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The use of MERIS Terrestrial Chlorophyll Index to study spatio-temporal variation in vegetation phenology over India

J. Dash *, C. Jeganathan, P.M. Atkinson

School of Geography, University of Southampton, Southampton, SO17 1BJ, United Kingdom

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ABSTRACT

India has a diverse set of vegetation types ranging from tropical evergreen to dry deciduous. The phenology of these natural vegetation types is often controlled by climatic condition. Estimating phenological variables will help in understanding the response of tropical and subtropical vegetation to climate change. The study investigated the annual and inter-annual variation in vegetation phenology in India using satellite remote sensing. The study used time-series data of the only available satellite measured index of terrestrial chlorophyll content (MERIS Terrestrial Chlorophyll Index) from 2003 to 2007 at 4.6 km spatial resolution. A strong coincidence was observed with expected phenological pattern, in particular, in inter-annual and latitudinal variability of key phenological variables. For major natural vegetation type the onset of greenness had greater latitudinal variation compared to the end of senescence and there was a small or no leafless period. In the 2003–04 growing season a late start for the onset of greenness was detected at low-to-mid latitudes and it was attributed to the extreme cold weather during the early part of 2003. The length of growing season varied from east to west for the major cropping areas in the Indo-Gangetic plain, for both the first and second crops. For the first time, this study attempted to establish a broad regional phenological pattern for India using remotely sensed estimation of canopy chlorophyll content using five years of data. The overall patterns of phenological variables detected from this study broadly coincide with the pattern of natural vegetation phenology revealed in earlier community level studies. The results of this study suggest the need for an organised network combining ground and space observation which is at presently missing in India.

1. Introduction

Climate influences vegetation growth: for example, increased temperature and levels of atmospheric carbon dioxide increase vegetation productivity and carbon sequestration and modify ecosystem function (Badeck et al., 2004; Harmon et al., 1990; Taylor & Lloyd, 1992; White et al., 2005). Research has shown that an increase in mean global temperature between 1982 and 1999 resulted in an increase in global net vegetation productivity by 6% (3.4 Pg of carbon) (Nemani et al., 2003). The prediction, in space and time, of vegetation phenological variables such as time of onset of 'greenness', time of end of 'greenness', duration of the growing season, rate of 'green up' and rate of senescence can provide the information needed to increase understanding of the effects of climate change on vegetation. Such phenological variables can be measured from ground or extracted from remotely sensed data. Ground-measured phenological variables provide species-specific information with high temporal resolution, but lack a spatial component (Studer et al., 2007). In contrast, temporally frequent remotely sensed data provide a unique opportunity to estimate phenological variables at a range of scales from the local to global. In addition, phenological variables extracted from remotely sensed data have the potential to characterise seasonal variation in the response (and function) of ecosystems to changes in climatic variables (Harmon et al., 1990; Malingreau, 1986; Reed et al., 1994). Such information, in turn, can be used as an input to global biogeochemical cycle modelling.

In the last four decades many studies have demonstrated the potential of multi-temporal remote sensing data to extract variables reflecting the phenological development of natural vegetation related to change in climatic variables (Goward et al., 1985; Justice et al., 1985; Lloyd, 1990; Reed et al., 1994; White et al., 2005). During the mid-to-late 1980s several studies used phenological variables extracted from Advanced Very High Resolution Radiometer (AVHRR) to study the seasonal pattern of natural vegetation and crops at regional to global scales (Goward et al., 1985; Justice et al., 1985; Lloyd, 1990; Malingreau, 1986; Townshend et al., 1987; White et al., 2005). Later, these phenological variables were linked to changes in climatic variables. For example, using phenological variables extracted from AVHRR satellite sensor images, it was shown that terrestrial vegetation between 45° N and 70° N had "greened-up" from 1981 to 1991 (Myneni et al., 1997), a phenomenon that was tightly linked

* Corresponding author.
E-mail address: J.Dash@soton.ac.uk (J. Dash).

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with positive changes in land surface temperature in this period (Myneni et al., 1997). It was also estimated that there had been an advance in the beginning of the growing season of about 8 ± 3 days and a lengthening of the growing season by 12 ± 4 days in northern temperate regions (latitudes 45–70° N). Recently, data from the MODerate-resolution Imaging Spectroradiometer (MODIS) sensor were used to estimate the phenological transition dates for natural vegetation in the northern mid-to-high latitudes (Zhang et al., 2004).

Most studies using satellite sensor extracted phenological variables used the normalized difference vegetation index (NDVI) to, first, extract phenological variables and then quantify ecosystem response to climate change over continents and decades (Myneni et al., 1997; Reed et al., 1994; White et al., 1997; Zhou et al., 2001). These studies have been made possible by the large correlation between NDVI and the amount of green vegetation biomass. However, most studies suffered from unexplained variation in a smooth growth curve, as a result of image mis-alignment, sensor mis-calibration (Vermote & Kaufman, 1995) and changing atmospheric conditions (Tanre et al., 1992), for example, temporal variation in the presence of cloud, water, snow or shadow (Goward et al., 1985; Huete et al., 2002). As a result, it has been difficult to extract phenological variables routinely and reliably from raw NDVI time-series data (Reed et al., 1994).

