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Vegetation dynamics and its response to climate change in Central Asia

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Abstract: The plant ecosystems are particularly sensitive to climate change in arid and semi-arid regions. However, the responses of vegetation dynamics to climate change in Central Asia are still unclear. In this study, we used the normalized difference vegetation index (NDVI) data to analyze the spatial-temporal changes of vegetation and the correlation of vegetation and climatic variables over the period of 1982–2012 in Central Asia by using the empirical orthogonal function and least square methods. The results showed that the annual NDVI in Central Asia experienced a weak increasing trend overall during the study period. Specifically, the annual NDVI showed a significant increasing trend between1982 and 1994, and exhibited a decreasing trend since 1994. The regions where the annual NDVI decreased were mainly distributed in western Central Asia, which may be caused by the decreased precipitation. The NDVI exhibited a larger increasing trend in spring than in the other three seasons. In mountainous areas, the NDVI had a significant increasing trend at the annual and seasonal scales; further, the largest increasing trend of NDVI mainly appeared in the middle mountain belt (1,700–2,650 m asl). The annual NDVI was positively correlated with annual precipitation in Central Asia, and there was a weak negative correlation between annual NDVI and temperature. Moreover, a one-month time lag was found in the response of NDVI to temperature from June to September in Central Asia during 1982–2012.

Keywords: NDVI; precipitation; temperature; vegetation dynamics; Central Asian countries

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Five Central Asian countries, i.e. Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan (United Nations Statistics Division, 2013), are all far from the seas and oceans. Therefore, only small amounts of moisture can reach these countries. Compared to the surrounding regions of Central Asia and the world as a whole, the Central Asian countries experienced a significant warming trend during the last three decades (Hu et al., 2014). Precipitation in Central Asia presents non-uniform spatial pattern (IPCC, 2012). In arid and semi-arid regions of Central Asia, the ecosystems especially the vegetation are sensitive and vulnerable to climate variations. Moreover, the variations of vegetation in Central Asia play an important role in the regional carbon cycle, which will affect the global carbon cycle (Li et al., 2013, 2015). Therefore, it is important and necessary to study the variations of vegetation in Central Asia, such as the temporal changes and spatial distributions. In addition, the responses of vegetation dynamics to climate factors also should be systematically investigated (Zhang et al., 2013).

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NDVI is the normalized ratio of red and near-infrared (NIR) reflectance, which is generally considered as a good indicator of vegetation activity (Tucker et al., 1985; Goetz and Prince, 1999; Guay et al., 2014). It has been used to detect the vegetation dynamics and land cover changes at the regional and global scales (Yang et al., 1997; Piao et al., 2003; Barichivich et al., 2013; Cai et al., 2014; Wu et al., 2015). China has experienced a significant increasing trend for the monthly and seasonal NDVI during 1982–1999, and the largest trend appeared in spring (Piao et al., 2003). At the global scale, more than half (56.0%) of the land surfaces showed significant changes in NDVI during 1982–2012, and almost half (46.1%) of the changes exhibited seasonal variations (Eastman et al., 2013).

Previous studies have suggested that the researches of relationships between NDVI and climate factors (such as precipitation and temperature) contributed to finding the key factors that control the changes in the terrestrial ecosystem carbon cycle and shedded light on the mechanisms of the response of terrestrial carbon storage on climate variability (Potter and Brooks, 1998; Wang et al., 2003; Piao et al., 2006; Peng et al., 2013). The positive correlations between precipitation and NDVI were found in arid and semi-arid regions (Ichii et al., 2002), particularly in Central Asia (Suo et al., 2009), South Africa and Australia (Ichii et al., 2002). Furthermore, the time lags were found in the response of NDVI to precipitation (Yang et al., 1997; Martiny et al., 2005; Camberlin et al., 2007). Moreover, a significant positive linear correlation between NDVI and temperature was found over the northern high latitudes (>40°N) (Myneni et al., 1997) and the Qinghai-Tibet Plateau (Shen et al., 2011), and there was a positive correlation between the maximum daily temperature and NDVI in wettest and coolest ecosystems while a negative correlation between the minimum daily temperature and NDVI over the Northern Hemisphere (Peng et al., 2013).

The effects of land use changes on spatial patterns of NDVI and the relationship between NDVI and climate factors may be significant in Central Asia. To date, the variations of vegetation dynamics in Central Asia are still unclear. Studies on the vegetation dynamics in Central Asia are significant for the sustainable development of the ecosystems. Therefore, this study was mainly focused on the spatial-temporal variations of vegetation in Central Asia at the seasonal, annual and growing season scales during 1982–2012. Furthermore, the responses of NDVI to climate variables were also detected to obtain the main climate factors which control the vegetation in Central Asia.

1 Study area and methods

1.1 Study area

The study area includes five Central Asian countries, i.e. Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan (Fig. 1). Because it is located in the Eurasian continent and far from the seas and oceans, the region is characterized by arid and semi-arid climate (Lioubimtseva and Cole, 2006). A quarter of the total study area is covered by low-lying desert (200–400 m) with dotted oases. Grasslands are mainly found at elevations from 300 to 500 m, and the mountains in the eastern part of the study area have an elevation of >1,000 m. Above the foothills, the mountains are covered by shrubs, forests and alpine meadows from low to high elevations (Hu and Zhang, 2014).

