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Seasonal and interannual changes in vegetation activity of tropical forests in Southeast Asia

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ABSTRACT

Tropical vegetation has been suggested to be vulnerable to future climate change. At the regional scale, few studies have focused on the fluctuations of vegetation activity of tropical forests in Southeast Asia, which is an important area of tropical vegetation. Here, we investigated the spatio-temporal variability of vegetation photosynthetic activity in Southeast Asia using three independent satellite-derived Normalized Difference Vegetation Index (NDVI) products (Global Inventory Modeling and Mapping Studies group using data from Advanced Very High Resolution Radiometer (GIMMS AVHRR) NDVI3 g, Système Pour l'Observation de la Terre VEGETATION (SPOT-VGT), and MODerate resolution Imaging Spectroradiometer (MODIS)). We also used the recently developed Sun-Induced chlorophyll Fluorescence (SIF) from the Greenhouse gases Observing SATellite (GOSAT), a proxy of actual photosynthesis, as a complement to NDVI. In forests with pronounced wet-dry seasonal cycle (the north and south regions of Southeast Asia), we found consistent relationships between NDVI and climate factors (precipitation, temperature and solar radiation). At the seasonal scale, all of the datasets showed that the NDVI continuously decreased during the dry season, particularly in deciduous forests (DF). Similarly, SIF in the north region also displayed a decreasing trend during the dry season, although the magnitude of the decrease was relatively small compared to that of the NDVI. This result is in contrast to that reported for the Amazon forest where a significant increase in vegetation greenness during the dry season has been observed. During the wet season, different seasonal variations were observed between SIF and the NDVI in the north region. For both evergreen forests (EF) and DF, the maximum SIF was observed in the months with the maximum precipitation, while the maximum NDVI value was observed at the end of the wet season. At the interannual scale, NDVI decrease nonlinearly along drought severity in dry seasons. During wet seasons, the greenness is insensitive to droughts but more related to radiation. Our results demonstrate that forests in Southeast Asia are water-limited during the dry season, indicating a vulnerability to future increase in the intensity of El Nino events and to temperature-driven increases in evapotranspiration.

1. Introduction

Studies using vegetation models have suggested that tropical rainforests are vulnerable to climate change (Cox et al., 2000; Sitch et al., 2008; Zeng et al., 2013). Understanding the response of tropical ecosystems to climate change based on present-day observations is critical for minimizing uncertainties in models, and for accurately predicting the future evolution of tropical ecosystems as well as any feedback to climate change (Friedlingstein et al., 2006; Piao et al., 2013). Temperature, solar radiation, and precipitation are generally considered to be the most important climate factors influencing vegetation growth. Nemani et al. (2003) investigated the relative contributions of climatic controls on vegetation using monthly climate data, suggesting that across most tropical rainforest regions, incident solar radiation, rather than precipitation and temperature, is the main limiting climate factor for vegetation growth. Consistently, the satellite greenness index and leaf

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area data in the Amazon showed a green-up during the dry season (Huete et al., 2006; Myneni et al., 2007). However, these results have been challenged by recent studies, which attributed the dry season greening to an increase in the near-infrared reflectance of leaves rather than the absorption of photosynthetically active radiation (PAR) (Asner and Alencar, 2010; Samanta et al., 2012b), or the seasonal variation of sun-sensor geometry (Morton et al., 2014). Evidence from direct flux tower measurements of increasing or stable dry season gross primary production (GPP) in the Amazon supports the theory of a limitation of GPP by radiation rather than by precipitation (Saleska et al., 2003). In contrast, long term in situ forest inventory and satellite data show a decline in Amazon forest growth in regions experiencing severe dry years, such as 2005 and 2010 (Phillips et al., 2009; Xu et al., 2011). This indicates that under severe dry conditions, precipitation instead of solar radiation becomes the limiting factor for primary production, implying that forests in the Amazon may resist slight droughts but can be significantly affected by severe droughts.

Southeast Asia covers a land area of 4.5 million km^2, with 2.1 million km^2 of forests (FAO, 2010). Southeast Asian rainforests account for 17% of the area of all tropical forests (Grainger, 2008) and 26% of the global tropical forest biomass carbon stock (Saatchi et al., 2011), meaning that they have a higher biomass density than other tropical regions. A recent study has also suggested that, the growth of intact forests and regrowth of secondary forests and plantations after deforestation in Southeast Asia results in an annually net uptake of about 0.7 Pg of carbon, offsetting about 80% of the carbon emission caused by deforestation in this region (Pan et al., 2011). It should be noted that Pan et al. (2011) estimated the forest carbon stock change of Southeast Asian rainforests by extrapolating values from Tropical American and African forests due to the lack of regional data, highlighting our limited knowledge of the carbon cycle in this region. Furthermore, compared to the Amazon (Huete et al., 2006; Myneni et al., 2007; Xu et al., 2011) and African tropical ecosystems (Asefi-Najafabady and Saatchi, 2013; Zhou et al., 2014), there have been few studies on the mechanisms, interactions, and impacts of climate on vegetation in Southeast Asia (Huete et al., 2008).

