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CLIMATE CHANGE IS LEADING TO RAPID SHIFTS IN SEASONALITY IN THE HIMALAYA

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ABSTRACT

Climate change has significantly impacted vegetation phenology across the globe. The general consensus is that the Earth's vegetation has experienced an advance in the spring phases and a delay in senescence. However, some studies from high latitudes and high elevations have instead shown delayed spring phenology, owing to a lack of chilling fulfillment and altered snow cover and photoperiods. We have used the MODIS satellite-derived view-angle corrected surface reflectance data (MCD43A4) to document the four phenological phases in the high elevations of the Sikkim Himalaya, and compared the phenological trends between below-treeline zones and above-treeline zones. This analysis of remotely sensed data for the study period (2001-2017) reveals considerable shifts in the phenology in the Sikkim Himalaya. Advances in spring phases (SOS) were more pronounced than delays in the dates for maturity (MAT), senescence (EOS), and advanced dormancy (DOR). The SOS significantly advanced by 21.3 days while the MAT and EOS were delayed by 15.7 days and 6.5 days respectively over the 17-year study period. The DOR showed an advance of 8.2 days over the study period. The region below the treeline showed more pronounced effects in phenology with respect to an advanced SOS and a delayed EOS and DOR. The MAT, however, showed a greater delay in the zone above the treeline than below. Lastly, there is no indication that winter chilling requirements are driving the spring phenology in this region, unlike other studies from high elevations. We discuss four possible explanations why vegetation phenology in the high elevations of the Eastern Himalaya may exhibit trends independent of chilling requirements and soil moisture due to mediation by snow cover.

KEYWORDS

Phenology, Himalaya, Phenology elevation gradient, Spring Phenology

INTRODUCTION

Climate change has significantly impacted vegetation phenology across the world (Walther et al. 2002; IPCC 2007; Menzel et al. 2020). Many different approaches have been used to record changes in phenology. Early work by Keeling et al.(1996) reported a seven-day advance in the start of the growing season based on long-term measurements of atmospheric CO2 concentration. This was followed by Myneni et al.(1997), who used normalized difference vegetation index (NDVI) satellite data to show an increase in the length of the growing season between 1981 to 1991. Several studies based on long-term ground truth observations and datasets on phenology showed advances in spring phenology accompanied by delayed autumn phases (Menzel and Fabian 1999; Walther et al. 2002; Parmesan and Yohe 2003; Menzel et al. 2006). Similarly, studies based on historical records kept by scientists, amateur naturalists, and herbaria records have also shown advances in spring phenology (Primack et al. 2004; Miller-Rushing and Primack 2008; Hart et al. 2014). In general, these studies, based on different sources of evidence, show that spring phases have progressively advanced since the 1960s, and, although less pronounced, autumn phases have been delayed.

However, some studies from high elevations have reported delayed spring phenology despite continued warming (Bawa et al. 2010; Paudel and Andersen 2013; Chen et al. 2017). This delay has been attributed to declining or delayed snow cover resulting in altered soil moisture and warmer winters, resulting in delayed plant chilling requirements (Yu et al. 2010; Inouye and Wielgolaski 2013; Wielgolaski and Inouye 2013; Richardson et al. 2013; Chen et al. 2017). In high-elevation and high-latitude regions, soil moisture and temperature are especially moderated by snow cover (Freppaz et al. 2008; Brooks et al. 2011). Plants in regions with cold winters have evolved to become dormant in the autumn and resume growth in the spring to avoid frost damage (Linkosalo et al. 2008; Richardson et al. 2013). Warmer winters may thus delay these dormant periods' chilling requirements, leading to later spring phases.

The high elevations of the Himalaya are one such region that has been significantly impacted by climate change. Rapid increases in temperature, altered precipitation, decreases in snowpack and glaciers, have all significantly impacted the biodiversity of the area (Xu et al. 2009; Shrestha et al. 2012; IPCC 2013). These impacts include altered range distributions in the flora (Telwala et al. 2013; Tiwari et al. 2017; Anderson et al. 2020) and fauna (Pandey et al. 2017) of the region as well as changes in phenology (Shrestha et al. 2012; Paudel and Andersen 2013; Hart et al. 2014). Shrestha et al.(2012) studied GIMMS-NDVI datasets for 13 ecoregions of the Himalaya between 1982 and 2006 and reported an advance in spring phenology by 1.9 days per decade. Hart et al. (2014) reported an advance in flowering by 2.27 days per 1 °C warming based on 10,295 herbarium specimens of Himalayan Rhododendron collected by plant hunters and botanists since 1884. In contrast to these studies, Paudel and Andersen (2013) reported a delay in the start of the growing season and a consequent decline in the overall length of the growing season in high elevations of the Trans Himalayan region of Nepal. This was attributed to a variation in soil moisture at different micro-climates following a decline and a delay in snow cover (Paudel and Andersen 2013).

Here we assess the impact of climate change on vegetation phenology in the high elevations of the Sikkim Himalaya along an elevation gradient. This is especially important since research in this region suggests that warming has been more pronounced in the higher elevations (Chaudhary and Bawa 2011; Telwala et al. 2013). We address three questions. First, how has climate change affected the different phenological phases in Sikkim? Shifts in phenological phases can have cascading impacts on species, communities, and ecosystems since they affect species interactions, community composition, and biogeochemical cycles (Keeling et al. 1996; Parmesan and Yohe 2003; CaraDonna et al. 2014; Thackeray et al. 2016).

