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Notable shifting in the responses of vegetation activity to climate change in China

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ABSTRACT

The weakening relationship between inter-annual temperature variability and vegetation activity in the Northern Hemisphere over the last three decades has been reported by a recent study. However, how and to what extent vegetation activity responds to climate change in China is still unclear. We applied the Pearson correlation and partial correlation methods with a moving 15-y window to the GIMMS NDVI dataset from NOAA/AVHRR and observed climate data to examine the variation in the relationships between vegetation activity and climate variables. Results showed that there was an expanding negative response of vegetation growth to climate warming and a positive role of precipitation. The change patterns between NDVI and climate variables over vegetation types during the past three decades pointed an expending negative correlation between NDVI and temperature and a positive role of precipitation over most of the vegetation types (meadow, grassland, shrub, desert, cropland, and forest). Specifically, correlation between NDVI and temperature ($P_{\text{NDVI-T}}$) have shifted from positive to negative in most of the station of temperature-limited areas with evergreen broadleaf forests, whereas precipitation-limited temperate grassland and desert were characterized by a positive $P_{\text{NDVI-P}}$. This study contributes to ongoing investigations of the effects of climate change on vegetation activity. It is also of great importance for designing forest management strategies to cope with climate change.

1. Introduction

Currently, the most challenging global environmental problem is climate change, as evidenced by rapid global warming and the increasing frequency of extreme climate events. Climate change can significantly affect vegetation activity (Myneni et al., 1997; Piao, 2003; Badeck et al., 2004; Garrity et al., 2011; Peng et al., 2011; Chen and Chen, 2013; Wu and Liu, 2013) and influence the terrestrial carbon cycle. Previous studies have reported both positive and negative influences of climate change on vegetation growth. For example, the observed increase in vegetation growth over the past several decades in the Northern Hemisphere was partly attributed to significant warming (Zhou et al., 2001), while as the increasing frequency of climate-driven extreme events, such as drought, was shown to possibly convert terrestrial ecosystems from carbon sinks to sources by constraining vegetation growth (Reichstein et al., 2013). Considering the great ecological importance of vegetation, which provides habitat for millions of species on Earth, either directly through plants or indirectly through animals or microbes that feed on plants via predation, parasitism, or decomposition (Alcamo et al., 2003), it is crucial to monitor and assess the response of vegetation to climate change.

The study of the response of vegetation growth to climate change on regional, continental, and global scales is receiving increasing attention (Myneni et al., 1997; Zhou et al., 2001; Lucht et al., 2002; Piao, 2003; Piao et al., 2006a, 2014; Anderson et al., 2010; Peng et al., 2011; Wu et al., 2012). Recent research has indicated a weakening relationship between inter-annual temperature variability and northern vegetation activity over the past three decades (Piao et al., 2014). However, how and to what extent the response of vegetation growth to climate variables has changed in China is still unclear.

Over the past three decades, vegetation growth has increased during the growing season in China (Peng et al., 2011; Xu et al., 2014), and climate change is a leading cause of this phenomenon. Consistent warming is considered to be a main driving force on vegetation growth in China, especially in southern China, where vegetation growth is limited by temperature. In northern China,

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where vegetation growth is limited by water, precipitation is the leading factor for vegetation growth. Before the 2000s, vegetation growth in this region was stimulated by increased precipitation, however, this increase was undermined by expanding drought in the last decade over northern China (Xu et al., 2012). Other factors, such as CO_2 fertilization, ecological protection, restoration, and increasing solar radiation, are also responsible for increasing vegetation growth in China (Peng et al., 2011; Xu et al., 2012). The correlation between the satellite-derived normalized difference vegetation index (NDVI) and climate variables has been shown to be spatially heterogeneous (Wang et al., 2003; Zhang et al., 2013; Xu et al., 2014). However, the link between climate change and vegetation growth in China, especially variations in these correlations, has not been adequately quantified.

The NDVI is an effective indicator of vegetation greenness (Zhou et al., 2001; Tucker et al., 2005; Xu et al., 2012; Liu et al., 2013, 2014), and it has been frequently used to portray temporal and spatial changes in vegetation activity (Myneni et al., 1997; Zhou et al., 2001, 2003; Ji and Peters, 2003; Liu et al., 2014). The newly issued Global Inventory Modeling and Mapping Studies (GIMMS) NDVI dataset (Tucker et al., 2005) from NOAA/AVHRR, covering the period from 1982 to 2011, allowed us to investigate long-term vegetation activity. The goal of this study was to assess the variation in the relationships between NDVI and climate variables from 1982 to 2011 by employing the Pearson correlation and partial correlation methods with 15-y moving windows to the GIMMS NDVI datasets and corresponding station-based meteorological datasets.

