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ORIGINAL PAPER

Response of vegetation NDVI to climatic extremes in the arid region of Central Asia: a case study in Xinjiang, China

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Abstract Observed data showed the climatic transition from warm-dry to warm-wet in Xinjiang during the past 30 years and will probably affect vegetation dynamics. Here, we analyze the interannual change of vegetation index based on the satellite-derived normalized difference vegetation index (NDVI) with temperature and precipitation extreme over the Xinjiang, using the 8-km NDVI third-generation (NDVI3g) from the Global Inventory Modelling and Mapping Studies (GIMMS) from 1982 to 2010. Few previous studies analyzed the link between climate extremes and vegetation response. From the satellite-based results, annual NDVI significantly increased in the first two decades (1981–1998) and then decreased after 1998. We show that the NDVI decrease over the past decade may conjointly be triggered by the increases of temperature and precipitation extremes. The correlation analyses demonstrated that the trends of NDVI was close to the trend of extreme precipitation; that is, consecutive dry days (CDD) and torrential rainfall days (R24) positively correlated with NDVI during 1998–2010. For the temperature extreme, while the decreases of NDVI correlate positively with warmer mean minimum temperature (*Tnav*), it correlates negatively with the number of warmest night days (*Rwn*). The results suggest that the climatic extremes have possible negative effects on the ecosystem.

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1 Introduction

The IPCC Fifth Assessment Report on Climate Change (2013) states that the warming of the climate system is unequivocal. The report further indicates that the climate system include not only changes in mean climate but also in climatic extremes (IPCC 2013; Fischer and Knutti 2015). Particularly, most of these studies show that the temperature and precipitation extremes had significant increasing trends over the recent decades (Rahmstorf and Coumou 2011; Perkins et al. 2012; Hansen et al. 2012; Donat et al. 2013).

Climate warming and changes in the extremes have eventually influenced vegetation dynamics in northern terrestrial ecosystems based on the modeling and observational studies (Myneni et al. 1997; Zhou et al. 2001; Nemani et al. 2003; Peng et al. 2013; Piao et al. 2015). Determining exactly how climate change impacts vegetation changes has received extensive attention in the past several decades, particularly in arid areas (e.g., Piao et al. 2003; Yang et al. 2012; Xu et al. 2015). Arid areas have been shown to be highly sensitive to climate change. In these areas, vegetation growth is limited by water scarcity (Roerink et al. 2003; Fensholt et al. 2009; Zhang et al. 2010). It is essential to understand the vegetation dynamic changes and responses to climate change to estimate the quality of ecosystem and maintain optimal ecosystem functioning (Mu et al. 2013). Li et al. (2015)

studied the potential impacts of climate change on vegetation dynamics in Central Asia.

Xinjiang is located in the hinterland of Central Asia's arid regions, is characterized by an extremely arid climate, and the local ecosystem responds most sensitively to climate change (Xu et al. 2015). For the variation of vegetation coverage in this area, Xu et al. (2015) showed that the normalized difference vegetation index (NDVI) was an increasing trend from 1982 to 2013 in grassland and cropland based on the extended NDVI datasets by the Global Inventory Modelling and Mapping Studies (GIMMS) and the Moderate Resolution Imaging Spectroradiometer (MODIS). Chen et al. (2015) and Zhao et al. (2011) demonstrate that the vegetation coverage and NDVI showed an increased trend from 1982 to 2000 and reversed to decrease since 2000. Fang et al. (2013) indicated that the Leaf Area Index (LAI) in Xinjiang increased from 1981 to 2011, and the gross primary production (GPP) and net primary production (NPP) decreased in the central and northernmost regions of Xinjiang from 2000 to 2010. Wang et al. (2013) exhibited that the vegetation coverage in the Tarim River Basin improved from 1982 to 2006.

These studies of the response of vegetation to climate change, however, can be reconciled when climatic extreme effects are considered. Many studies of vegetation response to climate change in Xinjiang confirmed the linkage between vegetation and precipitation, but their results are somehow at odds when reporting relationships with temperature. For example, the decrease of NDVI during the past 30 years reported by Chen et al. (2015) was verified in terms of NDVI and precipitation relationships but debated for NDVI and temperature (Li and Shi 2000; Guo et al. 2008; Li et al. 2009; Zhao et al. 2011; Cao et al. 2011; Fang et al. 2013). Wang et al. (2013) investigated that the temperature was the main stress factor for mountain vegetation and runoff for oasis vegetation in the Tarim River Basin from 1982 to 2006. Xu et al. (2015) indicated that NDVI was highly correlated with accumulated monthly precipitation, and there was a lagged effect of precipitation, temperature, and evaporation on NDVI change in Xinjiang from 2001 to 2013. These studies of the response of vegetation to climate change, however, can be reconciled when climatic extremes effects are considered.

The NDVI, taking advantage of the long-term, large-scale, and continuous observations, is frequently used as a proxy indicator of vegetation cover and changes (Gomez-Mendoza et al. 2008; Fensholt et al. 2012; Schmidt et al. 2014). Presently, most studies were based on short periods of NDVI data, for example, GIMMS NDVI are available only to 2006, and the MODIS NDVI starts from 2001 (Xu et al. 2015). More speculatively, the third-generation Normalized Difference Vegetation Index (NDVI3g) improved by the GIMMS group provides a long temporal dataset, from July 1981 to December 2011 (Pinzon and Tucker 2014). Zeng et al. (2013) confirmed that the GIMMS-NDVI3g data has been exhibited to represent real responses of vegetation to climate change at global scales. However, GIMMS NDVI3g estimates are not yet available in Central Asia.

The objective of this paper is to extract vegetation dynamics and their response to climate variables in arid area by taking Xinjiang in China from 1981 to 2010 as a case study. The study extends the GIMMS NDVI3g data used to extreme arid climate environments. We investigated vegetation dynamics with not only the response to precipitation and evaporation but also the response to climatic extremes (temperature and precipitation extremes), which is important to determinate the variability of vegetation.