Second, is climate change shifting phenological phases uniformly along an elevation gradient? We analyzed whether trends are more pronounced, at the lower elevations below the treeline that receive little to no snowfall, or at the higher elevations, above the treeline, where snow cover dynamics may play an important role. Temperature, snow cover, and chilling effects change over an elevation gradient. Thus, studying phenology along an elevation gradient allows for an ideal setting to understand the impacts of temperature and associated abiotic factors over smaller spatial and temporal scales. The results may be complementary to studies on latitudinal gradients over larger spatial scales (Lessard-Therrien et al. 2014). To address the two questions, we first used remotely sensed satellite imagery to extract the day of the year for four phases— (1) the Start Of the growing Season (SOS), marked by the onset of photosynthetic activity, (2) day of vegetation MATurity (MAT), the day on which plant green leaf area is maximum (3) the End Of the growing Season/ senescence (EOS) - indicated by a rapid decrease in green leaf area and photosynthetic activity and (4) the date of DORmancy (DOR), the day on which physiological activity becomes near zero. We then compared trends in phenological phases in the regions below and above-treeline.

Third, what is the effect of the altered chilling experience in the Sikkim Himalaya? As discussed, in high-elevation and high-latitude regions chilling requirements play an important role in delayed spring phenology (Yu et al. 2010; Paudel and Andersen 2013; Chen et al. 2017). We quantified the chilling experience below and above the treeline to check for effects of altered chilling fulfillment on phenology.

The results of the study have important implications for understanding the phenological response to climate change in the Himalaya, a region of immense biological and economic significance. The Himalaya is not only one of the 35 global biodiversity hotspots (Mittermeier et al. 2011), but also provides provisioning services to at least one-fifth of humanity (Xu et al. 2009).

METHODS

Study Area:

Sikkim is the second smallest (7097 km^2) and least populous state in India. In addition to being part of the Himalaya biodiversity hotspot (Mittermeier et al. 2011), it has a unique biodiversity of its own since it falls in the transition zone of the biogeographic zone 2C-Central Himalaya and the extreme southern fringe of the Turkmenian subregion of the Palaearctic region (Rodgers and Panwar 1988). The elevation gradient of the state ranges from 250 m above sea level (masl) to over 7000 masl (Fig. 1). This includes sub-tropical, temperate, and alpine vegetation on the windward side and the cold desert in the high elevations of the leeward side. The region below the treeline receives no or very little snowfall compared to the regions above the treeline.

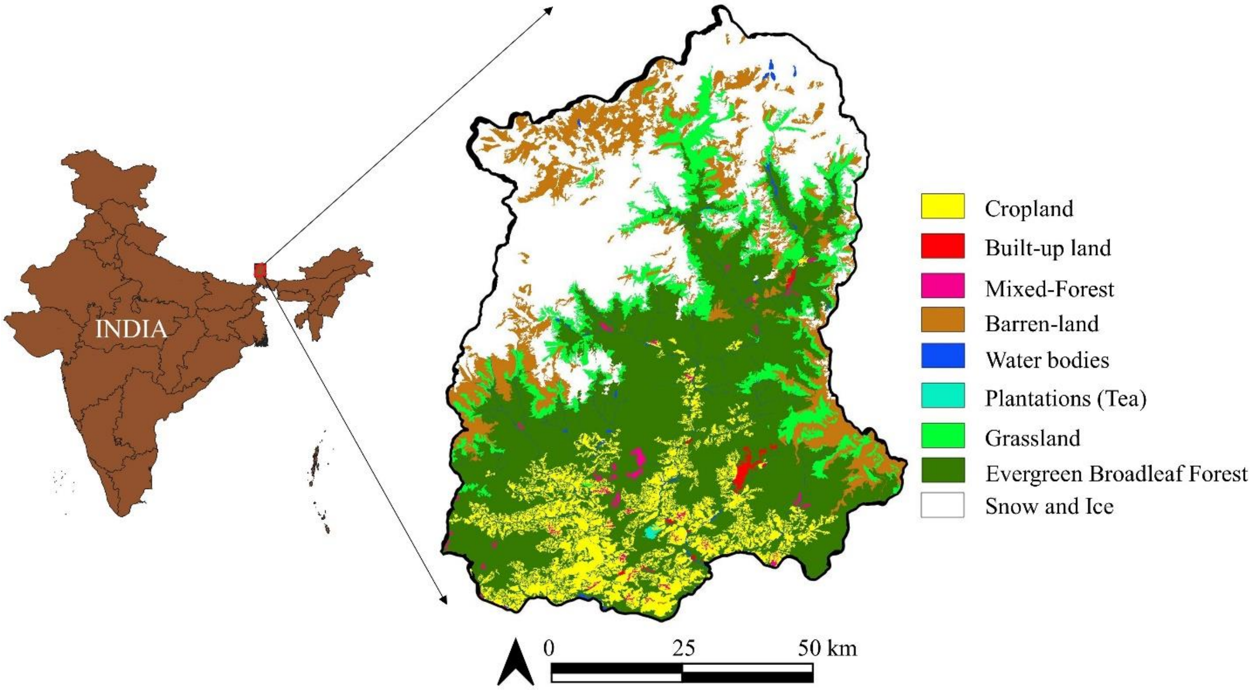

Figure 1: Map of the study site. Land use and land cover map was derived from Roy et al. (2016).

