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.

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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,
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 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 rainfall 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://ltpdac.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 × 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
EVI data to replace outliers, spikes, or missing values. However, this approach is sometimes insufficient to eliminate persistent cloud contamination, affecting particularly phenology detection in tropical climates. Therefore, annual data quality assessment maps were produced in order to compare the level of quality associated with annual EVI and annual phenological patterns. The data quality maps were processed by using reliability layers provided in the MOD13Q1 product to further eliminate poor quality data.

In order to validate satellite-derived phenological characteristics, field-based phenology data was also collected in Thailand. Field trips were made to visit different landscapes in Thailand and field surveys were carried out to record the timing of each phenological stage. The location-specific information was then compared with the same pixel location derived from satellite data to assess the accuracy of phenological information from satellites.

2.3. Phenological and rainfall seasonality extraction

The flowchart of phenology and rainfall analysis is shown in Fig. 2 and the following vegetation and rainfall parameters were used in this research:

- Mean annual EVI
- Vegetation phenology: The start (SGS), end (EGS), and length (LGS) of growing season derived from MODIS-EVI data using the TIMESAT program.
- Mean annual rainfall.
- Seasonal rainfall: The start (SRS), end (ERS), and length (LRS) of rainy season calculated from daily rainfall data.

2.3.1. Phenological extraction

The TIMESAT (Jönsson and Eklundh, 2010) program was employed to extract phenological parameters. It first implemented a simple median filter to remove noise and then applied the Savitzky-Golay (SG) filter to remove noise, spikes, and irregular values of original data due to cloud contamination, atmospheric conditions, and bidirectional effects in order to produce a smoothed EVI profiles. To obtain accurate EVI profiles and phenological parameters, the parameter thresholds in the TIMESAT program were determined by analyzing time-series data and tuning and testing against local conditions in MSEA from field surveys. To determine the start and the end of growing seasons, the ratio of EVI amplitudes to the annual lowest values in the early

![Fig. 1. Study area, the Indochina Peninsula in Monsoon Southeast Asia.](image-url)
and late growing season was calculated to reach a threshold (20% in this study).

2.3.2. Rainfall seasonality extraction

This study adopted the rainy season criteria provided by Jutakorn (2011) to determine the start and end of rainy seasons in MSEA, where the SRS was defined as the duration of time in which rainfall persists for five consecutive days and the amount of cumulative rainfall is higher than 10 mm, a critical climate threshold trigger for plants to grow. The first day of that rainfall period is the start of the rainy season. These criteria identified April of each year as the earliest month that rainfall could start in MSEA (Jutakorn, 2011). The ERS is defined using similar criteria except applied in reverse order, starting from December or November backwards. The period between the SRS and ERS defines the length of rainy season (LRS).

2.4. Spatial variation and trend analysis

First, the 10-year mean values of each parameter (EVI, phenological and rainfall parameters) were computed across the study area to analyze the spatial patterns. Then, the Mann–Kendall (MK) trend test and Sen’s methods (EPA, 2006; de Beurs and Henebry, 2005; de Beurs et al., 2009) were employed to determine the phenological trend from 2001 to 2010. The MK trend test is calculated by sorting the data according to date, computing all differences between measurements of a given year and those of the previous year, and then counting the number of positive and negative values (Yue et al., 2002; Xu et al., 2007; EPA, 2006; de Beurs et al., 2009). The sum of these values indicates the strength and direction of a trend. Sen’s method was then used to calculate the magnitude of the slope for geographic locations where trends are significant.

2.5. Correlation analysis

The correlations between phenology and rainfall patterns were calculated using the coefficient of correlation (R) to indicate the relationship between each pair of parameters (mean annual EVI vs. mean annual rainfall, SGS vs. SRS, EGS vs. ERS, and LGS vs. LRS). In addition, the p-value (probability associated with significance) was used to test the significance of the correlations at a 95% level, where a p-value < 0.05 is regarded as significant correlation.

2.6. Satellite-based phenology validation

To validate satellite derived phenological parameters, two hundred (200) field sites of different vegetation types (e.g., rice, cassava, sugarcane, corn) in central and northeast Thailand were visited to collect information on SGS and EGS in 2010. Statistical analysis was subsequently made to calculate the coefficient of determination ($R^2$) to test the level of agreement between MODIS phenology and field observation. The same analysis was also made on the TRMM rainfall and meteorological station data, where monthly station rainfall (123 stations covering all of Thailand) was compared with TRMM rainfall. The average ten-year mean of rainfall seasonality (SRS, ERS, and LRS) from the previous Thailand research (Jutakorn, 2011) was then used to compare with rainfall seasonality derived from TRMM data.

