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Assessing the implications of temperature extremes during the period 1959-2014 on the Inner Mongolia Plateau to sustainable development

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Abstract

The study sought to foster a better understanding of the nature of extreme temperature events and variations, and their implications to sustainable development, based on sixteen indices of extreme temperature obtained from forty-three meteorological stations on the Inner Mongolia Plateau (IMP). By using linear trend and Mann-Kendall abrupt change tests to investigate temporal variation trends, coupled with spatial distribution patterns and abrupt changes of extreme temperature events, the study revealed that the IMP has experienced extreme warming during 1959–2014 with warm extremes increasing significantly ($p < 0.01$) and cold extremes apparently decreasing ($p < 0.01$). The most significant increasing trends of warm extreme indices occurred in the desert steppe area (DSA) and sand desert area (SDA), suggesting that warming trends for night-time indices were larger than for daytime indices, while the most significant decreases in cold extreme indices were detected in forest area (FA) and forest steppe area (FSA). In addition, the significant cold day and cold night indices showed a decreasing trend, while warm day and warm night indices showed an increasing trend across the entire study area. Moreover, the study identified that topography has a large impact on the spatial distribution of extreme temperature indices, as does the type of grassland, and the ubiquity of the heat island effect in constructed urban regions. Finally, the study posits that to mitigate the effects of extreme temperatures, it is imperative to foster adaptive actions based on the principles of sustainable development.

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Zusammenfassung

Ziel dieser Arbeit war es, ein besseres Verständnis der Charakteristik extremer Temperaturereignisse und -schwankungen zu erlangen, sowie eine Abschätzung ihrer Auswirkungen auf die nachhaltige Entwicklung auf dem Innermongolischen Plateau (IMP) zu ermöglichen. Dazu wurden 16 Indizes extremer Temperaturen verwendet, die von 43 meteorologischen Stationen gewonnen wurden. Die zeitlichen Variationen dieser Indizes wurden auf lineare Trends mit abrupten Änderungen (Mann-Kendall Test) untersucht sowie die Muster der räumlichen Variabilität und der abrupten Änderungen in der Häufigkeit von extremen Temperaturereignissen ermittelt. Die Studie ergab, dass das IMP im Zeitraum 1959–2014 eine extreme Erwärmung erfahren hat, wobei die warmen Extreme signifikant zunahmen ($p < 0{,}01$) während die kalten Extreme offenbar abnahmen ($p < 0{,}01$). Die signifikantesten ansteigenden Trends der Indizes der warmen Extreme traten im Wüstensteppengebiet (DSA) und im Sandwüstengebiet (SDA) auf, was darauf hindeutet, dass die Erwärmungstrends bei den Nachtindizes größer waren als bei den Tagesindizes, während die signifikantesten Rückgänge der Indizes der kalten Extreme im Waldgebiet (FA) und im Waldsteppengebiet (FSA) festgestellt wurden. Darüber hinaus zeigten die Indizes für extrem kalte Tage und kalte Nächte einen abnehmenden Trend, während die Indizes für warme Tage und warme Nächte im gesamten Untersuchungsgebiet eine steigende Tendenz aufwiesen. Darüber hinaus stellte die Studie fest, dass die Topographie einen großen Einfluss auf die räumliche Verteilung der Extremtemperaturindizes hat, ebenso wie die Art des Graslands und die Allgegenwart des Wärmeinseleffekts in bebauten städtischen Regionen. Schließlich schlägt die Studie vor, dass zur Milderung der Auswirkungen extremer Temperaturen unbedingt Anpassungsmaßnahmen gefördert werden müssen, die auf den Prinzipien der nachhaltigen Entwicklung basieren.

Keywords extreme temperature, Inner Mongolia Plateau (IMP), sustainable development, influencing factors, adaptation

1. Introduction

As noted by IPCC (Intergovernmental Panel on Climate Change), the occurrence, frequency, and intensity of extreme temperatures may change with global warming, and extreme events may increase or be enhanced (*Holmgren* et al. 2006; *Wallace* et al. 2014; *Tao* et al. 2014). It is difficult to analyze the changes in specific climatic extreme events, as these events do not necessarily occur very often or at the same location. Although they are small probability events, they can have a bigger influence than a change in mean values. Global and regional climate change frequently produces negative weather patterns, such as heat waves, drought and snow (*Moberg* and *Jones* 2005), which result in the deterioration of the environment, and may seriously affect human lives.

The Inner Mongolia Plateau (IMP) is a mainly grassland-dominated area, which is not only the base of animal husbandry, but also an important ecological barrier in China. Its southern part is the main body of the windbreak and sand fixation belt. The IMP is also the transition zone between the arid and semi-arid northwest inland region, and the humid and semi-humid southeast coastal region affected by Asian monsoon (*Sun* et al. 2010). Thus, economy and ecosystems of the IMP are at a great risk from climate change and/or extreme climatic events. As a result, it has gained considerable attention by governments and international institutions. *Bai* et al. (2009, 2014) pointed out that with global warming, the frequency of extreme temperature and precipitation events in Inner Mongolia increased with extreme warm events increasing, and extreme cold events decreasing. *Yan* et al. (2014) obtained similar results about temperature extremes, but they found that extreme precipitation events showed a decreasing trend with a low frequency and intensity. *You* et al. (2010, 2014) analyzed the frequencies, distribution and change characters of extreme precipitation events in Inner Mongolia over the last 48 years. They also studied the variable of winter cold/warm events in Inner Mongolia during the period of 1961–2010. The results showed that rainfall associated with extreme precipitation events decreased in the middle and southeast, while it increased in the northeast and west, after the abrupt temperature increase in 1987. *Liu* (2014) studied the spatial-temporal changes of extreme weather events during 1970–2012 and identified similar changes.

Despite their relevance, many previous studies lacked a comprehensive analysis of regional trends, as they mainly focused on the spatial-temporal characteristics of part of the extreme climate indices as a whole. More importantly, fewer studies considered the regional differentiation of different grasslands. One exception is *Li* et al. (2018), who researched part of the existing climate extremes. It is well known that natural grasslands are one of the most important terrestrial ecosystems in the world (*Scurlock* et al. 2002) and in China they are the largest land ecological system, covering 40% of the total area, while grasslands in the Inner Mongolia Plateau mostly belong to the typical mid-latitude semi-arid temperate steppe ecosystem, accounting for 22% of the national grassland area. A full consideration of the changes of temperature extremes in different grasslands on the IMP and their responses are vital in adapting the extreme weather events associated with climate change.

The close links between climate change on the one hand, and sustainable development on the other, are a result of the fact that climate change is known to pose constraints which may endanger sustainable development. Considering this line of thinking, the implications of extreme temperatures to sustainable development in the Inner Mongolia Plateau are twofold. Firstly, climate extremes may negatively affect vegetation (*Li* et al. 2018), even crops and food production, leading to food insecurity. Depending on the severity, this could lead to economic losses. Secondly, since the poor may be the ones who are hardest hit, and least able to adapt, extreme temperatures can lead to a set of social problems, which may endanger livelihoods in some areas. Such hardships could be a driver for migration.

This study provides a comprehensive characterization of temperature extremes over the IMP, using 16 indicators based on daily temperature data from 43 meteorological stations over the period 1959–2014. The results provide a better insight on the impacts of climate change and help develop appropriate adaptation and mitigation strategies against the adverse effects of climate extremes. Section 2 describes the study area. The data source and the research methods are described in Section 3 which is followed by the analyses in Section 4. Sections 5 and 6 present the discussion and conclusion, respectively, also outlining the implications to sustainable development.

2. Study area

The Inner Mongolia Plateau (IMP), situated between latitudes 37°24′ N ~ 53°23′ N and longitudes 97°12′ E ~ 126°04′ E (*Fig. 1*), covers a total area of 1.18 million km^2. Given its vast size, the study area spans different climate zones. The winters on the IMP are very long, cold, and dry (*Zhang* et al. 2012). The average annual temperature varies approximately –1 to 10° C while the annual precipitation varies from 50 mm to 450 mm. Precipitation gradually decreases from east to west. As water and heat energy are two critical factors controlling the mid-latitude temperate grasslands, the dominant grassland vegetation types on the IMP are meadow steppe, typical steppe and desert steppe from east to west, respectively (*Wu* 1980).