Phenology data:

Changes in phenology over time were investigated in Sikkim for an area of 7098 km^2 using satellite imagery. Data from the Moderate Resolution Imaging Spectroradiometer (MODIS), onboard NASA's Terra and Aqua spacecraft, were used to detect changes in vegetation phenology over 17 years (2001-2017). The four key phenological phases, SOS, MAT, EOS, and DOR, for each year, were extracted from a combined dataset of land surface temperature acquired by the MODIS Terra Land Surface Temperature and Emissivity (MOD11A2) product (Wang et al. 2018) and the Nadir Bi-directional Reflectance Distribution Function (BRDF)-Adjusted Reflectance (NBAR) from the MODIS MCD43A4 product (Schaaf et al. 2002; Wang et al. 2018). The v6.0 MCD43A4 NBAR product models daily nadir reflectance values at a gridded 500m spatial resolution from all multi-angle, cloud-free, and atmospherically corrected surface reflectance data collected over a 16-day period (Schaaf et al. 2002, 2011; Wang et al. 2018) to retrieve an appropriate BRDF model that has been heavily weighted for that day of interest. This BRDF model is then used to correct for, and remove, the view angle effects of the day of interest. Elevation data obtained from the Global Multi-resolution Terrain Elevation Data 2010 (Danielson and Gesch 2011) were used to categorize pixels found below 3940 masl as below-treeline (BTL) and pixels at or above 3940 masl as above-treeline (ATL). The extent of the treeline was based on Pandey et al. (2018). The phenology data were filtered such that below-treeline, the analysis was restricted to shrublands and broadleaf, needleleaf, and mixed forests, land cover classes as identified by the MODIS product (MCD12) (Friedl et al. 2002). Above-treeline the land covers considered for the analysis were savannas, woody savannas, and grasslands. The daytime Land Surface Temperature (LST) for the study area is collected at 1km resolution at 8-day intervals. The dates closest to the day of interest were used for the phenology algorithm. The Normalized Difference Vegetation Index (NDVI) was used to quantify vegetation status. NDVI was calculated for each pixel in the study area from the daily NBAR data using the formula (Huete et al. 1997):

$$NDVI = \frac{NIR - R}{NIR + R}$$

Where NIR is the reflectance in the near-infrared spectrum (841-876 nm) and R is the reflectance in the red range of the spectrum (620-670 nm). The presence of snow and cloud cover was noted in the application of the phenology trends. Following Zhang et al. (Zhang et al. 2003, 2004) we used a piece-wise logistic (growth simulating) function to fit the (NDVI) curve and defined the local maxima and minima for the derivatives of the fitted NDVI curve. The two maximum values were identified as SOS and MAT and the two minimum values at the end of the cycle as EOS and DOR. The Length of Growing Season (LGS) was computed as the difference between EOS and SOS. The Mann-Kendall test was used to ascertain trends and the magnitude of the shift in the number of days (Sen's slope) for the four phenological events over the 17year period. Average Sen's slope of all the pixels was calculated to determine the change in phenological events.

The commonly assumed chilling temperatures required to break dormancy are generally between 0 – 8 °C (Vitasse et al. 2018). We calculated the number of days falling below mean temperatures of 8 °C from 1 November to the mean SOS (DOY 125) as a proxy for the amount of chilling experienced. Temperature data from the daytime Land Surface Temperature (LST) –MODIS Terra Land Surface Temperature and Emissivity (MOD11A2) product (Wan et al. 2015) were used for this analysis.

RESULTS

Over large areas of Sikkim, it was not possible to retrieve any high-quality data on vegetation phenology, especially during the SOS and MAT. This is driven by both continued and ephemeral snow and cloud cover. Snow cover ranges between 17.5% in October up to 50% in February (Basnett and Kulkarni 2012). Cloud cover is driven by the Indian summer monsoons, active from June to October and the pre-monsoons in April and May.

Despite this limitation, the spatial distribution of the average DOY for the four phenological events, SOS, MAT, EOS, and DOR are shown to be dependent on elevation (Fig. 2). The SOS starts from the lower elevations and moves towards the higher elevations from mid-April to mid-June while the EOS pushes from the higher elevations to the lower elevation. In Sikkim, as a whole, the average DOY for SOS, MAT, EOS, and DOR were 122.3,195.4, 297.9, and 326.6, respectively. In the BTL zone, the average DOY for SOS, MAT, EOS, and DOR were 120.4, 201.9, 301, and 339.9, respectively. In the ATL zone, the average DOY for SOS, MAT, EOS, and DOR were 125.6, 184.5 293.8, and 309.2, respectively. The average LGS for the state was 175.6 days. The average LGS was longer in the BTL (180.5 days)region than the ATL zone (168.1 days).

