VEGETATION DYNAMICS AND THEIR RELATIONS WITH CLIMATE CHANGE AT SEASONAL SCALES IN THE YANGTZE RIVER BASIN, CHINA

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Abstract. Knowledge on vegetation dynamics and its response to climate change is important for the sustainability of natural resources and understanding the changes in the ecosystems and its impact on the Earth’s environment. We have carried out an analysis of GIMMS (Global inventory modelling and mapping studies) NDVI3g (third generation normalized difference vegetation data), daily temperature (T) and precipitation (P) for the 1982-2015 period based on Linear Regression (LR) analysis, the Mann-Kendall (MK) test with Sen's slope estimator and Kriging interpolation method. We have investigated the spatiotemporal variations of NDVI and climatic factors in the Yangtze River Basin (YRB), China. The relationship between NDVI and climatic factors was also analyzed quantitatively. The results show that the mean NDVI has an increasing trend in all four seasons during 1982-2015, the increasing trend during spring and autumn seasons was higher compared to winter and summer seasons. The response of vegetation dynamics to temperature was more prominent than precipitation. The correlation analysis shows that the mean NDVI had a significant and positive correlation with seasonal temperature, and the correlation coefficients were the highest during spring, followed by winter, summer and autumn seasons.
Keywords: *vegetation variation, NDVI, temperature, precipitation, YRB*

Introduction

Vegetation, as the link between the soil, atmosphere and water, plays an important role in characterizing the energy exchange, carbon cycle and regional human activities (Eugster et al., 2010). Vegetation dynamics has become an indicator of global environmental changes (Qu et al., 2018). In addition, vegetation dynamics (degradation and restoration) can reflect natural evolution and the impact of human activities on the ecological environment (Jiang et al., 2017). Therefore, investigating vegetation dynamics is crucial to protect the ecological environment (Yu and Hu, 2013).

Remote sensing data is one of the most important data sources to monitor vegetation dynamics, which has become a widely used tool in the field of ecological protection due to their advantages, including large coverage area and time savings (Qu et al., 2018). The satellite-based normalized difference vegetation index (NDVI) has been considered to be an effective indicator to monitor vegetation dynamics at regional, continental and global scales (Pinzon and Tucker, 2014). The commonly used NDVI data mainly include NOAA/AVHRR data, EOS/MODIS data and SPOT Vegetation NDVI data. Recently, many scholars have used these datasets to investigate vegetation dynamics at different spatial scales (Peng et al., 2011; Pan et al., 2018). Recent studies show that vegetation activities have increased in the northern mid–high latitudes and vegetation

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stability is changing with the external environment (Nemani et al., 2003; Xu et al., 2013). Climate, especially the factors of temperature and precipitation, has an important impact on vegetation dynamics (Piao et al., 2003; Goetz et al., 2005). In the context of global warming, studies on the relationship between vegetation dynamics and climate change have become hot topics worldwide (Chu et al., 2019; Yao et al., 2019).

Many studies reveal that NDVI showed dramatic spatial variations in response to climate changes (Gong and Shi, 2003; Piao et al., 2015). Ichii et al. (2002) and Xu et al. (2013) found that vegetation dynamics has been strongly influenced by increasing temperature at a global scale. Pan et al. (2018) pointed out that drought possibly has an important impact on the increasing global vegetation browning trend and global vegetation growth is at risk of reversal from greening to browning in the future due to climate warming. Temperature has a positive impact on vegetation dynamics in China (Song and Ma, 2011; Piao et al., 2015). However, the correlation between precipitation and NDVI is characterized by the geographical heterogeneity. Precipitation has a positive effect on NDVI in most dry regions whereas in humid regions, there was a negative correlation between NDVI and precipitation (Wang et al., 2010; Xu et al., 2016). To data, most of the previous studies mainly focused on the correlation between vegetation dynamics and climate factors at annual scale (Zhou et al., 2001). However, climate factors in different seasons might have different impacts on vegetation changes. Therefore, it is meaningful to study the relationship at seasonal scale.

The Yangtze River basin (YRB) is the third-largest river basin in the world. The vegetation cover in YRB plays an important role in regulating ecological balance in China, adjacent areas and even in the world. In the past few decades, the YRB has experienced significant climate change (Cui et al., 2019). The vegetation in the basin has changed obviously (Qu et al., 2018). The present study focused on the spatiotemporal trends of vegetation, as well as its relations with climate factors at annual scale. This paper focuses on long-term vegetation variation and the correlation with climate change at seasonal scale in YRB, which will serve as a reference for further scientific understanding of vegetation dynamics at a large basin scale and provide a reliable scientific basis for vegetation planting and protection. This paper aims to (1) study the spatial and temporal variation of seasonal mean NDVI in YRB during 1982-2015; (2) investigate the correlation between the seasonal mean NDVI and climate factors in YRB; and (3) detect the response of NDVI to climate variables to investigate the major climate factors affecting the vegetation dynamics in YRB.

