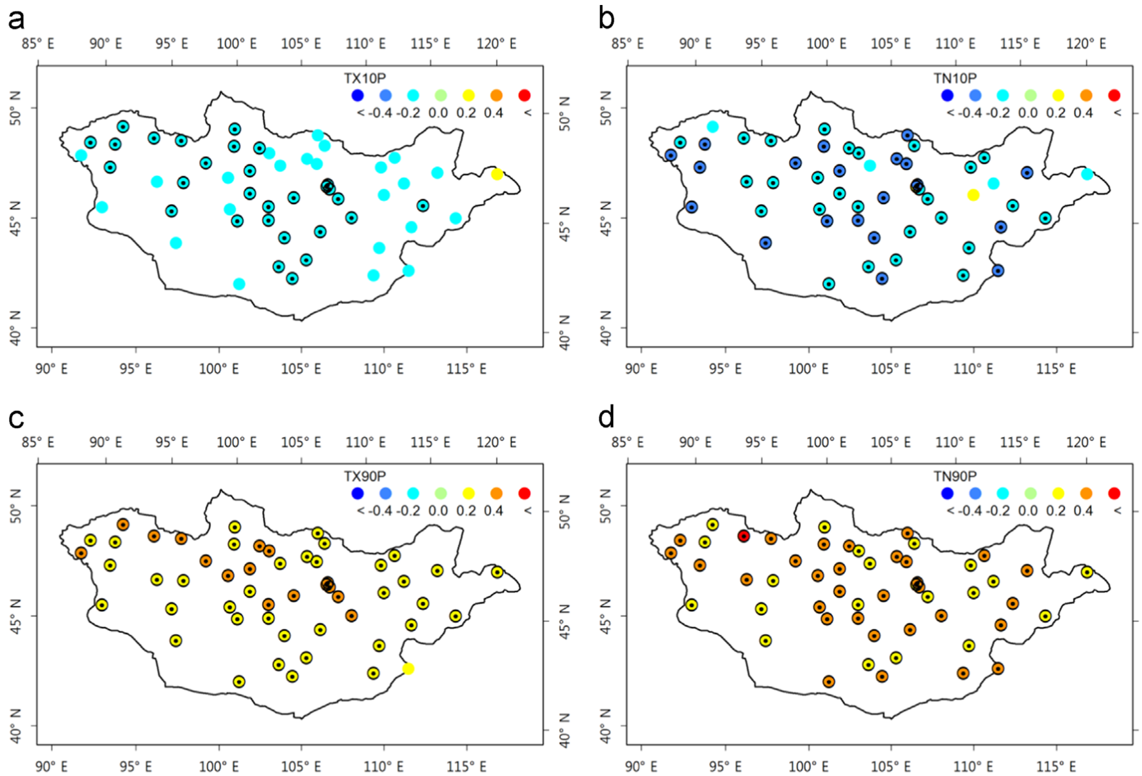

Fig. 6. Linear trends distribution in d decade^{-1} of (a) cool days (TX10p), (b) cool nights (TN10p), (c) warm days (TX90p), (c) warm nights (TN90p) in Mongolia. The symbols (⊙) indicate significant at the 95% confidence level.