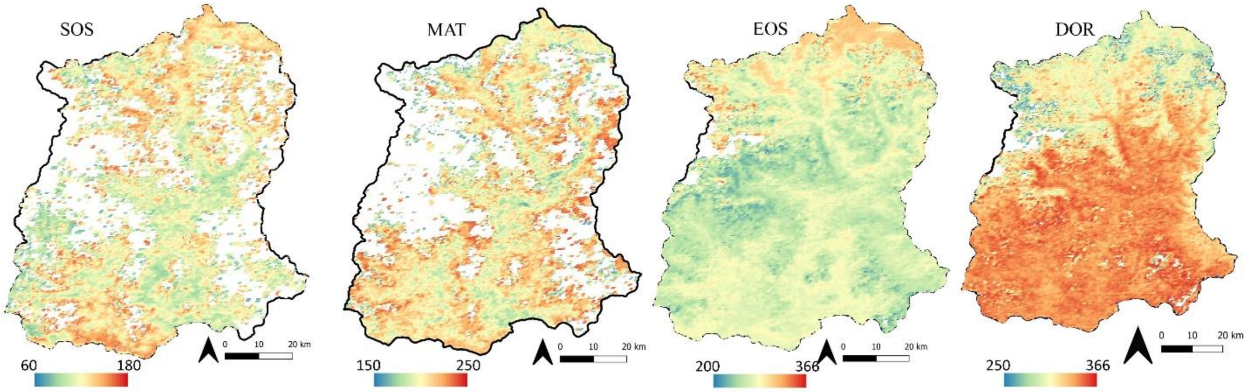

Figure 2: Spatial distribution of average DOY over 17-years (2001-2017) for the four phenological events SOS, MAT, EOS, and DOR. Blank areas within the maps (white) are regions that are missing value due to snow cover or persistent cloud cover.

Spatial distribution of trends in phenological parameters for the study region shows that the SOS has significantly ($P<0.05$) advanced by 21.3 days over the 17-years of the study (table 1, Fig. 3). The MAT and EOS were both delayed by 15.7 days and 6.5 days, respectively. Finally, the DOR showed an advance of 8.2 days. As a result of an advance in SOS and delay in EOS, the LGS increased by 27.8 days.

The data for the state were categorized according to elevation and trends were evaluated for BTL and ATL. SOS in the BTL zone showed a greater advance (20.1 days) than the ATL zone (16.3 days) over the 17-year study period (table 1, Fig. 3, Fig. 4). The MAT showed the opposite trend with greater delay in the ATL (23.1 days) than the BTL (14.01 days). EOS was delayed more in the BTL (9.1 days) than the ATL. The DOR showed little change with delays of 0.5 and 0.03 days over the 17-years study period in the BTL and ATL respectively. The LGS in the BTL extended by 29.2 days and by 22.3 days in the ATL. The spatial distribution of the Mann-Kendall test results for significance values and tau is shown in S1.