Materials and methods

Study area

The Yangtze River, with the length of about 6300 km, is the longest river in Asia. The river originates from the Tibetan Plateau (TP) in western China and finally flows into the East China Sea (Zhang et al., 2014). The YRB lies between 91-122° E and 25-35° N (*Fig. 1*) with an area of about 1.8×10^6 km^2 (Niu et al., 2019). The annual average temperature ranges from 12.6 to 28.0°C and annual average precipitation is about 476 mm (Qu et al., 2018). The northern YRB is adjacent to the temperate zone, and the southern YRB is near to the tropical zone (Sang et al., 2013).

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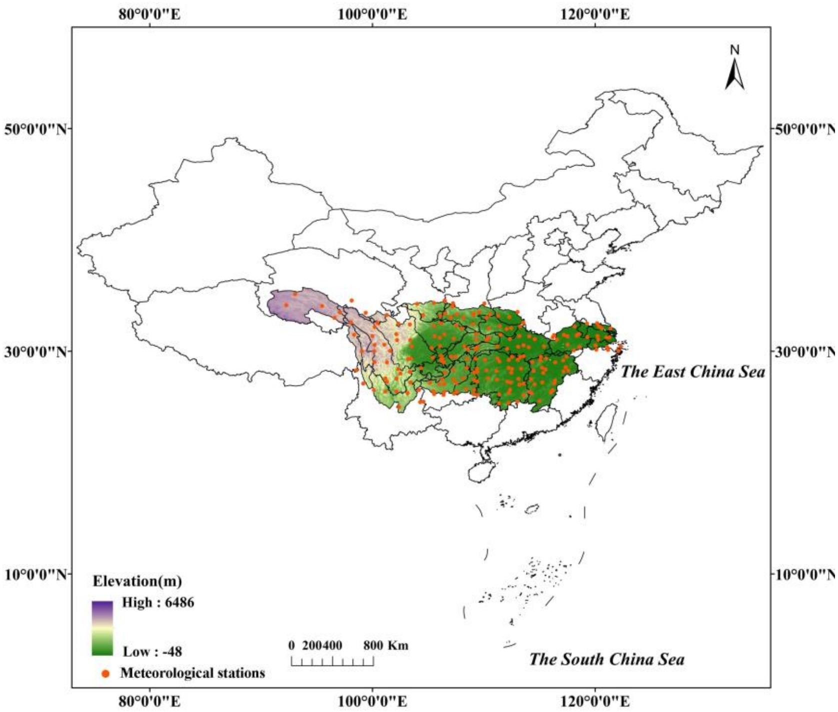

***Figure 1.** Location of the YRB in China*

Data

Meteorological data

The daily climate datasets that included temperature (*T*) and precipitation (*P*) were acquired from the Chinese Meteorological Science Data Sharing Service Network. In this study, the daily climate data from 214 meteorological stations in YRB (*Fig. 1*) were used to analyse the variations of temperature and precipitation during the period of 1982-2015.

NDVI data

This study used the GIMMS 3g dataset developed by the NASA Global Inventory Modeling and Mapping Studies group, with a spatial resolution of 8 km and a temporal interval of 15 days (Li et al., 2018). The dataset covering the period from 1982 to 2015 is helpfull for detecting long-term vegetation dynamics at regional and global scales (Qu et al., 2018). To avoid the partial effects from clouds and atmosphere, we calculated a monthly NDVI by Maximum-Value Composites (MVCs) method.

Methods

This study investigates the trends in the annual and seasonal NDVI, temperature and precipitation using the Linear Regression (LR) analysis and the Mann-Kendall (MK) test with Sen's slope estimator.

The linear equation is as follows:

$$y=ax + b, (x=n, n+1 ,..., N) \quad \text{(Eq.1)}$$

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where y is the trend of NDVI, temperature and precipitation; x is the year; a and b are the slope and intercept respectively; n represents the starting year of the time series.

A positive value of a indicates increasing trends, while a negative value of a denotes decreasing trends. The significance level (p-values) of 10%, 5% and 1% was used for the LR analysis.

In this study, we use the MK test to investigate long-term trends in meteorological data and NDVI time series. This method mainly contains two parameters: Z and β. The standard normal test statistic Z, used for detecting a significant trend of the time series (Cui et al., 2019). The parameter β estimates the slope within the time series.

The correlation coefficients between the NDVI and climatic variables were calculated using Pearson correlation coefficients (Jiang et al., 2017). A prewhitening procedure was applied to the series prior to correlation analysis to improve the accuracy.