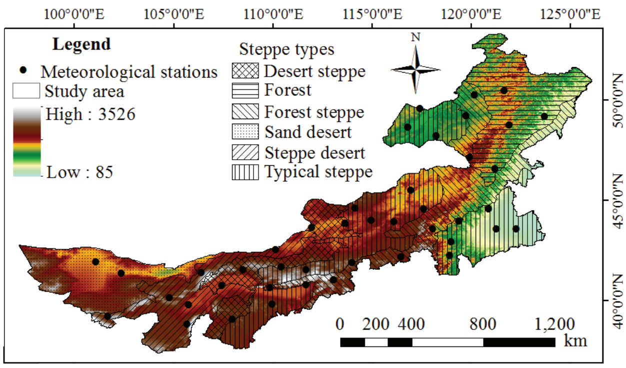

Fig. 1 Inner Mongolia Plateau and the distribution of the selected 43 stations and steppe types (DEM is Digital Elevation Model)

According to studies (*Li* 1962; *Li* et al. 1990; *Li* et al. 2018), the IMP is geographically divided into six subregions: desert steppe area (DSA), forest area (FA), forest steppe area (FSA), sand desert area (SDA), steppe desert area (STDA), and typical steppe area (TSA). The locations of the 43 meteorological stations are depicted in *Figure 1.*

3. Overview of sustainable development over time on the Inner Mongolia Plateau

An understanding of the connections between climate extremes and sustainable development is needed, since tracking progress towards achieving the UN Sustainable Development Goals (SDGs) can help the government to identify priorities for targeted policy action. *Xu* et al. (2020) have developed and tested systematic methods to quantify progress towards the 17 SDGs at national and subnational levels in China.

Based on their research, among the 17 SDGs, there is no SDG 14 (life below water) on the IMP. Compared with 2000, the scores of 14 of the 16 SDGs on the IMP have improved, while the scores of the remaining two SDGs have gradually declined (*Table 1*). The two SDGs with declining scores were SDG 12 (responsible consumption and production) and SDG 13 (climate action), respectively. The score of SDG12 (responsible consumption and production) may fall slightly as a result of factors such as per capita energy consumption and increased urban waste in China (*Xu* et al. 2020).

Table 1 Scores for SDGs at Inner Mongolia Plateau from 2000 to 2015. Individual summaries based on the research by Xu et al. (2020)

Year	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17
2000	30.7	44.3	60.1	30.4	40.7	32.7	19.4	22.7	8.8	14.2	38.9	73.1	54.4		30.5	55.3	5.8
2005	50.9	52.3	60.6	35.0	39.8	38.3	35.1	35.7	17.0	19.3	57.1	70.9	63.8		29.5	57.3	10.3
2010	51.8	58.1	69.6	45.5	42.3	41.4	36.2	36.9	31.2	28.5	56.6	58.7	51.6		31.6	61.6	25.0
2015	57.1	61.9	75	52.7	43.1	51.1	37.8	28.1	37.1	33.2	66.8	54.3	51.2		38.4	67.0	26.3
2005-2000	20.2	8	0.5	4.6	-0.9	5.6	15.7	13	8.2	5.1	18.2	-2.2	9.4		-1	2	4.5
2010-2000	21.1	13.8	9.5	15.1	1.6	8.7	16.8	14.2	22.4	14.3	17.7	-14.4	-2.8		1.1	6.3	19.2
2015-2000	26.4	17.6	14.9	22.3	2.4	18.4	18.4	5.4	28.3	19	27.9	-18.8	-3.2		7.9	11.7	20.5

The present study serves to deepen the research on how climate change, particularly temperature extremes changes on the IMP, and their influencing impactors, may influence the sustainability prospects of the IMP. This is because a better knowledge on how to mitigate the effects of extreme temperatures may provide valuable insights to support adaptive actions based on the principles of sustainable development.

4. Data and methods

4.1 Data preparation

Daily maximum and minimum temperature data for the 43 meteorological monitoring stations on the IMP were recorded during 1959–2014. The data were obtained from the Climate Data Center (CDC) of the National Meteorological Center of the China Meteorological Administration (CMA). Data quality control is a prerequisite for indices calculations and it was performed using the computer program RClimDex Software Version 1.1, release 131115 (*ETCCDI* 2020), which is a widely used approach, developed and maintained by Xuebin Zhang and Feng Yang at the Climate Research Branch of Meteorological Service of Canada (*Hyndman* and *Fan* 1996; *Zhang* et al. 2005a). Its flow chart can be found in *Fig. 2*.

As a first step, some stations such as Zalantun City, Ulan Hot City were removed, due to the fact that their records are less than 30 years. As a second step, the candidate stations were selected with data based on the requirements of the RClimDex Model. As a third step, the long-term, high-quality and reliable climate records with a daily time resolution were obtained, followed by data quality control. Here, the 43 stations (*Fig. 1*) on the IMP with the relevant data for at least 56 years (January 1, 1959, to December 31, 2014) were selected. Finally, based on RClimDex 1.1, all 16 core temperature indices listed in *Table 2* and eleven core precipitation indices were calculated.

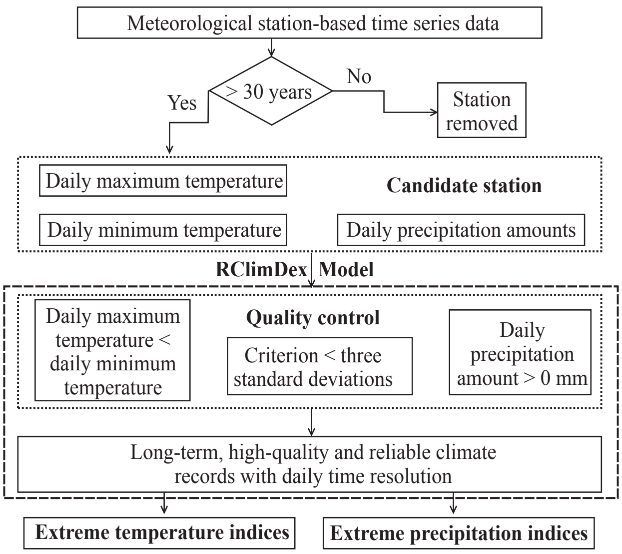

Fig. 2 Flow chart of extreme climate indices

Due to the need to provide a specific focus, only the temperature indices are being discussed in this paper.

Table 2 Temperature indices selected for this study with indicator names, definitions, and units

Temperature	Indicator name	Definitions	Units
FD0	Frost days	Count of days where TN (daily minimum temperature) < 0°C	days
SU25	Summer days	Count of days where TX (daily maximum temperature) > 25°C	days
ID0	Ice days	Count of days where TX < 0°C	days
TR20	Tropical nights	Count of days where TN > 20°C	days
GSL	Growing season length	Annual count of days between first span of at least six days where TG (daily mean temperature) > 5°C and first span in second half of the year of at least six days where TG < 5°C	days
Tn10p	Cool nights	Count of days where TN < 10th percentile	days
Tx10p	Cool days	Count of days where TX < 10th percentile	days
Tn90p	Warm nights	Count of days where TN > 90th percentile	days
Tx90p	Warm days	Count of days where TX > 90th percentile	days
WSDI	Warm spell duration indicator	Count of days in a span of at least six days where TX > 90th percentile	days
CSDI	Cold spell duration indicator	Count of days in a span of at least six days where TN > 10th percentile	days
DTR	Diurnal temperature range	Mean difference between TX and TN (°C)	°C
TXx	Max Tmax	Monthly maximum value of daily maximum temperature	°C
TNx	Max Tmin	Monthly maximum value of daily minimum temperature	°C
TXn	Min Tmax	Monthly minimum value of daily maximum temperature	°C
TNn	Min Tmin	Monthly minimum value of daily minimum temperature	°C

4.2 Methods

A linear trend was used to analyze the changes in temperature extremes, both spatially and temporally. In addition, the Mann-Kendall abrupt change test was used to detect the abrupt changes in annual temperature (*Li* 2019).

The Mann-Kendall abrupt change test (MK) which is a non-parametric test, was developed by *Mann* (1945) and *Kendall* (1962). This method is widely employed to detect monotonic trends in series of environmental data, as the required data are not placed in particular order, and is not affected by outliers compared with other analysis methods. Under the null hypothesis (no abrupt change point), the normally distributed statistic S_k can be calculated by the following formula:

$$S_k = \sum_{i=1}^{k} r_i \, , r_i = \begin{cases} 1, x_i > x_j \\ 0, x_i \leqslant x_j \end{cases}, (j = 1,2,\ldots; k = 1,2,\ldots,n) \quad 1)$$

Mean and variance of the normally distributed statistic S_k can be given by the following formulas:

$$E[S_k] = K(K-1)/4 \quad 2)$$

$$Var[S_k] = k(k-1)(2k+5)/72 \;\; (a \leqslant k \leqslant n) \quad 3)$$

The normalized variable statistic UF_k is estimated as follows:

$$UF_k = \left(S_k - E\,[S_k] / \sqrt{Var[S_k]}\right) \quad 4)$$

The normalized variable statistic UF_k is the forward sequence, and the backward sequence UB_k is calculated using the same equation but with a reversed series of data. The values of $UF_k(UB_k)$ constitute a forward sequence curve $UF(UB)$. For the given α significance level and $U\alpha$ (the critical value of the standard normal distribution), if $UF_k > U\alpha$, it means the forward sequence curve (UF) has a trend α significance level. The detection of an increasing ($UF_k > 0$) or a decreasing ($UF_k < 0$) trend is indicated. The intersection of the *UF* and *UB* curves of the test statistic appears in the confidence interval and indicates an abrupt change point.