2 Materials and methods

2.1 Regional settings

Xinjiang, located in the hinterland of Eurasian continent, is the largest province in China. It extends between 73.66°–96.38°E and 34.42°–49.17°E, with an area of 1.66 million km^2. There are three mountains, the Altai, Tianshan, and Kunlun Mountains, surrounded the vast desert basins from north to south, such as the Junggar and the Tarim Basin (Fig. 1; Zhang et al. 2012; Wang et al. 2014a, b). It is far from any ocean, a typical semi-arid and arid climate, with long-term average annual precipitation of 158 mm (from 1961 to 2010), only 25% of the average level in China, gradually decreasing from east to west. The Tianshan Mountains divide Xinjiang into two parts: northern Xinjiang and southern Xinjiang, resulting in two mountain-basin systems with different hydrological and thermal conditions (Xu et al. 2004). The unique humid mountains-arid basins landscape, a strong spatial heterogeneity in the hydro-climatic conditions, determines the uneven spatial-temporal distributions of water and energy variabilities and form different eco-domains. Its ecological environment is very fragile and very sensitive to climate change (Wang et al. 2014a, b; Wu et al. 2015).

2.2 Data source

Continuously observed daily meteorological data of 96 meteorological stations across Xinjiang were collected from the China Meteorology Administration (CMA), include daily precipitation (*P*/mm), temperature (*T*/°C), minimum temperature (Tmin/°C), maximum temperature (Tmax/°C), wind speed (*W*/m s), relative humidity (*H*/%), and sunshine duration (*S*/h) from 1961 to 2010. The torrential rainfall was defined as the precipitation of 24 h exceeded 24 mm or 12 h exceeded 20 mm in Xinjiang, and the torrential rainfall day was determined as the day of the torrential rainfall, accordingly. All the 96 meteorological stations selected for this study had been maintained following the standard of the China Meteorology

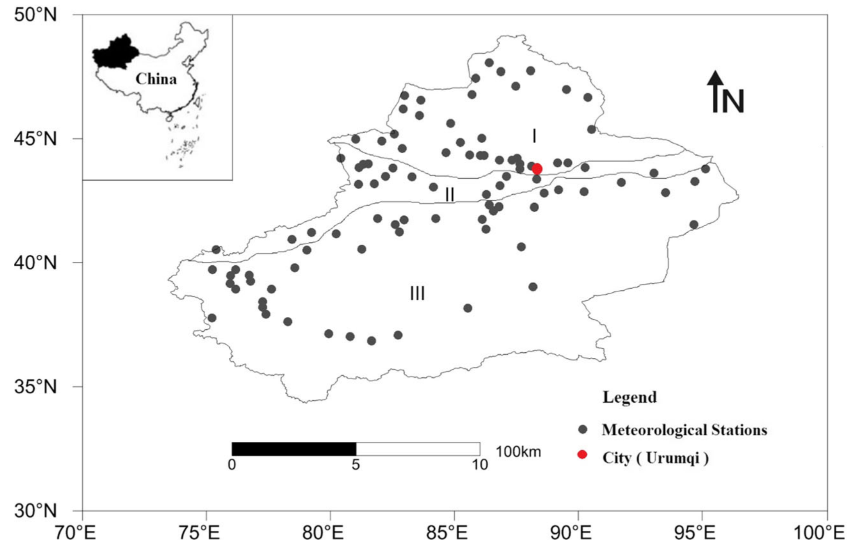

Fig. 1 Study area and meteorological stations in Xinjiang (*I* Northern Xinjiang, *II* Tianshan Mountains, *III* Southern Xinjiang)

Administration (CMA). The standard requires strict quality control processes including extreme inspection, time consistency check, and others before releasing these data. Monthly and yearly climatic data were calculated based on daily data.

Remote sensing is a very meritorious tool to estimate important information of the temporal-spatial changes in vegetation conditions (Gomez-Mendoza et al. 2008; Coops et al. 2009). The Normalized Difference Vegetation Index (NDVI) is generally used as a proxy indicator of vegetation changes and may be derived from the Advanced Very High-Resolution Radiometer (AVHRR) sensor on the National Oceanic and Atmospheric Administration (NOAA) Polar Operational Environmental Satellite (POES) series, among others (Gomez-Mendoza et al., 2008; Eastman et al. 2013). The data has been used to produce various versions of the global inventory modelling and mapping studies (GIMMS) NDVI datasets (Wang et al. 2014a, b). The newest version of the GIMMS NDVI datasets version 3 (GIMMS-NDVI3g), has been recently released and with a spatial resolution of 8 km, a temporal frequencies of 15-day and a temporal span from July 1981 to December 2010 (Zeng et al. 2013; Zhu et al. 2013). All data can be downloaded at http://ecocast.arc.nasa. Gov/data/pub/gimms/. The GIMMS-NDVI3g data in Xinjiang from 1982 to 2010 were extracted and applied in this study.

2.3 Methods

2.3.1 Climatic extreme indices

Extreme climate can be defined from various aspects, such as extreme temperature, extreme precipitation, or even storm events. As climatic extremes can be defined as large areas experiencing unusual climate values over a long period of time, one way to investigate the trends in climatic extremes over time is to develop indices (Chen et al. 2014).

Considering the climate characteristics of Xinjiang, we ran a factor analysis and chose 3 extreme temperature and 5 extreme precipitation indices from 57 extreme indices recommended by STARDX (soft and documentation available for download from http://www.cru.uea.ac.uk/projects/stardex/), which can calculate precipitation and temperature extremes on the basis of daily meteorological data. In those indices, some were calculated on the basis of station-related thresholds whereas others on the basis of fixed thresholds or absolute peak values. Table 1 lists the indices that have been used in this study.

We then ran a factor analysis and selected seven temperature extreme and five precipitation extreme indices for the following analysis (Table 1).

Time series related to extreme temperature and precipitation consisted of:

(a) Mean Tmin (Tnav) and Tmax (Txav): mean minimum and maximum temperature;
(b) Number of warmest night days (Rwn): total annual number of days with night temperature >90th percentile;
(c) Torrential rainfall (TR) and number of torrential rainfall days (R24): total annual precipitation and the number of days with precipitation ≥24 mm/day;
(d) Number of precipitation days (R0.1): total annual number of days with precipitation ≥0.1 mm/day;
(e) Consecutive dry days (CDD): on an annual basis, the longest consecutive number of rain days with precipitation <1 mm/day;
(f) Consecutive wet days (CWD): on an annual basis, the longest consecutive number of rain days with precipitation ≥1 mm/day.