Results

Vegetation dynamics in YRB

The mean NDVI during spring (March-May), summer (June-August), autumn (September-November) and winter (December-February) was approximately 0.50, 0.67, 0.56 and 0.41, respectively during 1982-2015 (*Figs. 2a-d*), and increased at the rate of 0.02/10yr (Z_{MK} = 4.12, $p < 0.01$), 0.002/10yr (Z_{MK} = 0.47, p = 0.58), 0.02/10yr (Z_{MK} = 2.70, $p < 0.01$) and 0.006/10yr (Z_{MK} = 1.25, p = 0.18), respectively (*Table 1*). A significant turning point (TP) of NDVI during spring, summer, autumn and winter was found in 1996, 1997, 1994 and 1994, respectively (*Fig. 3*), and the abrupt change was statistically significant detected by MK test (*Fig. 4*). The mean NDVI during spring, summer and autumn was 0.47 and 0.52, 0.68 and 0.67, 0.54 and 0.58, 0.40 and 0.41, respectively before and after TP (*Figs. 2a-d*). The seasonal changes in NDVI before and after TP did not reach the statistically confidence level except the trend before TP during summer season (*Table 1*).

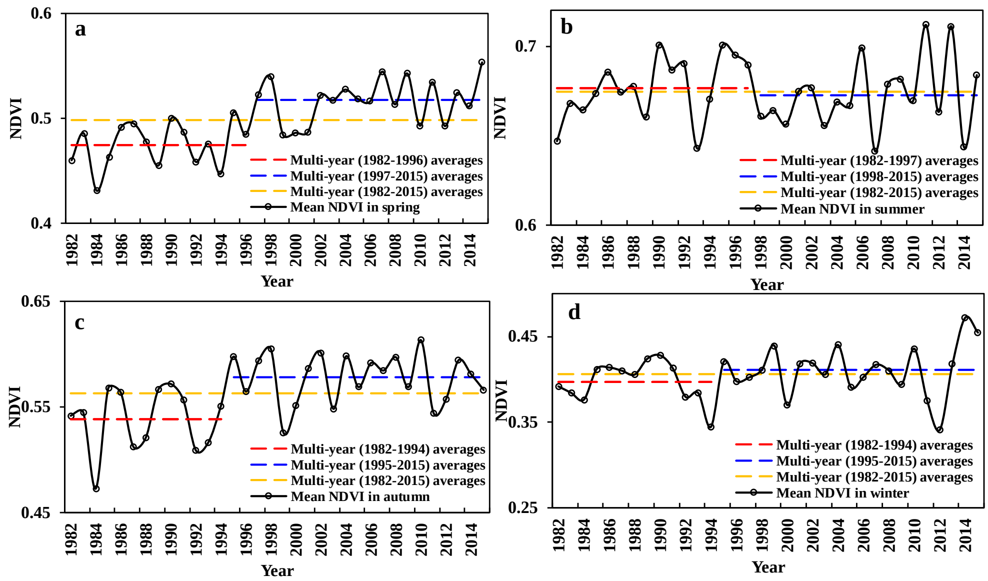

Figure 2. *Seasonal (a-d) mean NDVI of YRB during 1982-2015 and their Accumulated Anomaly Curve (f)*

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Table 1. *Trend test results (/10yr) of seasonal NDVI in YRB during 1982-2015, before and after the TP based on MK and LR analysis*

	Trend during1982-2015	Trend before TP	Trend after TP
Spring	$0.02^{***}/0.02^{***}$	0.01/0.01	0.01/0.01
Z_{MK}/p	<0.01	ns	ns
Summer	0.002/0.002	$0.02^{**}/0.02^{*}$	0.01/0.01
Z_{MK}/p	ns	<0. 1	ns
Autumn	$0.02^{***}/0.02^{***}$	0.00/0.00	0.00/0.00
Z_{MK}/p	<0.01	ns	ns
Winter	0.006/0.006	-0.004/-0.01	0.006/0.006
Z_{MK}/p	ns	ns	ns

ns denotes Not significant. *Trends at the 10% confidence level, **Trends at the 5% confidence level, ***Trends at the 1% confidence level

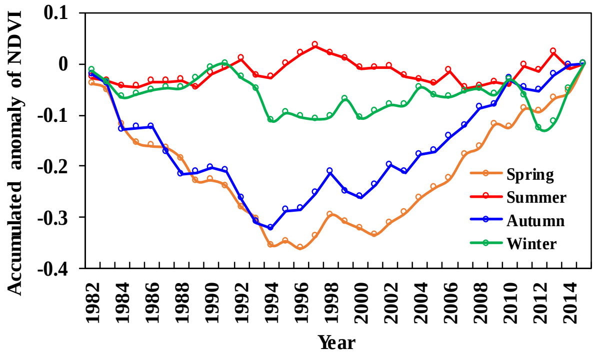

Figure 3. *Accumulated Anomaly Curve of seasonal mean NDVI of YRB during 1982-2015*