1.2 Data

We obtained the NDVI data set of the GIMMS (Global Inventory Modeling and Mapping Studies) based on the daily data record from the NOAA's Advanced Very High Resolution Radiometer (AVHRR; a spatial resolution of 8 km×8 km and a 15-day interval for the period from January 1982 to December 2012; ftp://ftp.glcf.umiacs.umd.edu/glcf/GIMMS/). It is the most popular NDVI data (Tucker et al., 1985) for long-term vegetation studies due to its long and continuous record, as well as its availability and improved performance over other AVHRR-based NDVI data sets (Beck and Goetz, 2011). Because it is of high quality and eliminates noise from volcano eruptions, solar angles and sensor errors, the GIMMS NDVI data set has been widely

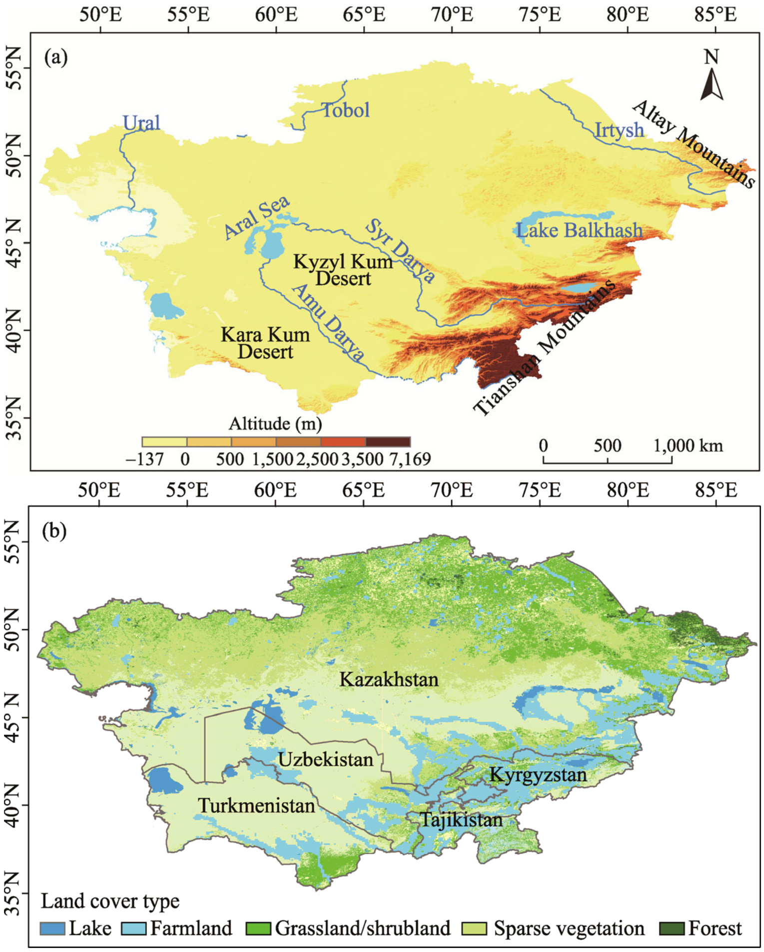

Fig. 1 Topography and the major land features (a) and land cover types (b) of five Central Asian countries

used in the studies of vegetation changes (Zhou et al., 2001; Anyamba et al., 2002; Piao et al., 2003; Goetz et al., 2005; Yuan et al., 2015), net primary productivity (NPP) (Mao et al., 2012) and biomass (Dong et al., 2003). In this study, we used the GIMMS NDVI data to discuss the spatial-temporal patterns of NDVI in Central Asia during 1982–2012.

For detecting the influence of climate factors on vegetation, we used the temperature and precipitation data sets from the Modern Era Retrospective-Analysis for Research and Applications (MERRA) project at the Global Modeling and Assimilation Office (Rienecker et al., 2011), which have good performance on the studies of climate change in this region (Hu and Zhang, 2014; Hu et al., 2015). MERRA has a spatial resolution of 0.5°×0.667° for the period of 1979 to today. The monthly temperature and precipitation data from 1982–2012 used in this study were downloaded from http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset.pl. The climate data were resampled on the spatial resolution of the GIMMS NDVI data.

1.3 Methods

The change trends of NDVI were computed using the linear least square method at the annual, seasonal (spring: March–May; summer: June–August; autumn: September–November; winter: December–February) and growing season (April–September) scales. The statistical significance of the trend was obtained by the *t*-test method. The abrupt change of NDVI during 1982–2012 was detected by the nonparametric Mann-Kendall (MK) method (Li et al., 2011; Mann, 2011). The Hurst index (H) computed by the R/S method (Koutsoyiannis, 2003) can be used to measure the long-range dependence (LRD, also referred to as long-term persistence, long memory or Hurst phenomenon), which denotes the property of time series to exhibit persistent behavior

(Racheva-Iotova and Samorodnitsky, 2003; Koutsoyiannis and Montanari, 2007; Samorodnitsky, 2007; Hu and Zhang, 2014). In this study, we used the Hurst index to detect whether the present tendency of NDVI will be continuous in the future. The analysis mentioned above was also studied separately in plain and mountainous areas (Hu et al., 2014).

For obtaining the spatial patterns of NDVI, we applied five empirical orthogonal function (EOF) modes (i.e. EOF-1, EOF-2, EOF-3, EOF-4 and EOF-5) (Lorenz, 1956) to the anomalies (from the average of 1982–2012) of NDVI at the seasonal, growing season and annual scales. The EOF method can identify the dominant spatial pattern of the variation in NDVI and also produce its index time series and the principal components (PC), which explain the magnitude of the variations of each EOF mode. Finally, we applied a significance test to distinguish the physical signal from the noise in the EOF mode (North et al., 1982).

The relationship between NDVI and climate factors (temperature and precipitation) was represented by the correlation coefficients. It is known that there exists a time delay between NDVI and precipitation. Therefore, in this study, the time-lag correlation coefficients were also computed. For obtaining the spatial correlation between NDVI and climate factors, we computed the correlation coefficients for all the pixels from the NDVI, temperature and precipitation data sets.

2 Results and discussion

2.1 Temporal changes of NDVI

There was a weak increasing trend overall for the annual NDVI in Central Asia during the study period of 1982–2012 (Fig. 2a). Specifically, the annual NDVI showed a significant increasing trend with a rate of 0.019/10a between1982 and 1994, and exhibited a decreasing trend since 1994. In mountainous areas, the annual NDVI showed an increasing trend with the rate of 0.0025/10a at a 95% significance level during 1982–2012 (Table 1). However, the annual NDVI had almost no increase in plain areas during 1982–2012.