2.3.2 Non-parametric Mann–Kendall method

The non-parametric Mann–Kendall method has been generally used in long-term trend and abrupt change analysis on

Table 1 Temperature and precipitation extremes indices selected for this study

ID	Indicator name	Definitions	Units
Temperature indices			
Tnav	Mean Tmin	Mean minimum temperature	°C
Txav	Mean Tmax	Mean maximum temperature	°C
Rwn	Number of warmest night days	Annual count of days when night temperature >90th percentile	Days
Precipitation indices			
TR	Torrential rainfall	Annual count when precipitation ≥24 mm	mm
R24	Number of torrential rainfall days	Annual count of days when precipitation ≥24 mm	Days
R0.1	Number of precipitation days	Annual count of days when precipitation ≥0.1 mm	Days
CDD	Consecutive dry days	Maximum number of consecutive days with RR <1 mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥1 mm	Days

meteorological and ecological factor time series and was considered statistically significant at 95% significance level (Chen et al. 2014; Yao and Chen, 2015).

In this method, H0 represents distribution of random variables, and H1 represents possibility of bi-directional changes. The test statistic S is given by

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

in which X_k and X_j are the sequential data values, n is the length of the data set, and

$$\operatorname{sgn}(\theta)=\begin{cases}+1, & \theta>0\\ 0\,, & \theta=0\\ -1, & \theta<0\end{cases} \tag{2}$$

In particular, if the sample size is larger than ten, the statistic S is nearly normally distributed, i.e., the statistic

$$Z_c=\begin{cases}\dfrac{S-1}{\sqrt{\operatorname{var}(S)}}, & S>0;\\ 0\quad, & S=0;\\ \dfrac{S+1}{\sqrt{\operatorname{var}(S)}}, & S<0;\end{cases} \tag{3}$$

is a standard normal random variable, whose expectation value and variance are

$$E(S)=0 \tag{4}$$

$$\operatorname{var}(S)=\left[n(n-1)(2n+5)-\sum_t t(t-1)(2t+5)\right]\Big/18 \tag{5}$$

in which t denotes the extent of any given tie and Σ denotes the summation over all ties.

In the Mann–Kendall test, another very useful index is the Kendall slope, which is the magnitude of the monotonic trend and is given by

$$\beta=\operatorname{Median}\left(\frac{x_i-x_j}{i-j}\right),\forall j<i \tag{6}$$

in which $1<j<i<n$. A positive value indicates an "upward" trend, i.e., an increase with time, and a negative value indicates a "downward trend," i.e., a decrease with time. In this study, we selected to characterize the trends and changes in precipitation index and NDVI in Xinjiang.

The potential evapotranspiration (PET) were calculated using the Penman-Monteith equation suggested by the Food and Agriculture Organization in this study (Allen et al. 1998). The climatic dryness index—the ratio of PET to P, is widely used to reveal climatic drying or wetting (Donohue et al. 2012).

In addition, linear regression analysis was used to evaluate the change of magnitude of precipitation and NDVI index time series. Spearman's correlation test was used to quantify the correlation between two variables (Chen et al. 2014). Temporal evolution of climatic factor is also examined with their annual anomalies from the 1981 to 2010 average in Xinjiang.

3 Results and discussion

3.1 Climate change in Xinjiang over the last 50 years

The mean annual temperature (MAT) in Xinjiang from 1961 to 2010 has increased by 0.32 °C/decade, showing a significant warming trend. The Mann–Kendall method indicated that the MAT exhibited significant increasing trends and step change points in 1987 at the 99% significance level (Fig. 2a). The warming trend is consistent with Central Asia and China, but is much lower than northwestern China (Brohan et al. 2006; Wang et al. 2008; Li et al. 2012a, b).