3. Results

3.1. Spatio-temporal variation of EVI, phenology and rainfall seasonality

The spatial distribution of 10-year mean EVI from 2001 to 2010 (Fig. 3) exhibited high values (more than 0.4) in productive
agricultural and forested areas. These areas were mostly located in the northern and southern portions of the Peninsula and in eastern Vietnam where deciduous and evergreen forests were found. In contrast, regions where crop conditions were poor or covered by low biomass and deforested areas tended to have low EVI values. Relatively low EVI values (less than 0.4) were found in central Myanmar and northeastern Thailand, where most agricultural lands are located.

Although the MSEA has similar climate, the spatial phenological patterns varied greatly, depending on geographic locations, ecosystem types and sometimes farming management (Fig. 3). The start of growing season, SGS, in MSEA ranged from March through May, shifting toward later dates from east to west. The typical SGS from March to April was obvious in the northeast and central portions of the Peninsula. However, there were some homogeneous patches, found in similar ecoregions. The phenological dates (e.g., SGS, EGS) appeared later (around May) in natural vegetation areas but started earlier in agricultural areas (around January). Forest areas had longer growing seasons than agricultural areas. Furthermore, the same crop types found in different locations were shown to have dissimilar phenological characteristics due to differences in soil, water, climate, and management, for example, in rice fields in northern Vietnam and central Thailand (Fig. 3).

Similar to the start of growing season, the end of growing season also varied greatly, depending on land cover type and land use management, ranging from June of the same year to January of the next year (Fig. 3). Generally, the EGS shifted toward the later dates from the east to west in the Peninsula. In the eastern region, many areas had the end of the growing season in earlier June. The corresponding starting dates in these areas ranged from late January through late March. These areas were mainly rice paddies of similar cropping pattern (i.e., similar SGS and EGS) as in the first growing season. In comparison, the northwest portion of the Peninsula (Myanmar) had a later growing season, starting in May and ending in January or February of the next year. The land use in this region consisted of mostly rainfed and irrigated croplands.

The average length of the growing season was approximately 180–240 days (Fig. 3), longer in the northwest through the northern portion of the Peninsula. Conversely, a large part of the central and eastern portions had shorter growing season lengths. The longer growing season in the northwestern and northern regions were likely due to moisture-rich environments, forests, and perennial crops compared to the crops found in the east.

The average rainfall amount in MSEA region ranged approximately 1000–2000 mm/year. A high rainfall (more than 2000 mm/year) was found in the southern Peninsula, particularly in southwestern Cambodia (Fig. 3). In contrast, low rainfall (less than 1000 mm/year) was observed in the northwestern Peninsula, even though this region tended to have a longer rainy season. The rainy season in MSEA typically started in April or May. The southern part of the Peninsula tended to have more rainfall and an earlier SRS due to year round rainfall resulting from its rainy tropical climate. The average ERS occurred from September to December, with an average LRS of 180–240 days with the exception of the southern peninsula, which exhibited a later ERS and longer rainy season.
3.2. Trend analysis

The overall regional trend of EVI in MSEA was decreasing from 2001 to 2010 (Fig. 4), particularly in western Myanmar, northern Thailand, and northern Vietnam. The overall changes of SGS, EGS, and LGS were within a two-week period. The areas of distinct positive EVI trends were in southern Cambodia and Vietnam. The overall declining EVI trend suggested a reduction in total biomass production in the region, which may be associated with shifts in phenology and climate change.

The overall phenological trends as shown in Fig. 4 appeared to shift towards a later and slightly longer growing season in the Peninsula (0–14 days), as reflected in SGS and EGS, although some significant trends toward earlier SGS were observed in western Myanmar, central, northeastern and eastern Thailand, and the eastern part of the Peninsula. Rainy season in MSEA tended to start early and end late resulting in a longer growing season (approximately 0–7 day) (Fig. 4), suggesting that an early raining season may not trigger an early growth as plant grow is controlled by both soil moisture and temperature. It was also noted that the amount of rainfall had decreased from 2001 to 2010. The annual rainfall decreased (less than 200 mm/year) across most of the western and northern regions of the Peninsula but increased (more than 200 mm/year) across the eastern region of Thailand. Distinctive rainy season patterns were observed in Myanmar, as the season tended to start later and had a shorter duration. Conversely, the southern portion of the Peninsula had an earlier start of rainfall and a longer rainy season.

3.3. Relationship between phenological change and rainfall

The mean annual EVI showed a decreasing trend from 2001 to 2010, with considerable decreases in 2005 and 2010, which corresponded to the trend of mean annual rainfall (Fig. 5). In addition to the general trend, phenological characteristics and rainfall patterns corresponded with major climate events such as EL Niño. For example, the years 2005 and 2010 were EL Niño years with remarkably low rainfall, which had significant impacts on total vegetation growth in this region. There was a temporary increase in EVI and rainfall after 2006, reflecting ecosystem recovery after the EL Niño event in 2005.