At the seasonal scales, the increasing trends of NDVI appeared in spring and summer (Figs. 2b and c), while the decreasing trends existed in autumn and winter (Figs. 2d and e) over Central Asia in the period of 1982–2012. The variations of NDVI in plain areas had the similar trend with that in the entire area (Table 1). In mountainous areas, there was a significant increasing trend of NDVI in all seasons except the decreasing trend in winter. Moreover, the largest magnitude of increasing trends appeared in spring in plain areas and in summer in mountainous areas (Table 1).

Table 1 Hurst index (H), slope of linear trend (k) and mean values of NDVI at different time scales during 1982–2012 in Central Asia

Time scale	The entire study area			Plain areas of Central Asia			Mountainous areas of Central Asia		
	H	k (10^{-4})	Mean NDVI	H	k (10^{-4})	Mean NDVI	H	k (10^{-4})	Mean NDVI
Annual	0.86	0.56	0.18	0.83	0.11	0.18	1.02	2.50	0.18
Spring	0.87	7.43	0.16	0.83	7.80	0.20	0.92	5.80	0.15
Summer	0.86	2.61	0.23	0.82	1.80	0.28	0.97	6.30	0.31
Autumn	0.90	–0.60	0.15	0.91	–1.80	0.17	0.85	4.50	0.18
Winter	0.94	–7.36	0.06	0.93	–7.60	0.07	0.98	–6.70	0.07
Growing season	0.79	4.53	0.22	0.76	4.10	0.27	0.93	6.60	0.26

Further, we analyzed the inter-annual variations of NDVI to show the differences in different months during 1982–2012 (Fig. 3a). The monthly NDVI in plain areas had the same variation with that in the entire area, and the largest value appeared in May. However, in mountainous areas, the largest NDVI appeared in July, which was consistent with the monthly temperature change (Fig. 3b). The two-month delay of the largest NDVI in mountainous areas could be well explained by the temperature. That is, the highest temperature value was over than 20°C in plains areas and the entire study area, whereas it was below 15°C in mountainous areas. In fact, both the monthly temperature and precipitation affected the variations of monthly NDVI (Figs. 3b and c).

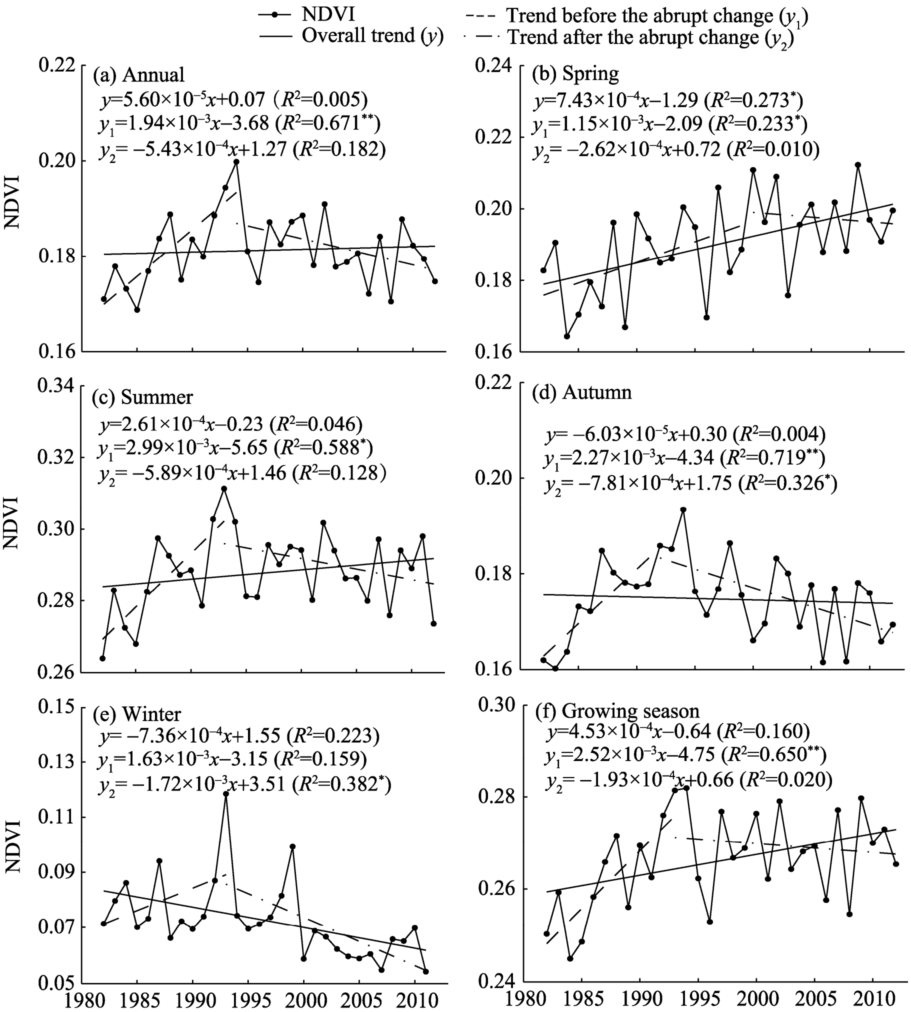

Fig. 2 Variations and abrupt change detection of annual (a), seasonal (b–e) and growing season (f) NDVI from 1982 to 2012 in Central Asia. * and ** mean significance at $P<0.05$ and $P<0.01$ levels, respectively.

2.2 Abrupt change and LRD of NDVI

The abrupt changes and the LRD characteristics of NDVI were detected by the MK and R/S methods, respectively. Generally, NDVI exhibited an increasing trend firstly and then showed a decreasing trend (Fig. 2). The most significant increasing trend of NDVI was detected in autumn, and 1992 was the abrupt year for autumn during the study period; while the most significant decreasing trend was observed in winter, and the abrupt change year was 1993 for winter (Table 2). NDVI in plain areas of Central Asia displayed the same abrupt change as that in the entire area. The values of Hurst index (H) were all larger than 0.5 in plain areas, mountainous areas and the entire study area (Table 1), indicating that NDVI will maintain the same change tendency in the future. In other words, the increasing trend will be continuous for the annual, growing season, spring and summer NDVI, while the decreasing trend will be continuous for the autumn and winter NDVI in the entire Central Asia.