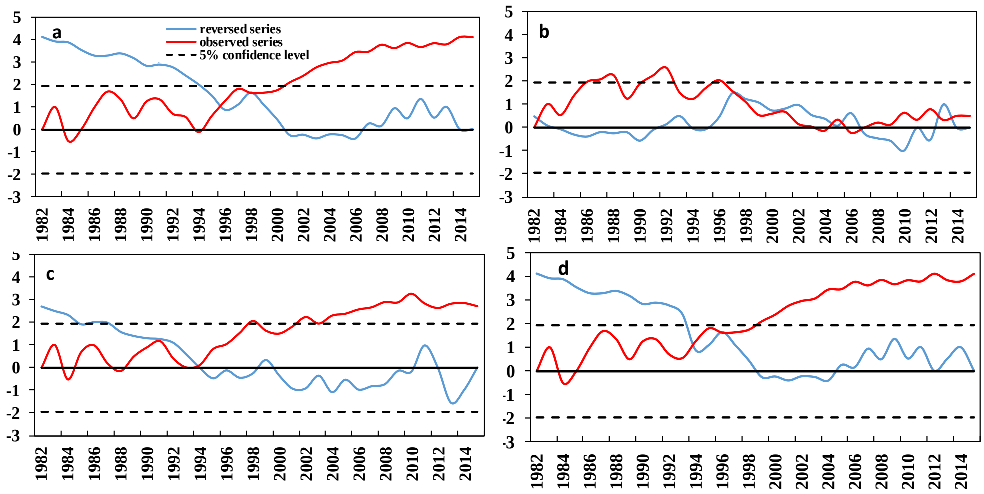

Figure 4. *The significant test of abrupt change in spring, summer autumn and winter NDVI (a, b, c, d) in YRB during 1982-2015*

The seasonal mean NDVI during spring, summer and autumn was generally high over the whole YRB except the north-western dry region and a small part of eastern YRB during 1982-2015 (*Figs. 5a-c*). The mean NDVI during winter was lower over the study area except the south-western and south-eastern YRB (*Fig. 5d*). The seasonal

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changes in NDVI also show strong spatial heterogeneity during 1982-2015 (*Fig. 6*). Parts of the eastern YRB show a significant and continuous increase in vegetation greenness (NDVI ≤0.03/10yr), especially during spring season. However, in most parts of YRD vegetation greenness decrease (NDVI ≤0.03/10yr), especially during summer season. Most parts of the central-south YRB show an increasing trend during spring (NDVI ≤0.05/10yr), and show decreasing trend during winter season (*Figs. 6a, g*). In addition, the mean NDVI in the north-western parts of YRB increase during summer and decrease during autumn (*Figs. 6c, e*).

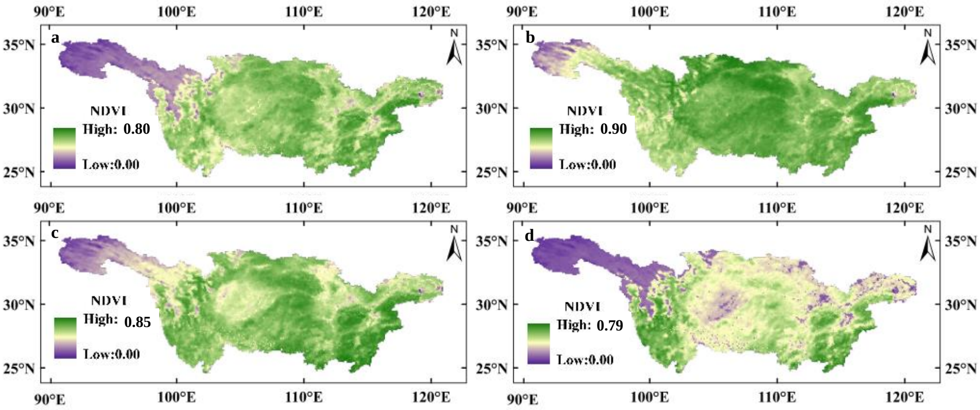

Figure 5. *Spatial distribution of seasonal mean NDVI in YRB during 1982-2015 (spring (a), summer (b), autumn (c) and winter (d))*

