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Spatial patterns of vegetation phenology metrics and related climatic controls of eight contrasting forest types in India – analysis from remote sensing datasets

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With 3 Figures

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Summary

Leaf phenology describes the seasonal cycle of leaf functioning and is essential for understanding the interactions between the biosphere, the climate and the atmosphere. In this study, we characterized the spatial patterns in phenological variations in eight contrasting forest types in an Indian region using coarse resolution NOAA AVHRR satellite data. The onset, offset and growing season length for different forest types has been estimated using normalized difference vegetation index (NDVI). Further, the relationship between NDVI and climatic parameters has been assessed to determine which climatic variable (temperature or precipitation) best explain variation in NDVI. In addition, we also assessed how quickly and over what time periods does NDVI respond to different precipitation events. Our results suggested strong spatial variability in NDVI metrics for different forest types. Among the eight forest types, tropical dry deciduous forests showed lowest values for summed NDVI (SNDVI), averaged NDVI (ANDVI) and integrated NDVI (I-NDVI), while the tropical wet evergreen forests of Arunachal Pradesh had highest values. Within the different evergreen forest types, SNDVI, ANDVI and INDVI were highest for tropical wet evergreen forests, followed by tropical evergreen forests, tropical semi-evergreen forests and were least for tropical dry evergreen forests. Differences in the amplitude of NDVI were quite distinct for evergreen forests compared to deciduous ones and mixed deciduous forests. Although, all the evergreen forests studied had a similar growing season length of 270 days, the onset and offset dates were quite different. Response of vegetative greenness to climatic variability appeared to vary with vegetation characteristics and forest types. Linear correlations between mean monthly NDVI and temperature were found to yield negative relationships in contrast to precipitation, which showed a significant positive response to vegetation greenness. The correlations improved much for different forest types when the log of cumulative rainfall was correlated against mean monthly NDVI. Of the eight forest types, the NDVI for six forest types was positively correlated with the logarithm of cumulative rainfall that was summed for 3–4 months. Overall, this study identifies precipitation as a major control for vegetation greenness in tropical forests, more so than temperature.

1. Introduction

Leaf phenology describes the seasonal cycle of leaf functioning and is essential for understanding the interactions between the biosphere, the climate and biogeochemical cycles (Myneni et al., 1997; Schwartz and Reed, 1999; Menzel, 2000; Reed et al., 1994; Nemani et al., 2003). Leaf phenology depends primarily on the climatic conditions for a given biome. It strongly affects land-surface boundary conditions and the exchange of matter and energy with the atmosphere, influencing the surface albedo, roughness and the dynamics of the terrestrial water cycle (Botta et al., 2000;

Myneni et al., 1997). Furthermore, the timing and progression of plant development may provide information to help researchers make inferences about the conditions of plants and their environment such as soil moisture, soil temperature, illumination, temperature, etc. (Reed et al., 1994). The phenological growing season is thus an important parameter for several biophysical as well as ecological phenomena. The dates when phenophases occur and the length of the phenological growing season are principle state variables that may be used to assess the impact of seasonal and inter-annual climate change on terrestrial vegetation and to evaluate the role of vegetation in the seasonal CO_2 cycle (Chen et al., 2001). These phenophases also influence both the amplitude and timing of variations in atmospheric CO_2 (Jolly and Running, 2004). Changes in the phenological events may therefore signal important year-to-year climatic variations or even global environmental change (Botta et al., 2000; Arora and Boer, 2005). Although the importance of phenology in climate change studies has been well recognized extensive databases on the phenological observations describing specific events like budburst, flowering and leaf unfolding for different plants are relatively few. Moreover, such databases focus mostly on specific plant species and are mostly point observations (Beaubien and Hall-Beyer, 2003). On the other hand, several biophysical as well as terrestrial ecological models relating to climate change studies require phenology information at large spatial scales. Within this discipline the potential of remote sensing data for inferring phenological characteristics of vegetation is increasingly regarded as key to understanding large area seasonal phenomena. Repeated observations from satellite-borne multispectral sensors provide a mechanism to gather data from plant-specific to regional scale studies of phenology (Justice et al., 1986; Suzuki et al., 2003). Of the several vegetation indices derived from remote sensing, the normalized difference vegetation index (NDVI) calculated as $(\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED})$ where NIR is the near infrared reflectance and Red is the red reflectance, has been extensively used to characterize phenology events in several regions of the world. NDVI is related to several biophysical parameters including chlorophyll density (Tucker et al., 1985), percent canopy cover (Yoder and Waring, 1994), absorbed photosynthetically active radiation (Myneni and Williams, 1994), leaf area index (Spanner et al., 1990), and net primary productivity (Goward and Dye, 1987; Prince et al., 1995). The NDVI has been shown as a key indicator for inferring the dynamics of vegetation structure and function (Goward, 1989; Nemani et al., 2003).