2.3 Spatial variations of NDVI

The spatial distributions of NDVI were detected in this study (Fig. 4). Figure 4a showed that the higher annual NDVI values appeared in northern and southeastern Central Asia during 1982–2012; while the lower values appeared in southwestern Central Asia. The autumn NDVI exhibited the same spatial distribution as the annual NDVI did (Fig. 4d); while the spring, summer and growing season NDVI showed the same distributions (Figs. 4b, c and f).

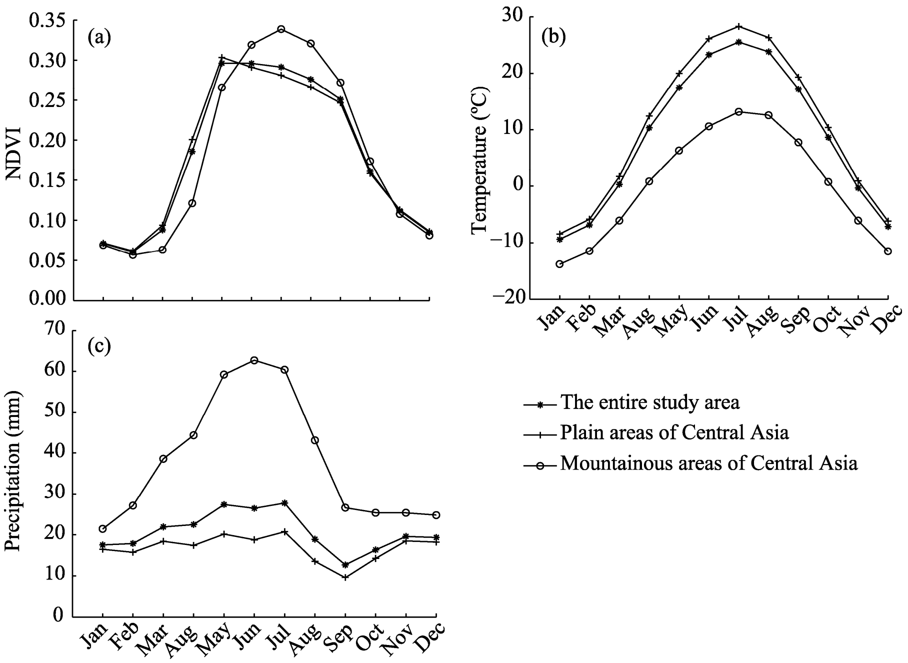

Fig. 3 The mean monthly NDVI (a), monthly mean temperature (b) and monthly precipitation (c) from 1982 to 2012 in Central Asia

Table 2 Abrupt changes of NDVI at different time scales during 1982–2012 in Central Asia

Region	Time scale	Abrupt year	Before the abrupt year			After the abrupt year		
			k_1 (10^{-3})	Mean NDVI	RMSE (10^{-2})	k_2 (10^{-3})	Mean NDVI	RMSE (10^{-2})
The entire study area	Annual	1994	1.94	0.18	0.90	–0.54	0.18	0.72
	Spring	2000	1.15	0.18	1.20	–0.26	0.19	1.10
	Summer	1993	2.99	0.29	1.40	–0.59	0.29	0.98
	Autumn	1992	2.27	0.17	0.90	–0.78	0.18	0.85
	Winter	1993	1.63	0.08	1.31	–1.72	0.07	1.10
	Growing season	1993	2.52	0.26	1.10	–0.19	0.27	0.88
Plain areas of Central Asia	Annual	1994	2.10	0.18	1.00	–0.61	0.18	0.79
	Spring	1992	1.30	0.19	1.30	0.49	0.20	1.20
	Summer	1993	3.13	0.28	1.50	–0.75	0.28	1.20
	Autumn	1992	2.30	0.17	1.02	–0.92	0.17	0.90
	Winter	1999	0.50	0.08	1.40	–1.50	0.07	1.20
	Growing season	1993	2.70	0.26	1.20	–0.30	0.27	1.00
Mountainous areas of Central Asia	Annual	1994	1.52	0.18	0.70	–0.28	0.18	0.54
	Spring	1997	0.80	0.15	1.40	–0.07	0.16	1.00
	Summer	1991	2.83	0.32	1.22	0.16	0.33	0.64
	Autumn	1993	2.10	0.18	0.81	–0.26	0.19	1.20
	Winter	1999	0.51	0.08	1.10	–0.86	0.06	1.20
	Growing season	1991	2.20	0.27	0.90	0.32	0.28	0.57

Note: k_1 and k_2 represent the slopes of linear trend before and after the abrupt changes, respectively. RMSE denotes root means square error.

In Central Asia, the regions where the annual NDVI increased mainly appeared in mountainous areas with larger change rates of 0.1–0.2/10a in 1982–2012 (Fig. 5). However, the regions where the annual NDVI decreased were mainly distributed in western Central Asia. The regions where the annual NDVI increased occupied 46% of the study area, and 16% of the total area exhibited a significant increasing trend ($P<0.05$) (Table 3). More than 65% of the study area exhibited increased NDVI in spring, and this increase was significant in more than 30% of the study area.