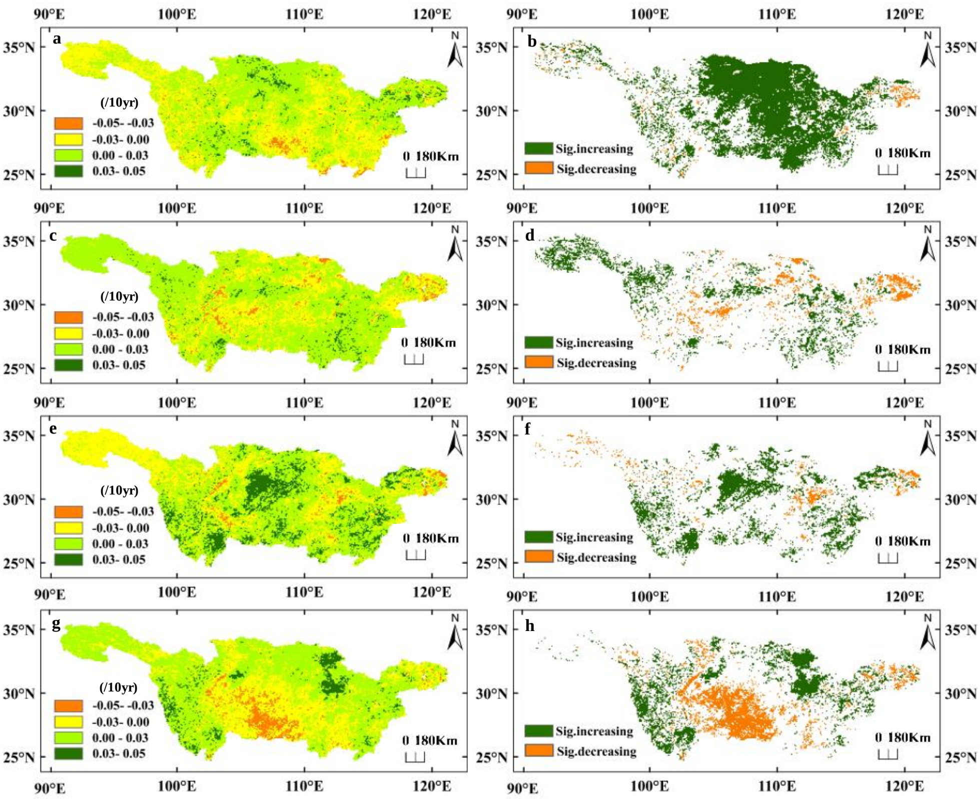

Figure 6. *Spatial distribution of NDVI variation trend in spring, summer autumn and winter (a, c, e, g) and its significant test (b, d, f, h) in YRB during 1982-2015*

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Long-term climate variability in YRB

The seasonal mean temperature during spring, summer, autumn and winter were 14.44, 23.70, 15.33 and 4.40°C, respectively over the whole YRB during 1982-2015 (*Table 2*).

Table 2. *Multi-year means of seasonal NDVI, temperature (T) and precipitation (P) in YRB during 1982-2015*

	NDVI	T(°C)	P(mm)
Spring	0.50	14.44	322.23
Summer	0.67	23.70	518.90
Autumn	0.56	15.33	225.90
Winter	0.41	4.40	108.70

The seasonal mean temperature shows statistically significant increasing trends, and the highest warming magnitude during spring ($p < 0.01$), followed by winter ($p < 0.05$), autumn ($p < 0.01$) and summer ($p < 0.01$) during 1982-2015 (*Table 3*). *Table 3* shows that seasonal mean temperature before TP and after TP also presents an increasing trend in four seasons. The spatial distribution of seasonal mean temperature shows strong seasonal variability (*Figs. 7a-d*): the mean temperature during spring and autumn seasons has a significant increasing trend in the whole YRB, while a decreasing trend during summer and winter seasons was detected in a small part of the YRB (*Figs. 7b-d*). *Figs. 7a-d* also shows the most warming areas in the four seasons were located in the western source region of the Yangtze River and Yangtze River Delta (YRD) due to the rapid population growth and the rapid expansion of built-up areas.

Table 3. *Trend test results of temperature (°C/10yr) and precipitation (mm/10yr) in YRB during 1982-2015, before and after the TP of NDVI trend based on MK and LR analysis*

	Trend during1982-2015		Trend before TP		Trend after TP	
	T	P	T	P	T	P
Spring	$0.55^{***}/0.51^{***}$	-3.56/-8.12	0.00/0.05	$63.95^{***}/67.07^{***}$	0.22/0.18	-21.19/-30.47
p	<0.01	ns	ns	<0.01	ns	ns
Summer	$0.25^{***}/0.30^{***}$	-8.05/-13.43	0.32/0.35	$93.56^{**}/98.04^{**}$	0.17/0.33	-85.16/-70.80
p	<0.01	ns	ns	<0.05	ns	ns
Autumn	$0.32^{***}/0.31^{***}$	-8.65/-8.58	-0.31/-0.22	-48.53/-31.40	0.32/0.27	14.63/10.12
p	<0.01	ns	ns	ns	ns	ns
Winter	$0.41^{**}/0.29^{**}$	-2.95/-2.86	$0.82^{**}/0.94^{**}$	$50.33^{*}/52.73^{**}$	0.30/0.12	-14.75/-13.95
p	<0.05	ns	<0.05	<0.05	ns	ns

ns denotes Not significant. *Trends at the 10% confidence level, **Trends at the 5% confidence level, ***Trends at the 1% confidence level

