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Research Paper

Changes in global vegetation activity and its driving factors during 1982–2013

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ABSTRACT

Vegetation activity plays a crucial role in the global carbon cycle and climate. Many studies have examined recent changes in vegetation growth and the associated local climatic drivers. They revealed a global greening trend during the recent decades. However, few studies have analyzed how remote oceanic conditions affect land vegetation growth through atmospheric teleconnection, and the causes of the recent greening needs further investigation. In this study, we investigate the spatio-temporal variations (including trends) of vegetation activity using satellite data of growing-season normalized difference vegetation index ($NDVI_{gs}$), and examine their relationship to local and remote climate oscillations and external anthropogenic forcing by statistical means. As expected, there is an increasing trend in global-mean $NDVI_{gs}$ from 1982–2013, with significant greening over Europe and many other land areas. $NDVI_{gs}$ is temperature-limited at northern high-latitudes, but water-limited in arid and semi-arid regions, and radiation-limited in the Amazon and eastern and southern Asia. Globally, El Niño-Southern Oscillation (ENSO) is the leading climatic driver of interannual variability of $NDVI_{gs}$, especially over southern and eastern Africa, eastern Australia, northeastern Asia, and northern South America. Consistent with previous modeling studies, a regression-based attribution analysis suggests that historical anthropogenic forcing (mainly increases in greenhouse gases) explains about two thirds of the $NDVI_{gs}$ trend from 1982 to 2013, with the rest coming mainly from the Atlantic Multi-decadal Oscillation (AMO). Contributions to the recent $NDVI_{gs}$ trend from ENSO and Pacific decadal variability and Artctic Oscillation appear to be small.

1. Introduction

Vegetation is the main component of the terrestrial ecosystem and it plays a critical role in global carbon, water and energy cycles. Under global warming, how plant's photosynthesis responds to warmer temperature and other extreme events, such as frequent and prolonged droughts (Dai, 2011a,b, 2013; Trenberth et al., 2014; Dai and Zhao, 2017), has become increasingly important for understanding the impact of climate change on terrestrial carbon fluxes and thus atmospheric CO_2 concentrations.

Many studies have showed that global vegetation activities have changed during the last several decades over various climate zones, vegetation types, and soil types. These changes include the greening in Europe (Zhou et al., 2001; Julien et al., 2006), the eastern U.S. (Xiao and Moody, 2005), China (Peng et al., 2011; Xu et al., 2014), India (De Jong et al., 2012), the Sahel (Anyamba and Tucker, 2005; Olsson et al., 2005), and western and southern Australia (Ukkola et al., 2015); and the browning over southern Africa (Ichii et al., 2002), southern South America (Xiao and Moody, 2005), northern North America (De Jong et al., 2013) and Southeast Asia (Zhang et al., 2016). These vegetation changes can affect the air-land carbon exchange. During the 1980s and 1990s, the global terrestrial ecosystems were a net carbon sink (Dai and Fung, 1993; Schimel et al., 2001). From 2000 to 2009, however, vegetation productivity declined over large parts of the Southern Hemisphere (SH), which offset the greening in the Northern Hemisphere (NH) and resulted in a reduction in global productivity (Zhao and Running, 2010; Piao et al., 2011).

Based mainly on statistical analyses, previous studies have also examined local climate drivers for vegetation change. The three leading climatic drivers are precipitation, temperature and radiation, which act as the limiting factor for 52%, 31%, and 5% of global vegetated areas, respectively (Churkina and Running, 1998). Their effects vary across climate zones, ecosystem types, biomes and plant species. Temperature dominates vegetation growth in northern high-latitudes (Churkina and Running, 1998; Zhou et al., 2001; Nemani et al., 2003; Xiao and Moody, 2005; Piao et al., 2014), while precipitation dominates in arid and semiarid areas (Kawabata et al., 2001; Nemani et al., 2003; Hickler et al., 2005; Fensholt et al., 2012), with radiation as the limiting factor

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only in tropical rainforests (Nemani et al., 2003; Schuur 2003). Drought, manifested as both water deficit and high temperatures, was found to limit vegetation growth in the Amazon (Phillips et al., 2009; Doughty et al., 2015), North America (Ji and Peters, 2003; Quiring and Ganesh, 2010), Europe (Ciais et al., 2005; Pasho et al., 2011), Congo rainforests (Zhou et al., 2014), and other regions (Vicente-Serrano et al., 2013).

Most previous studies have focused on the relationship between vegetation and local climatic factors. Few studies have examined the teleconnection of local vegetation growth to remote oceanic conditions. However, many studies have shown that natural climate oscillations, such as the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) or the Inter-decadal Pacific Oscillation (IPO), the Arctic Oscillation (AO), and the Atlantic Multi-decadal Oscillation (AMO) (Liu, 2012) can have large impacts on temperature and precipitation over many remote land areas (e.g., Ropelewski and Halpert, 1989; Thompson and Wallace, 1998; Dai and Wigley, 2000; Buermann et al., 2003; Dai, 2013; Gu and Adler, 2013, 2015; Dong and Dai, 2015). Thus, natural climate variations originated from the oceans could contribute to recent variations and changes in terrestrial vegetation activity through their influences on climate fields. Philippon et al. (2014) have highlighted the impact of ENSO on vegetation dynamics in Africa through its influences on rainfall, solar radiation, and temperature. El Niño events were found to be associated with the negative NDVI anomaly in central India (Bothale and Katpatal, 2014) and northeastern Brazil (Erasmi et al., 2014). Previous studies also found that ENSO and AO were the principal drivers of interannual variability in NH greenness during 1982–1998 (Buermann et al., 2003), while PDO and AMO could explain about half of NH NDVI variations during 2000–2015 (Bastos et al., 2017). In general, warm ENSO and PDO/IPO events are associated with decreased greenness in Australia, Southeast Asia, northeastern South America and southern Africa, but increased greenness in eastern Africa, central Asia, and northern North America (Woodward et al., 2008; Miralles et al., 2014).