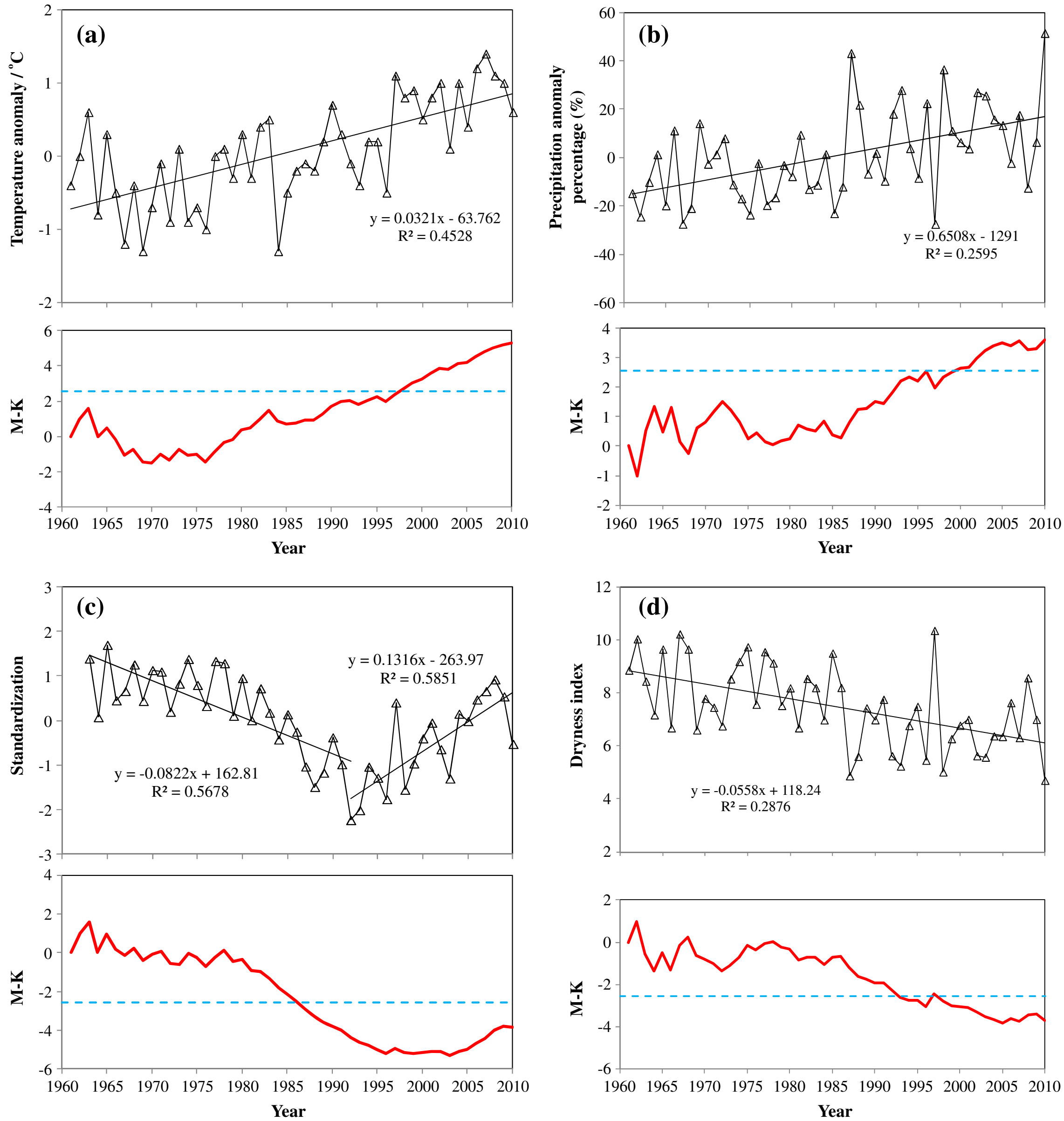

Fig. 2 The trends and the abrupt change tested by the Mann–Kendall method for the annual temperature anomaly (**a**), annual precipitation anomaly (**b**), annual potential evapotranspiration (**c**), and dryness index (**d**) in Xinjiang from 1961 to 2010. In here, as the *blue dashed line* represents the confidence line (p = 0.01), the *red solid line* is the Mann–Kendall trends over the confidence line

Among the different regions, northern Xinjiang had the highest increasing rate of 0.37 °C/decade, followed by the Tianshan Mountains with a rate of 0.34 °C/decade, and southern Xinjiang has the lowest rate of 0.26 °C/decade. The Mann–Kendall method revealed that the increasing trends are statistically significant at the 99% significance level. The mean annual precipitation (MAP) from 1961 to 2010 was generally increased by 6.51% per decade and step change points occurred in 1987 at the 99% significance level (Fig. 2b). Spatially, the increase in magnitude of MAP reached 9.48, 6.80, and 4.61% in southern and northern Xinjiang and Tianshan Mountains, respectively. Figure 2c displays the total annual PET and its changes in Xinjiang from 1961 to 2010. The mean annual PET was 1129.23 mm, with a maximum of 1204.45 mm in 1965 and a minimum of 1030.04 mm in 1992. The mean annual PET was significant decreased by 30.80 mm/decade from 1961 to 1990 and then showed opposite change trends of PET after the 1990, with a rate of 52.62 mm/decade.

The dryness index in the Xinjiang from 1961 to 2010 has decreased by 0.558/decade, showing a wetting trend. The Mann–Kendall method indicated that the step change points occurred in 1987 at the 99% significance level.

Temperature and precipitation time series had obvious increasing trends, providing evidence of the climate change in Xinjiang from 1961 to 2010. Figure 3 showed the

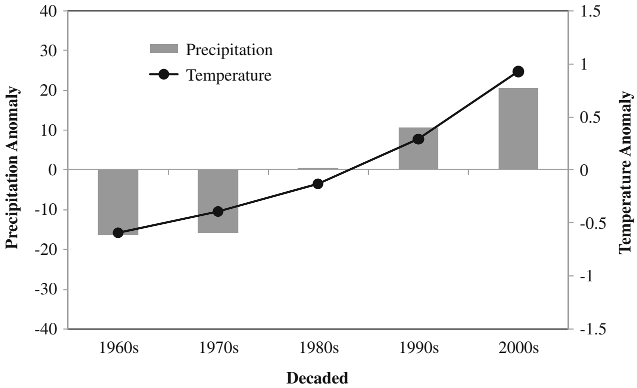

Fig. 3 Temperature and precipitation inter-decade anomaly changes in Xinjiang based on observed data from 1961 to 2010

inter-decadal anomaly change in Xinjiang over the last 50 years. These results confirm the climatic transition from warm-dry to warm-wet in Xinjiang based on observed data, which is consistent with previous studies on climate and environmental change (Shi et al. 2002, 2003, 2007; Zhao et al. 2009; Xu et al. 2010; Li et al. 2011, 2012a, b, 2013; Fang et al. 2013). Fang et al. (2013) further indicated the climatic transition in Xinjiang based on multiple model simulation results from CMIP5.

3.2 Climatic extreme change in Xinjiang over the last 50 years

The Mann–Kendall method showed that the temperature extreme indices mean minimum temperature (Tnav) and number of warmest night days (Rwn) in the entire Xinjiang region had significant increasing trends, while mean maximum temperature (Txav) had a slightly increasing trend. Except for the Txav, the Tnav and Rwn time series passed statistical test at the 99% significance level (Table 2, Fig. 4a, b). Spatially, Tnav had obvious increasing trends in northern and southern Xinjiang and the Tianshan Mountain, with rates of 0.87, 0.66, and 0.65 °C/decade, respectively, indicating that the Tnav in northern Xinjiang has been rising faster than other regions. The Rwn increased by 39.83 days from 1961 to 2010 at a rate of 6.74 days/decade and the average increasing rate after 1998 is up to 12.82 days/decade.