5. Results

5.1 Temporal variations of temperature extremes

Analysis of the annual regional time series of temperature indices indicated that changes in temperature extremes over the 1959–2014 period reflected overall warming in this region. *Figure 3* (p. 250/251), presents the magnitude of the trends. The linear trends (*Fig. 3,*) of the coldest days (TXn), coldest nights (TNn), warmest days (TXx), and warmest nights (TNx) were 0.30, 0.50, 0.27, 0.39° C/decade, respectively; all of these indices (except TXn) showed a strong significant ($p < 0.01$) increase, while TNn showed the strongest magnitude. TNn and TNx were basically consistent and exhibited increases with fluctuations. These indices indicate that warming at night was greater than in the daytime.

The annual percentage of warm days and nights analyzed through the Tx90p and Tn90p indices showed pronounced fluctuation between 1959 and 2014. There was a steady increasing trend until the mid-1980s and a strong increasing trend until 2014, with a rate of 1.28 days per decade and 1.29 days per decade, respectively. Conversely, the number of cold days and nights, analyzed through Tx10p and Tn10p, decreased at a rate of 0.85 days per decade and 2.32 days per decade, respectively. These linear trends were mostly consistent and revealed that the warming trend was higher for nighttime indices than for those of daytime indices. These characteristics indicated that the increasing temperatures were more pronounced at night than in the daytime.

Frost days (FD0) (–3.56 days/decade) and ice days (ID0) (–1.82 days/decade) decreased significantly ($p < 0.01$) over time. Summer days (SU25) (3.32 days/decade) and tropical nights (TR20) (1.45 days/decade) increased significantly ($p < 0.05$) over time, though it underwent a slight decrease from 1959 to 1989 and a rapid increase from 1990 to 2014. From this analysis, a warming trend was identified on the IMP.

In the time series (*Fig. 3*), warm spell duration days (WSDI) and growing season length (GSL) increased by 1.51 and 3.44 days/decade, respectively; while cold spell duration days (CSDI) decreased by 1.28 days/decade and the diurnal temperature range (DTR) decreased by 0.15° C/decade. The values of the WSDI and CSDI were relatively small; however, the inter-annual changes were volatile. It is well known that the annual minimum temperature was much cooler than the annual maximum temperature during the period prior to the 1940s (*Vincent* 1998), which led to a considerable decrease in DTR at the beginning of the 1950s. The causes of this increase in nighttime temperatures during the 1950s are uncertain. The change in trends of these four indices exhibits significant trends ($p < 0.01$).

Therefore, from *Figure 3* it is obvious that it had experienced extreme warming on the IMP during 1959–2014. The warm extremes (Tn90p, Tx90p, SU25, TR20, and WSDI) increased significantly ($P < 0.05$), while cold extremes (Tn10p, Tx10p, FD0, ID0, and CSDI) decreased apparently ($P < 0.05$). Magnitudes in night extremes (TNx, TNn, Tn10p, and Tn90p) appeared to be greater than those of day extremes (TXx, TXn, Tx10p, and Tx90p). Changes were more evident in the nighttime temperature at most locations than the daytime temperature as more stations showed pronounced trends on the IMP.

5.2 Spatial variations of temperature extremes

The spatial distribution of the variation of annual temperature indices at each station shown in *Figure 4* (p. 252/253), displays, in general, a large spatial coherence.

For TNn, stations showing an increased account for 95.3% of the total and the decreasing trend mainly occurred in STDA; 60% of these stations' trends surpassed the significance test at the 5% level. The variations at the stations had non-significant characteristics of spatial aggregation and were evenly distributed in the study area. Regarding TXx, the temperature at 100% of the stations increased over time; 60% of these stations passed the significance test at the 5% level. The non-significant stations were mainly located in FSA, and the large increasing trend was mainly distributed in TSA. Comparing the TNn and TXx, the former displayed a larger increasing trend, which indicated that the IMP experienced a sharp warming trend. TXn showed similar variations to TXx; the temperature of 93% of the stations increased over time, but only approximately 47% of these stations exhibited a significant trend; these stations were scattered along the south-east area of the IMP. Regarding TNx, 100% of the stations showed a temperature increase for the entire study area; 81% of these stations' trends surpassed the significance test at the 5% level; they were evenly distributed in each sub-region.

For Tx10p and Tn10p, approximately 90% of the stations showed a decreasing trend for both indices; about 80% of these stations' trends surpassed the significance test at the 5% level. The magnitude of the decrease in the trends at most stations for Tn10p was higher for Tn10p, indicating that the warming was greater in Tn10p than in Tx10p. Conversely, for Tn90p and Tx90p, all stations showed increasing trends over time; approximately 98% of these stations' trends reached the 5% significance level. While the magnitude trends in most stations were higher for Tn90p than for Tx90p, it was evident that the warming was greater in Tn90p than in Tx90p. Overall, it seemed that the significant cold days and cold nights had a decreasing trend while warm days and warm nights had an increasing trend across the entire study area. The trends for these indices had the same sign for each of the sub-regions but the magnitude of the changes was greater for Tn10p and Tx10p than Tn90p and Tx90p.

Figure 4 displays the high spatial coherence of the regional warming trend, particularly for TR20 and SU25. TR20 and SU25 both showed a pronounced increase at approximately 95% of the total stations across the study area during 1959–2014, whereas SU25 showed a larger magnitude, especially in the SDA. The increasing trend of TR20 was SDA > STDA > DSA > TSA > FSA > FA, which indicated that the temperature in FA had a lower value of TR20, likely due to the micro-weather condition of FA which can cool down the region nearby. Conversely, FD0 and ID0 showed regional cooling trends at about 93% and 90.7% of the total stations, respectively. The trend for FD0 was more significant, as 93% of the stations surpassed the significant test at the 5% level. FD0 decreased sharply in SDA, DSA, and STDA, while in the FA and FSA it changed by a small amplitude. ID0 showed an obvious decreasing trend in the TSA and DSA, and most of them passed the significance test, while SDA experienced an increasing trend, but the data did not pass the significance test.

For GSL, about 97.7% of the stations displayed an increasing trend, which was statistically significant at about 49% of the stations with larger trend magnitude. As found in previous studies (*Zhang* et al. 2005b; *Liu* et al. 2009; *Yan* et al. 2015), GSL displayed a significant warming trend in China, while on the IMP the largest trend occurred in the SDA. The DTR displayed a decreasing trend among 76.7% of the total stations and 70% of stations passed the significant test at the 5% level, which emphasized the result that TXx and TNn had asymmetrical trends. GSL in SDA, STDA, and DSA, had a large magnitude trend, whereas it was lower in TSA, FSA and FA, suggesting that greater climate warming occurred in desert areas. CSDI showed a significant decreasing trend at 90.7% of the stations and about 70% of stations passed the significant test at the 5% level. The largest trend in CSDI occurred in the FA and FSA but did not pass the significant test; meanwhile in the TSA and DSA the significant change with a moderate decreasing trend. However, WSDI showed a strong significant warming trend in the study area with the largest and smallest significant trends in the SDA and FA, respectively. The spatial coverage of significant trends for WSDI was much higher than for CSDI, peaking at 93% of the total stations. These results illustrate that the FA can act to cool down the temperature in a micro-region and have a great influence on extreme temperatures.

6. Discussion: Influencing factors analysis and adaptation options

6.1 Analysis of influencing factors of temperature extremes

6.1.1 Effects of regional warming

This discussion session departs from two main questions: in the context of global warming: (1) Does the IMP also experience a warming trend? (2) How do extreme temperature events change under global warming on the IMP? In order to answer these questions, and explore the factors affecting the temperature extremes after the annual average temperature of the IMP is warming, it is necessary to find the change trends and time points related to the annual average temperature of the IMP. *Figure 4* indicates that annual temperatures showed a significant upward trend and 1989 is the change year. Based on *Figure 5*, after the change year, temperature indices showed general increase trends, which indicate that the temperature extremes are sensitive to global warming on the IMP during the study period. With global warming, temperature extremes increased in general. These is consistent with previous research (*Tong* 2019).