Thus, the ability of the NDVI to monitor intra-annual and inter-annual spatial variability of vegetation provides a basis for spatio-temporal phenological investigations (Schwartz and Reed, 1999; Nightingale and Phinn, 2003). Several studies used the remotely sensed NDVI to characterize phenological events, particularly using National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) remote sensing data (Goward and Dye, 1987; Justice et al., 1986; Malingreau and Tucker, 1987; Townshend and Justice, 1986; Tateishi and Ebata, 2004). Both the temporal density of the data (availability from 1982-present) and the moderate spatial resolution (8 to 1 km) of this sensor make it well suited for studying large area phenology. Classifications of global vegetation cover have been carried out based on NDVI-derived phenological relationships using this data (Norwine and Greegor, 1983; DeFries and Townshend, 1995). Further, as climatology has a specific role in explaining phenology patterns, several remote sensing studies demonstrated these relationships on regional and continental scales (Justice et al., 1986; Goward, 1989; Tucker and Sellers, 1986; Townshend and Justice, 1986; Malo and Nicholson, 1990; Davenport and Nicholson, 1993; Nicholson and Farrar, 1994; Myneni et al., 1997; Juarez and Liu, 2001; Suzuki et al., 2003; Gensuo et al., 2002; Wang et al., 2003). These studies and several others, conclude that there is a strong relationship between climate variability and fluctuations in satellite-derived vegetation indices at local, regional and continental scales (Justice et al., 1986; Tateishi and Kajiwara, 1992; Paruelo and Lauenroth, 1998; Myneni et al., 1997; Schwartz and Reed, 1999; Ichii et al., 2002; Nemani et al., 2003; Zhou et al., 2004; Jolly and Running, 2004).

In contrast to the several studies conducted at a wide variety of scales and at varied ecological zones, studies examining the climate influences of satellite measures of vegetation index and phenology events are relatively few in tropical regions. In particular, very few attempts have been made in the Indian region to infer phenological characteristics from the climate-NDVI relationships using NOAA AVHRR data (Srivastava et al., 1997; Bawa et al., 2002; Roy and Joshi, 2002). The degree by which important climatic controls such as temperature and precipitation affect plant phenology events has been shown to vary with location (Jolly and Running, 2004). In particular, the rules that predict the phenology in temperate regions do not apply to tropical regions. For example, several factors such as changes in water level stored by plants (Reich and Borchert, 1984), seasonal variations in rainfall (Opler et al., 1976), changes in temperature (Ashton et al., 1988), photoperiod (van Schaik, 1986), irradiance (Wright and van Schaik, 1994) or sporadic climatic events (Sakai et al., 1999) have been proposed as the main causes of leaf production or leaf abscission in tropical forest plants. Further, the relationship between phenological data and NDVI is ecosystem dependent and can be highly site specific (Reed et al., 1994; Nicholson and Farar, 1994; Chen et al., 2001; White et al., 1997). In such a context, evaluating the phenological characteristics of vegetation in an Indian region that has highly diverse forest types, gains significance. India is mainly a tropical country but due to great altitudinal variations, almost all climatic conditions from hot deserts to cold deserts exist. Forests in India show greatest variation and range depending upon rainfall, soil topography and climatic factors. They range from tropical rainforests to dry thorn forests and temperate-mountain forests. A wide variety of evergreen, semi-evergreen and deciduous tree cover types often lie in close proximity depending on climatic and soil conditions. There are four major forest types and 16 detailed forest types in the country. There are four seasons: (i) winter (December–February), (ii) summer (March–June), (iii) south-west monsoon season (June–September), and (iv) post monsoon season (October–November). These seasonal differences create highly diverse climatic conditions that play an important role in the diversity of forests. Understanding the phenology cycles and their climatic controls in varied forests types is thus a challenging task. The objectives of this study are three fold: (1) Compare the spatial patterns in NDVI metrics for different forest types that are influenced by different temperature and precipitation gradients. (2) Characterize the phe-

