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PHENOPHASE SHIFTS ACROSS ELEVATIONS ON MAJOR MOUNTAINS IN NORTH CHINA

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Previous studies have reported plant phenological changes along horizontal belts in North China, however, little is known about elevation effects on mountain phenophases in China, such as how vegetation phenophases shift across elevation on mountains, and how they change under background of global change. In this context, by application of remote sensing data, Moderate Resolution Imaging Spectroradiometer (MODIS), changes of spring phenophases across elevation on 6 typical mountains in North China, namely Wuling, Xiaowutai, Guandi, Migang, Huashan and Taibai Moutians, and the effects of elevation on phenophases along altitudinal gradients, were studied in current work. Preliminary results showed that, similar to our findings of phenological changes in plain area in North China, the onset of vegetation phenophases in spring advanced on these mountains, while the ending time for autumn phenophases delayed in the past two decades. Trends for advanced spring phenophase increased significantly with altitude in some mountain regions, and spring phenophase sensitivities to altitude are stronger in lower latitude than in higher latitude regions. Similar to foreign studies, it is reported for the first time that global warming has led to a more uniform spring phenology across elevation in North China mountains in recent years. Findings will not only benefit policy making for the government in the field of ecological constructions, but also will be helpful to evaluate future climate change on vegetation in such areas.

Keywords: *spring phenology, global change, mountain, North China.*

Introduction

Although a variety of studies have revealed distributions of spring phenophases and their shifts across horizontal gradients in North China [1-3], little is known about elevation effects on phenophases across different elevation on mountains, or on phenological shifts under background of global warming in China. It is learned from studies on mountains in Europe [9] that global climate change has altered bio-climatic law regarding the phenological shifts across elevations [5] by contracting the elevation-induced shift in the time of spring phenophases in four common tree species in Swiss Alps between low and high elevation by 35%. However, it is more interesting to know if the observed contraction in elevation-induced shifts in spring phenophase is a local pattern in the European Alps or is also happening in other regions of the world along elevation and latitudinal gradients [8]. In this context, by studying spatial and temporal changes of spring and autumn phenophaeses through remotely sensed data on typical mountains in north China, we aimed to examine: (1) whether the trend of phenophase shifts is consistent along elevation gradients; (2) whether altitudinal sensitivity of phenophase is constant over time on each of these mountains.

Data and methods

The study area is in North China (30°–40°N, 100°–135°E), which is comparatively rich in temperate or subtropical flora components, with wide distribution of broadleaved deciduous forest. This research focused on 6 typical mountains (200×200 pixels in MODIS imagery or 1°×1° per site) along latitude gradients throughout the study area (Figure 1), namely Wuling, Xiaowutai, Guandi, Migang, Huashan and Taibai from north to south. All the mountains studied are dominated by broadleaved deciduous forest and are characterized by abrupt slopes and altitudes over 2000 meters above sea level (m. a. s. l.). We derived phenological metrics from time series of NDVI products processed by Liu and Liu [6] through Moderate Resolution Imaging Spectroradiometer (MODIS) imageries with spatial and temporal resolution of 500 m and 8-days, respectively. An inflexion-based cloud detection algorithm was proposed in the above work and performed generally better than other cloud masks accompanying with the MOD09 products [6]. The Digital Elevation Model (DEM) data set was produced by the Shuttle Radar Topography Mission (SRTM) project, with 30m spatial resolution. The vegetation data sat was extracted and rasterized from