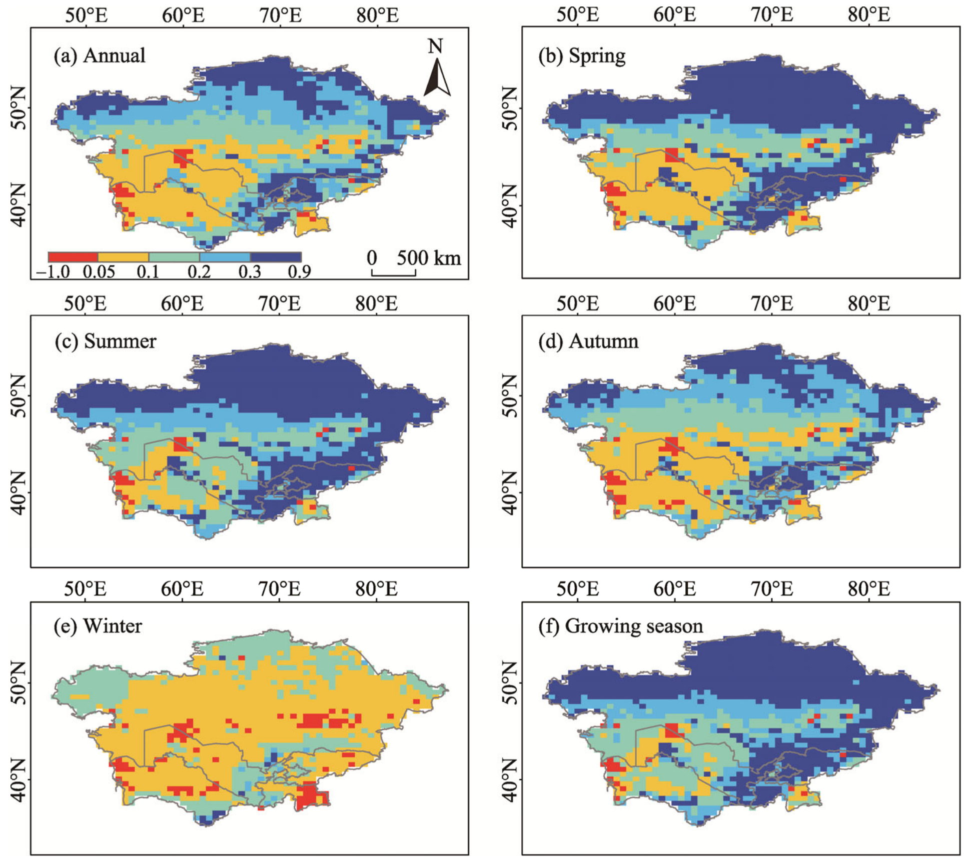

Fig. 4 Spatial distributions of mean NDVI at the annual (a), seasonal (b–e) and growing season (f) scales from 1982 to 2012

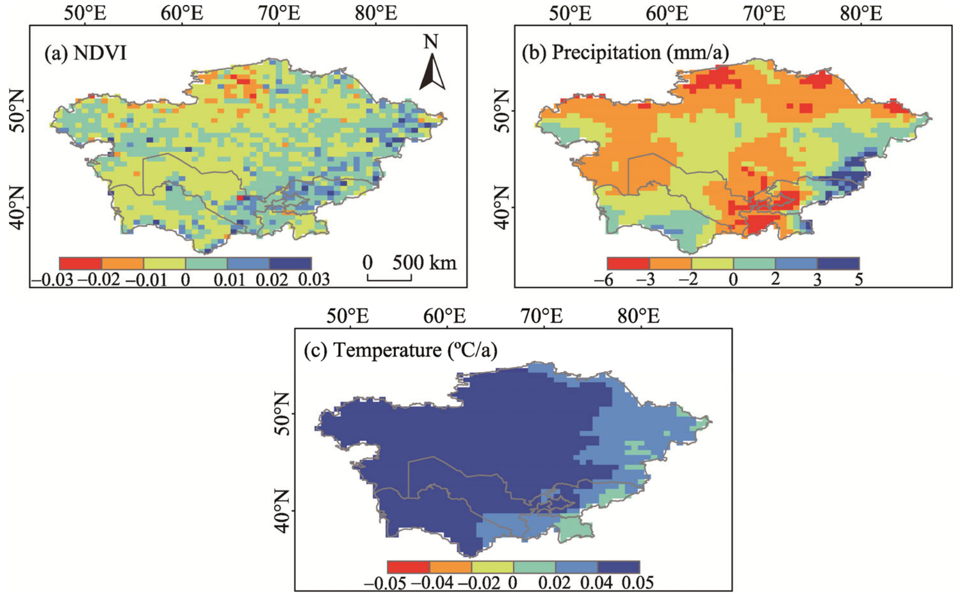

Fig. 5 Spatial distributions of the change rates of annual NDVI (a), annual precipitation (b) and annual temperature (c) from 1982 to 2012

For detecting the decadal change of NDVI during 1982–2012, we obtained the differences of mean NDVI between the following periods: 1982–1989, 1990–1999 and 2000–2012 (Fig. 6). More than 78% of the total area exhibited larger NDVI values in the period 1990–1999 than in the period 1982–1989, while 73.17% of the total area showed smaller NDVI values during 2000–2012 than during 1990–1999. The vegetation changes were particularly focused on the plain areas: 61.75% of the total plain area had larger NDVI values in the period 1990–1999 than in the period 1982–1989, while 60.25% of the total plain area exhibited smaller NDVI values during 2000–2012 than during 1990–1999.

The EOF analysis can be used to further understand the spatial-temporal variations of NDVI in Central Asia during 1982–2012. Results of the EOF mode are provided in Table 4. The first EOF mode (EOF-1) explained 18%–55% of the total spatial-temporal variations of NDVI.

Table 3 Area percentage (%) of the increased and decreased NDVI at different time scales during 1982–2012 in Central Asia

Region	Time scale	Area percentage of NDVI (%)			
		Increase	Significant increase	Decrease	Significant decrease
The entire study area	Annual	46	16	54	24
	Spring	65	31	35	16
	Summer	49	14	51	20
	Autumn	37	12	63	29
	Winter	18	4	82	47
	Growing season	60	24	40	19
Plain areas of Central Asia	Annual	35	11	47	21
	Spring	52	25	30	14
	Summer	38	9	44	18
	Autumn	26	9	56	25
	Winter	14	3	68	39
	Growing season	50	16	32	14
Mountainous areas of Central Asia	Annual	11	5	7	3
	Spring	13	6	5	2
	Summer	12	5	6	2
	Autumn	11	4	7	3
	Winter	4	1	14	7
	Growing season	13	7	5	2

Note: Area percentage of significant increased NDVI is the percentage of area of significant increased NDVI to the total study area, so as to the area percentage of significant decreased NDVI.