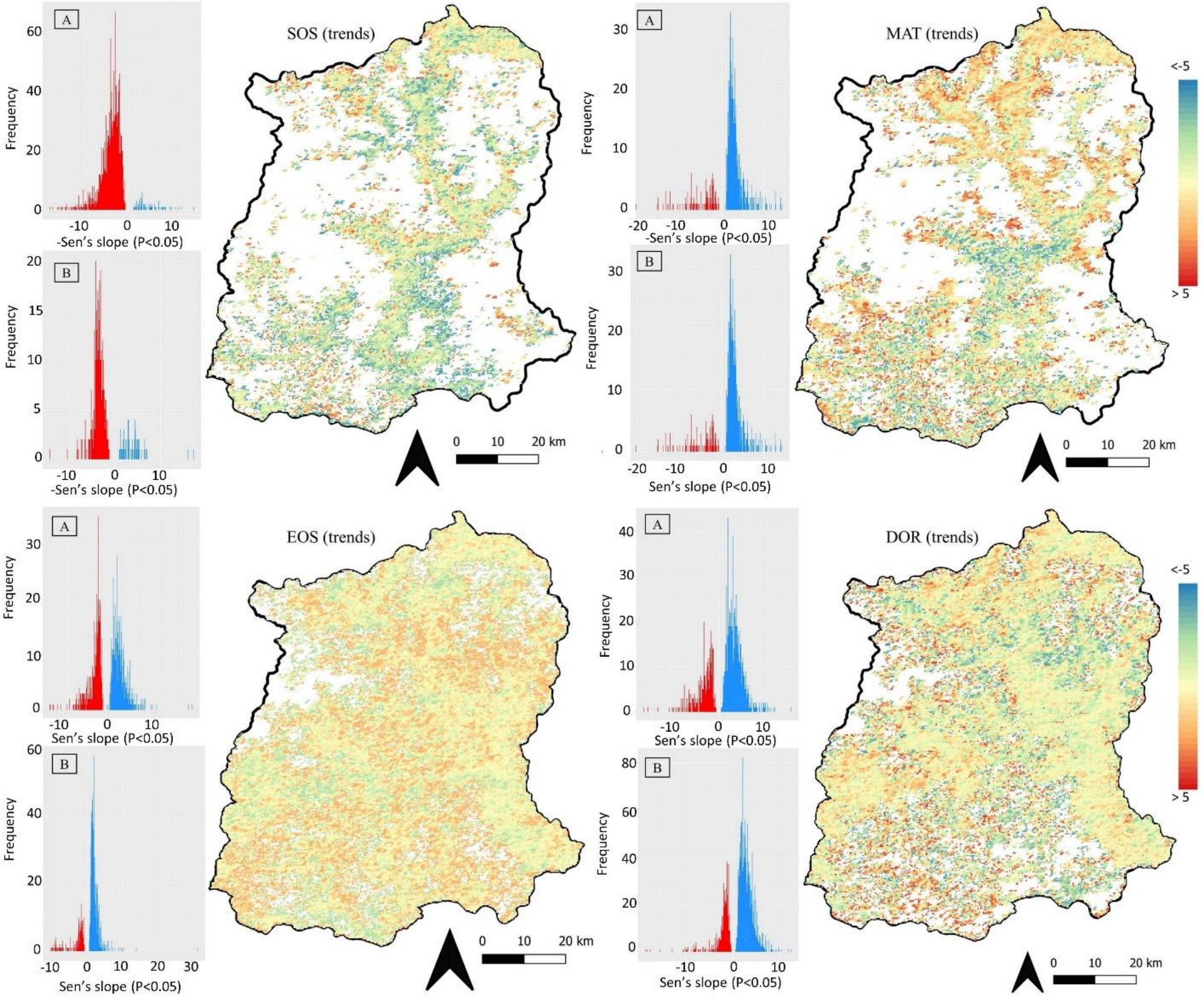

Figure 3: Spatial distribution of trends (Sen's slope) for SOS, MAT, EOS, and DOR over the 17year study period (2001-2017). Histogram for significant trends ($P<0.05$) (A) above-treeline and (B) below-treeline. Blue frequencies represent positive trends and red represent negative trends.

SOS	pos % (all)	neg % (all)	pos % (P<0.05)	neg % (P<0.05)	pos % (P<0.1)	neg % (P<0.1)	Sen's slope	tau	p value
All elevations	34.36	65.64	6.73	93.27	11.68	88.32	-1.252	-0.426	0.0188
BTL	31.54	68.46	4.58	95.42	10.01	89.99	-1.18	-0.265	0.149
ATL	40.65	59.35	15.33	84.67	18.16	81.84	-0.961	-0.279	0.127

MAT	pos % (all)	neg % (all)	pos % (P<0.05)	neg % (P<0.05)	pos % (P<0.1)	neg % (P<0.1)	Sen's slope	tau	p value
All elevations	51.82	48.18	58.07	41.93	57.38	42.62	0.9241	0.294	0.108
BTL	48.18	51.82	42.68	57.32	46.02	53.98	0.824	0.147	0.433
ATL	59.01	40.99	83.70	16.30	78.36	21.64	1.361	0.324	0.077

EOS	pos % (all)	neg % (all)	pos % (P<0.05)	neg % (P<0.05)	pos % (P<0.1)	neg % (P<0.1)	Sen's slope	tau	p value
All elevations	57.82	42.18	73.69	26.31	70.18	29.82	0.3825	0.279	0.127
BTL	59.87	40.13	75.39	24.61	71.54	28.46	0.536	0.412	0.0234
ATL	55.01	44.99	70.85	29.15	67.98	32.02	0.353	0.176	0.343

DOR	pos % (all)	neg % (all)	pos % (P<0.05)	neg % (P<0.05)	pos % (P<0.1)	neg % (P<0.1)	Sen's slope	tau	p value
All elevations	51.19	48.81	66.22	33.78	59.31	40.69	-0.48	-1.6	0.108
BTL	51.37	48.63	78.79	21.21	64.67	35.33	0.0344	0.0735	0.71
ATL	50.94	49.06	54.64	45.36	53.50	46.50	0.0016	0.0294	0.901

Table 1: Percentage of pixels showing positive (delay) and negative (advance) trends for all pixels (all) and at different significance levels ($P<0.05$ and $P<0.1$) for the four phenological events along with the results of the Mann-Kendall test (Sen's slope, tau, and P) for annual aggregates of all pixels.