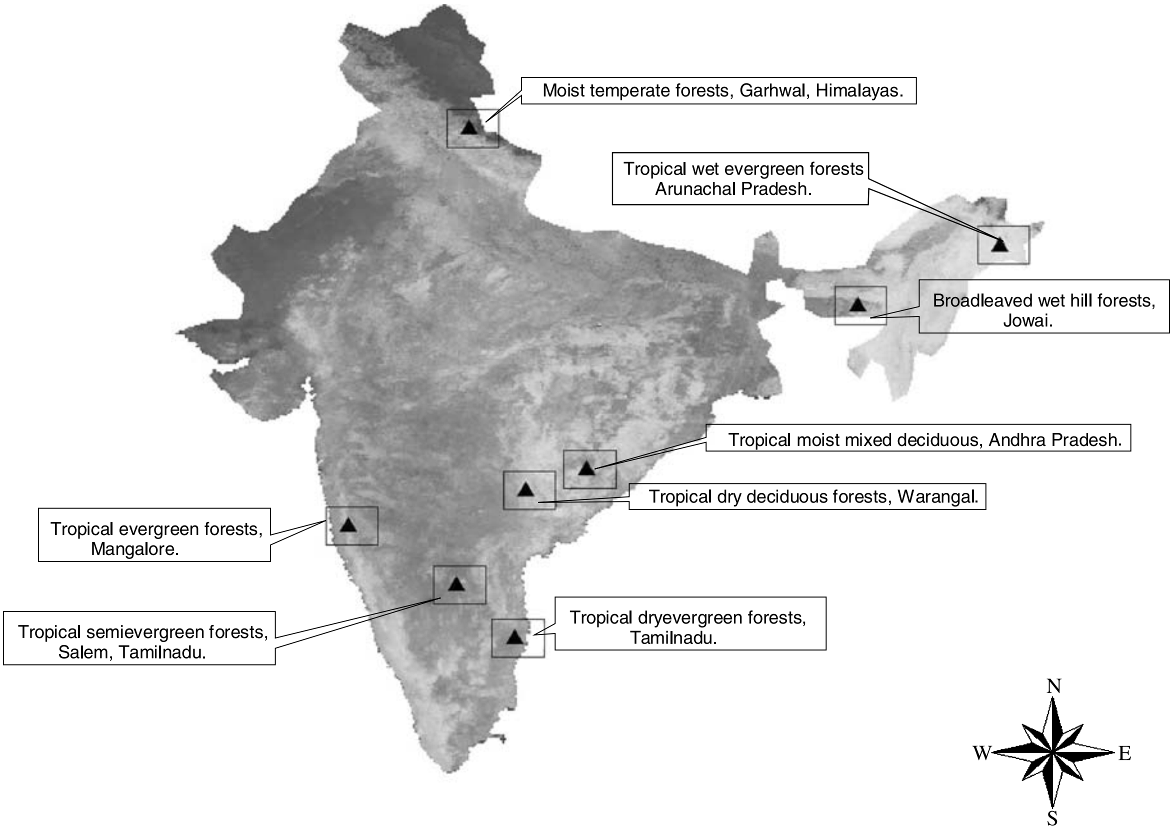

Fig. 1. Location points of the study area depicting eight contrasting forest types in the Indian region

Table 1. Species composition and geographical location of forest types of the study area

S. no.	Forest types	Latitude–longitude	Species composition
1	Tropical Dry deciduous forests, Warangal, Andhra Pradesh	11°33′ N and 76°47′ E	Dominants: *Haldenia cordifolia, Bombax ceiba, Bridelia retusa, Cleistanthus collinus, etc.* Co-dominants: *Aegle marmelos, Mallotus philippensis Emblica officinalis, Terminalia alata, etc.*
2	Tropical moist mixed deciduous forests, Eastern Ghats region, Andhra Pradesh	19°09′ N and 82°04′ E	Dominants: *Xylia xylocarpa, Pterocarpus marsupium, etc.* Co-dominants: *Terminalia alata, Anogeissus latifolia, Cleistanthes collinus, Chloroxylon swietenia, Lannea coromandelica, Macaranga peltata, etc.*
3	Tropical wet evergreen forests, Arunachal Pradesh	27°36′ N and 91°49′ E	Dominants: *Dipterocarpus macrocarpus, Shorea assamica, Terminalia myriocarpa, Altingia excelsa, etc.* Co-dominants: *Mesua ferrea, Elaeocarpus ganitrus, Bischofia javanica, Terminalia citrina, Aesculus assamicus, Mangifera sylvatica, etc.*
4.	Tropical dry evergreen forests, Tamil Nadu	11°46′ N and 79°39′ E	Dominants: *Diospyros ebenum, Memecylon umbellatum, Pterospermum canescens, Garcinia spicata, etc.* Co-dominants: *Canthium dicoccum, Pterospermum xylocarpum, Flacourtia India, Ficus benghalensis, etc.*
5	Moist Temperate forests, Garhwal Himalayas	38°29′ N and 77°50′ E	Dominants: *Cedrus deodara, Pinus roxburghii, Querqus leucotrichophora, etc.* Co-dominants: *Lyona ovalifolia, Symplocos chinensis, Aesculus indica, Quercus Floribunda, etc.*
6	Broadleaved Wet Hill forests, Jowai, Meghalaya	25°33′ N and 92°14′ E	Dominants: *Lithocarpus fenestrata, Engelhartia spicata, Persea odoratissima, Fraxinus floribunda, Elaeocarpus floribundus, etc.* Co-dominants: *Vaccinium sprengilii, Xantolis assamica, Ficus lamponga, Rhododendron arboreum, etc.*
7	Tropical Evergreen forests, Mangalore	14°16′ N and 15°46′ E	Dominants: *Persea macrantha, Diospyros candolleana, Dipterocarpus indicus, etc.* Co-dominants: *Calophyllum tomentosum, Cullenia exarillata, Mesua ferrea, etc.*
8	Tropical Semi-evergreen forests, Salem, Tamil Nadu (TN)	11°46′ N and 78°12′ E	Dominants: *Syzygium cumini, Canthium dicoccum, Chionanthus paniculata, Ligustrum perrottetii, etc.* Co-dominants: *Pittosporum napaulense, Scolopia crenata, Gmelina arborea, Bridelia crenualata, Rapanea wightiana, etc.*

nological events of onset, offset and growing season length (in days) for different forest types. (3) Determine the relationship between NDVI and climatic parameters and assess which climatic variable (temperature or precipitation) best explain variation in NDVI. In addition to these, we also assessed how quickly and over what time periods does NDVI respond to different precipitation events. To address these objectives, we use multi-temporal NOAA AVHRR pathfinder datasets in conjunction with climatic data. The results obtained from this study are expected to provide information relating to spatial differences in phenology events as well climatic controls of vegetation vigor (NDVI) in highly contrasting forest types.

2. Study area

In this study, we selected eight widely different forest patches covering different climatic, physiographic and topographical gradients. The location map of these patches is shown in Fig. 1 and the species composition, climatic and altitude data are given in Tables 1 and 2. The classification of these forest types was based on Champion and Seth (1968).