Seasonal precipitation shows a decreasing trend in the four seasons during 1982-2015 (*Table 3*). However, precipitation presents a significant increasing trend during spring ($p < 0.01$), summer ($p < 0.05$) and winter season ($p < 0.05$) before TP. The spatial variation of seasonal precipitation trend (*Figs. 7e-h*) shows regional differences. The region where precipitation increased was located in parts of the western YRB during spring season (*Fig. 7e*) and in eastern parts of YRB during summer and winter seasons (*Figs. 7f, h*). A decreasing seasonal precipitation was found in located in middle YRB during summer, most parts of YRB during winter season (*Figs. 7f, h*) and in the eastern parts of YRB during spring and autumn seasons (*Figs. 7e, g*).

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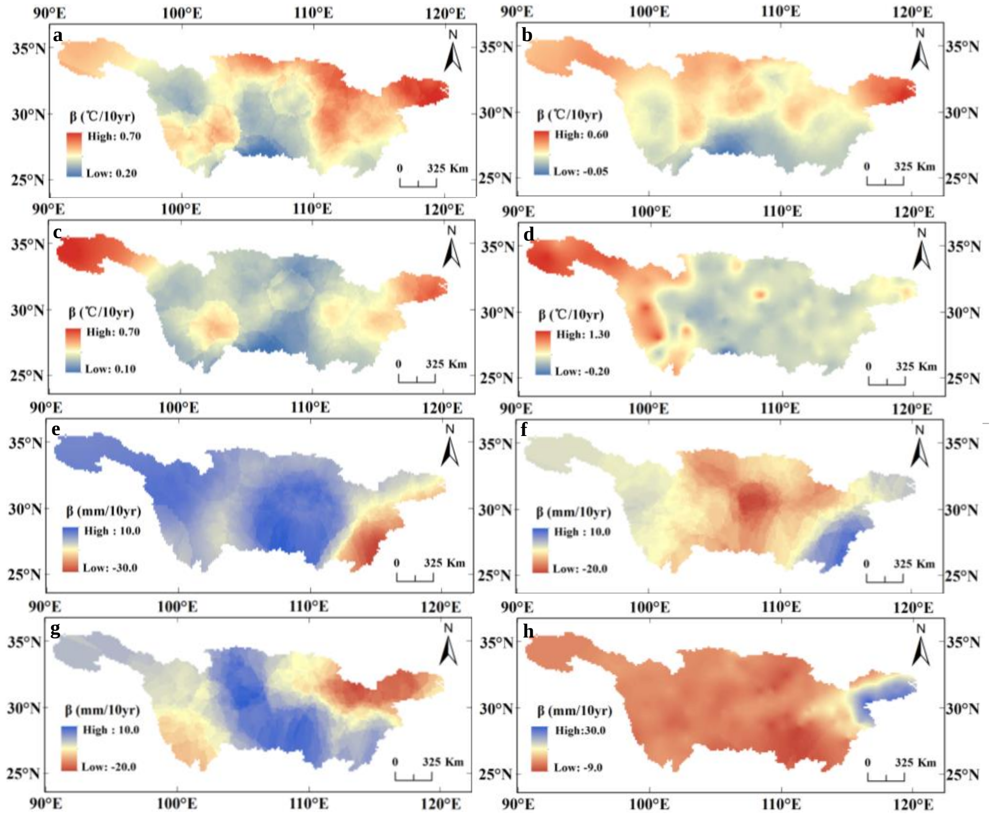

Figure 7. *Spatial distribution of seasonal mean temperature (a-d) and precipitation (e-h) trends in YRB during 1982-2015*

Correlation between vegetation dynamics and climatic variations

Table 4 shows that the mean NDVI had a statistically significant and positive correlation with seasonal temperature, and the correlation coefficients were the highest during spring (R = 0.65, p<0.01), followed by winter (R = 0.50, p<0.01), summer (R = 0.43, p<0.01) and autumn (R = 0.38, p<0.05) seasons. Moreover, the increasing rate of seasonal mean NDVI and temperature during spring season was also the highest during 1982-2015 (*Tables 1, 3*). These results show that climate warming in the beginning of the growing season has a positive effect on NDVI in YRB during 1982-2015. In addition, the mean NDVI shows a significant and positive correlation with temperature during winter season after TP (R = 0.60, p < 0.05) and during summer season before and after TP (R = 0.60, p < 0.01; R = 0.46, p < 0.05). *Fig. 8a* shows a significant and positive correlation between the mean NDVI and seasonal temperature during spring over most of the study area, with the correlation coefficients upto 0.50-0.80. The correlation coefficients in other seasons show spatial heterogeneity. During summer season, the significant and positive correlations were detected in the source region of Yangtze River and eastern YRB, whereas negative correlations were found in parts of the northern and southern YRB (*Fig. 8b*). During autumn season, the correlation coefficients were statistically significantly positive correlation in western and middle YRB, and statistically negative in parts of eastern YRB (*Fig. 8c*). During winter season, the mean NDVI was positively correlated with temperature in the whole YRB, especially statistically significant in the western and southern YRB (*Fig. 8d*).