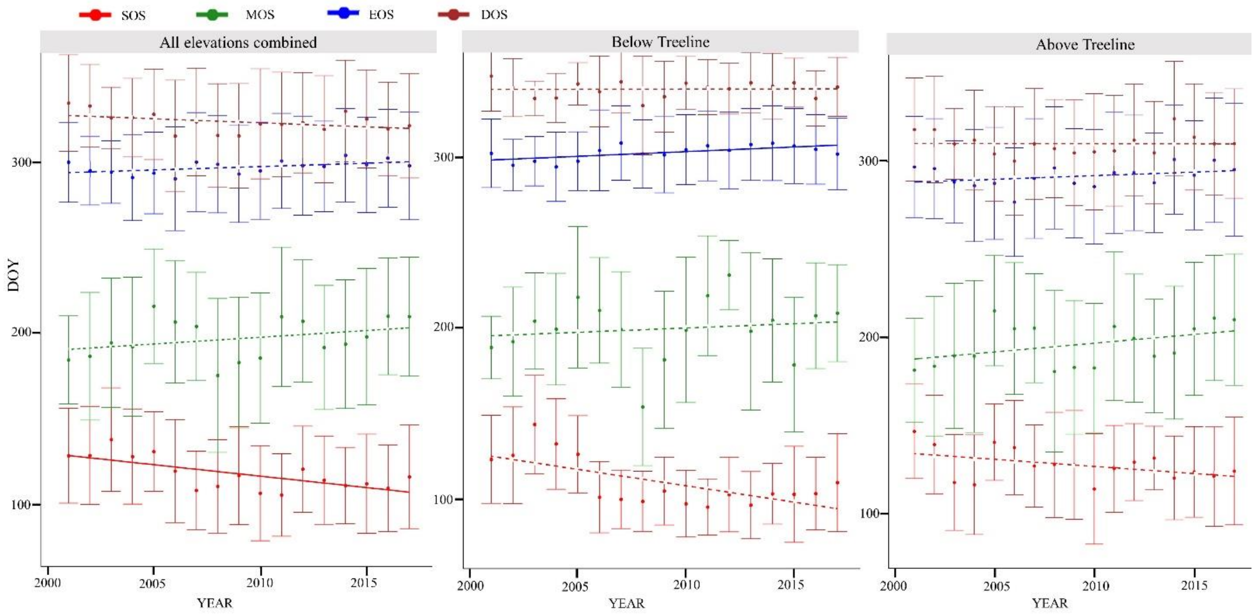

Figure 4: Changes in phenological events (SOS, MAT, EOS, and DOR) between 2001 and 2017 as derived from MODIS MCD43A4 product. The points represent the estimates for each year, together with the standard deviations, which we derived from the MODIS pixels analyzed. The lines represent linear regressions and can be interpreted as the trend for each phenological event for the study period. Mann-Kendall test results for the trends are given in table 1. Solid lines represents significant ($P<0.05$) trends and dotted lines shows non significant ($P<0.05$) trends.

Although, a significant advance in the SOS was observed at the entire state level, at the pixel level, both an advance and a delay of SOS were observed. However, the frequency of the significant negative trends (advance) of SOS is much greater than that of positive trends (delay) (table 1 & Fig. 4). The EOS and DOR show greater frequency of positive slopes at different significance levels ($P<0.1$, $P<0.05$, and all pixels) (table 1 & Fig. 4). The day of MAT showed more pixels with positive slopes in all elevations and ATL zone but more pixels with negative slopes in the BTL zone (table 1).

The number of chilling days showed a significant decreasing trend in the BTL (Fig. 5). The number of chilling days reduced by 42.5 days over the 17-year study period. No significant trend was observed in the ATL (Fig. 5).