3. Datasets and methodology

AVHRR-NDVI time series data from 1990–2000 were derived from NOAA NASA Land (PAL) datasets, which are ten-day composites and have a resolution of 8 km. These datasets were further processed by the center from Environmental Remote Sensing (CEReS), Chiba University, Japan and the details were discussed by Park and Tateishi (1999). Specifically, CEReS applied two types of processing to the source data. One is the transformation of the map projection from Interrupted Goode Homolosine projection to Plate Carree projection for easier usage, reducing cloud effects, and to account for the changes in NDVI variations due to atmospheric attenuation, solar zenith angle (SZA) and cloud. Park and Tateishi (1999) employed Temporal Window Operation (TWO) on the PAL NDVI datasets to remove these affects. The TWO algorithm starts at the beginning of the NDVI (start point) curve and checks whether the NDVI for the current period is equal to or greater than the previous NDVI value within the window. If it is higher, the current value is assigned as the start point of next window (window 1, s1 → s2). If there is no higher value within the window, it selects the biggest value as the next start point and replaces these with a linearly interpolated value from current start point to the next start point (window 6, s6 → s7). Using these datasets, we selected NDVI values corresponding to eight contrasting forest types, each covering eight sample locations/pixels. This sample size was quite sufficient to represent the homogenous forest patches with representative species composition (Table 1), and thus phenological characteristics. Furthermore, for each data set 36 NDVI values from the period 1990–2000, have been used for analysis (representing one every 10 days). To examine the spatial variability and seasonality in the vegetation greenness for different forest types, the multiyear average vegetation index denoted as $X(p,m)$, of pixel 'p' and month 'm' is given as (Zhang et al., 2004)

$$X(p,m) = 1/N_y \sum_{y=1990}^{2000} X(p,m,y)$$

where N_y is the number of years (y). In this study, we used an average of the 11 year time series

Table 2. Climatic parameters and altitude characteristics for the selected forested regions

S. no.	Forest types	Mean monthly temperature (°C)	Altitude	Mean annual rainfall (mm)
1	Tropical Dry deciduous forests, Warangal, Andhra Pradesh	28.1	330	1042
2	Tropical moist mixed deciduous forests, Eastern Ghats region	23.3	880	1479
3	Tropical wet evergreen forests, Arunachal Pradesh	21.3	477	3071
4	Tropical dry evergreen forests, Tamil Nadu	28.5	80	1160
5	Moist Temperate forests, Garhwal Himalayas	9.8	2000	1259
6	Broadleaved Wet Hill forests, Jowai Meghalaya	20.3	1250	5282
7	Tropical Evergreen forests, Mangalore	26.9	113	3270
8	Tropical Semi-evergreen forests, Salem, Tamil Nadu	26.0	315	1380

NDVI ($N_y = 11$). The climatic data has been obtained from the nearest meteorological stations, district census books and from Parthasarathy et al. (1995). Monsoon season total rainfall for 29 meteorological subdivisions over India from 1871–2000 along with subdivisonal rainfall data at a district level have been processed by Parthasarathy et al. (1995) and have been freely available from the website of the Indian institute of tropical meteorology.

Variation in annual mean precipitation and NDVI has been examined for different lag periods. Additionally, to assess the spatial variability in NDVI for different forest types, we computed the annual sum of NDVI (S-NDVI), amplitude of NDVI (A-NDVI), maximum NDVI (MAX-NDVI), coefficient of variation in NDVI (CV-NDVI) and time integrated NDVI (I-NDVI) (using a trapezoidal rule (Reed et al., 1994)), for different forest types.

3.1 Phenology events – SOS-EOS and GSL

In order to characterize the intra annual variations among the growing season parameters, we used the methodology of White et al. (1997) to detect the start of the growing season or onset (SOS), end of the growing season (EOS) or offset and growing season length (GSL) across different forest types. The state of the forest ecosystem is assessed with the transformation of NDVI (White et al., 1997) as:

$$\mathrm{NDVI}_{\mathrm{ratio}} = \frac{\mathrm{NDVI} - \mathrm{NDVI}_{\mathrm{min}}}{\mathrm{NDVI}_{\mathrm{max}} - \mathrm{NDVI}_{\mathrm{min}}}$$

where $\mathrm{NDVI}_{\mathrm{ratio}}$ is the output ratio, ranging from 0–1, NDVI is the daily NDVI, $\mathrm{NDVI}_{\mathrm{max}}$ is the annual maximum NDVI and $\mathrm{NDVI}_{\mathrm{min}}$ is the annual minimum NDVI. An $\mathrm{NDVI}_{\mathrm{ratio}}$ of 0 corresponds to the annual minimum NDVI; an $\mathrm{NDVI}_{\mathrm{ratio}}$ of 1 represents the annual maximum NDVI. White et al. (1997) tested a range of thresholds for different landcover types to identify the periods of greatest increase (SOS) or decrease (EOS) in the $\mathrm{NDVI}_{\mathrm{ratio}}$ curve. In this study, after exploring different thresholds, we used a threshold of 0.35 for generating dates of onset, offset of greenness, and calculated the total growing season length between these two dates. The growing season length (GSL) has been computed as the period that is covered between EOS and SOS.