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Table 4. *Correlation coefficients between seasonal NDVI and temperature (precipitation) during 1982-2015, before and after TP of NDVI trend*

Indicator		NDVI		
		1982-2015	Before TP	After TP
Temperature	Spring	0.65***	0.03	0.38*
	Summer	0.43***	0.60**	0.46**
	Autumn	0.38**	0.11	0.09
	Winter	0.50***	-0.04	0.60***
Precipitation	Annual	-0.23	-0.07	-0.23
	Spring	-0.26	-0.11	-0.26
	Summer	-0.13	-0.05	-0.37*
	Autumn	-0.15	0.13	-0.15
	Winter	-0.11	-0.23	-0.06

* At the 10% confidence level, ** At the 5% confidence level, *** At the 1% confidence level

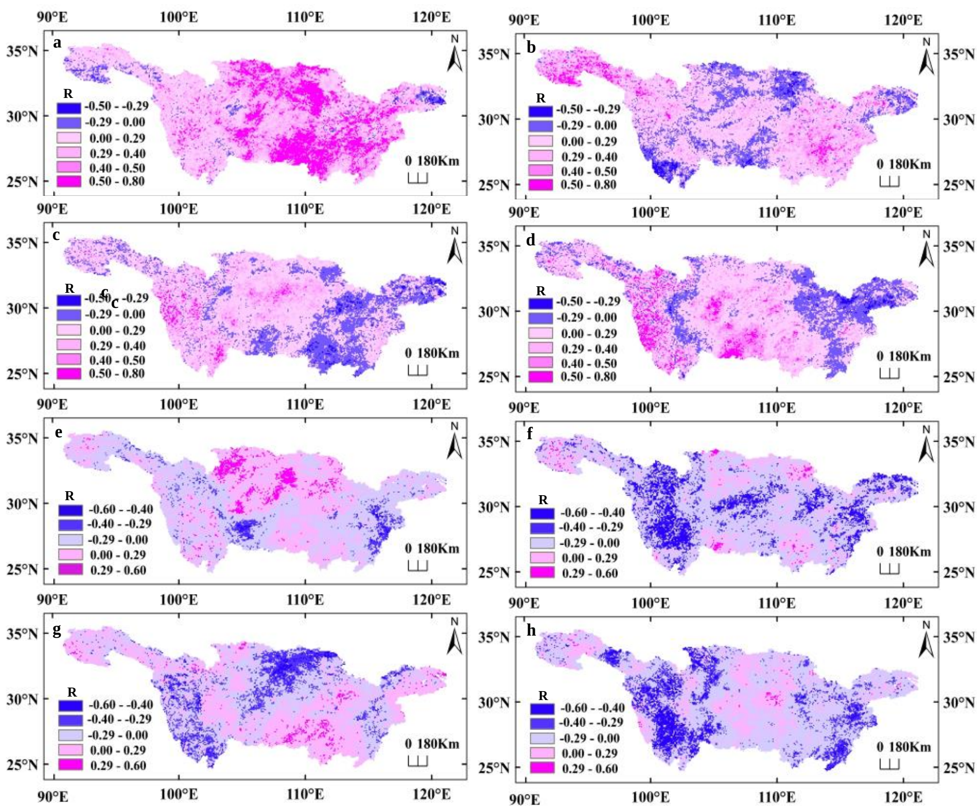

Figure 8. *Spatial distribution of correlation coefficients between seasonal mean NDVI and temperature (a-d), precipitation (e-h) during 1982-2015. (The values of 0.29 is corresponding to 5% significant level of those correlation coefficients during 1982-2015)*

Table 4 shows that the mean NDVI was negatively correlated with seasonal precipitation over the whole study period, before and after TP, but a statistically significant trend was observed during summer season after TP (R = -0.37, $p < 0.1$). The correlation coefficients between NDVI and seasonal precipitation were characterized by seasonal and spatial differences (*Figs. 8e-h*). *Fig. 6e* shows that during spring, the

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regions with significant and negative correlation were located in a small parts of the eastern and southern YRB, while those with significant and positive correlation in parts of the northern YRB. During summer and winter seasons, a negative correlation was observed in most parts of YRB, and the correlation coefficients were significant in the eastern and western YRB (*Figs. 8f, h*). During autumn, the significant and negative correlations were observed in the northern, parts of the western and eastern YRB (*Fig. 8g*).