During the past 50 years, torrential rainfall (TR), number of torrential rainfall days (R24), number of precipitation days (R0.1), and consecutive wet days (CWD) had positive trends in Xinjiang, and consecutive dry days (CDD) had a negative trend (Table 2). Figure 4 show the temporal series of the extreme precipitation indices in Xinjiang from 1961 to 2010. Figure 4c exhibited that the TR has significant increased trends since the middle of the 1980s, with a rate of 1.78 mm/decade. Spatially, the increase in rate of the TR reached 1.74, 0.65, and 4.96 mm per decade in northern and southern Xinjiang and Tianshan Mountains, respectively. Scrutiny of the time series in Fig. 4d reveals that the number of torrential rainfall days (R24) has obviously increased by 0.05 day/decade and the possible step change points occurred in 1987. Among the three regions, Tianshan Mountains had the highest rate (0.14 day/decade), followed by northern Xinjiang (0.05 day/decade) and southern Xinjiang (0.02 day/decade). The number of precipitation days (R0.1) had highly positive trends in northern, southern Xinjiang and Tianshan Mountains, with rates of 2.54, 1.42, and 1.72 day/decade, respectively (Fig. 4e). For the CWD, the northern Xinjiang had a highest positive trend (0.22 day/decade) than those of the southern Xinjiang (0.07 day/decade) and the Tianshan Mountains (0.001 day/decade) (Fig. 4f). The CDD had a decreasing trend in Xinjiang and sub-regions (northern Xinjiang, Tianshan Mountains, and southern Xinjiang), with rates of

Table 2 The trend test results of the climatic indices from 1961 to 2010 in the Xinjiang

Indices	Trend test				Units
	Xinjiang	Northern Xinjiang	Southern Xinjiang	Tianshan mountains	
Tav	0.32**	0.37**	0.26**	0.34**	°C/decade
Tnav	0.75**	0.87**	0.65*	0.66**	°C/decade
Txav	0.08	0.09	0.09	0.04	°C/decade
Rwn	6.74**	7.21**	5.24*	6.98**	Days/decade
Pav	10.28**	13.06**	5.60*	15.56**	mm/decade
PETav	−15.78**	−17.26**	−13.21*	−15.24**	mm/decade
TR	1.77**	1.74**	0.65*	4.86**	mm/decade
R24	0.05**	0.05**	0.02*	0.14**	Days/decade
R0.1	1.93**	2.54**	1.42*	1.72**	Days/decade
CDD	−1.97*	−1.06*	−3.08	−1.43*	Days/decade
CWD	0.11*	0.22**	0.07	0.001	Days/decade

Significant at $*p < 0.05$; $**p < 0.01$

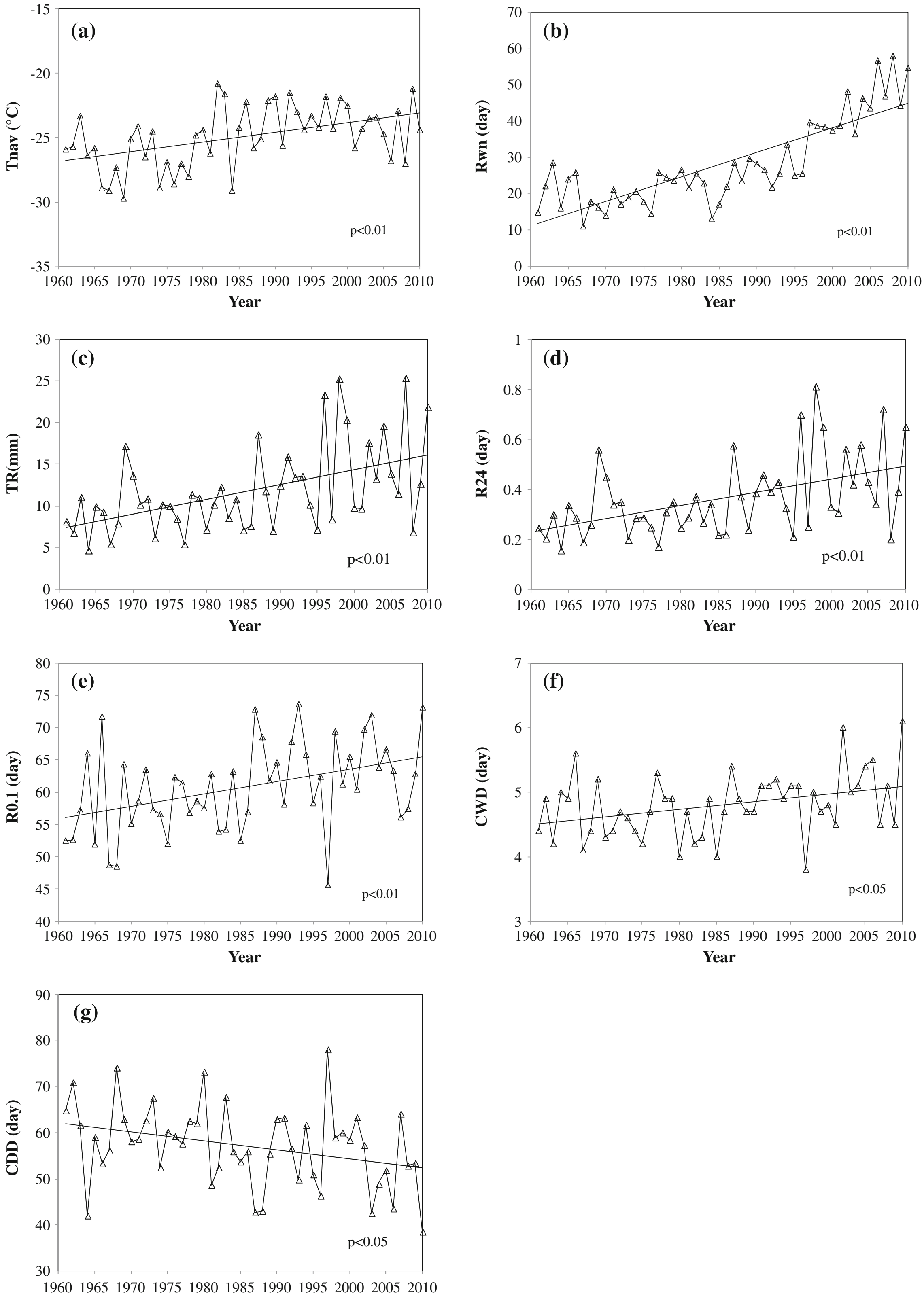

Fig. 4 The trends of the Tnav (**a**), Rwn (**b**), TR (**c**), R24 (**d**), R0.1 (**e**), CWD (**f**), and CDD (**g**) in Xinjiang based on meteorological station observations from 1961 to 2010