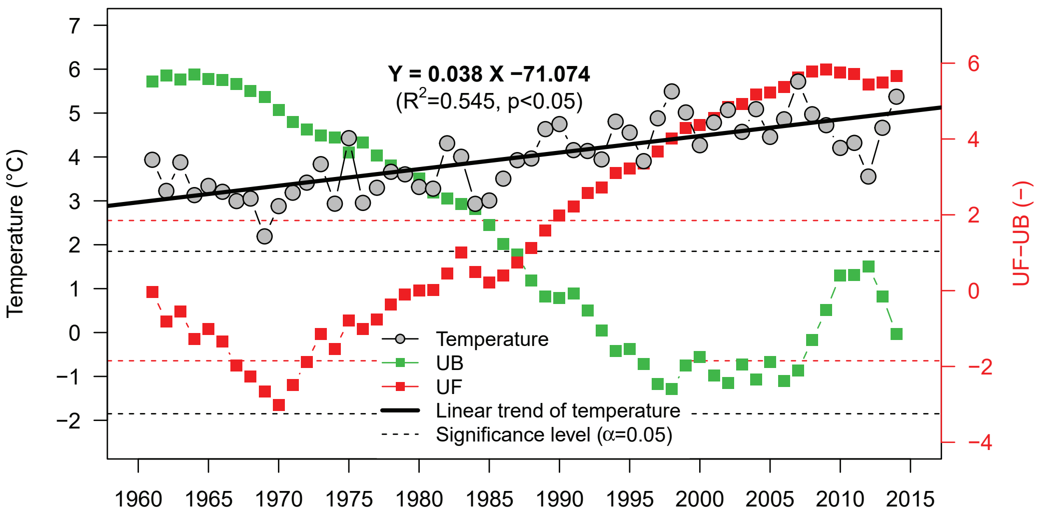

Fig. 5 Flow chart of extreme climate indices

6.1.2 Extreme temperature indices

To further clarify the interaction and relationships between different extreme climate indices, Pearson correlation coefficients were calculated for pairs of the sixteen extreme temperature indices.

The warm indices versus warm indices (Tn90p, Tx90p, SU25, TR20, and WSDI) and cold indices versus cold indices (Tn10p, Tx10p, FD0, ID0, and CSDI) showed positive correlations, almost significant at the 0.05 level (*Table 3*); while cold indices versus warm indices showed significant negative correlations (all at the 0.05 level). The above analysis showed that warm indices experienced an upward trend over the past 56 years on the IMP, while cold indices showed a downward trend, which indicates that in the context of global warming, the IMP turns into warming from the view of extreme temperatures. The opposite trends of two types of indices were observed clearly; the negative correlation in *Table 3* confirmed the above analysis. DTR, TXn, TNn, TXx, TNx, and GSL showed negative correlations with each other.

Table 3 Correlations of temperature indices on the IMP during 1959–2014

Indices	CSDI	DTR	FD0	GSL	ID0	SU25	Tn10p	Tn90p	TNn	TNx	TR20	Tx10p	Tx90p	TXn	TXx	WSDI
CSDI	1															
DTR	0.438**	1														
FD0	0.353**	0.570**	1													
GSL	-0.097	-0.246	-0.654**	1												
ID0	0.388**	0.044	0.302*	-0.213	1											
SU25	-0.309*	-0.120	-0.312*	0.071	-0.198	1										
Tn10p	0.769**	0.677**	0.679**	-0.367**	0.457**	-0.472**	1									
Tn90p	-0.479**	-0.634**	-0.783**	0.444**	-0.472**	0.580**	-0.763**	1								
TNn	-0.609**	-0.311*	-0.303*	0.267*	-0.238	0.135	-0.619**	0.308*	1							
TNx	-0.192	-0.353**	-0.441**	0.263	-0.210	0.482**	-0.460**	0.618**	0.231	1						
TR20	-0.146	-0.235	-0.181	0.011	0.079	0.414**	-0.219	0.367**	0.130	0.717**	1					
Tx10p	0.627**	0.182	0.518**	-0.343**	0.638**	-0.541**	0.790**	-0.580**	-0.537**	-0.379**	-0.153	1				
Tx90p	-0.416**	-0.279*	-0.633**	0.397**	-0.571**	0.626**	-0.596**	0.881**	0.267*	0.620**	0.357**	-0.574**	1			
TXn	-0.410**	-0.082	-.230	0.291*	-0.319*	0.087	-0.458**	0.147	0.849**	0.095	-0.057	-0.480**	0.159	1		
TXx	-0.065	0.075	-0.176	0.146	-0.194	0.570**	-0.194	0.363**	0.133	0.527**	0.485**	-0.354**	0.526**	0.050	1	
WSDI	-0.279*	-0.295*	-0.464**	0.238	-0.205	0.571**	-0.411**	0.694**	0.207	0.479**	0.384**	-0.332*	0.718**	0.017	0.440**	1

Based on historical observational data and extreme indices, this study analyzed the situation of temporal variations and spatial distributions of extreme events on the IMP over the past 56 years. Changes in cold extremes (Tn10p, Tx10p, ID0, and CSDI) were almost larger in magnitude than those in most warm extremes (Tn90p, Tx90p, SU25, TR20, and WSDI), and changes in night extremes (TNx, TNn, Tn10p, Tn90p) appeared to be greater than those in day extremes (TXx, TXn, Tx90p, Tx10p).

6.1.3 Topography

It was well known that topography has a large direct impact on climate factors (*Liu* et al. 2015), and indirectly on its calculated indices. Since temperature changes distinctly with elevation, the elevation of the meteorological stations would inevitably have an impact on the observed and calculated results (*Li* 2019). Therefore, it can be easily concluded that topography can affect extreme climate indices to some extent.

6.1.4 Urban heat island

It is obvious that the ubiquity of the heat island effect in urban constructed regions is also an important impact indicator on extreme climate events (*Du* and *Yu* 2012; *Richter* 2016), but on the IMP, it is much more complicated because this area is a grassland-dominated area. Previous research (*Xia* et al. 2010) found that night warming caused greater increases in nighttime mean and daily minimum in the grassland area than day warming did. It can imply that grassland can influence the extreme climate indices. To find out how extreme climate indices change in urban areas and grassland areas on the IMP, take Hohhot City (urban area) and Siziwang Banner (rural area) as good examples, because these two areas have a similar location and elevation, but population density and urban development in Siziwang Banner were much lower, and its grassland area was greater. *Figure 3* showed the trends of cold extreme temperature indices (e.g. FD0, Tx10p, Tn10p) decreased and warm extreme temperature indices (e.g. WSDI) increased both much higher in Hohhot City than in Siziwang Banner, which illustrates that the urban area is warmer than the rural area on the IMP due to the heat island effect. Meanwhile the grassland effect cannot be ignored. For example, DTR in Hohhot City changed more obviously than that in Siziwang Banner. It is easy to understand that vegetation can regulate the regional climate, lowering the maximum temperature during the day, raising the minimum temperature at night, and reducing the difference in temperature between day and night. Moreover, green plants regulate temperature mainly through transpiration and photosynthesis, absorbing heat from the air and carbon dioxide. Therefore, grassland on the IMP also can influence extreme temperature indices. Planting more vegetation in the urban area is one appropriate adaptation and mitigation strategy to cope with the adverse effects of climate extremes in urban areas. Previous research gave more focus to the heat island effect on the temperature, seldom considering the effect vegetation has on extreme climate change. This is why it is emphasized in this study.

6.1.5 Grassland types

Grassland type is another important impact indicator. By changing surface properties such as surface albedo, roughness and soil moisture, the vegetation cover can affect processes such as radiation balance and water balance, and ultimately lead to regional temperature, humidity, evapotranspiration and other climate changes. *Figure 6* (p. 254/255) obviously indicates that different types of grassland showed various responses of extreme climate indices. In other words, different types of grassland can influence extreme climate indices through the micro-climate change, especially in FA. Obviously, forest can reduce extreme temperatures to some extent (e.g., TR20, TNn, TNx and TXn in *Fig. 6*) compared with the other five sub-regions, and different types of vegetation in forest can have various responses to the climate change (*Jägerbrand* et al. 2009; *Zhang* et al. 2010; *Hou* et al. 2012); therefore, the trend of extreme climate indices in FA was different from the other sub-regions (*Fig. 6*). In addition, some researchers proved that the coverage of vegetation and land-use change can influence climate change extreme indices (*Deo* et al. 2009). It is a reasonable hypothesis to think that warming is higher at night than daytime, which suggests that carbon emitted from vegetation at night is more powerful in triggering heat than at daytime. It is clear that climate extremes can trigger vegetation shifts, since these events can induce generalized mortality, disrupting a situation in which vegetation would either remain stable or follow successional replacement in equilibrium under stable climate conditions (*Lloret* et al. 2011; *Tan* et al. 2015), but conversely, during the unstable condition period, vegetation can also influence the extreme climate change in order to get into a stable condition. Thus, it can be concluded that vegetation can influence the temperature extremes.