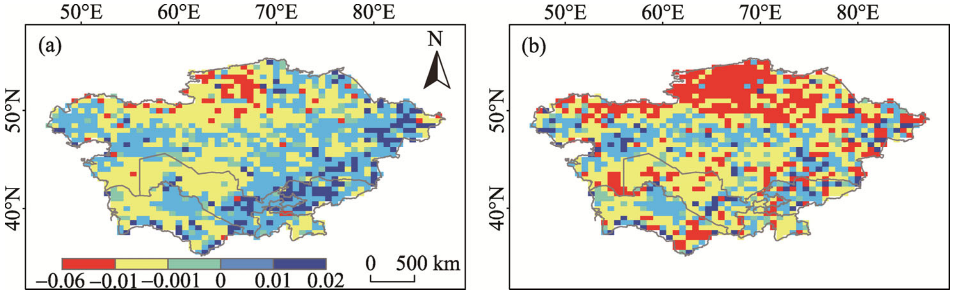

Fig. 6 Spatial differences of NDVI between 1982–1989 and 1990–1999 (a) and between 1990–1999 and 2000–2012 (b)

Table 4 The eigenvalues and variance contributions of the EOF modes at different time scales

Time scale	λ_1	R_1 (%)	λ_2	R_2 (%)	λ_3	R_3 (%)	λ_4	R_4 (%)	λ_5	R_5 (%)
Annual	0.17	25	0.12	18	0.06	9	0.04	6	0.03	5
Spring	0.59	30	0.27	14	0.16	8	0.12	6	0.08	4
Summer	0.59	24	0.38	15	0.22	9	0.14	6	0.14	6
Autumn	0.28	18	0.24	15	0.12	8	0.11	7	0.08	5
Winter	0.70	55	0.12	9	0.06	4	0.05	4	0.04	3
Growing season	0.36	24	0.24	16	0.16	11	0.09	6	0.08	5

Note: λ_1 to λ_5 represent the eigenvalues of the first to fifth empirical orthogonal function (EOF) modes (EOF-1–EOF-5), respectively. R_1 to R_5 represent the variance contributions of the first to fifth EOF modes.

In this study, only the results of EOF-1 and time coefficients of PC-1 (the first principal component) for spatial-temporal variations of NDVI are shown in Fig. 7. The annual NDVI exhibited almost positive values over the whole Central Asia (Fig. 7a), which indicated the same inter-annual tendency. The time coefficients of PC-1 for annual NDVI (Fig. 7b) exhibited the same change trend with the annual NDVI variations in 1982–2012. The spatial distribution of spring NDVI based on EOF-1 was similar to that of annual NDVI (Figs. 7a and c). The time coefficients of PC-1 for spring NDVI had negative values before 1996 and positive values for most of the years after 1996 (Fig. 7d). Additionally, the negative center of summer and autumn NDVI variations was mainly found in northern Kazakhstan (Figs. 7e and g). Results of EOF-1 and time coefficients of PC-1 for winter and growing season NDVI can be found in Figs. 7i –l.

2.4 Changes of NDVI in different elevations of the mountainous areas

In Central Asia, the mountainous areas mainly distribute in Kazakhstan, Kyrgyzstan and Tajikistan. The mountainous areas are the main water resources for the most rivers in Central Asia (Ran et al., 2015; Cheng et al., 2016). With the increasing elevation, the temperature decreases while the precipitation increases. In general, the vegetation in mountainous areas is mainly controlled by temperature. In order to detect the variations of NDVI and its response to the climate change in mountainous areas, we divided the mountainous areas into alpine belt (2,650–7,169 m), middle mountain belt (1,700–2,650 m) and low mountain belt (<1,700 m) (Chen et al., 2003; Hu, 2004). The change rates of annual NDVI over alpine belt, middle mountain belt and low mountain belt during 1982–2012 are shown in Table 5, which showed that the largest change rate in the growing season and the smallest change rate in winter all appeared in the middle mountain belt (Table 5).

Table 5 Change rates of annual, seasonal and growing season NDVI during 1982–2012 in different elevations of the mountainous areas

Mountain belt	Elevation (m)	Area percentage (%)	Change rate of NDVI (10^{-4}/a)					
			Annual	Spring	Summer	Autumn	Winter	Growing season
Alpine belt	2,650–7,169	10	0.82	2.03	3.10	2.10	–4.50	2.81
Middle mountain belt	1,700–2,650	5	5.01	12.02	11.00	6.40	–9.70	13.03
Low mountain belt	<1,700	85	0.21	7.60	2.00	–1.40	–7.63	4.20

2.5 Changes of NDVI, precipitation and temperature in the grasslands of northern Kazakhstan

Grassland is an important ecosystem in arid and semi-arid regions and studies on NDVI of grasslands contribute to understanding the responses of grassland ecosystems to climate change (Propastin et al., 2012). In Central Asia, the grasslands mainly distribute in northern Kazakhstan, which accounts for 27.3% of the total study area. In the grasslands of northern Kazakhstan, there was a decreasing trend for annual NDVI and precipitation while an increasing trend for annual temperature during 1982–2012 (Table 6). In winter, the mean NDVI, precipitation and temperature all exhibited a decreasing trend. However, in the growing season, the mean NDVI and temperature increased while the precipitation decreased.