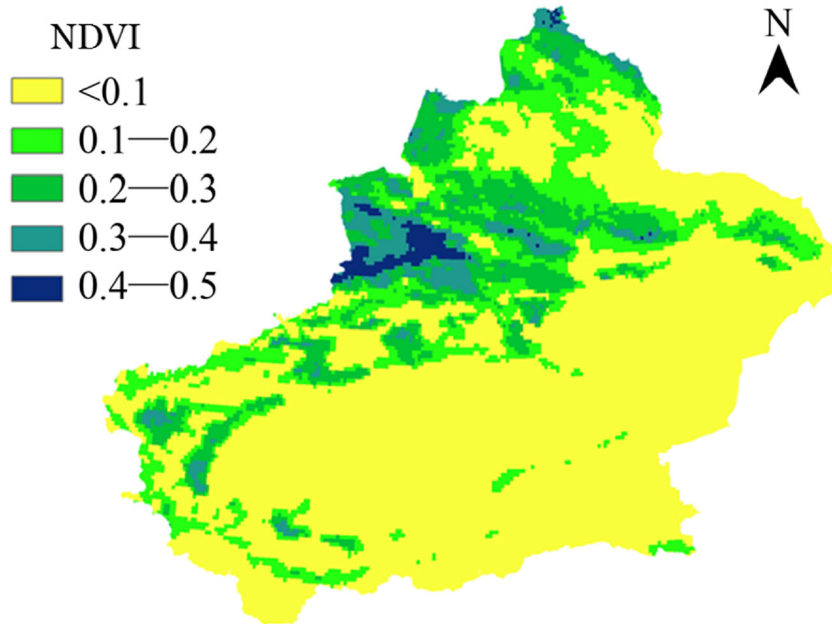

Fig. 5 Spatial pattern of average annual NDVI from 1982 to 2010

1.97, 1.06, 1.43, and 3.08 day/decade, respectively, indicating that the CDD in northern Xinjiang has been rising slowest than other regions (Table 2, Fig. 4e).

3.3 Vegetation dynamic based on GIMMS-NDVI3g in Xinjiang from 1982 to 2010

Figure 5 shows the spatial pattern of the average annual maximum NDVI in Xinjiang. Overall the regions where the NDVI is more than 0.1, approximately 33.7% of all pixels in Xinjiang are mainly located in the Tianshan Mountain and inner alluvial fan oases, especially in the Ili River Valley, Altay Mountains, Tacheng Region, and the northern slope of the Tianshan Mountain. This is mainly because the vegetation is distributed mainly along rivers or the oases, which contains above 90% population and production activities. Long-term average NDVIs are lesser in the Taklimakan Desert, Gurbantunggut Desert, and the transition zone between mountain and oasis, where there are limited available water resources and the groundwater levels are opposed for plant growth.

The annual average NDVI is 0.108 from 1982 to 2010 in Xinjiang, with a maximum of 0.116 in 1994 and a minimum of 0.102 in 1985. Figure 6 indicates the trends of the average NDVI of the Xinjiang in valued pixels over the last 30 years. The annual average NDVI was significant increased by 0.004/decade from 1982 to 1998, and then showed obvious decreased trends after the 1998, with a rate of 0.005/decade. Furthermore, the spatial trends and significant level of the NDVI changes over the entire Xinjiang from 1982 to 2010 was shown in Fig. 7. The trends can be divided into three levels: significant increasing (statistics of NDVI trend (S_{NDVI}), $S_{NDVI} \geq 0.0005$), non-significant ($-0.0005 < S_{NDVI} < 0.0005$) and significant decreasing ($S_{NDVI} \leq -0.0005$) with the area ratio of 18.57, 25.43, and 56%, respectively. These results reveal significantly different trends among different regions: NDVI trends showed significant decreasing in the northernmost regions of Xinjiang, especially in the Ili River Valley, Altay Mountains, and Tacheng Region, where the annual average NDVI also have higher values. They significantly increased in the region of the northern slope of the Tianshan Mountain and around the Tarim Basin, especially along the Tarim River. The most obvious increased area was the most active area in terms of human activities in Xinjiang over the last decade, i.e., developed oasis and Tarim River Water Conveyance Project.

3.4 Response of vegetation to temperature and precipitation extremes

To evaluate the effects of temperature and precipitation extreme change on the NDVI in Xinjiang, the statistical