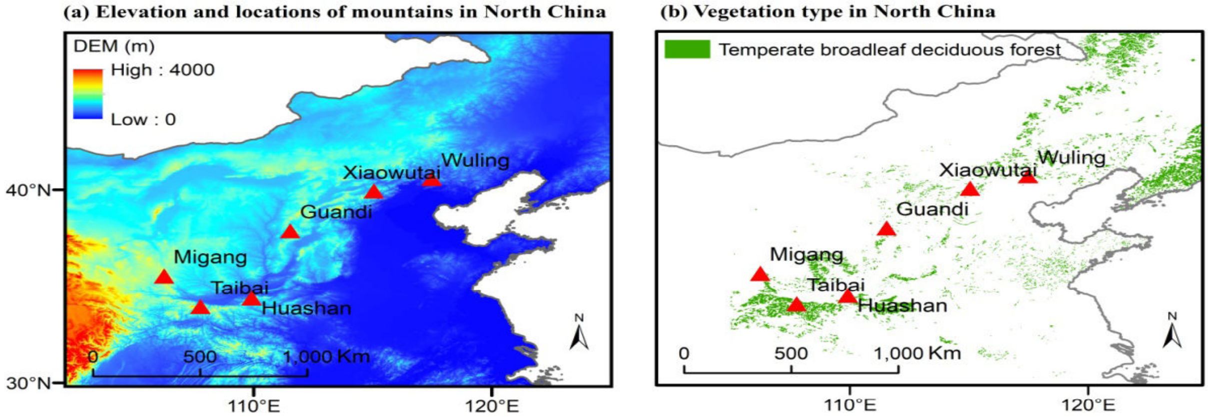

Figure 1. Locations of typical mountains in North China: (a) elevation in North China; (b) distribution of temperate broadleaf deciduous forest in North China

1:1 000 000 Vegetation Map of China, which was produced by Chinese Academy of Sciences from the land resource investigation (http://westdc.westgis.ac.cn) [4]. The only vegetation type we studied was the temperate broadleaf deciduous forest. Both DEM and vegetation type data were resampled to 500m spatial resolution to match the MODIS NDVI products.

We examined the growing season shifts between 2001 and 2017. The double logistic model (DL) approach was applied for the gap filling of NDVI time series. With reference to Shang et al. [7], the threshold at the inflexion point is 9.18% of vegetation growth amplitude, and thus, a dynamic threshold of 9.18% was used to extract inflexion point of NDVI. Seasonal phenological metrics for start-of-season (SOS) and end-of-season (EOS) were extracted pixel-by-pixel for 2001 through 2017. SOS and EOS were then masked by temperate broadleaf deciduous forest type on the vegetation map. A simple linear regression model between phenological metrics and corresponding years was applied to calculate the trend of SOS and EOS. For each mountain, the trend of phenological metrics was summarized, as advancing (trend < 0), delaying (trend<0), significant advancing (p-value < 0.05), and significant delaying (p-value < 0.05). Trends for SOS and EOS during the study period were then averaged along altitude gradients respectively to test whether they were consistent along altitudinal gradients. Finally, the phenological sensitivity to altitude (altitudinal sensitivities) was calculated during the study period for each mountain.

Results

Phenological trend on major mountains in North China

Similar to phenological shifts in spring and autumn in plain areas, a general advancing of the spring phenophase and a delaying of the autumn events were found in most part of the study area (Table 1). From 2001 to 2017, SOS advanced in 73.3%–99.4% pixels and significantly advanced in 2.1%–26.3% pixels on all 6 typical mountains in North China, while EOS delayed in 71.2%–90.4% pixels on most typical mountains except Wuling, and in 3.2%–22.4% pixels the delaying trend is significant. Overall, growing season length for the mountain temperate broadleaf deciduous forest on these mountains extended during the study period. This is similar to results we obtained for phenological shifts along horizontal belt in temperate areas in China in the last few decades [3].

Trend of SOS and EOS along altitude gradients

We analyzed changes of trend for SOS and EOS respectively across the altitudinal gradients, and found that, (1) trends for SOS increase significantly with altitude from lower elevations to higher elevations in half of the 6 mountains, namely, Migang, Huashan and Taibai (Figure 2: (d), (e) and (f)); but it shows no clear tendencies on two mountains, Wuling and Guandi, and a decreasing tendency along altitude from lower elevations to higher elevations on Mountain Xiaowutai is found. Overall, it is showed that the tendency for SOS trend across altitude gradients increase with elevations. (2) However, the tenden-

Table1

Summary on the percentage of SOS trend and EOS trend for 6 mountains in North China. The phenological metrics trend was classified as advancing-, delaying, significant advancing (p-value < 0.05), and significant delaying (p-value < 0.05)

Phenophase	Mountain name	Percentage for different shift trend			
		Advancing	Delaying	Significant advancing	Significant delay-ing
SOS	Wuling	99.4%	0.6%	26.3%	0.0%
	Xiaowutai	98.6%	1.4%	16.8%	0.0%
	Guandi	85.4%	14.6%	6.2%	0.0%
	Migang	85.4%	14.6%	9.3%	0.2%
	Hua	83.3%	16.7%	4.5%	0.8%
	Taibai	73.3%	26.7%	2.1%	0.3%
EOS	Wuling	46.2%	53.8%	1.5%	1.2%
	Xiaowutai	24.3%	75.7%	0.4%	3.2%
	Guandi	28.8%	71.2%	0.4%	7.0%
	Migang	26.6%	73.4%	0.3%	4.7%
	Hua	9.6%	90.4%	0.1%	22.4%
	Taibai	18.8%	81.2%	0.2%	9.3%