There was a strong positive correlation in most of the MSEA between EVI and rainfall and between SGS and SRS (Fig. 6). In particular, the EVI and rainfall exhibited a strong positive correlation ($R > 0.5$) in the northern, northwestern, and eastern portions of the Peninsula, whereas SGS and SRS were highly correlated ($R > 0.5$) in Myanmar, Malaysia and some areas of Thailand, Laos, and Vietnam. EGS and ERS showed a strong positive correlation ($R > 0.5$) in Myanmar and Thailand. A significant positive correlation between LGS and LRS ($R > 0.5$) was also apparent in some parts of Myanmar, Thailand and Vietnam. In general, areas of positive correlations were found in rainfed ecosystems, where vegetation growth is dependent on rainfall. In contrast, areas of negative correlations were found to be in irrigated agricultural lands scattered across the region.
3.4. Validation of phenology and rainfall

The correlations between the 200 field observations of SGS and EGS in Thailand, and those derived from MODIS were quite high, with R² values of 0.6 and 0.9, respectively (Fig. 7). It was noticed, however, that the SGS and EGS obtained from MODIS tended to occur later than those observed in the field. In addition, the SGS and EGS values from MODIS had a variability while the field observations appeared stationary. The discrepancies were likely due to that fact that MODIS phenology was extracted from integrated canopy greenness from remote sensing, while the field data was collected from field surveys. Nevertheless, the correlation results suggest that MODIS-derived phenology is a reasonable approximation of reality on the ground and, therefore, can be used to estimate regional phenological changes in MSEA.

The annual rainfall extracted from TRMM was strongly correlated with that from the weather stations with R² values ranging 0.6–0.8 from 2001 to 2010 (Fig. 8). The slope of the regression line was lower than the 1:1 line, indicating that the TRMM underestimated the regional precipitations, particularly for heavy rainfall, which agrees with previous studies (Huffman et al., 2007; Chokngamwong and Chiu, 2008). The TRMM-derived SRS, ERS,
and LRS were highly correlated with those from meteorological station data (Fig. 9) with $R^2$ values of 0.5, 0.8, and 0.6, respectively. However, the rainfall seasonality of TRMM showed earlier dates than what was estimated from the station data. Despite this, the overall results suggested that rainfall from TRMM could be used to predict rainfall seasonality.

4. Discussion and conclusions

The phenological patterns and trends were correspondent with rainfall seasonality in MSEA. Extreme climate events associated with the ENSO phenomenon (National Intelligence Council, 2009) had a significant impact on EVI and land surface phenology in the region, where sudden changes occurred in the years of EL Niño (dry year) and La Niña (wet year). The EVI and rainfall overall exhibited similar patterns suggesting that vegetation dynamics were closely related to the regional climate. The shift and change in phenological patterns and rainfall seasonality in this region varied spatially and were correlated with climate trends and human managements.

Climate extremes such as floods, droughts, and tropical cyclones in this region had strongly affected vegetation dynamics and resulted in adjustments in farm management practices in

Fig. 8. Comparison of annual rainfall between TRMM and station data in Thailand.

Fig. 9. Comparison of rainfall parameters derived from TRMM and station data in Thailand.
response to climatic variation in agricultural areas (ADB, 2009). The most commonly used adaptation techniques in the agriculture sector in MSEA involved changes in crop variety, cropping patterns, cropping calendar, and improved farm management (Lasco et al., 2011). As a result, these adjustments led to changes in vegetation phenology. For example, due to the later start of the rainy season, farmers had to delay the planting dates. Not only has climate variability had substantial impacts on agriculture, it also negatively affected natural vegetation. Climate change could result in a replacement of high-quality forests with low-quality forests, which were likely to lead to a significant biodiversity loss (NIC, 2009).

In addition to the influence of climate on phenological changes, land use change was also an important determinant in phenological changes and trends in the region. Socio-economics and improved farm management were likely the dominant drivers of land use change in response to changes in crop prices. Furthermore, policy and planning changes could also result in expansion and intensification of agricultural practices. These factors could all have affected the crop planting timing and production, resulting in phenological changes over time. An interplay between climatic and anthropogenic factors was also possible to affect the regional phenology. More explicit data for these changes are required for a site-by-site analysis and decouple the effects. However, the phenological patterns and changes that were influenced by human management are likely to become an increasingly important issue in this region.

In conclusion, MODIS data and rainfall data from TRMM data were proven to be useful for assessing phenological patterns and changes in MSEA. Correlation analyses provided a better understanding of the potential impacts of climate change on the ecosystems. Human interventions such as shift in management practices are likely to have a major impact on land surface phenology and its associated ecological processes. Therefore, future studies need to focus on the ecological consequences resulting from changes in phenology to fully understand the nexus of climate change, ecological consequences and human interventions.

Acknowledgements

This research was supported by NASA Land Cover Land Use Change Grant (NNX08AH50G) at Michigan State University. Partial support was also made available from Asian Pacific Network (APN) sponsored project, ARCP2014-15MY-WU and “One-Thousand-Talent Program” at Zhejiang University, China.

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