Table 6 Change rates and mean values of NDVI, precipitation and temperature at different time scales during 1982–2012 in the grasslands of northern Kazakhstan

Time scale	NDVI			Precipitation			Temperature		
	Change rate (10^{-3}/a)	Mean	RMSE (10^{-2})	Change rate (mm/a)	Mean (mm)	RMSE	Change rate (°C/a)	Mean (°C)	RMSE
Annual	–0.13	0.29	1.39	–1.94*	323.25	41.06	0.05*	4.88	0.90
Spring	1.05*	0.30	2.35	0.08	77.47	13.90	0.11**	5.64	1.75
Summer	0.60	0.50	2.68	–0.01	103.57	21.73	0.05**	22.34	1.00
Autumn	–0.39	0.28	1.76	–1.10*	73.63	18.88	0.08**	5.09	1.55
Winter	–0.16*	0.10	2.96	–0.82*	68.58	14.78	–0.06	–13.52	2.03
Growing season	0.76*	0.45	1.96	–0.70	177.98	29.93	0.07**	17.32	0.99

Note: * and ** mean significance at $P<0.05$ and $P<0.01$ levels, respectively.

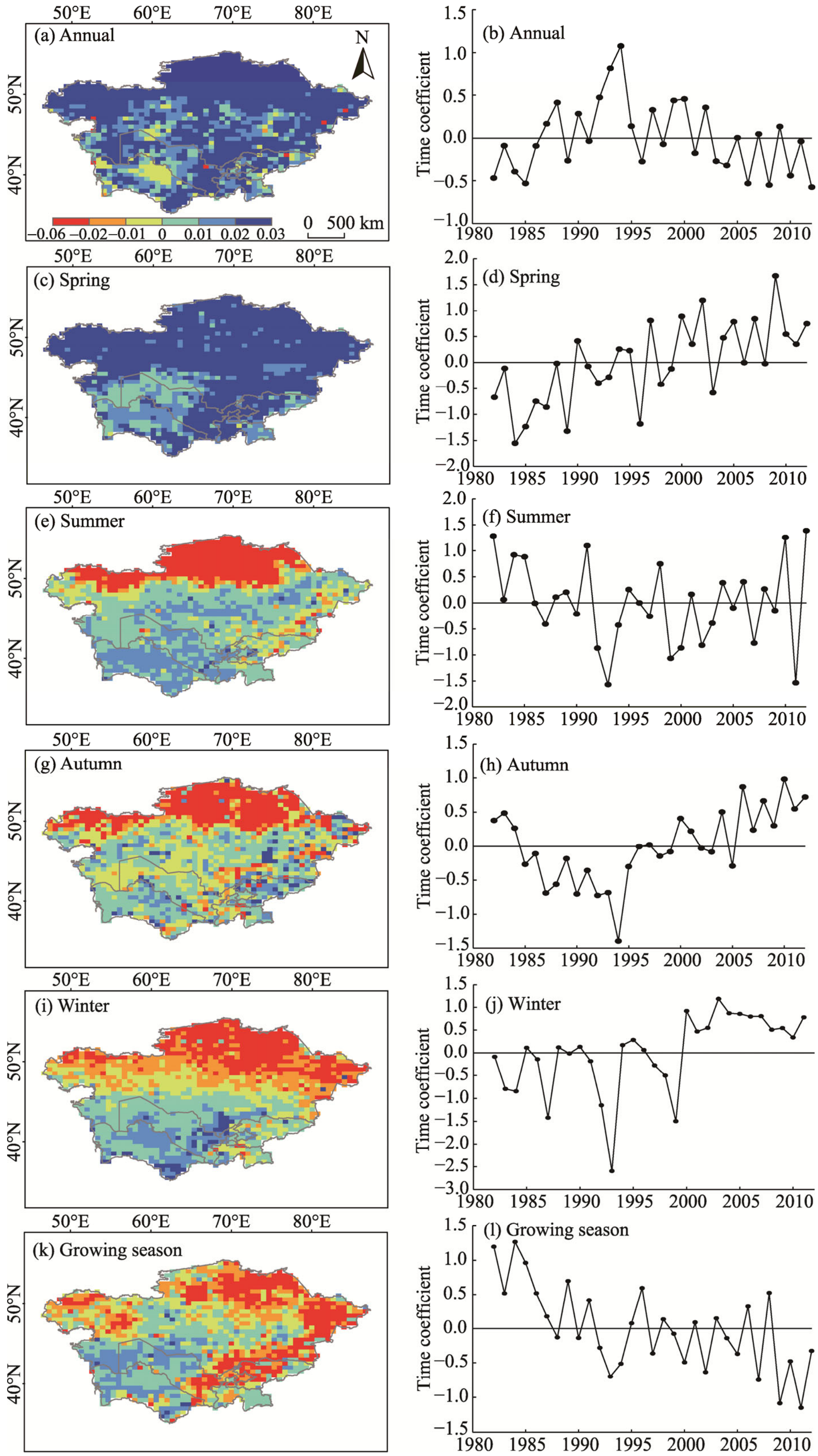

Fig. 7 Results of EOF-1 (left column) and time coefficients of PC-1 (the first principal component; right column) for spatial-temporal variations of annual, seasonal and growing season NDVI during 1982–2012

2.6 Relationship between NDVI and climate factors

It is well accepted that the variations of climate have significant influences on NDVI (Piao et al., 2006; Peng et al., 2013; Hu et al., 2015). In this study, the relationships of NDVI with temperature and precipitation were discussed at the monthly, seasonal and annual scales. The correlation coefficient between annual NDVI and annual precipitation was 0.25 (data are not shown). Positive correlations were found between NDVI and precipitation in summer (R^2=0.24) and winter (R^2=0.20). There was a negative correlation between NDVI and precipitation in spring and autumn. The NDVI was positively correlated with precipitation (R^2=0.28) in the growing season. The NDVI was negatively correlated with temperature in summer, autumn, winter and the whole year, while significantly positively correlated with temperature in spring (R^2=0.62, P<0.01). Moreover, the growing season NDVI showed little correlation with growing season temperature (R^2=0.002).