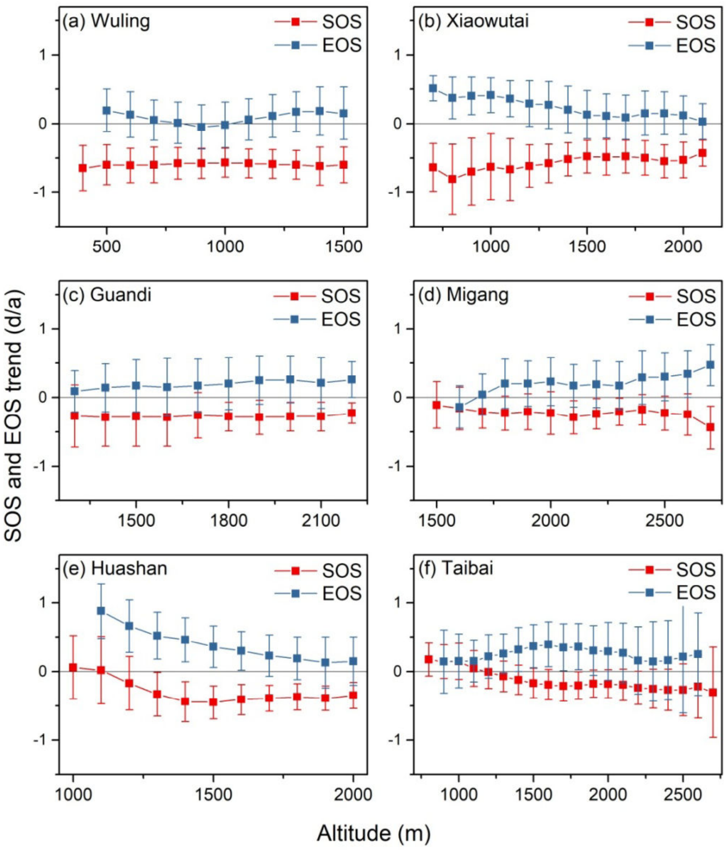

Figure 2. SOS and EOS Trend (d/a) along altitude gradients for 6 typical mountains in North China. Panel (a)–(f) represent SOS and EOS Trend (d/a) on mountain Wuling, Xiaowutai, Guandi, Migang, Hua and Taibai respectively. SOS Trend is marked by red square, and EOS Trend is marked by blue square. Error bars represent standard deviation of Phenological trend within 100 m interval of altitude

Table 2

Summary on correlation analysis between SOS/EOS trend and altitude.
Pearson's R represents Pearson correlation coefficient.
The significance is indicated with '*' (p-value < 0.05)

Mountain		Summit elevation(m)	Longitude,°E	Latitude, °N	Pearson's R	P-value
SOS	Wuling	2116	117.5	40.6	0.286	0.367
	Xiaowutai	2882	115.0	39.9	0.835*	0.000
	Guandi	2830	111.5	37.9	0.382	0.276
	Migang	2931	106.2	35.6	−0.655*	0.015
	Huashan	2155	109.9	34.4	−0.729*	0.011
	Taibai	2767	107.8	34.0	−0.965*	0.000
EOS	Wuling	2116	117.5	40.6	−0.044	0.891
	Xiaowutai	2882	115.0	39.9	−0.939*	0.000
	Guandi	2830	111.5	37.9	0.908*	0.000
	Migang	2931	106.2	35.6	0.862*	0.000
	Hua	2155	109.9	34.4	−0.955*	0.000
	Taibai	3767	107.8	34.0	0.010	0.969

cies for EOS trends changing with altitude on these 6 mountains (Figure 2 and Table 2) are quite complicated, as they decrease significantly in Xiaowutai and Huashan along altitudinal gradients from lower elevations to higher elevations, but increase along altitudinal gradients from lower elevations to higher elevations on Migang mountain and Taibai mountain, with the former showing significant increase. The tendency for EOS trend along the altitudinal gradients on Wuling is not manifest. (3) The changing tendencies for both SOS and EOS along altitudinal gradients from lower elevation to higher elevation on two mountains, Migang and Taibai are similar, increasing with altitude.