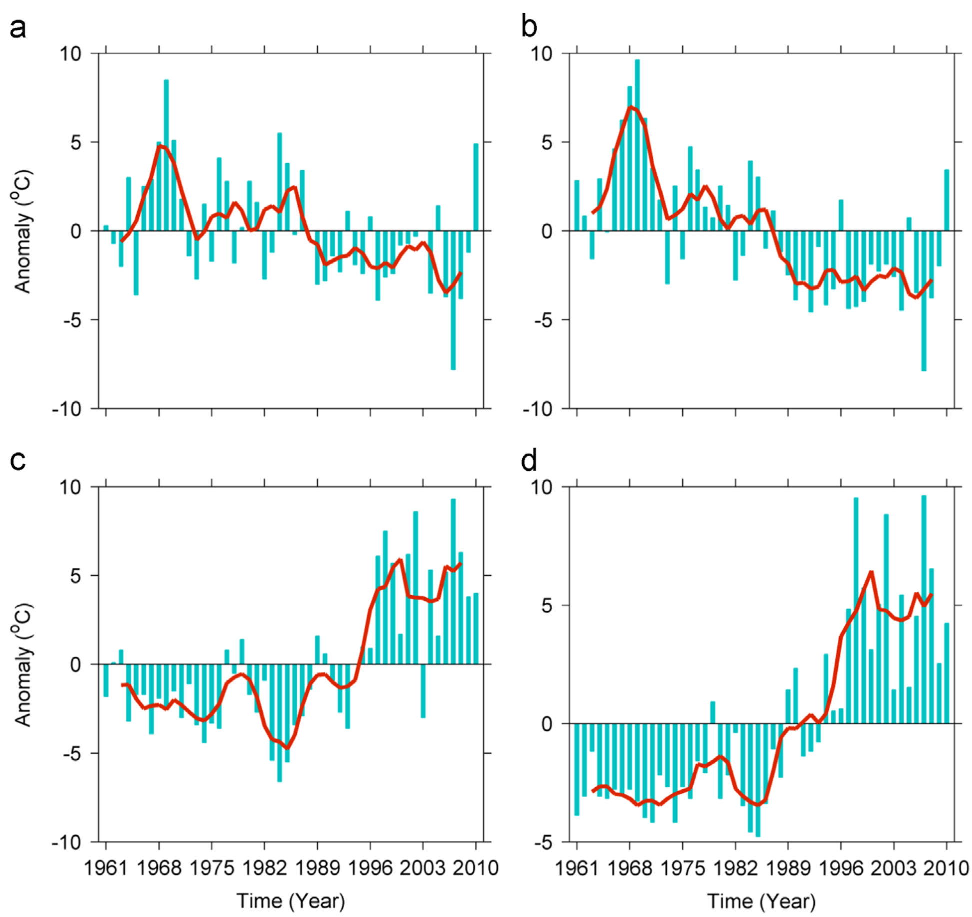

Fig. 7. Anomalies of the country-averaged (a) cool days (TX10p), (b) cool nights (TN10p), (c) warm days (TX90p), and (d) warm nights (TN90p) over Mongolia, from 1961–2010. The anomalies are relative to 1971–2000 mean values. The red curves show 5-years running means.

observed at mainly stations in the central region and the western Mongolia (Fig. 6c). However, for warm nights (TN90p), those higher than 2 d decade^{-1} were observed in most regions of Mongolia (Fig. 6d). The warm extreme indices have significantly increased, while the cold extreme indices have significantly decreased in the country during the study period. In addition, the indices related to minimum temperatures have changed larger than those related to maximum temperatures. The increase in warm extreme indices can be linked to the rapid warming in maximum temperature relative to minimum temperature. The trend analysis shows that the hot extreme values (e.g. TX90p, TN90p, TXx, and TNx) increase in the frequency rather than in cold extreme indices (e.g. TN10p, TX10p, TXn, TNn). Mongolian regions seem to be more sensitive to warming effect during summer time.

In examining the seasonal change (Table 3), the reduction of cool days/nights occurred in four seasons, and the highest change was observed in summer. The most significant increase in frequencies of warm days/nights occurred in summer. Cool winter nights/days and warm summer days/nights are good indicators for cold periods and heat waves, respectively, in climatic applications. An analysis of the four series of indices reveals that the most significant changes occurred for cool winter nights and warm summer nights, with corresponding trends reaching −1.9 and 3.5 d decade^{-1} (Table 3 and Fig. 8). The frequencies of cool winter nights/days were relatively stable before the year 1982, but rapidly declined after the year 1986 and have generally remained at a low level for the last 2 decades (Fig. 8). The frequencies of warm summer days/nights (Fig. 8c and d) tended to increase since the year 1990.

To gain a better understanding of the extreme indices defined here, correlations were calculated between time series of area-averaged index values and annual mean temperatures. Indices based on maximum and minimum temperature were correlated with annual mean maximum and minimum temperature, respectively. The magnitude of correlations between weighted averages of numbers of extreme days or nights and the relevant annual mean temperatures from 1961 to 2010 ranged between 0.59 and 0.91.

Table 3
Linear trends in seasonal cool nights and warm days in Mongolia from the year 1961 to the year 2010.