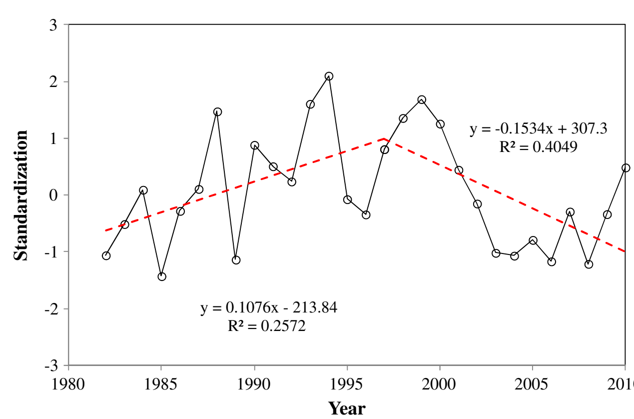

Fig. 6 NDVI trends in Xinjiang based on GIMSS-NDVI from 1982 to 2010

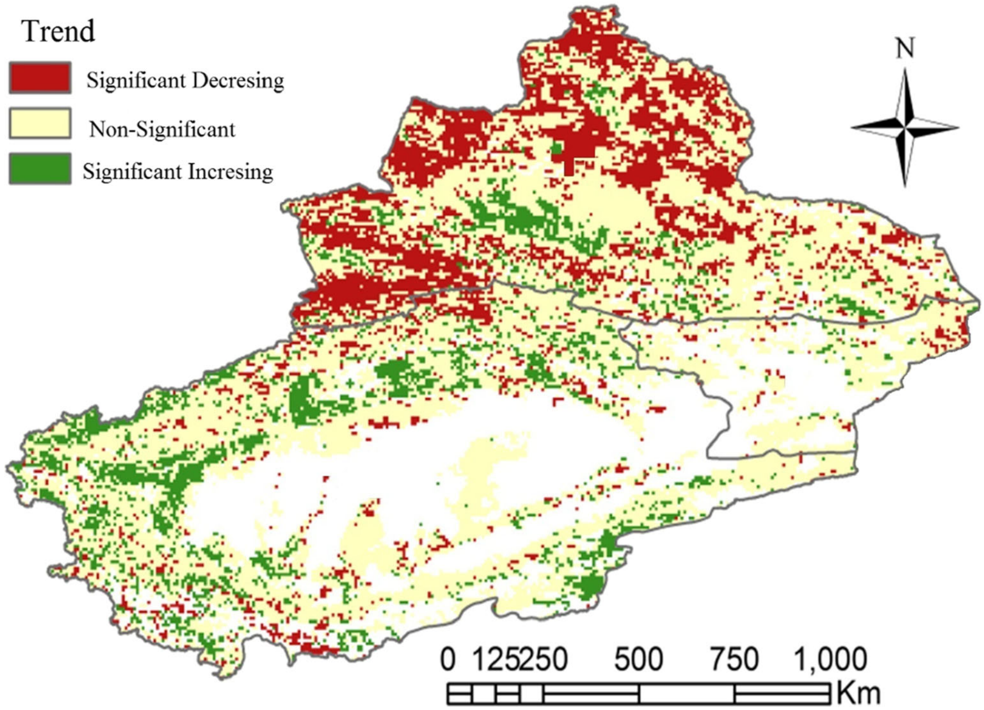

Fig. 7 Trends of the average annual NDVI from 1982 to 2010 ("Significant" represents the statistically significant at the 95% significance level)

relationships between the NDVI changes and eight climatic extremes indices were investigated using the GIMMS-NDVI3g datasets over the period of 1982–2010 and 1998–2010. These correlations in Xinjiang from 1982 to 2010 were also shown in Tables 3 and 4.

Climate warming enhances vegetation dynamic in the Arctic. We did find a significant negative correlation between NDVI and dryness index ($R = -0.42$, $p < 0.01$) for the period of 1998–2010 than 1982–1998 ($R = -0.34$, $p < 0.05$). Generally, NDVI had a positive correlation with precipitation while a negative correlation with PETav, which implies that the precipitation was the key factor for vegetation growth while PETav was the competing factor (Piao et al. 2006; Li et al. 2002; Xu et al. 2015). However, there is a transition of the NDVI after 1998, which shows the NDVI decreased with precipitation increasing and with temperature rising. The significant negative correlation between NDVI and PET (Fig. 8b) suggests an ET-induced drying effect of the soil water in the arid regions. Yang et al. (2006, 2007) indicated the actual evaporation in the arid region (i.e., Xinjiang) was dominated by the change in water variables (Pav) rather than in energy variables (PETav). Thus, the NDVI change was determined by the precipitation, eventually.

Table 3 show the correlation between the precipitation extremes (TR, R24, R0.1, CDD, and CWD) and NDVI from 1998 to 2010. The consecutive wet days *(CDD)* and the number of torrential rainfall days *(R24)* had a stronger correlation coefficient with the NDVI and relatively stronger for the torrential rainfall (TR) (Table 3, Fig. 8c, d). The correlations between the NDVI and the other precipitation extremes (R0.1 and CWD) were weak or insignificant (Table 3). Zhao et al. (2014) indicated the precipitation extremes accounts for up to 50% or more of the precipitation in Xinjiang, which implies that the precipitation increased was dominated by the precipitation extremes

Table 3 The correlation coefficient between NDVI and precipitation indices

Indices	GIMMS-NDVI3g	
	1982–2010	1998–2010
Pav	0.30*	0.33*
PETav	*−0.49***	*−0.58***
TR	0.20	0.36**
R24	0.24	*0.45***
R0.1	0.31*	0.13
CDD	0.27*	*0.48***
CWD	0.05	−0.20

Significant at *$p < 0.05$; **$p < 0.01$

Table 4 The correlation coefficient between NDVI and temperature indices

Indices	GIMMS-NDVI3g	
	1982–2010	1998–2010
Tav	−0.06	−0.13
Tnav	0.07	*0.42**
Txav	−0.12	−0.14
Rwn	−0.14	*−0.53**