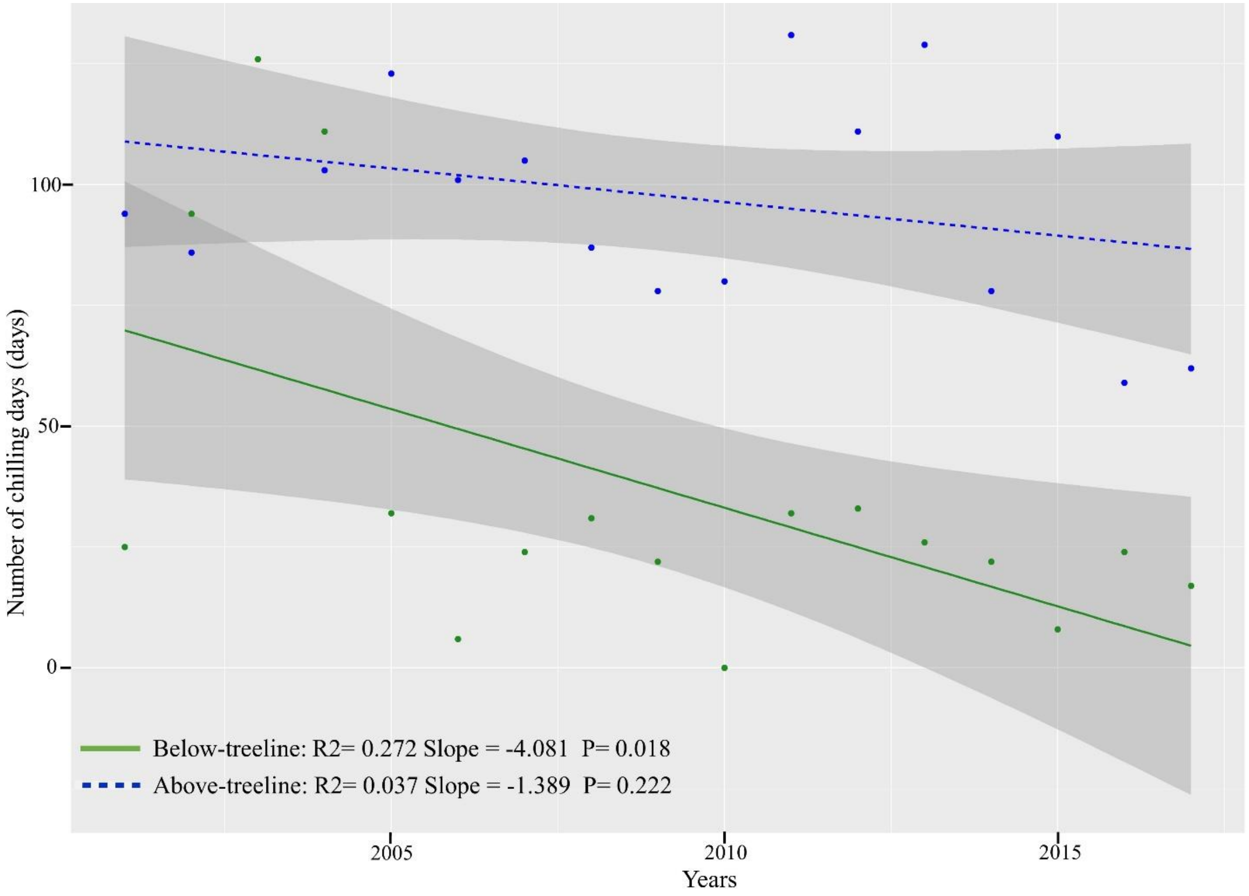

Figure 5: Number of chilling days below and above-treeline during the study period 2001–2017. The lines are the result of the linear regression and can be interpreted as the trend for the number of chilling days over the study period. A chilling day corresponds to a day when the mean temperature is between 0 °C and 8 °C from November to the mean date of SOS across years. Inset: Mann-Kendall test results for the annual number of chilling days. Solid line represents significant ($P<0.05$) trends and dotted lines shows non significant ($P<0.05$) trends.

DISCUSSION

The results of our study show that seasonality, as reflected by vegetation phenology, has changed considerably over the 17-year period (2001-2017). The changes were more pronounced during the SOS. While the SOS showed a significant ($P<0.05$) advance, the MAT, EOS, and DOR showed a delay. The histograms (Fig. 3 inset) clearly show a greater frequency of pixels showing a significant ($P<0.05$) negative trend (advance) in the SOS and positive trends (delays) in the MAT, EOS, and DOR. The LGS thus showed an extension, primarily driven by an advance in SOS. The

MODIS 500m gridded NDVI (Campagnolo et al. 2016) is not ideal for the complex mountainous terrain of the Sikkim, however, the daily temporal resolution and the 20-year data record support its use for this study. Additionally, MODIS 500m gridded products have shown good results over complex, higher-elevation terrains in phenological studies across mountainous regions of the United States (Hudson Dunn and de Beurs 2011; Norman et al. 2017; Liu et al. 2019). The results of our study are consistent with a recent study from Sikkim that studied coarser-resolution AVHRR data to show an extension in the LGS by 8.6 days per decade and a significant advance in SOS by 6.2 days per decade (Prakash Singh et al. 2020). As with our study, the magnitude of change was greater in the SOS than EOS although EOS showed an advance of 1.7 days per decade. Our results are also consistent with studies from other parts of the world. Piao et al's. (2019) meta-analysis of phenological records from different sites reported an advance in spring phases by 5.5 days per decade in China, 4.2 days per decade in Europe, and 0.9 days per decade in the USA, between 1982-2011. The magnitude of change for delayed autumn phases has been comparatively less than springtime SOS with a delay of 2.11–2.29 days per decade in China (Ge et al. 2015) and 0.2 days per decade in Europe (Menzel et al. 2006). However, in the USA, the LGS has increased with a greater change (delay) in the EOS than the SOS (Jeong and Medvigy 2014). Studies have also shown a delayed SOS as a result of a lack of fulfillment of winter chill requirements and altered photoperiods and snow cover (Yu et al. 2010; Paudel and Andersen 2013; Laube et al. 2014; Tang et al. 2016). Fu et al's. (2014) study indicated a delay in the SOS between 2000-2011 but an advance in the SOS for an earlier period (1982-2000). Similar reversals in advancing trends for SOS after 2000 have also been recorded in the Northern hemisphere (Jeong et al. 2011; Piao et al. 2011).

The results of our study further suggest that the impact on phenology was more pronounced in the BTL than ATL. The BTL showed a greater advance in the SOS, by 3.7 more days, and a delay in the EOS, by 3.1 more days than the ATL. The impact on the day of maturity was more pronounced in the ATL with a greater advance by 9.1 more days than BTL. Little impact was shown on the DOR day in both the BTL and ATL. The LGS thus showed a greater extension in the BTL, by 6.9 more days, than the ATL. The BTL showed a greater decrease in the number of chilling days than the ATL (Fig. 5). Our results differ from Vitasse et al.'s (2018) paper that recorded the opposite impact with a greater advance in SOS the high elevations (1.9 days per decade) than the lower elevations (0.4 days per decade), accompanied by an increase in the number of chilling days in the high elevations and a decrease in the lower elevations.

Therefore, in general, our results do not suggest a lack of chilling was the primary factor leading to a delayed SOS in the high elevations of the Sikkim Himalaya. There are several reasons to explain this. First, the winter temperatures in the high elevations were too cold for effective chilling hence plants may depend more on the autumn and spring chilling. The number of chilling days for spring (March to average SOS day) and autumn (average EOS day to November) did not show any significant change for both BTL and ATL. Second, most herbaceous plants as found in the ATL, keep their meristem underground to protect against frost (Vandvik et al. 2018). Further, the extensive snow cover largely present in the ATL tends to dissociate the effect of cold winter temperatures from the apical meristems, thus making chilling requirements unlikely (Vandvik et al. 2018). Lastly, phenological patterns may be influenced to a greater degree by other factors such as illumination/cloud cover and precipitation associated with the monsoons. In the Himalaya rainfall is an important factor that governs the growth and phenology of the vegetation. In the high-elevations, the Indian summer monsoons are active from July to September and the region receives enough soil moisture required for vegetation growth physiology (Prakash Singh et al. 2020).

