Environmental Research 147 (2016) 621–629

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Understanding spatio-temporal variation of vegetation phenology and rainfall seasonality in the monsoon Southeast Asia

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ARTICLE INFO

Article history:
Received 14 May 2015
Received in revised form
25 December 2015
Accepted 4 February 2016
Available online 26 February 2016

Keywords:
Phenology
Rainfall
Monsoon Southeast Asia
Climate change
Remote sensing
Vegetation index
EVI
MODIS
TRMM

ABSTRACT

The spatio-temporal characteristics of remote sensing are considered to be the primary advantage in environmental studies. With long-term and frequent satellite observations, it is possible to monitor changes in key biophysical attributes such as phenological characteristics, and relate them to climate change by examining their correlations. Although a number of remote sensing methods have been developed to quantify vegetation seasonal cycles using time-series of vegetation indices, there is limited effort to explore and monitor changes and trends of vegetation phenology in the Monsoon Southeast Asia, which is adversely affected by changes in the Asian monsoon climate. In this study, MODIS EVI and TRMM time series data, along with field survey data, were analyzed to quantify phenological patterns and trends in the Monsoon Southeast Asia during 2001–2010 period and assess their relationship with climate change in the region. The results revealed a great regional variability and inter-annual fluctuation in vegetation phenology. The phenological patterns varied spatially across the region and they were strongly correlated with climate variations and land use patterns. The overall phenological trends appeared to shift towards a later and slightly longer growing season up to 14 days from 2001 to 2010. Interestingly, the corresponding rainy season seemed to have started earlier and ended later, resulting in a slightly longer wet season extending up to 7 days, while the total amount of rainfall in the region decreased during the same time period. The phenological shifts and changes in vegetation growth appeared to be associated with climate events such as EL Niño in 2005. Furthermore, rainfall seemed to be the dominant force driving the phenological changes in naturally vegetated areas and rainfed croplands, whereas land use management was the key factor in irrigated agricultural areas.

1. Introduction

Vegetation phenology is the study of recurring patterns of vegetation growth and development, as well as their connection to climate (White et al., 1997). Land surface phenology (LSP) is the seasonal pattern of spatio-temporal variation in the vegetated land surfaces observed from remote sensing (White and Nemani, 2006; de Beurs and Henebry, 2010) and is a key indicator of ecosystem dynamics under a changing environment (Xiao et al., 2009). Therefore, phenological properties, such as the timing and rate of green-up, amplitude and duration of the vegetation growth, and timing and rate of vegetation senescence have become emerging indicators of global environmental changes. Changes in plant phenology also have significant implications to carbon, water, and energy cycles (Xiao et al., 2009). Even slight changes in plant growing season length or magnitude can result in large changes in annual gross primary production.

With decades of remote sensing imagery, it is possible to quantify phenological changes through time and space, thus enabling phenological monitoring at local, regional and global scales (e.g. Myneni et al., 1997, 2007; Zhang et al., 2006). The Moderate Resolution Imaging Spectroradiometer (MODIS) provides valuable data for monitoring ecosystem dynamics with appropriate spatial and temporal resolutions and substantially improved geometric and radiometric properties (Zhang et al., 2006). One of the MODIS products, Enhanced Vegetation Index (EVI), was developed to: 1) enhance the vegetation signal with improved sensitivity in high biomass regions, 2) reduce atmospheric and soil effects, and 3) reduce the impact of smoke from biomass burning in tropical areas (Huete et al., 2002; Xiao et al., 2009). These characteristics of EVI make it an ideal dataset to study phenological dynamics,

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http://dx.doi.org/10.1016/j.envres.2016.02.005
0013-9351/

particularly in tropical zones where clouds and forest fires occur frequently.

Satellite time-series data enable researchers to derive phenological information at different spatial and temporal scales. Myneni et al. (1997) and Tucker et al. (2001) were among the first to use satellite data to identify some of the key phenological parameters from NDVI (Normalized Difference Vegetation Index) time series to examine temporal changes in vegetation dynamics. Reed et al. (1994) derived quantitative phenological parameters from 1989 to 1992 across the United States to assess the spatial patterns of phenology. Moulin et al. (1997) assessed the main phenological stages of the vegetation at the global scale with remotely sensed imagery to compare and contrast phenology patterns. These studies focused on general and broad categories of vegetation. Attempting to better represent agricultural crop development, Zhang et al. (2003) proposed to use four key transition dates—green up, maturity, senescence, and dormancy—to assess phenological characteristics in the Northeastern United States. Even more specific crop phenology analysis was made by Xiao et al. (2006) with a new geospatial database of paddy rice agriculture for 13 countries on South and Southeast Asia (SEA) using MODIS-derived vegetation indices. Similarly, Tottrup et al. (2007) focused on forest ecosystems with a new approach to mapping fractional forest cover across the highlands of mainland of SEA using regression tree modeling and multi-temporal MODIS 250 m data.