6.1.6 Coverage of lakes

The coverage of lakes is also a crucial factor affecting the results of the extreme climate indices. Water has a far greater specific heat capacity than land, which can affect climate change to some extent. *Li* et al. (2008) found that water body areas have the lowest temperature and the maximum humidity. Furthermore, the size and the distribution of the water body contributes greatly to micro-climate effects. Because night lakes are warmer than land surface, causing movement of cold air from land to water bodies, more surface warming prevails around the lake at night. *Table 4* shows that a large number of small lakes are located in the TSA. Thus, it was reasonable that DTR in the TSA changed significantly. It is mainly due to the temperature that gets cooled in the day by the large lakes and decreases gradually at night by the micro-environment change. Compared with Tx10p and Tx90p, increasing trends of TXx, and decreasing trends of DTR between Ejin Banner station (around three lakes) and Guaizi lake station (far away from the lake) in the SDA are further evidence of this effect. Furthermore, the lake is likely to be responsible for the disparity in Tn90p and Tx90p being more significant than that between Tn10p and Tx10p in six subregions (*Fig. 6*).

Table 4 The number of lakes distributed in the six sub-regions of the IMP

	0–10 km^2	10.1–50 km^2	50.1–100 km^2	> 100 km^2
DSA	21			1
FA	5			
FSA	30		1	1
SDA	11	1		
STDA	8			
TSA	194	8		1

6.2 Adaptation options

The 2018 Intergovernmental Panel on Climate Change report heralded the need to accelerate global climate change adaptation (*IPCC* 2018). This places a growing and time-sensitive need on the development and implementation of adaptation policies and practices (*Doktycz* and *Abkowitz* 2019). Even though some great progress has been made during the 12th five-year plan period, tackling climate change issues (such as the increase carbon sinks from forest and grassland and exceeding carbon intensity target), there are still many difficulties and problems such as the strong vulnerability to extreme weather events and the imperfect early disaster warning and release mechanism (*IMAR* 2020). At present, decision-makers face significant challenges when adopting suitable strategies in respect of adaptation action. While this research provides a good insight regarding tackling climate extremes, the usage of indicators is one means of qualifying adaptable capacity for the use of policy-makers. After analysis, the multiple causal factors of extreme climate indicators are identified. Topography, elevation and elevation are exceptions; such non-human factors cannot be easily changed with current technologies. Furthermore, building a large reservoir is not necessary as Inner Mongolia Plateau is a semi-dry area, however, protecting and promoting grasslands diversity and reducing the heat island effect are feasible and effective measures which could be taken immediately. Although some climate change adaptation measures are being undertaken, these efforts must be expanded and implemented more rapidly than previously anticipated (*Doktycz* and *Abkowitz* 2019). All adaptation options are expected to promote the positive development of SDG13 (climate action).

7. Conclusions

This study analyzed changes in extreme climate indices on the IMP, based on daily minimum and maximum temperatures for the period 1959–2014. Data were quality-controlled by RClimDex1.1. Many temperature series were excluded from the study due to inhomogeneity. Nevertheless, the study could improve the understanding of recent spatial-temporal changes in extreme climate events on the IMP via systematic analysis of the climate extremes indices. The following changes in temperature indices were observed throughout the study area.

(1) Warm extremes (Tn90p, Tx90p, SU25, TR20, and WSDI) on the IMP experienced an apparently significant ($P < 0.01$) increasing trend between 1951 and 2014, while cold extremes (Tn10p, Tx10p, ID0, and CSDI) showed significant ($P < 0.01$) decreasing trends. Changes in night extremes (TNx, TNn, Tn10p, and Tn90p) appeared to be greater than those in day extremes (TXx, TXn, Tx90p, and Tx10p). These observations correspond to findings in previous studies relating to significant changes in temperature extremes with warming. Most increasing trends and high significance throughout the study areas were observed, implying that warming trends for nighttime indices were larger than for daytime indices. Spatially, the significant cold days and cold nights displayed a decreasing trend while warm days and warm nights displayed an increasing trend across the entire study area. The trends for these indices had the same sign for each of the sub-regions, but the magnitude of the change was greater in Tn10p and Tx10p than Tn90p and Tx90p.

(2) The warm indices versus warm indices and cold indices versus cold indices both showed positive correlations significant at the 5% level. Cold indices versus warm indices showed negative correlations significant at the 5% level.

(3) The elevation has a large impact on the spatial distribution of extreme temperature indices, as do grassland types. The ubiquity of the heat island effect in urban regions also had an impact on the amplitude of variation in extreme temperature. In addition, the size and distribution of lakes were also one of the main influencing factors of extreme climate indices.

(4) Relatively effective and implementable measures to mitigate extreme temperatures include protection of grassland types diversity and reduction of the heat island effect and should be considered immediately by policymakers.

A further study on annual and seasonal changes in temperature on the IMP is in preparation, which will compare different analysis periods. The data from the present work is expected to assist future policy-making, since, apart from the need to better understand the relationship between changes in atmospheric circulation and their contribution to the observed trends in temperature extremes, there is a need to establish and implement policies to handle them in a more systematic way.

The paper has shown that the extreme temperatures have caused some problems in the past. If left unattended, they may also cause problems in the future. They may also compromise the key development goal of poverty reduction.

Therefore, dealing with the causes of extreme temperatures is a precondition for sustainable development. Further studies should investigate this matter at a greater level of detail. In particular, technologies and policies which may help to address climate change as a whole and extreme temperatures in particular, may lead to tangible economic, health and environmental co-benefits.

Author contributions

Data curation: all co-authors, formal analysis: C.L., D.D., W.L.F., D.Y.A., investigation: all co-authors; methodology: C.L., J.W.; project administration: W.L.F., C.L., G.B., Y.S., Y.H.; writing: C.L., review and editing: C.L., D.D., W.L.F., Y.E. and D.Y.A.