2. Data and methods

2.1. NDVI data

We used the latest version of GIMMS NDVI dataset from NOAA/AVHRR with a spatial resolution of 0.083° and 15-d interval over the period from 1982 to 2011. To avoid the influence of non-growing season data, during which the NDVI may be affected by non-vegetated areas and bare soil, we confined the investigation period to the growing season (from April to October) (Zhou et al., 2001; Peng et al., 2011; Piao et al., 2011). The raw NDVI dataset was processed as follows. First, pixels with an average NDVI from April to October less than 0.05 were considered as non-vegetated areas and removed from the study to minimize the impact of soil variations in bare and sparsely vegetated regions (Zhou et al., 2001; Peng et al., 2011; Piao et al., 2011). To further reduce residual cloud contamination, atmospheric, and bidirectional effects, we produced a monthly NDVI dataset using the maximum value composite (MVC) method to obtained monthly NDVI (Holben, 1986; Piao, 2003; Fang, 2004; Peng et al., 2011), which were averaged with the growing season NDVI for further analyses. The bilinear interpolation method was used to extract the NDVI values corresponding to the station data based on grid vegetation data with a spatial resolution of 0.083° (Vu et al., 2012). Finally, monthly NDVI sequence data, corresponding to select climate stations in China and spanning the period from 1982 to 2011, were generated.

2.2. Meteorological data

The station-based climate data from 1982 to 2011, including temperature and precipitation, were obtained from China's Meteorological Data Sharing Service System website (http://cdc.nmic.cn/home.do). This dataset was quality controlled prior to being published. To produce the growing season climate data, basic monthly temperature data was downloaded and averaged from April to October of each year, and the precipitation data was evaluated as the sum of the monthly precipitation over this period. The climate data from 518 out of 726 meteorological stations, which were of high quality and covered the study period, were used in the analysis. The other 208 stations were excluded owing to poor qualifications such as missing data during growing season.

2.3. Vegetation types

Ecosystem distribution in China is controlled by climate (Chen and Chen, 2013). For the purpose of investigating changes in vegetation response to climate variables in different biomes, this analysis was based on the vegetation maps with a scale of 1:1,000,000 from the Atlas of China's Vegetation. All biomes were classified into seven types: forest, shrub, grassland, cropland, meadow, desert and others (Zhao et al., 2011) (Fig. 1). And for better understanding the response of vegetation to climate change, we separated China into two parts, north China and south China, according to the map of Chinese North–South demarcation zone (Tan, 2011).

2.4. Methodology

The relationships between NDVI and temperature and precipitation were examined on national scale and at individual station using Pearson correlation analysis (Pearson correlation coefficients of NDVI and temperature and precipitation were abbreviated as $P_{\text{NDVI-T}}$ and $P_{\text{NDVI-P}}$, respectively). To examine these relationships on a national scale, each of the three variables obtained from the 518 stations were averaged together.

For the purpose of portraying the correlations of NDVI with temperature and precipitation, we applied the linear detrending method to produce the anomalies, or residuals, associated with internally driven climate phenomena. Then, we interpreted the time series of the residuals of NDVI, temperature, and precipitation, respectively (Piao et al., 2014). As vegetation variables are influenced by several factors (e.g., temperature, precipitation, cloud cover, solar radiation, anthropogenic activity, etc.), partial correlation analyses were also conducted to study the apparent responses of NDVI to temperature and precipitation, with the intention of eliminating the covariate effects of other factors.

More precisely, both Pearson correlation and partial correlation analyses were performed to analyze the correlations of NDVI with mean growing season temperature and total growing season precipitation with a 15-y moving window (Piao et al., 2014). The correlation of NDVI and climate variables can be influenced by general changes in background climate over a period of 15 years (Piao et al., 2014). For example, the correlations of NDVI with temperature and precipitation were calculated in the first 15-y window (1982–1996). The window then moved forward 1 year to represent the second 15-y window (1983–1997), and so on until the last 15-y window. In this way, we described the changes in vegetation growth responses to climate variability from 1982 to 2011. Pearson correlations over 9-year and 19-year moving windows were also investigated to avoid the influence of window width. The data processing and calculations were conducted with the Interactive Data Language (IDL) program, ArcGIS10.1 software, SPSS, and R software.

3. Results

3.1. Trends of national inter-annual changes of vegetation and climate variables

Inter-annual changes in China's annual NDVI, temperature, and precipitation from 1982 to 2011 were revealed in Fig. 2.