In high elevation habitats that have short growing seasons, the timing and duration of phenological events of interacting mutualists like plants and their pollinators are essential. Insect pollination is predominant in the temperate alpine areas (Kudo 2016). In the Eastern Himalaya bumblebees and flies are the most prominent pollinators in the high elevations (>3800 masl) and birds in lower elevations (Basnett et al. 2019). Climate change-induced changes in phenology and range distribution threaten this synchrony. This would affect populations because of few reproductive success driven by pollinator scarcity (Inouye 2008; Lessard-Therrien et al. 2014). There are little data on changes in flowering seasonality and no data on pollinators that move along an elevational gradient in the Himalaya.

CONCLUSION

In this study, we address three important questions about the vegetation phenology in the Sikkim Himalaya. First, the analysis of remotely sensed data for the 17-year study period reveals a considerable shift in the phenology in the Sikkim Himalaya. An advance in the SOS was more pronounced than a delay in MAT, EOS, and DOR. Second, the region below the treeline showed more pronounced effects in phenology, with respect to an advanced SOS and a delayed EOS and DOR. The MAT showed a greater delay in the ATL than the BTL zone. Lastly, there is no indication that winter chilling requirements predominantly drive spring phenology in this region, unlike several other high-latitudes and high-elevation studies. However, caution should be taken with this last point since our study faced some limitations. First, phenological trends are not uniform across species, life stages, aspects, slope, and vegetation types, to name a few. This is evidenced by a large number of pixels not showing a significant trend and the few pixels that did record significant trends showing trends opposite to the majority of the pixels in the region. There is clearly a need to develop species-specific long-term monitoring efforts in the region. Second, the analysis was based on a rather short time series (i.e., 17-years) and as such, it is hard to estimate the long-term trend of phenology. Nonetheless, the results of the study have important implications for understanding the phenological response to climate change in the Himalaya, a region of immense biological and economic significance.

AUTHOR CONTRIBUTIONS

KSB and TI conceived the presented idea. TI, AE and XZ performed the analyses. TI and AE drafted the manuscript and designed the figures. CS, XZ and KSB provided critical feedback on the manuscript.

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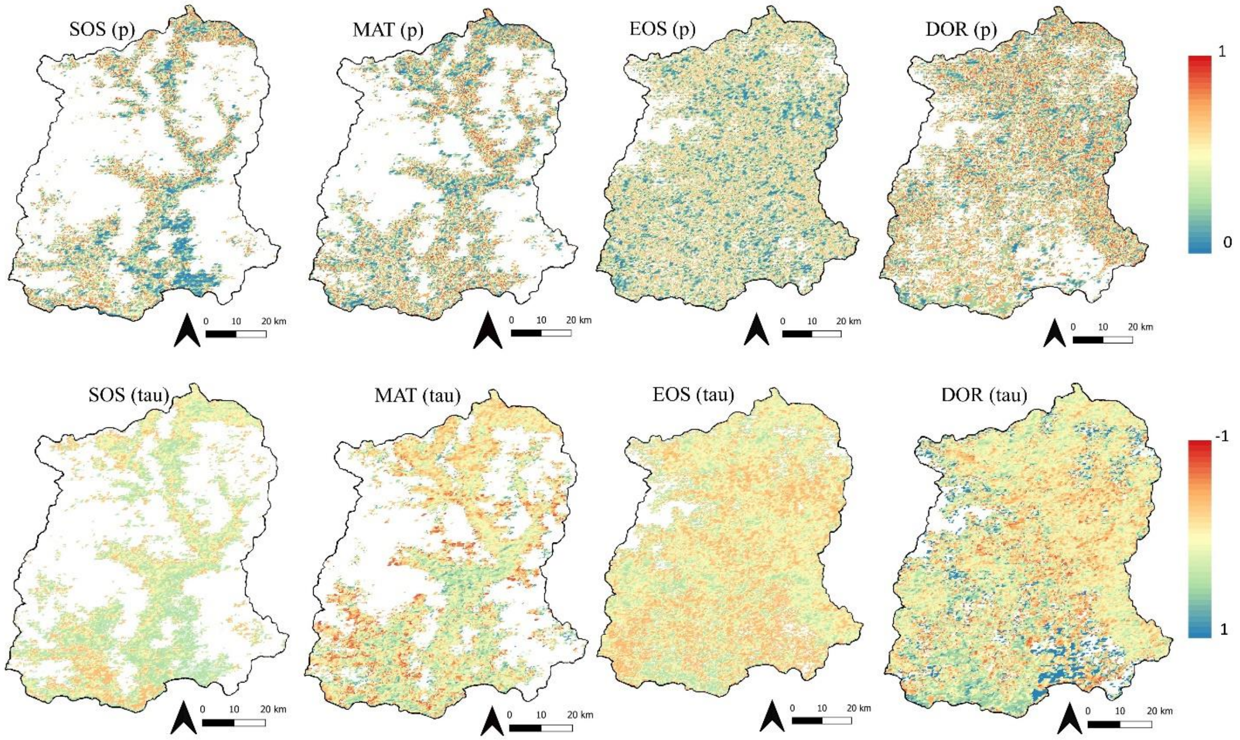
Supplementary material



S1: Spatial distribution of Mann-Kendall test results (p values and tau) over the 17year study period (2001-2017) for greenup (SOS), maturity (MAT), senescence (EOS), and dormancy (DOR).