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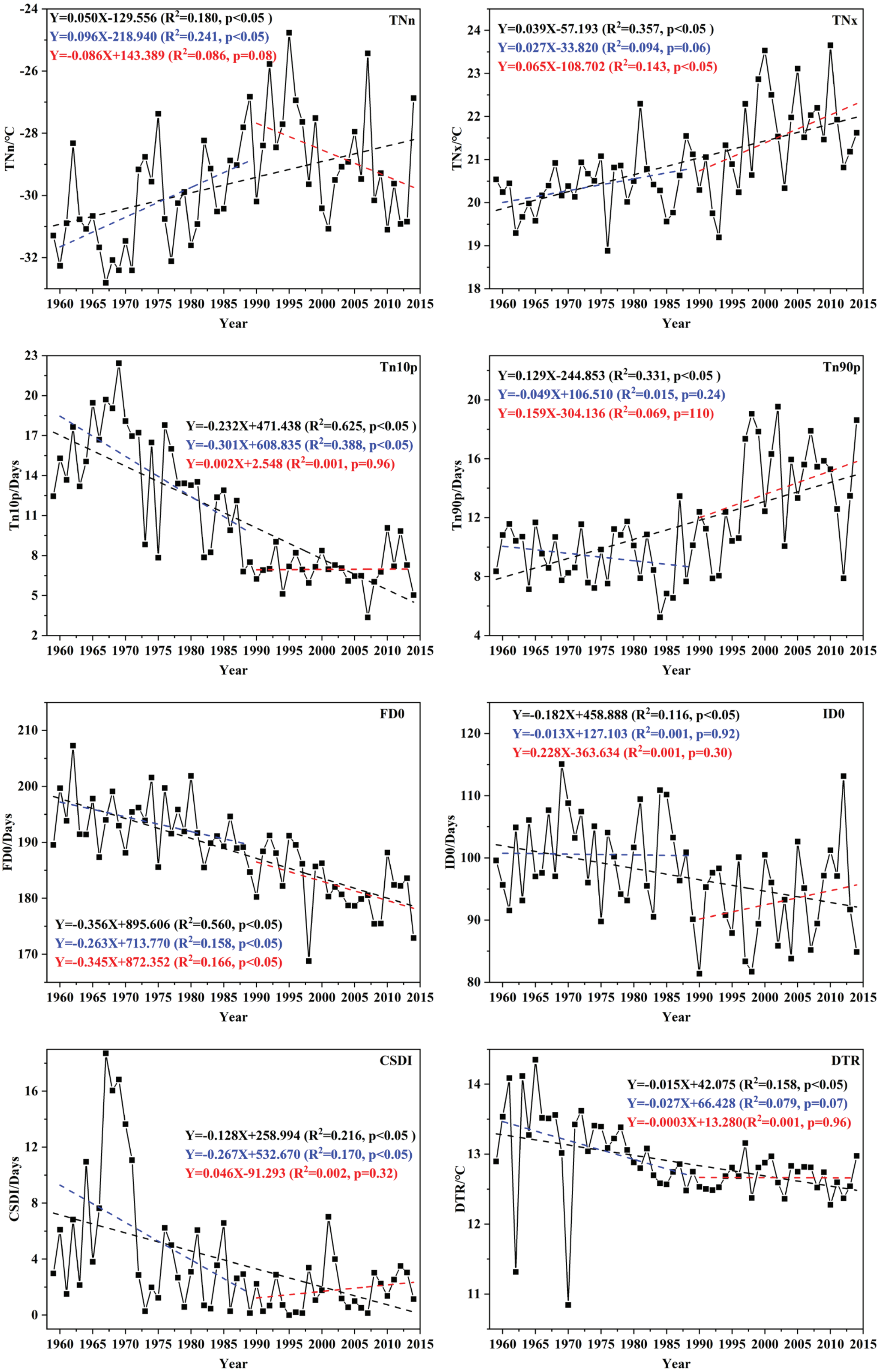
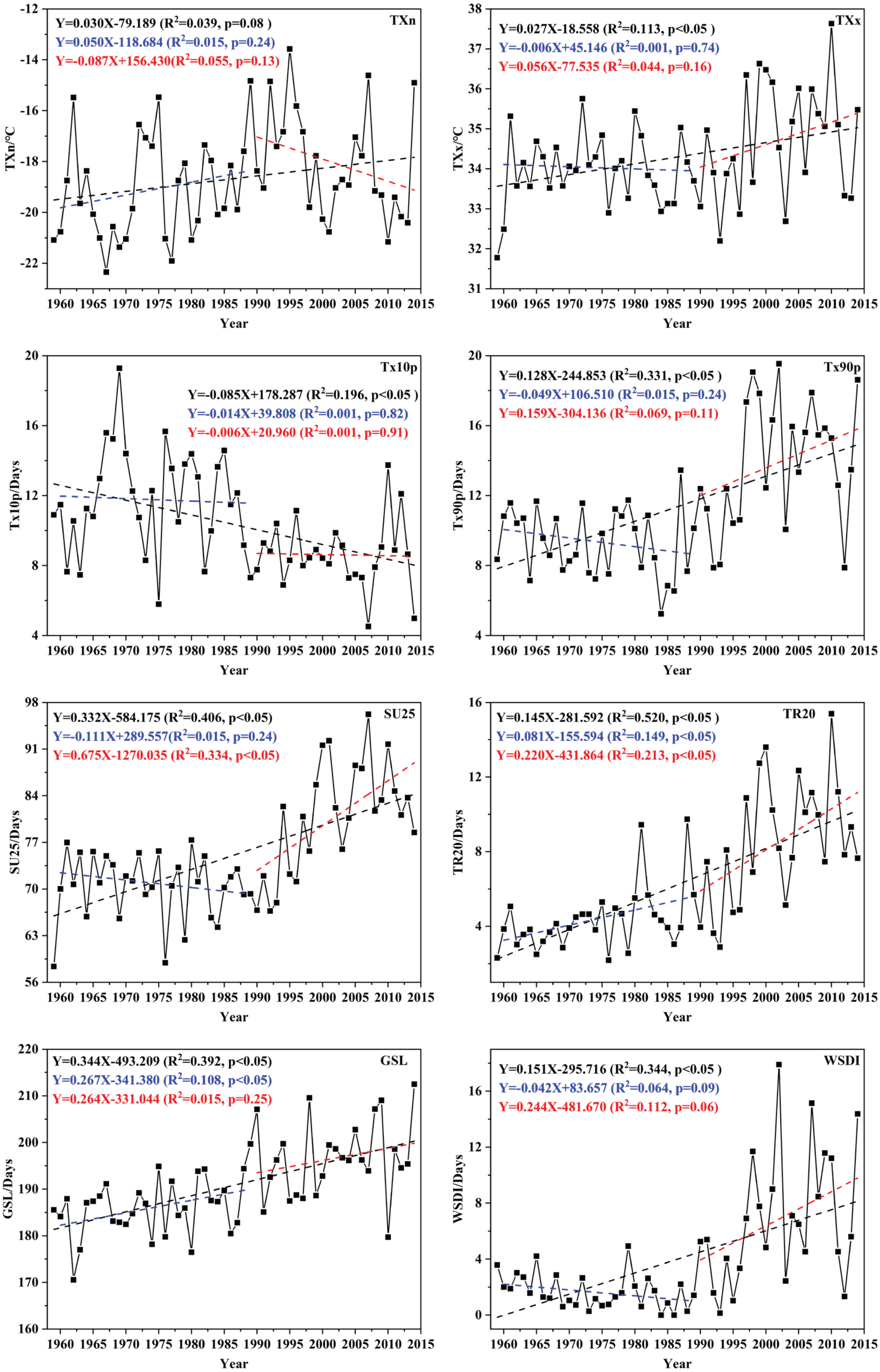


Fig. 3 *Averaged regional trends for temperature indices during 1959–2014 on the IMP. The black, blue and red dashed lines are linear trend of annual temperature indices, abrupt before and abrupt after, respectively.*


TXn
Y=0.030X-79.189 (R2=0.039, p=0.08)
Y=0.050X-118.684 (R2=0.015, p=0.24)
Y=-0.087X+156.430(R2=0.055, p=0.13)
TXn/°C
Year
TXx
Y=0.027X-18.558 (R2=0.113, p<0.05)
Y=-0.006X+45.146 (R2=0.001, p=0.74)
Y=0.056X-77.535 (R2=0.044, p=0.16)
TXx/°C
Year
Tx10p
Y=-0.085X+178.287 (R2=0.196, p<0.05)
Y=-0.014X+39.808 (R2=0.001, p=0.82)
Y=-0.006X+20.960 (R2=0.001, p=0.91)
Tx10p/Days
Year
Tx90p
Y=0.128X-244.853 (R2=0.331, p<0.05)
Y=-0.049X+106.510 (R2=0.015, p=0.24)
Y=0.159X-304.136 (R2=0.069, p=0.11)
Tx90p/Days
Year
SU25
Y=0.332X-584.175 (R2=0.406, p<0.05)
Y=-0.111X+289.557(R2=0.015, p=0.24)
Y=0.675X-1270.035 (R2=0.334, p<0.05)
SU25/Days
Year
TR20
Y=0.145X-281.592 (R2=0.520, p<0.05)
Y=0.081X-155.594 (R2=0.149, p<0.05)
Y=0.220X-431.864 (R2=0.213, p<0.05)
TR20/Days
Year
GSL
Y=0.344X-493.209 (R2=0.392, p<0.05)
Y=0.267X-341.380 (R2=0.108, p<0.05)
Y=0.264X-331.044 (R2=0.015, p=0.25)
GSL/Days
Year
WSDI
Y=0.151X-295.716 (R2=0.344, p<0.05)
Y=-0.042X+83.657 (R2=0.064, p=0.09)
Y=0.244X-481.670 (R2=0.112, p=0.06)
WSDI/Days
Year