4. Results and discussion

To examine the inter-annual response of the satellite measured vegetation phenology to climate variability, several different NDVI metrics were analyzed (Table 3). These metrics were calculated using the 11-year mean NDVI data. Results suggested strong spatial variability in forest NDVI metrics. Among the eight forest types, tropical dry deciduous forests showed lowest values for sum of NDVI (SNDVI), averaged NDVI (ANDVI) and integrated NDVI (I-NDVI), while the tropical wet evergreen forests of Arunachal Pradesh had highest values. Further among the different evergreen forest types, SNDVI, ANDVI and INDVI were highest for tropical wet evergreen forests of Arunachal Pradesh, followed by tropical evergreen forests of Mangalore, tropical semi-evergreen

Table 3. NDVI metrics derived from NOAA AVHRR satellite data, averaged over eleven year time period

S. no.	Forest type	SNDVI	Amplitude NDVI	CV NDVI	I-NDVI	Average NDVI
1	Tropical dry deciduous forests, Warangal, Andhra Pradesh	5.0	0.36	0.30	4.50	0.42
2	Broadleaved wet hill forests, Jowai, Meghalaya	5.34	0.25	0.17	4.89	0.44
3	Tropical moist mixed deciduous forests, Eastern Ghats region	6.23	0.31	0.18	5.36	0.51
4	Moist temperate forests, Garhwal Himalaya	5.77	0.18	0.12	5.23	0.48
5	Tropical dry evergreen forests, Tamil Nadu	6.51	0.28	0.15	5.87	0.54
6	Tropical evergreen forests, Mangalore	7.41	0.20	0.11	6.72	0.61
7	Tropical semi-evergreen forests, Salem-TN	6.80	0.17	0.10	6.15	0.56
8	Tropical wet evergreen forests, Arunachal Pradesh	8.47	0.22	0.10	7.70	0.70

forests of Salem, Tamil Nadu, and least for tropical dry evergreen forests of Tamil Nadu. The amplitude of the NDVI (A-NDVI) curve is theorized to differentiate between evergreen (low amplitude) and deciduous (high amplitude) vegetation types (White et al., 1997). Consistently low A-NDVI values were observed for evergreen compared to deciduous (0.36) and mixed deciduous forests (0.31). Thus, the amplitude of NDVI can be used to distinguish these forest types. However among the different evergreen forest types, rather than A-NDVI, integrated NDVI and sum of NDVI are more useful to differentiate these forests. Dry deciduous forests had higher values of intra-annual amplitude and low mean NDVI, also coinciding with a high standard deviation and thus high coefficient of variation (CV-NDVI). Similar results were reported by Oindo (2002) in semi-arid forested regions of Kenya. In contrast, evergreen forests had relatively low CV-NDVI for most of the forest types, except tropical dry evergreen forests, which showed relatively high CV-NDVI (0.15). The CV-NDVI values were very close for broad-leaved wet hill forests of Jowai and tropical moist mixed deciduous forests of the Eastern Ghats region. The above differences in NDVI metrics for these forest types were mainly attributed to the differential response of species composition to seasonal variations in climate and environmental conditions. The onset, offset and growing season length for different forest types is given in Table 4. It is interesting to note that all the evergreen forests had a growing season length of 270 days, with varying onset and offset dates. Moist temperate forests of Garhwal Himalaya and broadleaved wet hill forests of Meghalaya had similar onset, offset and growing season length. Furthermore, we also assessed the cumulative growing season NDVI (GS-NDVI) for different forest types (Fig. 2). These results clearly suggest relatively high GS-NDVI for tropical wet forests of Arunachal Pradesh.

Table 4. Phenological characteristics of different forest types. Start of growing season (*SOS*), end of the growing season (*EOS*) and growing season length (*GSL*) have been determined using NDVI thresholds

S. no.	Forest type	SOS	EOS	GSL
1	Tropical dry deciduous forests, Warangal, Andhra Pradesh	180	30	210
2	Broadleaved wet hill forests, Jowai, Meghalaya	180	60	240
3	Tropical moist mixed deciduous forests, Eastern Ghats region	150	60	270
4	Moist temperate forests, Garhwal Himalaya	180	60	240
5	Tropical dry evergreen forests, Tamil Nadu	150	60	270
6	Tropical evergreen forests, Mangalore	300	210	270
7	Tropical semi-evergreen forests, Salem, Tamil Nadu	330	240	270
8	Tropical wet evergreen forests, Arunachal Pradesh	240	150	270

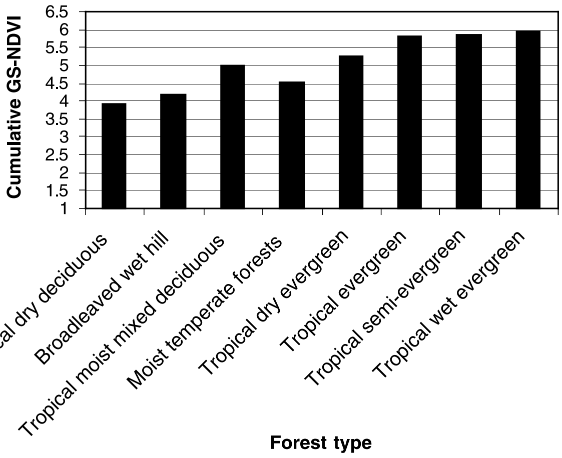

Fig. 2. Cumulative growing season NDVI for different forest types

To assess the relationship between the climatic parameters, we first assessed the linear correlations between mean monthly NDVI and temperature (Fig. 3a–f). Except for the tropical evergreen forests of Mangalore (Fig. 3d), all other forest types had a negative slope. Also, the correlations were poor suggesting that temperature is not a major control of NDVI response. Similar results were obtained by Tateishi and Ebata (2004) from some of the tropical regions in Asia. They concluded that NDVI patterns are also less influenced by the changes in air temperature while analyzing the global datasets utilizing NOAA AVHRR data. In addition to temperature, we also assessed the linear correlation between mean 11-year, monthly NDVI and the log of rainfall over the same period. Correlations have been assessed for concurrent values of rainfall and NDVI, as well as for up to six lag intervals. The results for different forest types are given in Table 5. Though the correlations were not strong, these