Discussion

Climate change in YRB

Global warming has influenced the climatic pattern of YRB (Cui et al., 2019). The increasing rate of global mean land-surface air temperature was 0.18 ± 0.04°C/10yr in 1951-2012, while the most significant warming was found during 1979-2012, with the highest warming rate of 0.25 ± 0.05°C/10yr (IPCC, 2013). With economic development in China, especially in the past 30 years, the urbanization has been made a large contribution to climate warming (Jin et al., 2015). The amount of urban area rapidly increased from 3376 km^2 to 13073 km^2 in the eastern YRB during 2001-2013. Moreover, a significant and positive correlation existed between land surface temperature and urban area (Yao et al., 2017). Under global warming, the continual increases in temperature in QTP will seriously accelerate the melting of glaciers (Jiapaer et al., 2015). Glacier melt will lead to a drop in river and groundwater recharge, which would be fatal for ecological environment in the source region of Yangtze River due to most vegetation growth relying on rivers and groundwater. Thus local governments should focus on such environments and propose feasible countermeasures to alleviate these risks.

Seasonal precipitation shows a decreasing trend in YRB during 1982-2015. However, a statistically wetting trend was observed in the source region of Yangtze River (Zhang et al., 2017). A similar wetting trend was also found in the western inland river basin and south-eastern China (Zhang et al., 2013). The increase in precipitation is helpful to improve local ecological environments. Recent research reported that the area of the closed inland lake on the QTP has expanded from 2.56×10^4 km^2 to 3.23×10^4 km^2 in approximately the past 20 years, and the number of new lakes reached 99 in approximately the past 40 years, which was mainly caused by a change to a warm and humid climate on the QTP (Zhang et al., 2017).

Variations of NDVI in YRB

This study analysed the spatiotemporal dynamics of seasonal mean NDVI in YRB for the period 1982-2015. The results provide a new understanding of vegetation dynamics in YRB in recent decades. In our past study, we found a significant statistically increasing trend in annual mean NDVI. However, the changes of annual mean NDVI before and after TP (1994) was slight without showing the statistically confidence level (Cui et al., 2019). The spatial distribution of NDVI observed was similar to those of Wang et al. (2015). At seasonal scale, the mean NDVI during spring and autumn increased faster. Earlier study suggested that the vegetation growth in China increased faster during spring (Piao et al., 2003).

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Relationship between NDVI and climatic variables

In this study, the correlation analysis between seasonal mean NDVI and temperature/ precipitation was performed. The statistically significant and positive correlations between seasonal NDVI and temperature were generally observed in YRB. These results were consistent with those from Richardson et al. (2010) and Peng et al. (2011). However, it was found in this study that the correlation was negative between NDVI and precipitation over the whole YRB and did not reach a statistically confidence level, which indicated that vegetation growth was least affected by precipitation condition in this region during the study period. A widely accepted viewpoint is that vegetation growth is mainly affected by temperature in humid regions, while precipitation is not a limited factor for vegetation growth due to abundant rainfall (Wang et al., 2015). For example, the climate in the source region of Yangtze River is characterized by lower temperature and relatively abundant precipitation, which indicates that the effect of temperature on vegetation in this region is more than that of moisture (Zhang et al., 2016). Karnieli et al. (2010) found that when energy was the limiting factor for vegetation growth in the North American continent at higher latitudes and elevations, the NDVI was positively correlated with temperature. On the contrary, precipitation for vegetation growth is more important compared to the temperature due to lower rainfall in the arid region (McGwire et al., 2000). The increasing temperature will have a positive impact on vegetation growth by extending growing season and increasing photosynthesis if the temperature ranges from baseline to optimum value (Thornthwaite, 1948; Slayback et al., 2003; Hua et al., 2017). However, vegetation growth will be limited if the increasing temperature exceeds the optimum value (Thornthwaite, 1948). Hence, the regions with higher increasing rate of temperature should pay more attention to protecting ecological environments to mitigate and adapt to climate warming.

Conclusion

In this study, the daily meteorological data (T and P) were used to analyze the spatiotemporal variation of seasonal temperature and precipitation in YRB during 1982-2015. Additionally, the vegetation dynamic and the response to climate change were also investigated. The main findings of the present study are summarized as:

(1) Seasonal mean temperature show significant increasing trend over the whole YRB during 1982-2015 which is mainly attributed to an obvious warming during spring season. The warming rates in the north of the study area were observed to be higher compared to those in the south and the highest warming rate was observed in the eastern YRB with intense human activities and the western source region of Yangtze River in QTP.

(2) The mean NDVI during spring and autumn show significant increasing trends over the whole study area. The seasonal NDVI also shows strong spatial heterogeneity.

(3) The correlation coefficients between the mean NDVI and seasonal temperature (precipitation) were strongly dependent on the season with pronounced spatial difference.

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