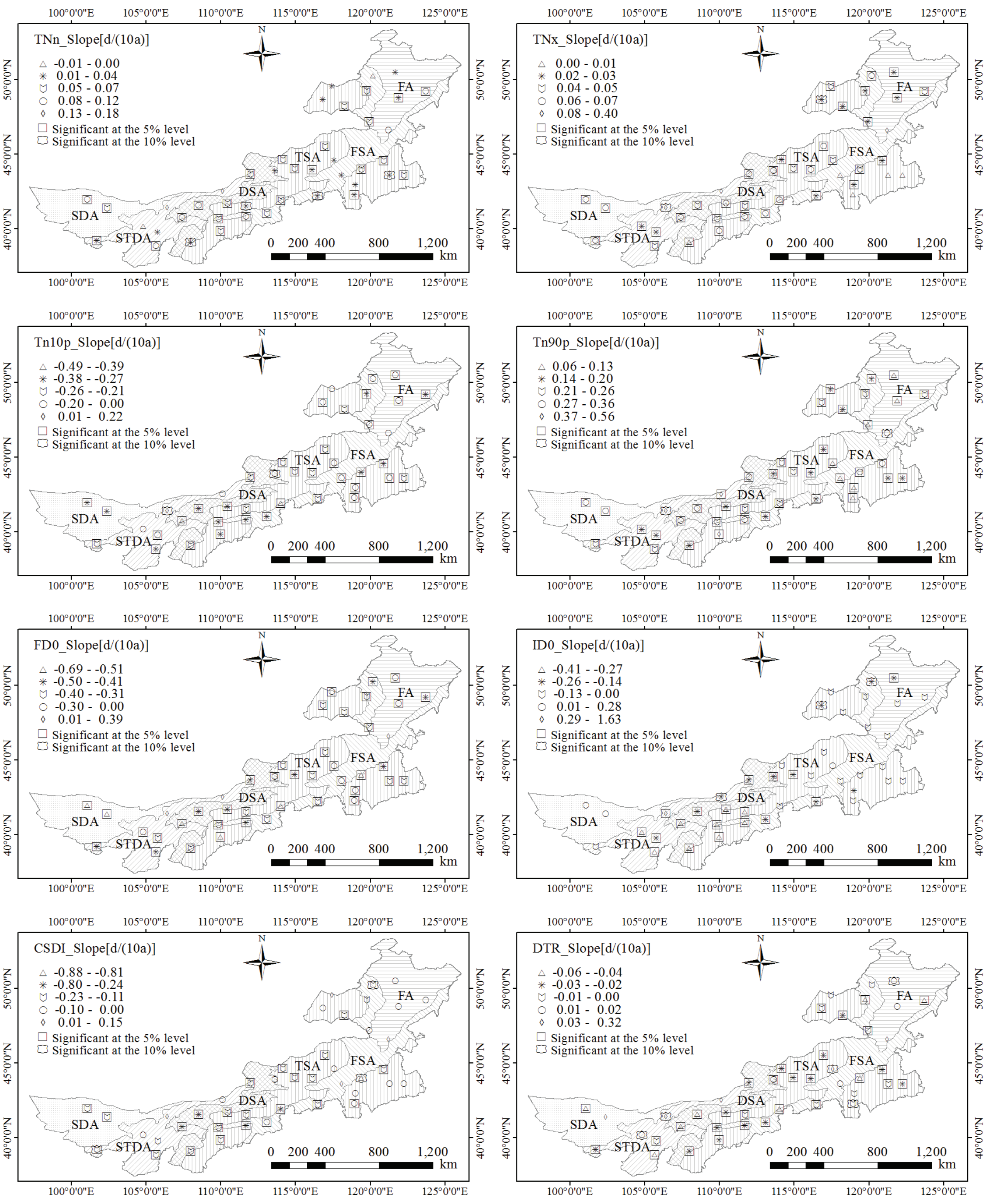
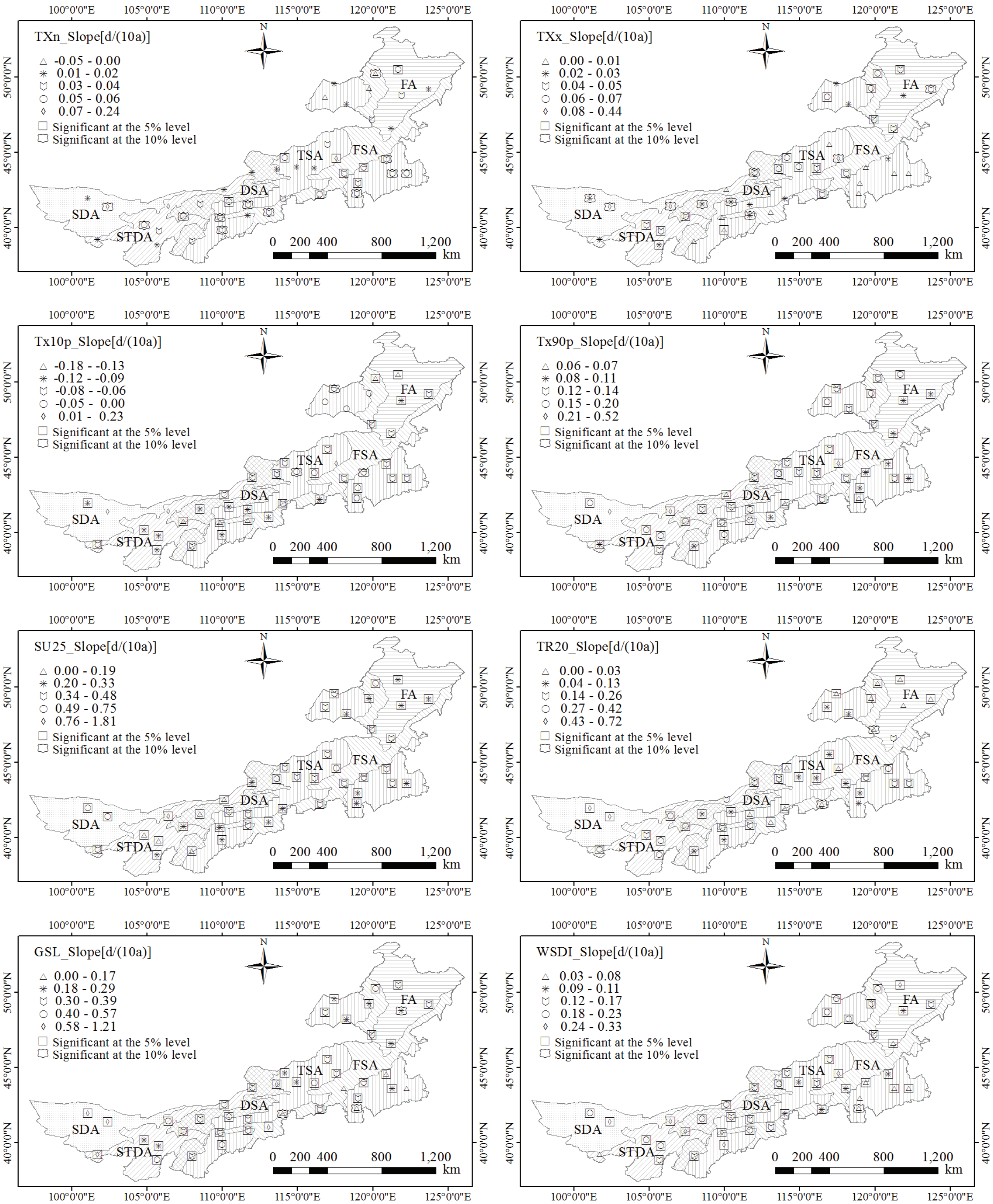


Fig. 4 Spatial variation of extreme temperature indices on the IMP during 1959–2014


TXn_Slope[d/(10a)]
-0.05 - 0.00
0.01 - 0.02
0.03 - 0.04
0.05 - 0.06
0.07 - 0.24
Significant at the 5% level
Significant at the 10% level
TXx_Slope[d/(10a)]
0.00 - 0.01
0.02 - 0.03
0.04 - 0.05
0.06 - 0.07
0.08 - 0.44
Significant at the 5% level
Significant at the 10% level
Tx10p_Slope[d/(10a)]
-0.18 - -0.13
-0.12 - -0.09
-0.08 - -0.06
-0.05 - 0.00
0.01 - 0.23
Significant at the 5% level
Significant at the 10% level
Tx90p_Slope[d/(10a)]
0.06 - 0.07
0.08 - 0.11
0.12 - 0.14
0.15 - 0.20
0.21 - 0.52
Significant at the 5% level
Significant at the 10% level
SU25_Slope[d/(10a)]
0.00 - 0.19
0.20 - 0.33
0.34 - 0.48
0.49 - 0.75
0.76 - 1.81
Significant at the 5% level
Significant at the 10% level
TR20_Slope[d/(10a)]
0.00 - 0.03
0.04 - 0.13
0.14 - 0.26
0.27 - 0.42
0.43 - 0.72
Significant at the 5% level
Significant at the 10% level
GSL_Slope[d/(10a)]
0.00 - 0.17
0.18 - 0.29
0.30 - 0.39
0.40 - 0.57
0.58 - 1.21
Significant at the 5% level
Significant at the 10% level
WSDI_Slope[d/(10a)]
0.03 - 0.08
0.09 - 0.11
0.12 - 0.17
0.18 - 0.23
0.24 - 0.33
Significant at the 5% level
Significant at the 10% level
N
FA
FSA
TSA
DSA
SDA
STDA
0 200 400 800 1,200
km
100°0'0"E 105°0'0"E 110°0'0"E 115°0'0"E 120°0'0"E 125°0'0"E
40°0'0"N 45°0'0"N 50°0'0"N