*Significant at $p < 0.01$

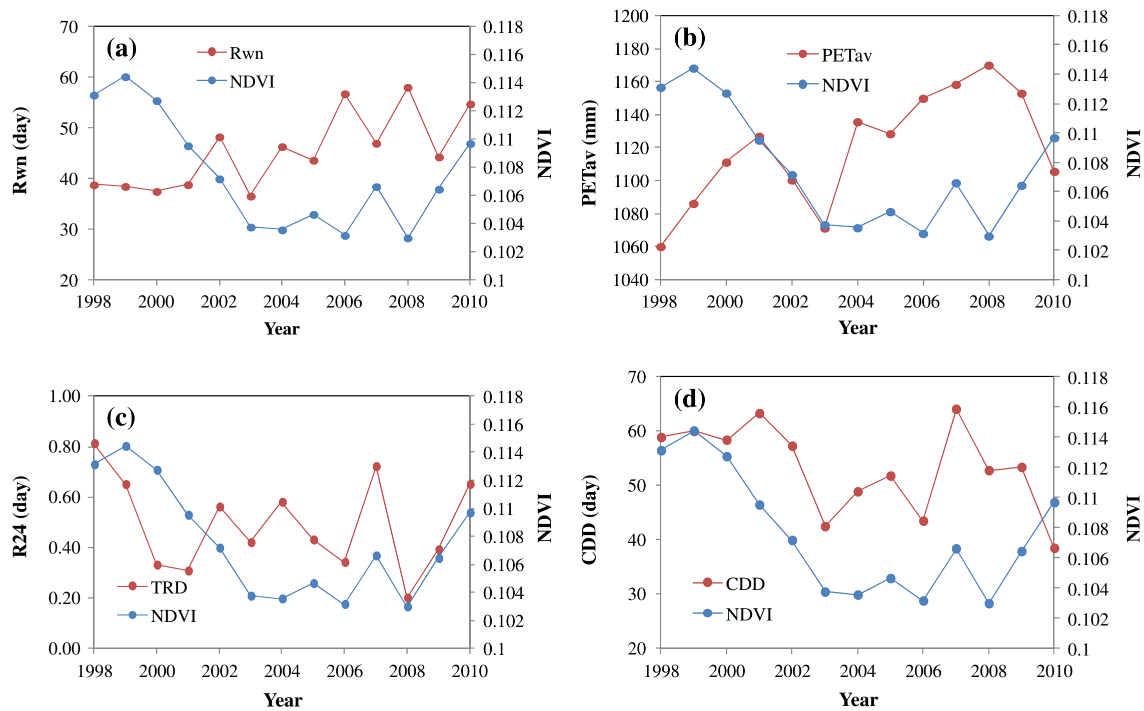

Fig. 8 The relationship between the NDVI and climatic extremes indices (**a** Rwn, **b** PETav, **c** TRD, **d** CDD) in Xinjiang from 1998 to 2010

increasing. The increases of evaporation, R24, and decreases of the consecutive wet days (CDD) may conjointly cause a heavy loss of soil moisture, which leads the shallow roots of desert plants to weaken and die, thereby reducing species diversity and vegetation cover (Chen et al. 2014). Thus, we consider that precipitation extremes (CDD and R24) are very important in NDVI change in Xinjiang.

The correlation coefficient indicated that the number of warmest night days (Rwn) and the mean minimum temperature (Tnav) had closely tied with the NDVI (Table 4). Peng et al. (2013) found that the positive correlation between NDVI and Tnav in temperate grassland regions (i.e., in central North America and temperate China). Night-time warming can influence vegetation productivity in two opposite ways: via enhanced autotrophic respiration, and indirectly via stimulation of plant photosynthesis during the following daytime through decreasing frost risk (Kim et al. 2012; Gu et al. 2008), and physiological regulatory mechanisms (Turnbull et al. 2002; Griffin et al. 2002; Prasad et al. 2008; Wan et al. 2009; Peng et al. 2013). We found that the correlation between NDVI decreased and warmer Tnav is positive but exhibits a negative in the relationships between decreased NDVI and Rwn (Fig. 8a). It implies that the temperature extremes can influence vegetation productivity, but further work is needed to support these inferences.

The aforementioned results (Tables 3 and 4 and Fig. 8) indicate that temperature/precipitation extremes in Xinjiang had effects on the vegetation cover. Rising temperatures enhances evaporation capacity, accelerate the global or regional water cycle, and exacerbate extreme precipitation and temperature events, and lead to the spatiotemporal heterogeneity of water resources in different scales, and to have stronger impacts of the vegetation activity. Furthermore, vegetation productivity has influenced by temperature extremes. Chen et al. (2015) indicated the increases of temperature and PET induced by negative ecological effects of the northwest arid region. Shen et al. (2015) also found the decrease in the growing season NDVI over the past decade in the southwest of the Tibetan Plateau, is associated with a delayed vegetation green-up date. We show that the vegetation activity decrease over the past decade may conjointly triggered by the increases of temperature and precipitation extremes (e.g., Rwn and R24). Admittedly, the quantitatively examining ecological response to the climatic extreme indicators should be studied using high-resolution vegetation data and observational datasets, as well as advanced numerical model tools, to investigate this mechanism in future. Furthermore, terrestrial vegetation dynamics are closely influenced by land use/cover change caused by human activities. The rapid growth of population and expansion of cultivated land by humans were mainly sourced from reclamations of wasteland and natural grassland (Wang et al. 2014a, b). Furthermore, additional information concerning human activities and these ecological response should be further examined in future research, e.g., land use and land cover changes (LULC), especially irrigation (Peng et al. 2013; Fang et al. 2013).

4 Conclusions

Generalizing from these results, there are several conclusions that can be shown from this analysis of the GIMMS NDVI3g record and responses to climatic extremes in Xinjiang, China:

1. Temperature and precipitation extreme indices had significant trends in Xinjiang from 1961 to 2010. The Mann–Kendall method showed that the mean minimum temperature (Tnav) and the number of warmest night days (Rwn) had significant increasing trends, while the mean maximum temperature (Txav) had slightly increasing trend. For the precipitation extreme indices, TR, R24, R0.1, and CWD had positive trends, but CDD had a negative trend during the past 50 years. Those changes in temperature and precipitation extreme indices indicate that the Xinjiang is becoming warmer and wetter.
2. From the satellite-based results, the annual average NDVI was significant increased and then showed obviously decreased trends after the 1998, trends significant decreasing in the northernmost regions of Xinjiang.
3. The correlation analyses demonstrated that the significant negative correlation between NDVI and potential evapotranspiration. NDVI change was determined by the precipitation. The precipitation increased was dominated by the precipitation extremes increasing. The trends of NDVI closely the trend of extreme precipitation, the consecutive dry days (CDD) and the number of torrential rainfall days (R24) were positively correlated with NDVI during the 1998–2010. The decreases of the R24 and CDD may conjointly cause a heavy loss of soil moisture, thereby reducing vegetation cover. The correlation between NDVI decreased and warmer minimum temperature (Tnav) is positive, but exhibits a negative in the relationships between NDVI decreased and the number of warmest night days (Rwn). The increases of the minimum temperature and the number of warmest night days (Rwn) can influence vegetation productivity. It implies that the NDVI decrease over the past decade may conjointly induce by the increases of temperature and precipitation extremes.

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