The NDVI, varies with both the amount of green vegetation biomass and the concentration of chlorophyll (Gitelson & Merzlyak, 1998; Huete et al., 2002; Mutanga & Skidmore, 2004) and saturates at high levels of both. Satellite sensor systems such as the Earth Observation System (EOS) and Envisat and, in the future, Sentinel 3 could go some way to addressing this constraint. An operational European Space Agency Envisat product, the Medium Resolution Imaging Spectrometer (MERIS) Terrestrial Chlorophyll Index (MTCI), is related directly to canopy chlorophyll content (Dash & Curran, 2004), which is, in turn, a function of chlorophyll concentration and leaf area index (LAI). The MTCI is calculated as the ratio of the difference in reflectance (R) between band 10 and band 9 and the difference in reflectance between band 9 and band 8 of the MERIS standard band setting.

$$MTCI = \frac{R_{\text{Band }10} - R_{\text{Band }9}}{R_{\text{Band }9} - R_{\text{Band }8}} = \frac{R_{753.75} - R_{708.75}}{R_{708.75} - R_{681.25}} \quad (1)$$

Where $R_{753.75}$, $R_{708.75}$, and $R_{681.25}$ are reflectance in the centre wavelengths of band 8, 9 and 10 in the MERIS standard band setting.

MTCI has limited sensitivity to atmospheric effects and also soil background and view angle (Dash et al., 2008) and with the availability of near real-time weekly and global MTCI composites (Curran et al., 2007) enables researchers to extract phenological variables accurately. This research evaluates the potential of MTCI to extract phenological variables and monitor change in phenological variables over the last five years in India.

2. Study area

India exhibits much variation in climate and vegetation type. Climate in India can be classified into four seasons: (i) winter (December–February), (ii) summer (March–June), (iii) south-west monsoon season (June–September), and (iv) post monsoon season (October–November) (Prasad et al., 2007). Variation in vegetation type is mainly attributed to soil type, availability of rainfall and temperature. The major vegetation types broadly constitute tropical evergreen, semi-evergreen, moist and dry deciduous (Fig. 1). Depending on the climate and soil condition, evergreen, semi-evergreen and deciduous vegetation types are often found in close proximity. The phenology of these natural vegetation types is often controlled by climatic condition. In India, relatively few studies have investigated climate-driven change in phenology. Most earlier studies related change in climatic variables to vegetation response at higher latitudes of the globe and very few have investigated these effects in tropical and subtropical regions (Badeck et al., 2004; Jeyaseelan et al., 2007; Menzel et al., 2006). The phenological patterns of some tropical and subtropical species are quite different to those found at higher latitude. Therefore, estimating their phenological parameters will help in understanding the response of tropical and subtropical vegetation to climate change. Relatively few studies used remote sensing to extract phenological variables over India (Jeyaseelan et al., 2007; Sarkar & Kafatos, 2004; Prasad et al., 2007). Most of these studies were limited to specific vegetation types or have limited spatial coverage (Prasad et al., 2007). Therefore, it is anticipated that this research will extract, for the first time, the vegetation phenological pattern over India and later will be useful for annual monitoring of phenological events.

3. Data

Two data sources were used for this research: (i) 8-day temporal composites of MERIS MTCI and (ii) a landcover map derived from the Global Landcover 2000 data set.

The MTCI product effectively combines information on LAI and the chlorophyll concentration of leaves to produce an image of chlorophyll content. The MTCI is simple to calculate and yet it is sensitive to a wide range of values of chlorophyll content. Coupled with the virtues of the MERIS sensor (e.g., radiometrically it is the most accurate imaging spectrometer in space (Curran & Steele, 2005); fine spectral resolution; moderate spatial resolution (300 m and 1 km); three-day repeat cycle) this has lead to the adoption of the MTCI as an operational ESA Level 2 land product. MTCI has been validated for several different species using data from the laboratory (Boyd et al., 2007), field (Zhang et al., 2008) and even at the MERIS spatial resolution (Dash et al., in press). For each of these experiments there was a large positive correlation between MTCI and chlorophyll content. The MTCI has now been used in applications of varying scope (Berberoglu et al., 2007; Dash & Curran, 2006; Espana-Boquera et al., 2006) and its ready availability should lead to wider adoption of the index. Given that the MTCI is the only available chlorophyll index from a spaceborne sensor there is now a real opportunity for monitoring vegetation function and condition systemically and reliably.

Eight day composites of MERIS MTCI data at 4.6 km spatial resolution from 2003 to 2007 were obtained from the NERC Earth Observation Data Centre (NEODC) website (http://www.neodc.rl.ac.uk). MTCI data were composited from standard ESA Level 2 (geophysical) products using an arithmetic mean. Because the arithmetic mean composite technique is less sensitive to temporal biases compared to the widely used maximum value compositing, with an optimised cloud mask it can produce images with greater spatial and spectral consistency than other techniques.

The land cover data used in this study were derived from the Global Land Cover Map (Bartholome & Belward, 2005). The GLC2000 product was created using daily S1 data acquired by the VEGETATION sensor on-board SPOT-4 acquired between 1st November 1999 and 31st December 2000 (Bartholome & Belward, 2005). The GLC2000 Map was created using various classification methods (e.g., supervised, unsupervised and hybrid classification methods) chosen by regional experts on the basis of their local suitability. This approach had the advantage of making the product more accurate as local expert knowledge was taken into consideration during the development of the map. The clusters derived from the regionally tuned classification methods were analysed, grouped together and labelled into a global legend system with 22 classes. For this research, the existing regional landcover map for the Indian sub-continent derived from the GLC global database (http://www-gem.jrc.it/glc2000) was used to locate major vegetation types to be considered in later analysis.

4. Pre-processing

The methodology used to extract phenological variables from the MTCI time-series data consists of four major procedures:

(i) data cleaning and flagging
(ii) data smoothing