Altitudinal sensitivity trends over time

In 6 North China mountains, we found the altitudinal sensitivity of SOS is smaller at high latitudes than at low latitudes. Figure 3 shows average altitudinal sensitivity of SOS on 6 typical mountains during 2001-2017. Along latitude gradients, the mountains in higher latitudes have significantly smaller altitudinal sensitivity than lower latitudes, and this is in accordance with studies in European mountains [8]. For example, Mountain Wuling (40.6°N) has lower altitudinal sensitivity than Mountain Huashan (34.4°N) and Mountain Taibai (34.0°N). At low latitudes, response of plant phenology to altitude tends to be stronger, which is similar to the previous study conducted by Vitass et al. [9].

Generally speaking, the altitudinal sensitivity of SOS showed a decreasing tendency from 2001 to 2017. This shows the conclusions that global climate change in recent decades leads to more uniform spring phenology across elevations [9], drawn from studies of shifts of spring phenophase on European Alps are also suitable on North China mountains. The results

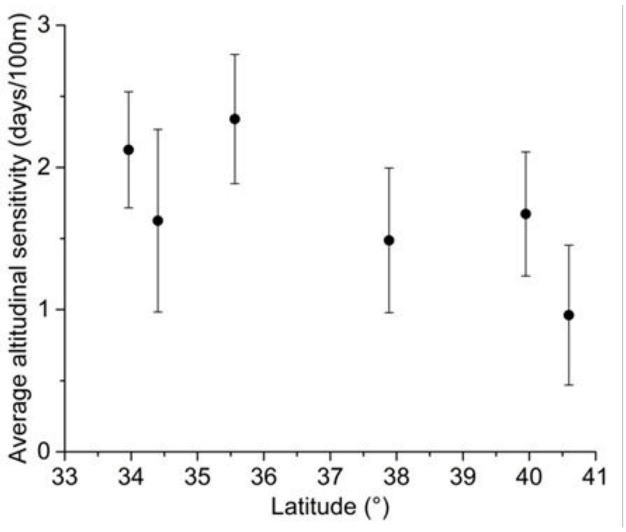

Figure 3. Average altitudinal sensitivity of SOS on 6 typical mountains along latitude gradients. Error bars represent 1 σ altitudinal sensitivity uncertainties during 2001–2017

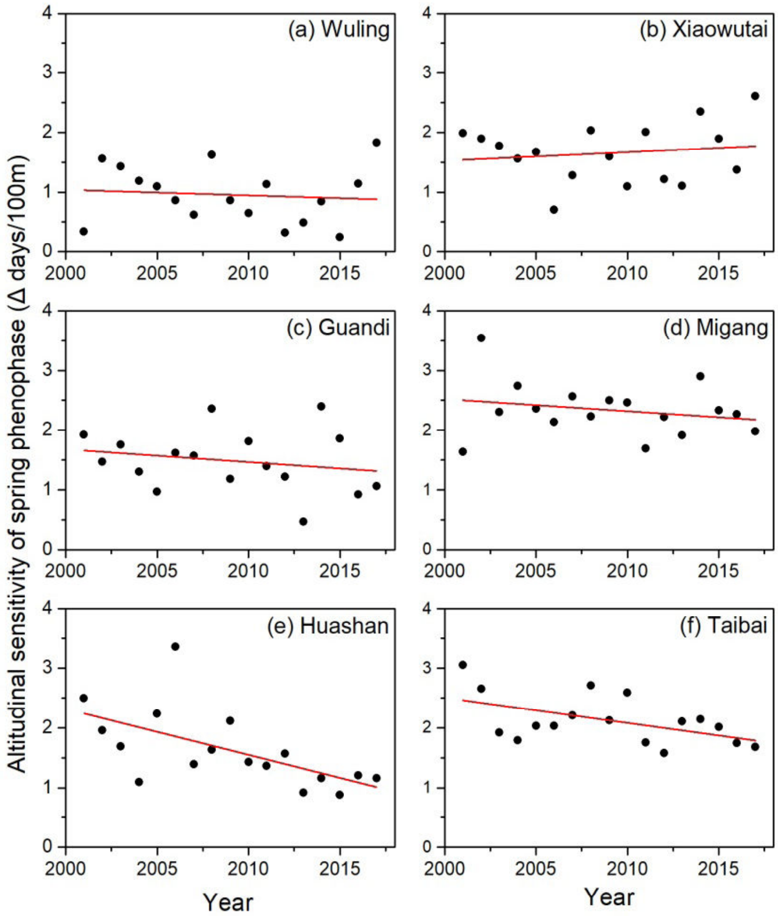

Figure 4. Time series of altitudinal sensitivity of SOS for 6 mountains in North China, panel (a) to (f) represent different mountains in North China, and the red lines are linear fits by regression analysis