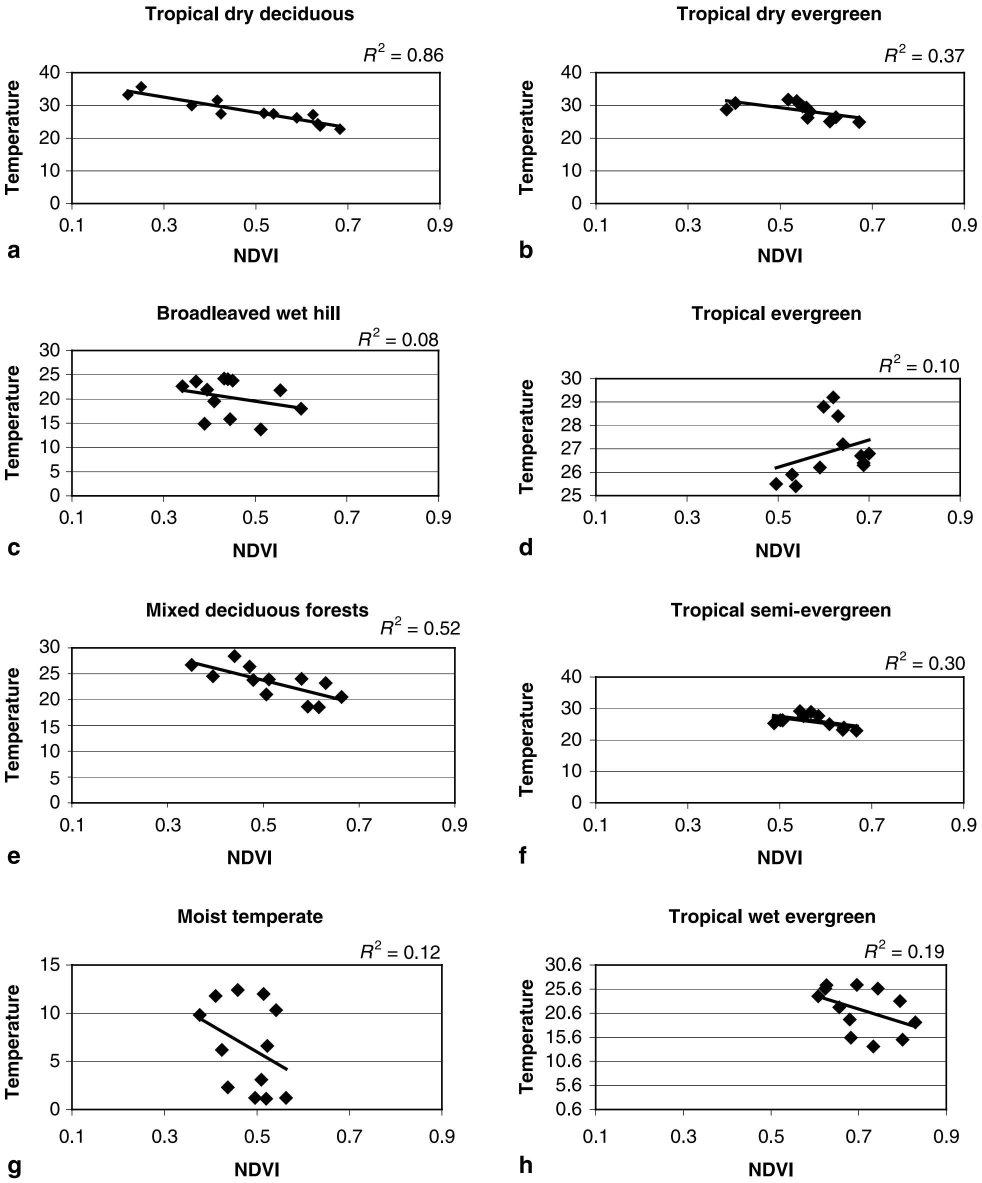

Fig. 3(a–h). Correlation between mean monthly temperature (°C) and mean monthly NDVI for forests

results suggested a differential response of NDVI to precipitation. The correlations were much improved for different forest types when the log of cumulative rainfall was used against mean monthly NDVI (Table 6). Of the eight forest types, the NDVI for six forest types was positively correlated with the logarithm of cumulative rainfall that was summed for 3–4 months. However, for tropical dry evergreen forests of Tamil Nadu, the lag of two-month precipitation correlated well ($R^2 = 0.73$) compared to cumulative rainfall summed over three ($R^2 = 0.63$) and four months ($R^2 = 0.36$). Moreover for the tropical semi-evergreen forests of Salem, Tamil Nadu the correlation was relatively poor ($R^2 = 0.39$) compared to others. These results clearly suggest that the NDVI-precipitation relationships are site specific and vary according to forest type and period over which they are summed. The lag terms for rainfall events observed in our study implies that vegetation does not respond to immediate rainfall, rather it is affected by the history of soil moisture buildup (cumulative rainfall). We attribute the improved correlations with different lag periods for different forest types mainly to soil moisture variations and growing season length. Depending on capability of soils for storing moisture, the vegetation response can be different. In addition