Further attempts were made to associate phenological changes in vegetation with climate patterns, particularly with rainfall data. Zhang et al. (2005) explored the response of vegetation phenology to precipitation across Africa using MODIS and rainfall data. The results demonstrated that vegetation phenology was strongly dependent on the seasonality of precipitation. Zhang et al. (2006) further extended the African analysis to global scale, finding that phenological parameters exhibited strong correspondence with temperature patterns in mid and high latitude climates, with rainfall seasonality in seasonally dry climates, and with cropping patterns in agricultural areas. Focusing on specific crops, Sakamoto et al. (2006) estimated the spatial distribution of heading date and rice-cropping system in the Mekong Delta and attributed to the seasonal changes in water resources in 2002 and 2003.

Although there have been some research efforts to study vegetation phenology in the Monsoon Southeast Asia (MSEA), most of these studies focused on rice cropping systems or forest ecosystems. There is a need to address the trends and changes of vegetation phenology at a regional scale and to analyze the relationships between phenology and climate variability because the climate variability is becoming more important due to its significant impact on ecosystem dynamics in the region.

The Monsoon Southeast Asia (MSEA) presents challenges in capturing the phenological dynamics from remote sensing. First, the monsoon climate patterns exhibit a strong spatio-temporal variability, with frequent extreme climate events, such as floods and droughts, which has a significant impact on phenology in this region (Zhang et al., 2005). Second, the landscapes are mosaics of small patches of different land uses and covers, which may present challenges for remote sensing analyses at the MODIS spatial resolution. Third, spatial heterogeneity in land management practices such as irrigation and rainfed agriculture result in complex patterns of land surface phenology. Further, ecosystems in this region are less sensitive to temperature but are highly dependent on rainfall to trigger the emergence of green leaves and to control vegetation growth duration (Kramer et al., 2000; Cleland et al., 2007). Finally, this region has gone through a much rapid land use change and rapid economic development, making it even more challenging to capture phenological dynamics with remote sensing.

The objectives of this paper are first to test the suitability of MODIS EVI to capture the vegetation phenology in the Monsoon Southeast Asia (MSEA), to analyze the spatial characteristics of the phenology and rainfall seasonality from 2001 to 2010 to determine their temporal trends, and to examine the relationships between seasonal rainfall fluctuations and phenological parameters. The goal is to improve regional understanding of the phenological characteristics of MSEA and environmental changes.

2. Material and methods

2.1. Study area

The Monsoon Southeast Asia consists of two dissimilar portions: the Indochina Peninsula and the Insular Southeast Asia (Archipelagic Nations). This research focuses on the seasonal dynamics in the countries located in the Indochina Peninsula: Thailand, Vietnam, Cambodia, Lao PDR (Laos), Myanmar, and Malaysia (Fig. 1). This is because phenology can be extracted in the Indochina Peninsula while there is little variation in seasonal vegetation cycles in the Insular Southeast Asia due to the rainy tropical climate and the ecology of the rainforests. For convenience, countries in the Indochina Peninsula are simply referred to as "Monsoon Southeast Asia (MSEA)" in this research.

The MSEA has a humid subtropical climate with a winter dry season with much of it receiving a considerable amount of annual precipitation (Southeast Asia, 2009). With these climate characteristics, the Peninsula has a tropical maritime climate featuring relatively high temperatures, high humidity, and abundant rainfall. Most of MSEA is covered with tropical forests, including rainforests (tropical evergreen forests with high annual rainfall) and monsoon forests (tropical deciduous forests with seasonal rainfall pattern) (Southeast Asia, 2009). According to National Intelligence Council (2009), MSEA has a regular pattern of seasonal monsoons and the periodic extremes in regional climate caused by ENSO (EL Niño-Southern Oscillation events, a global climate phenomenon that recurs irregularly every 2–7 years and is associated with changes in ocean surface temperature and prevailing winds). Seasonal monsoons can cause extreme weather events, such as floods and droughts. Moreover, ENSO can further intensify floods and droughts in this region.

2.2. Data sets

MODIS EVI 16-day composite time-series at 250 m spatial resolution (MOD13Q1 product V5, downloaded from: https://lpdaac.usgs.gov/data_access/data_pool) from 2001 to 2010 were used in this study to derive land surface phenology. Daily rainfall data from Tropical Rainfall Measuring Mission (TRMM) at $0.25 \times 0.25°$ spatial resolution (TRMM3B42 daily product, downloaded from: http://mirador.gsfc.nasa.gov/) from 2001 to 2010 were used to derive seasonal rainfall patterns. Field-based phenological data was also collected in Thailand to compare with and validate satellite-derived phenology, whereas meteorological station rainfall data (monthly rainfall from 2001 to 2010 acquired from Thai meteorological stations) was used to verify the TRMM data. Landsat images (2001, 2004, 2005, 2006, and 2007 downloaded from http://glovis.usgs.gov) were used for fine scale phenological interpretation and inference of land uses or land management practices.

Pre-processing of satellite data was needed and subsequently carried out in this study. While the MODIS EVI product provides enhanced temporal information of land surface phenology, it is still constrained by cloud contamination and atmospheric effects as well as by the associated blue band degradation. To overcome these problems, a smooth filtering function, the Savitzky-Golay filter built within the TIMESAT program, was applied to the MODIS