Remote sensing provides useful data for monitoring the spatial details and temporal changes of vegetation properties over large regions. In this study, we investigated the relationships between vegetation photosynthetic activity and climate variables (precipitation, temperature, and solar radiation) over Southeast Asia, especially the response of vegetation activity to different levels of drought severity. The proxy of photosynthetic activity was the Normalized Difference Vegetation Index (NDVI) from three satellite datasets: MODerate resolution Imaging Spectroradiometer (MODIS), Système Pour l'Observation de la Terre VEGETATION (SPOT-VGT), and National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR). In addition, because the NDVI may be subject to saturation effects in dense rainforest canopies, we also used the Greenhouse gases Observing SATellite (GOSAT) measurements-derived sun-induced chlorophyll fluorescence (SIF), as an independent proxy of photosynthesis to supplement the NDVI data.

2. Datasets and methods

2.1. Study area

The study area was located between longitudes 92°E and 137°E and latitudes 12°S and 29°N, covering the Indo-China Peninsula and the majority of the Malay Archipelago. The area could be divided into three regions according to the precipitation regime: the north region (10°N–29°N) with a dry season from December to March; the middle region (5°S–10°N) with monthly precipitation higher than 150 mm throughout year and no significant dry season; and the south region (5°S–12°S) experiencing a dry season from June to September (Fig. 1).

2.2. NDVI datasets

The NDVI is a remotely-sensed vegetation index derived from the red and near-infrared reflectance. It has been linked to the fraction of absorbed photosynthetically active radiation (fAPAR) and to net primary productivity (NPP) using a light use efficiency model (Tucker and Sellers, 1986; Myneni and Williams, 1994). NDVI data from coarse and moderate resolution sensors is sensitive to sub-pixel cloud contamination, aerosols, and sun-sensor geometry, especially in tropical regions (Samanta et al., 2012a; Morton et al., 2014). To reduce the uncertainties caused by these disturbances, this study used three NDVI datasets derived from different radiometers, with different atmospheric corrections and sun-sensor geometry. The three datasets were: (1) the 15-day 8 km NDVI3 g dataset for the period from July 1981, developed by the Global Inventory Modeling and Mapping Studies (GIMMS) group using data from AVHRR instruments onboard the NOAA series satellites (Pinzon and Tucker, 2014) (hereafter referred to as AVHRR NDVI); (2) the MODIS 16-day 1 km NDVI product (MOD13A2, Collection 5) for the period from February 2000, derived from instruments onboard the Terra satellite (https://lpdaac.usgs.gov) (hereafter referred to as MODIS NDVI); and (3) the SPOT-VGT 10-day 1 km NDVI product (http://www.vgt.vito.be) (hereafter referred to as VGT NDVI), for the period from May 1998 to July 2013. These datasets are well calibrated and have been widely used to study vegetation dynamics in tropical regions (Asner et al., 2004; Erasmi et al., 2009; Silva et al., 2013).

2.3. Fluorescence data

Plants absorb shortwave radiation for photosynthesis reactions. However, not all the shortwave radiation absorbed by chlorophyll is used for carboxylation. Excess energy may damage the photosynthetic apparatus and must be dissipated as heat or light. This re-emitted light has been referred to as chlorophyll fluorescence. Previous studies have found that chlorophyll fluorescence is closely related to not only the PAR received by chlorophyll but also complex biotic and abiotic leaf stress (Baker, 2008). Thus it has been proposed as a more direct indicator of photosynthesis than the NDVI. It has recently been reported that remotely sensed SIF is strongly correlated to model simulated and in situ observed GPP (Meroni et al., 2009; Frankenberg et al., 2011; Yang et al., 2015).

We used SIF from June 2009 to May 2012 retrieved from Fourier Transform Spectrometer (FTS) measurements onboard the Japanese Greenhouse gases Observing SATellite (GOSAT) using the same approach as Joiner et al. (2011), Frankenberg et al. (2011) and Lee et al. (2013). The retrieved fluorescence data were cloud-free monthly sparse samples with an approximate 10 km footprint. Each sample was measured at 757 nm and 771 nm in two perpendicular polarizations (referred to as s and p).

2.4. Climate data

In this study, we used precipitation, air temperature, and solar radiation as the potential driving factors of vegetation growth. The precipitation and temperature data used in this study were from the Climate Research Unit (CRU) TS3.21 dataset (Harris et al., 2014), which is available on the CRU website (http://www.cru.uea.ac.uk). The 0.5 × 0.5° monthly data are interpolations based on worldwide climate station records. In terms of solar radiation, we used surface incoming shortwave radiation data based on the Surface