Table 5. Cross correlations between NDVI and rainfall at different lag intervals (0 indicates the current 10 day period, 1 indicates the first previous period and so on. Rainfall data has been log transformed prior to correlations

Forest type	0	1	2	3	4	5	6
Tropical dry deciduous forests, Warangal, Andhra Pradesh	−0.239	0.173	0.519	**0.672**	0.531	0.278	0.041
Broadleaved wet hill forests, Jowai, Meghalaya	−0.473	−0.010	0.249	0.275	0.363	**0.576**	0.282
Tropical moist mixed deciduous forests, Eastern Ghats region	−0.043	0.487	**0.734**	0.739	0.522	0.290	0.040
Moist temperate forests, Garhwal Himalaya	−0.075	0.261	**0.409**	0.354	0.226	0.086	−0.026
Tropical dry evergreen forests, Tamil Nadu	0.163	0.669	**0.720**	0.325	−0.032	−0.186	−0.217
Tropical evergreen forests, Mangalore	−0.638	−0.425	−0.204	0.124	0.492	**0.688**	0.678
Tropical semi-evergreen forests, Salem, Tamil Nadu	−0.392	0.029	0.168	0.243	0.331	0.355	**0.479**
Tropical wet evergreen forests, Arunachal Pradesh	−0.613	−0.071	0.371	0.625	**0.705**	0.573	0.339

Table 6. Cross correlations between mean monthly NDVI and logarithm of cumulative rainfall at different lag intervals (0 + 1 indicates from current period to first previous period, etc)

Forest type	0 + 1	0 + 1 + 2	0 + 1 + 2 + 3	0 + 1 + 2 + 3 + 4
Tropical dry deciduous forests, Warangal, Andhra Pradesh	0.463	**0.725**	0.734	0.475
Broadleaved wet hill forests, Jowai, Meghalaya	0.311	0.507	**0.559**	0.33
Tropical moist mixed deciduous forests, Eastern Ghats region	0.711	**0.830**	0.697	0.364
Moist temperate forests, Garhwal Himalaya	0.541	**0.656**	0.575	0.458
Tropical dry evergreen forests, Tamil Nadu	0.416	**0.630**	0.360	0.08
Tropical evergreen forests, Mangalore	0.078	0.102	0.312	**0.508**
Tropical semi-evergreen forests, Salem, Tamil Nadu	0.13	0.25	0.36	**0.39**
Tropical wet evergreen forests, Arunachal Pradesh	0.54	0.64	**0.71**	0.42

to these, spatial differences in lag periods were also attributed to seasonal variations in rainfall in different forested regions of India. For example, forests in the western part of India receive most of the rainfall due to the southwest monsoon from June through September due to predominating southwest maritime winds compared to forests in north east India, which mostly receive the northeast, or retreating monsoon from October and November.

These above findings of sensitivity of NDVI to rainfall are in general agreement with several other studies conducted in some of the tropical areas (Ichii et al., 2002; Tateishi and Ebata, 2004). However, these results differ from northern latitudes where surface temperature has been identified as a major limiting factor of phenological events (Myneni et al., 1997; Zhou et al., 2004; Tateishi and Ebata, 2004). Our results on correlations between NDVI and rainfall at varying time lags are also in agreement with other studies (Poccard and Richard, 1996; Schultz and Halpert, 1995; Potter and Brooks, 1998; Damizadeh and Gieske, 2001). For example, Richard and Poccard (1998) studied the sensitivity of NDVI to seasonal and inter-annual rainfall variations in Southern Africa and reported the strongest correlations when NDVI monthly values are compared with the preceding bimonthly rainfall amounts, attesting to a time response of one to two months. Further, their analysis using multivariate statistics, suggested differences in rainfall-NDVI associations based on geographical conditions, similar to that found in this study. Farrar et al. (1994) found that while the correlation between NDVI and precipitation is highest for a multi-month average, NDVI is controlled by soil moisture in the concurrent month. In addition, several studies reported the, relationship between NDVI to rainfall to be no longer sensitive to rainfall variations beyond a given rainfall threshold, particularly in wet tropical areas (Davenport and Nicholson, 1993; Wang et al., 2003). This rainfall amount has been shown to be 200 mm month^{-1} over equatorial

Africa (Richard and Poccard, 1998), east Africa at 1200 mm yr^{-1} (Nicholson and Farar, 1994) or 600 mm yr^{-1} (Fuller and Prince, 1996) above which NDVI curve saturates. For the forest types studied in India, this rainfall threshold seems to be 1259 mm yr^{-1}, recorded for moist temperate forests of Garhwal Himalaya, wherein the sum of NDVI reached its maximum beyond which no linear relationship between NDVI and precipitation could be found (tropical dry deciduous forests, Warangal, Andhra Pradesh (1042 mm/yr yr and SNDVI of 5; tropical dry evergreen forests, Tamil Nadu – 1160 mm/yr and SNDVI of 5.77 and tropical semi-evergreen forests, Salem-TN – 1130 mm/yr and SNDVI of 7.41 and no linear response thereafter beyond 1259 mm/yr). Also, Richard and Poccard (1998) inferred that reciprocally, a minimum of 200 mm yr^{-1} seems necessary to induce NDVI sensitivity to interannual rainfall anomalies (Nicholson and Farar, 1994; Davenport and Nicholson, 1993).