	Cool nights (TN10p)	Cool days (TX10p)	Warm nights (TN90p)	Warm days (TX90p)
Spring	−1.3	−0.5	1.8	1.4
Summer	−1.9	−1.2	3.4	3.5
Autumn	−1.5	−0.8	1.9	1.5
Winter	−1.7	−0.8	1.2	0.5

Data are given in d decade^{-1}.

4. Summary and discussion

In this study, 11 extreme temperature indices over Mongolia were analyzed to investigate the temporal and spatial changes from 1961 to 2010. The following conclusions were drawn:

(1) Positive trends were mostly observed on SU25, TXx, TNx, TN90p and TX90p indices, whereas negative trends were found on Fd0, TN10p and TX10p indices.
(2) The mean and maximum (minimum) values of daily maximum and minimum temperatures showed overall increasing trends, and DTR decreased significantly. The mean maximum temperature began to rise significantly after the year 1990, while the mean minimum temperature had begun to steadily rise since the year 1986. The reduction in DTR mainly occurred before the year 1983. TXn and TNn significantly increased after the year 1996, while TXx and TNx did not increase until the year 1995. TXn and TNn significantly increased across the whole country.
(3) Number of summer days (SU25) has been increasing all over Mongolia. Especially, the large trends were found in Gobi part stations. Frost days (FD0) are decreasing about 15 days in last 50 years.
(4) The series of the relative indices related to minimum temperature changed more significantly than those related to

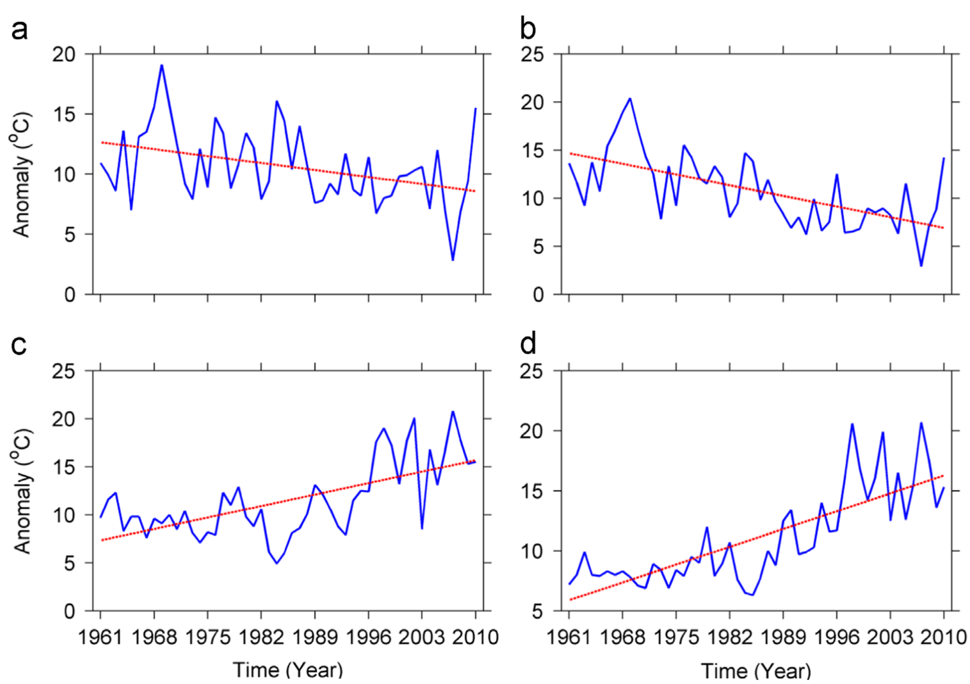

Fig. 8. Country-averaged (a) cool days (TX10p) and (b) cool nights (TN10p) for winter, and (c) warm days (Tx90p) and (d) warm nights (TN90p) for summer in over Mongolia, 1961–2010. The dashed lines show liner trends.

maximum temperature. The significant reduction of cool nights and days occurred after the year 1990, while the significant increase in warm nights and days occurred after the year 1996. The most significant changes in cool nights and days were observed in Western Mongolia.

(5) The significant reduction of cool days and nights mostly occurred in summer, and the frequencies of warm days and nights increased more significantly in summer. Warm summer days and nights increased more prominently in Central Mongolia. The days with extreme high temperatures increased in most regions, mainly in summer, while the nights with extreme high temperatures increased more significantly, resulting in an increase in summer heat waves.

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