A few studies have focused on attribution of recent greening trends through model simulations. Although limited by modeling uncertainties, these studies suggest that CO_2 fertilization is the dominant contributor to the recent global trend in NDVI (Los, 2013) and leaf area index (LAI) (Mao et al., 2013; Zhu et al., 2016), followed by climate change, nitrogen deposition and other factors (Zhu et al., 2016). Mao et al. (2016) have gone a further step to attribute the greening of the northern extratropical land surface to anthropogenic forcing, primarily human-produced greenhouse gases (GHGs).

This study aims to investigate the variations and changes of global vegetation activity from 1982 to 2013 using the NDVI dataset from the Global Inventory Monitoring and Modeling Systems (GIMMS) (Tucker et al., 2005), and examine the relationship between NDVI and local climate factors and remote climatic oscillations. Another focus is on the attribution of the recent global NDVI trends and variations to external anthropogenic forcings (such as increases in GHGs) and internal modes of climate variability (such as ENSO, AO and AMO). This study differs from the previous studies by making an extra step to explain the variations and changes in global vegetation growth in terms of internal climate modes of variability (mainly of oceanic origin) as well as external climate forcing. The results should improve our understanding of the underlying drivers of recent changes in global terrestrial vegetation activity based on observational analyses, in contrast to previous modeling studies.

2. Data and methods

2.1. NDVI data

To quantify vegetation activity, we used the latest GIMMS3g NDVI dataset (http://ecocast.arc.nasa.gov/) derived from the Advanced Very High-resolution Radiometer (AVHRR) on satellites operated by the National Oceanographic and Atmospheric Administration (NOAA) (Tucker et al., 2005). It spans from January 1982 through December 2013 on a 1/12° grid and is available twice a month. This study focuses on the vegetation activity in the growing season, which is defined here as April–October for 20°N–70°N, October–April for 20°S–60°S, and January–December (i.e., the whole year) for 20°S–20°N. We first calculated the time series of NDVI for growing season ($NDVI_{gs}$) over each 1/12° pixel with NDVI > 0 during the growing seasons. To match with climate data, the raw $NDVI_{gs}$ data were simply averaged onto a 2.5° × 2.5° grid. Additionally, areas with very sparse vegetation cover (long-term mean $NDVI_{gs} < 0.1$) were masked out as well as the Arctic regions (north of 70°N). Time series of the global (60°S–70°N) mean $NDVI_{gs}$ from 1982 to 2013 were obtained by averaging over all the pixels with $NDVI_{gs} \geq 0.1$ using area as the weighting.

2.2. Climate data

Observational data for monthly surface air temperature (T) over land were obtained from the Climate Research Unit (CRU) at the University of East Anglia (TS3.22; Harris et al., 2014). The CRU TS 3.22 dataset covers 1901–2014 on a 0.5° grid and was derived by interpolating T anomalies from ~4000 weather stations (Mitchell and Jones, 2005). The CRU monthly temperature data were simply averaged onto the 2.5° grid.

Monthly precipitation (P) data were obtained from Global Precipitation Climatology Centre (GPCC) v7 dataset, which covers 1901–2010 (Schneider et al., 2014). The Global Precipitation Climatology Project (GPCP) v2.2 (Huffman et al., 2009) data for 2011–2013 were used to extend the P series to 2013. Before merging, the two datasets were adjusted to have the same mean over a common period (1981–2010) at each grid box on a 2.5° grid.

Monthly data of sea surface temperatures (SSTs) were obtained from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST) (Rayner et al., 2003), which was derived from *in-situ* observations and covers our study period (1982–2013) with a spatial resolution of 1° × 1°.

Monthly data for photosynthetically active radiation (PAR) were from the NASA/Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget (SRB3.0) dataset, which were obtained from the NASA Langley Research Center Atmospheric Science Data Center (https://eosweb.larc.nasa.gov). The PAR data were generated using an updated version of the University of Maryland's shortwave and longwave flux algorithm and the International Satellite Cloud Climatology Project (ISCCP) DX radiance and cloud parameters (Rossow and Schiffer, 1999). The PAR dataset only covers 1984–2007 on a 1° × 1° grid, which was first assigned onto a 0.5° grid and then averaged onto the 2.5° grid.

We used the monthly self-calibrated Palmer Drought Severity Index with Penman-Monteith potential evapotranspiration (sc_PDSI_pm) produced by Dai et al. (Dai et al., 2004; Dai, 2011a,b, 2013; Dai and Zhao, 2017) as a measure of surface aridity. The sc_PDSI_pm was calculated using historical meteorological data on the 2.5° grid for 1850-present and is available from http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html.

We used indices for ENSO and IPO (ENSO&IPO thereafter, Dong and Dai, 2015), AMO (Liu, 2012), and AO (Thompson and Wallace, 1998) to represent the leading modes of climate variability originated from the tropical Pacific Ocean, the North Atlantic Ocean, and the northern mid-high latitude atmosphere, respectively. We chose these climate modes because they are the most studied, well-known oscillations that have significant impacts on global climate. ENSO is the dominant mode of interannual (2–7 year) variations in sea surface temperatures (SSTs) and winds over the tropical Pacific Ocean, which can influence weather and climate in many regions of the world through atmospheric teleconnections (Ropelewski and Halpert, 1989; Dai and Wigley, 2000). The PDO and IPO refer to the decadal to multi-decadal variations in