In several ecosystems, the underlying causes of phenological events, such as photoperiod, temperature and moisture have been shown to vary with location and geographical gradients (Monasterio and Sarmiento, 1976; van Schaik et al., 1993; Newstrom et al., 1994, etc). For example, Corlett and Lafrankie (1998), divided the Asian tropics into three major regions, based on climatic controls of phenological events: The marginal tropics, where seasonal low temperature may limit the growth of tropical plants (mean temperature of the coldest month <18 °C), the monsoon tropics, where water availability, but not temperature, is seasonally limiting (mean rainfall of the driest month <50 mm) and the aseasonal tropics, where temperature and water supply are adequate for growth year round (although droughts may occur in supra-annual intervals). Several of the forest types currently studied fall into the monsoon tropics. Moreover, in the extra-tropical ecosystems, the timing of leaf offset in trees has been shown to depend not only on temperature but also by the length of the day whereby shorter days induce dormancy or offset of greenness (Nooden and Weber, 1978). In contrast, in tropical regions the evergreen, semi-evergreen, semi-deciduous and deciduous nature of forest canopies are primarily regulated by the seasonality of precipitation (Newstrom et al., 1994), that is found in this study too and by others researchers (Nilsen and Muller, 1981; Borchert, 1994). Furthermore, in the tropical regions, several studies have shown that moisture is the primary control for both ‘leaving and senescence.’ This has been attributed to the ability of the trees to access deep soil water through their root systems (van Schaik et al., 1993; Eamus, 1999). Also, dry ecosystems are characterized by the period of plentiful water supply alternating with periods of drought. The alternating and highly fluctuating rainfall regimes further regulates the soil moisture levels that further control the deciduous/evergreen nature of vegetation, along with the other phenological events such as onset, offset and growing season length (van Schaik et al., 1993). Thus, the timings of flushing and flowering are considered of eliminating water deficit mechanism and the differences in phenology events within and between species of evergreen, semi-evergreen, wet evergreen, dry forests, are caused due to access to subsoil water and in stem storage capacity (Borchert, 1994; Corlett and Lafrankie, 1998).

In summary, it may be stated that phenological patterns in the tropical regions are far more diverse due to highly varying species composition than in extratropical ecosystems. Phenological aspects for these forests are far less understood. As the phenological data on these forest types are relatively limited, it is necessary to explore different methodologies as well as sample areas to detect the growing season dynamics over different time periods as attempted in this study. With respect to the limitations of this study, though the methodology selected for detecting phenological events from NOAA AVHRR is somewhat coarse, the threshold method which defines onset and offset as the period of greatest increase and decrease in NDVI seems to be valid for different ecosystems (White et al., 1997; Fisher, 1994; Markon et al., 1995; Lloyd, 1990). Uncertainties in maximum NDVI values resulting from calibration errors between different NOAA AVHRR sensors (Rao and Chen, 1995; Los, 1998) were not addressed in this study. The NDVI maximum composite datasets used in this study came from CeRES, Japan and account for artefacts resulting from water vapour effects and cloud cover. Also, maximum value NDVI data compositing tends to select pixels acquired in a near-nadir mode with minimum atmospheric effects, thus reducing inter calibration problems. However, the products from Global Inventory Modelling and Mapping Studies (GIMMS; Tucker et al., 2004 and references therein; Lotsch et al., 2003) that are more robust than CeRES PAL datasets available from global land cover facility (GLCF, 2005) can also be tested. One of the study analysing residual sensor degradation and sensor inter calibration differences using these GIMMS and PAL datasets, suggests that that errors are mostly in areas with snow cover (Tucker et al., 2004). As several of the forested regions in this case, occurred outside the snow-regions, we infer that maximum NDVI values obtained from CeRES datasets represented typical patters for different forest types. Most importantly, we believe that, seasonal analysis attempted in this study (averaging the data over 11 years) instead of inter annual analysis (variations in NDVI for each year), has considerably reduced the error component. The overall signature patterns (averaged for eleven years) are believed to vary little compared with monthly signatures. This study captured the synoptic correlations between vegetation greenness and precipitation events (rather than trends). Further, we infer that identifying the precise trigger of onset and offset is difficult due to many interacting factors that operate or may change at the same time, including rainfall, humidity, solar radiation and daily temperature range (Ashton et al., 1998). Also, there is no reason to expect that different species will use the same trigger (Newstrom et al., 1994). In such a context, this study may be considered preliminary. However, this study demonstrated the differences in climatic controls of vegetation vigor, and highlights precipitation as a ‘key control’ or ‘regulatory’ parameter governing phenology in the tropical forested regions. These results on leaf phenological characteristics have implications for the climate change research studies relating to energy, water and CO_2 fluxes. We also recognize the importance and need to collect extensive ground truth information relating to phenology events of different tropical species to better describe plant phenological patterns and events which may further be linked to regional phenology and terrestrial ecosystem models. Such an attempt is underway, through collecting the phenology as well as biophysical information from varied ecoregions and forest types of India.

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