The poor relationships of NDVI with temperature and precipitation in Central Asia may be caused by the opposite correlations in different regions. Therefore, we analyzed the spatial distributions of correlation coefficients between NDVI and climate factors (temperature and precipitation) at the annual and growing season scales (Fig. 8). The positive center of correlation coefficient between annual NDVI and annual temperature mainly appeared in southeastern Central Asia, while the negative center was mainly distributed in northern and southwestern Central Asia (Fig. 8a). For the growing season, the positive center of correlation coefficient between annual NDVI and annual temperature mainly appeared in the center of Kazakhstan and the Tianshan and Altay mountains (Fig. 8b). The spatial distributions of correlation coefficient between NDVI and temperature at the annual and growing season scales were mainly affected by the spatial characteristics of the temperature along the latitude. The positive center of correlation coefficient between annual NDVI and annual precipitation was mainly distributed in western Central Asia (Fig. 8c). However, negative correlations between annual NDVI and annual temperature were found in these regions (Fig. 8a). The result indicated that the vegetation in these regions was mainly controlled by precipitation. In the growing season, the regions of the positive correlation between NDVI and precipitation were distributed almost in all Central Asia (Fig. 8d). In addition, we found that the vegetation distributed in the belt of 46°–48°N in Kazakhstan was mainly controlled by temperature (Figs. 8b and d).

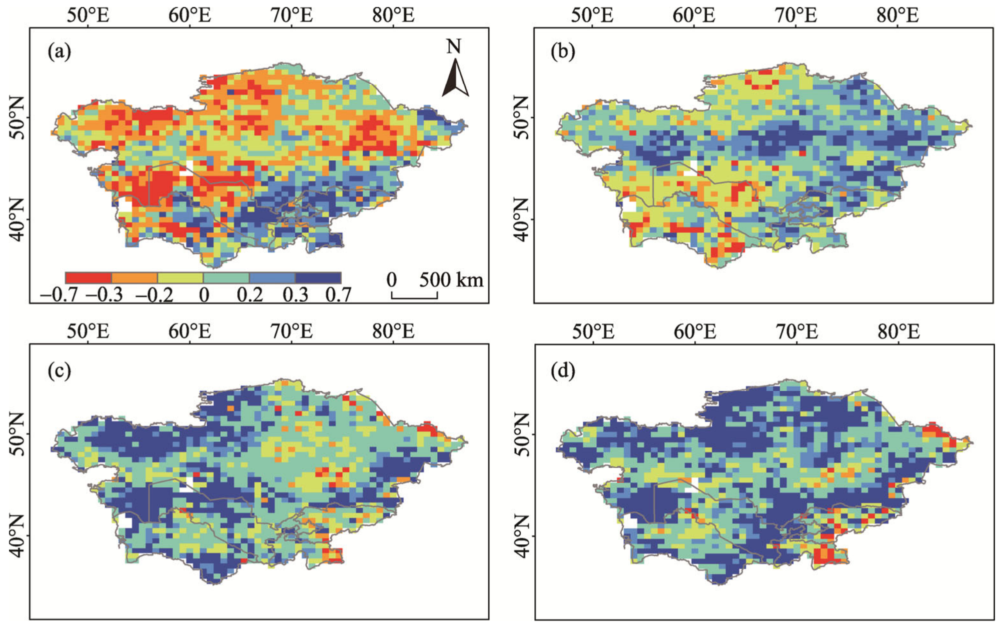

Fig. 8 Spatial distributions of correlation coefficients between (a) annual NDVI and annual temperature, (b) growing season NDVI and growing season temperature, (c) annual NDVI and annual precipitation, and (d) growing season NDVI and growing season precipitation during 1982–2012 in Central Asia

Finally, this study also found that there was a temporal lag in the response of vegetation to climate factors, which has also been observed in the previous studies (Yang et al., 1997; Piao et al., 2006). A one-month time lag was found in the response of NDVI to temperature from June to September in Central Asia. The NDVI in August was significantly positively correlated with temperature in July ($P<0.01$), and the NDVI in September had a positive correlation with August temperature ($P<0.01$). For the NDVI in plain areas of Central Asia, there was also a one-month time lag for the temperature from June to September, and the significant positive correlation was only found in September. In mountainous areas of Central Asia, the NDVI had a one-month time lag in response to temperature from July to September, and a significant positive correlation was also found as that in plain areas of Central Asia. However, there was no time lag between NDVI and precipitation during the growing season. In April, the NDVI had a significant positive correlation with precipitation at the 99% level in plain areas and the entire area, and this significant positive correlation was also found in mountainous areas from April to June.

3 Conclusions

The annual NDVI experienced a weak increasing trend overall in Central Asia during 1982–2012. Specifically, a weak increasing trend was found in plain areas, and a significant increasing trend with the rate of 0.0025/10a appeared in mountainous areas. At the seasonal scales, the spring NDVI showed a significant increasing trend ($P<0.01$) with the largest rate of 0.008/10a. In autumn and winter, there was a decreasing trend for the NDVI, and the decreasing trend was significant at a 95% level in winter. In plain areas, an increasing trend of NDVI was found in spring and summer; in mountainous areas, the NDVI exhibited a significant increasing trend in the spring, summer, autumn and the growing season ($P<0.05$). Results of the nonparametric Mann-Kendall method showed that there were significant abrupt changes in the variations of NDVI during 1982–2012. The LRD result indicated that the present change trend of NDVI may be continuous in the future. The values of NDVI in the grasslands of northern Kazakhstan and the mountainous areas of Kyrgyzstan and Tajikistan were higher, and the regions where the NDVI increased mainly appeared in mountainous areas. The annual NDVI was positively correlated with annual precipitation in Central Asia, and there was a weak negative correlation between annual NDVI and annual temperature. Further, a one-month time lag was found between NDVI and temperature from June to September in Central Asia during 1982–2012. In the growing season, the vegetation was mainly controlled by precipitation in most areas of Central Asia, which indicated that precipitation plays an important role in the vegetative growth in Central Asia.

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