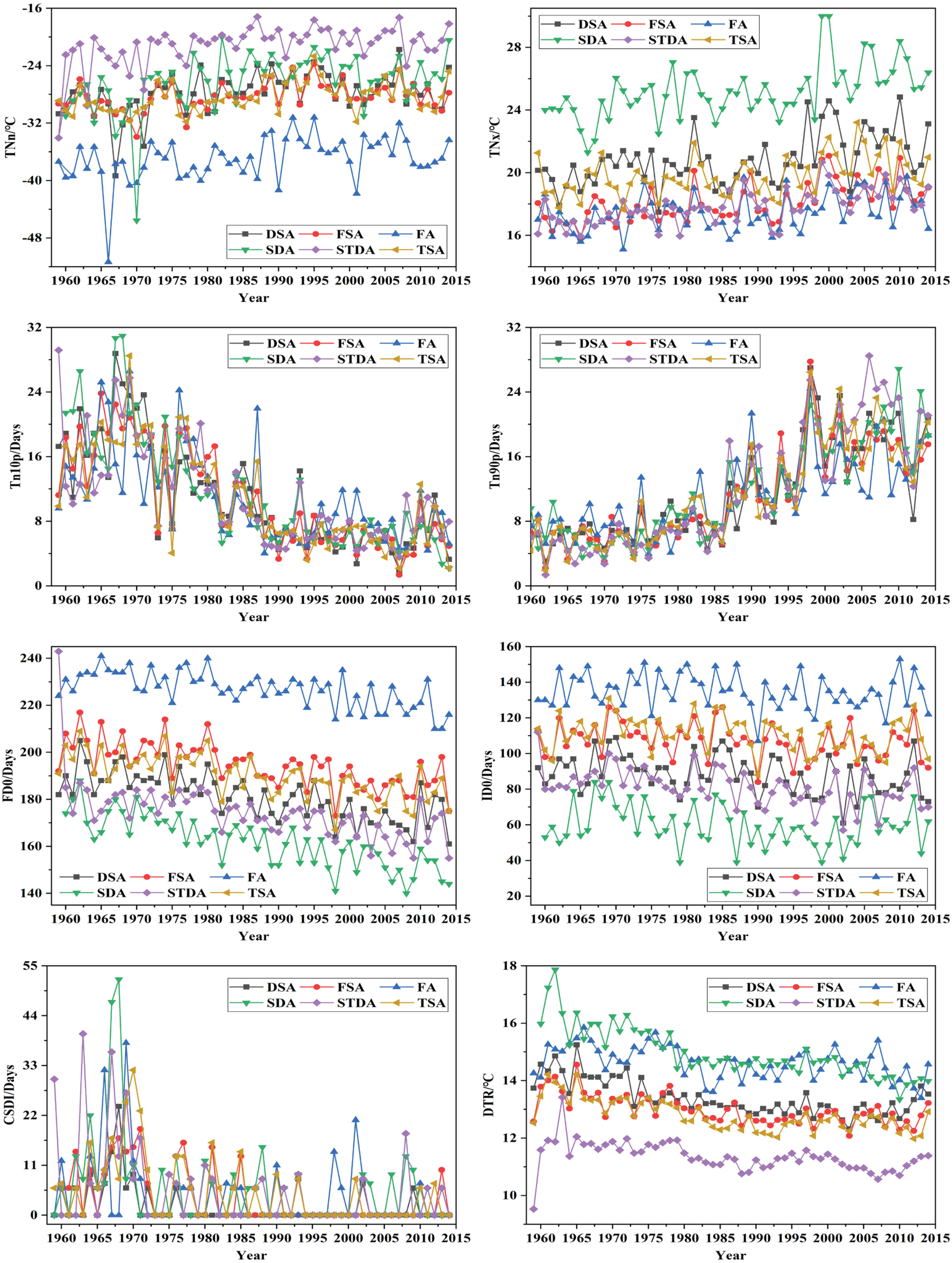
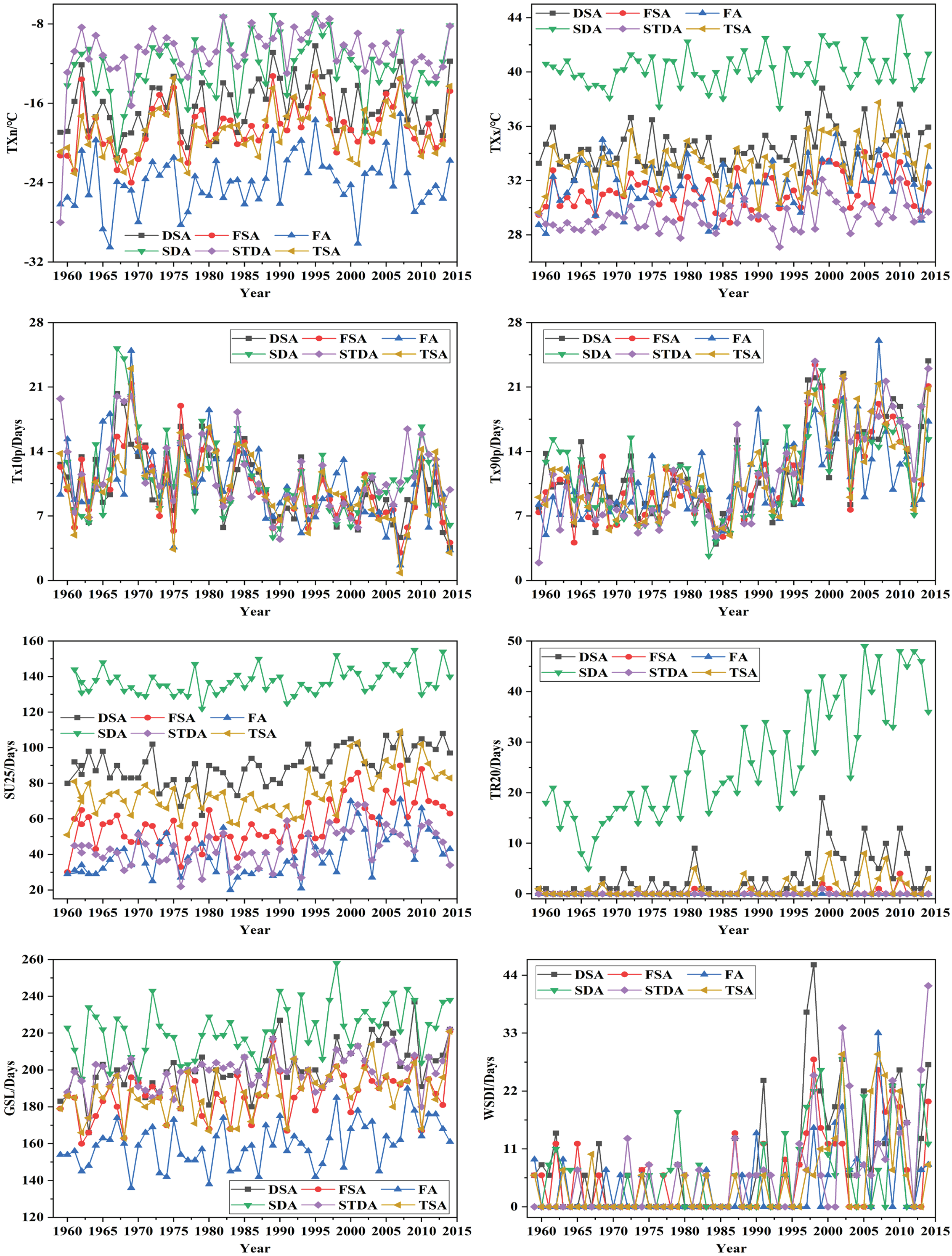


Fig. 6 *Temperature indices in six grassland types of the IMP during 1959–2014*


TXn/°C
TXx/°C
Tx10p/Days
Tx90p/Days
SU25/Days
TR20/Days
GSL/Days
WSDI/Days
Year
DSA
FSA
FA
SDA
STDA
TSA

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