of linear regression analysis indicate that altitudinal sensitivity of SOS is negative related to year for 5 of the 6 mountains we studied, except Xiaowutai (Figure 4). Among them, altitudinal sensitivity of spring phenophase of Huashan and Taibai exhibit significant decreasing trend. During 2001 and 2017, altitudinal sensitivity of SOS in these 2 mountains has decreased by 0.042–0.077 days/100m per year (p-value < 0.05) (Table 3). At low latitudes, the dates of SOS became closer between higher and lower altitudes, because the altitudinal sensitivity of SOS has decreased 0.71–1.31 days/100m from about 3 day /100m during the last 17 years. However, at high latitudes, there is no significant change in SOS altitudinal sensitivity over time. Change of EOS altitudinal sensitivity is also not significant in last 17 years. In general, altitudinal sensitivity of SOS has become lower at low latitudes from 2001 to 2017 due to the underlying warming trend, while altitudinal sensitivity of SOS at higher latitudes or altitudinal sensitivity of EOS has no significant change.

Conclusions and discussions

We studied phenological changes on 6 high mountains in North China, and found preliminarily the following facts. (1) Similar to phenological studies relating to plain area in North China, growing season length for the mountain temperate broadleaf deciduous forest on these mountains extended during the study period, as results of advances of SOS and delay of EOS. (2) SOS and EOS trends along altitudinal direction are very important for mountain ecological studies. Overall, the tendency for SOS trends across altitude gradients increase with altitude from lower elevations to higher elevation in most of the 6 mountains studied. However changes for EOS trend along with elevation did not show very manifest ten-

Table 3

Results of linear regression analysis of Altitudinal sensitivity time series.
Slope represents the change of Altitudinal sensitivity (d/100m) per year during 2001 and 2016. The significance is indicated with '*' (p-value < 0.05) and '·' (p-value < 0.1)

Mountain		Summit elevation(m)	Longitude,°E	Latitude, °N	Slope	P-value
SOS	Wuling	2116	117.5	40.6	−0.009	0.70
	Xiaowutai	2882	115.0	39.9	0.014	0.57
	Guandi	2830	111.5	37.9	−0.021	0.41
	Migang	2931	106.2	35.6	−0.020	0.39
	Huashan	2155	109.9	34.4	−0.077*	0.01
	Taibai	3767	107.8	34.0	−0.042*	0.03
EOS	Wuling	2116	117.5	40.6	−0.008	0.75
	Xiaowutai	2882	115.0	39.9	−0.042	0.11
	Guandi	2830	111.5	37.9	0.021	0.58
	Migang	2931	106.2	35.6	0.041·	0.07
	Huashan	2155	109.9	34.4	−0.060	0.12
	Taibai	3767	107.8	34.0	−0.012	0.51

dencies. (3) As far as the altitudinal sensitivities of SOS and EOS are concerned, the former showed a decreasing trend in the last 17 years, especially at low latitudes, while the later has no clear trend during the study period. This is the report from China for the first time that global warming also leads to more uniform spring phenology across elevations on mountains in North China. Characteristics of these changes over time or altitude may be attributed to climatic factors' changes, especially the temperature changes and the number of chilling days as indicated by Vandvik et al. [8]. Calculation of temperature changes, the statistics of number of chilling days on these mountains, as well as the relationship between climatic variables and phenological changes will be our future work.

The mean annual temperature in different places on mountains decreases with altitude. In Europe to north Asiatic regions, for each additional 100 m in altitude, the temperature drop is approximately the same as the mean annual decrease in temperature over a distance of 100 km on lower altitude from lower latitude to higher latitude. The width of the altitudinal belts on mountains is 1000 times narrower than the vegetation zones in the lower land from south to north [10]. However, the change patterns for climate variables along elevation gradients on mountains and along horizontal direction in plain areas from south to north are quite different. Therefore, comparison of vegetation phenology and phenological shifts on mountains and in lower latitudes are very crucial under background of global warming and worth further study.

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