Postprint: Impacts of Diurnal Asymmetric Warming on Vegetation Green-up in the Mongolian Plateau (2001–2020)

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Date: 2023-06-28T00:00:00+00:00

Abstract

Based on two remote sensing vegetation indices—the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI)—from 2001 to 2020, together with monthly maximum temperature, minimum temperature, and precipitation data from 94 meteorological stations on the Mongolian Plateau, we extracted the vegetation green-up date using two phenological identification methods: the extreme curvature method of the cumulative NDVI Logistic curve and the dynamic threshold method. We then analyzed the spatiotemporal variation of asymmetric diurnal warming and its impact on vegetation green-up. The results show that: (1) During the six months preceding the growing season (November of the previous year to April of the current year) from 2001 to 2020, both the average maximum temperature [0.7 ℃ · $(10a)^{-1}$] and minimum temperature [0.3 ℃ · $(10a)^{-1}$] on the Mongolian Plateau exhibited increasing trends, with the warming rate of maximum temperature being 2.3 times that of minimum temperature. (2) Pre-season asymmetric diurnal warming advanced the vegetation green-up date; however, compared with maximum temperature, minimum temperature exerted a greater influence on green-up date with a more extensive spatial coverage. (3) Pre-season asymmetric diurnal warming affected the green-up date differently across vegetation types; daytime warming had a more pronounced effect on the green-up of shrubs, cropland, and sparse vegetation, whereas nighttime warming showed a stronger influence on forests and grasslands, particularly in forested regions (25.5%). Investigating the effects of asymmetric daytime and nighttime warming on vegetation phenology on the Mongolian Plateau is crucial for elucidating the mechanisms through which temperature influences spring vegetation phenology.

Full Text

Effects of Asymmetric Warming of Daytime and Nighttime on the Start of Growing Season on the Mongolian Plateau from 2001 to 2020

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Abstract: Based on normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) remote sensing data from 2001 to 2020, together with monthly maximum temperature, minimum temperature, and precipitation data from 94 meteorological stations, this study extracted the start of growing season (SOS) on the Mongolian Plateau using two phenological identification methods: the logistic curve curvature extreme value method and the dynamic threshold method of cumulative NDVI. The spatiotemporal variations of asymmetric diurnal warming and its impacts on vegetation SOS were analyzed. The results show that: (1) The average maximum temperature [$0.7\ ^\circ\mathrm{C} \cdot (10\mathrm{a})^{-1}$] and minimum temperature [$0.3\ ^\circ\mathrm{C} \cdot (10\mathrm{a})^{-1}$] during the 6-month pre-season (November to April) on the Mongolian Plateau from 2001 to 2020 both exhibited increasing trends, with the warming rate of maximum temperature being 2.3 times that of minimum temperature. (2) Asymmetric warming during the pre-season advanced the SOS, but compared with maximum temperature, minimum temperature had a greater impact on SOS and over a wider spatial extent. (3) Asymmetric diurnal warming had differential effects on SOS across vegetation types. Daytime warming more noticeably affected SOS in shrubland, cropland, and sparse vegetation, while nighttime warming had stronger effects on forest and grassland, particularly in forest regions (25.5%). Investigating the effects of asymmetric daytime and nighttime warming on vegetation phenology on the Mongolian Plateau is crucial for revealing the mechanisms by which temperature influences spring vegetation phenology.

Keywords: maximum temperature; minimum temperature; asymmetric warming; start of growing season; Mongolian Plateau

Introduction

Vegetation phenology is one of the most important and sensitive indicators of global climate change, as even minor climatic fluctuations are recorded by changes in vegetation phenology [?]. Consequently, research on the relationship between vegetation phenology and climate change has become a key focus in global change studies [?]. Among various phenological metrics (spring green-up date, autumn senescence date), the spring green-up date is particularly critical, as its variation directly affects annual vegetation growth and biomass accumulation [?]. For instance, in rice, high maximum temperatures during flowering can directly damage chloroplasts, reducing photosynthesis and pollen production, leading to spikelet sterility and significant yield losses [?]. The green-up date is highly sensitive to climate change, and studying its response is essential for assessing and predicting future vegetation phenological dynamics and understanding terrestrial ecosystem carbon and water cycling processes [?].

Temperature is a key factor influencing vegetation phenological changes [?], with its effects varying by vegetation type, study region, and temperature metric (e.g., maximum, minimum, or mean temperature) [?]. The IPCC Sixth Assessment Report indicates that current climate system changes are dominated by global warming, with a persistent warming trend over the past 20 years [?]. Global warming exhibits asymmetric characteristics in both diurnal and seasonal patterns [?], such as nighttime temperatures rising faster than daytime temperatures, leading to decreasing diurnal temperature ranges [?]. In the Northern Hemisphere mid-to-high latitudes, summer warming rates exceed those of spring and autumn [?], creating seasonal asymmetry in climate change.

Numerous studies have shown that ecosystems respond sensitively and diversely to climate change, particularly temperature variations. Consequently, increasing numbers of scholars are analyzing the effects of asymmetric diurnal warming on global vegetation phenology using remote sensing and meteorological data. Piao et al. [?] demonstrated that in the Northern Hemisphere, daytime warming more effectively accumulates the heat required for leaf expansion and enhances atmospheric CO_2 absorption. Shen et al. [?] further investigated the seasonally asymmetric effects of diurnal warming on green-up dates in China's temperate grasslands, finding that maximum temperature had greater influence in winter, while minimum temperature was more important in spring. Peng et al. [?] found that in cold, humid regions of the Northern Hemisphere, daytime temperature increases benefit vegetation growth, whereas in temperate arid and semi-arid zones, they are detrimental. Nighttime warming shows the opposite pattern. In the Tibetan Plateau region, however, Shen et al. [?] found that vegetation green-up date changes were more closely related to minimum temperature increases, likely because higher minimum temperatures reduce frost damage, while maximum temperature increases may intensify cold stress in arid regions. Compared to the cold, dry Tibetan Plateau, the Mongolian Plateau is warmer and drier, making it extremely sensitive to climate change [?]. Vegetation in this region may have adapted well to historical temperature conditions regarding low-temperature requirements and heat accumulation during spring development, but cannot readily adapt to recent sustained global warming. Therefore, in the arid Mongolian Plateau, understanding the mechanisms by which temperature affects spring vegetation phenology requires studying the effects of both maximum and minimum temperature changes on spring green-up dates.

This study utilized 2001–2020 vegetation index data (NDVI and EVI) and monthly maximum temperature, minimum temperature, and precipitation data to analyze spatiotemporal variations in temperature and precipitation on the Mongolian Plateau. Using two different phenological extraction methods to calculate average green-up dates, we examined the effects of maximum and minimum temperatures on green-up dates across different vegetation types. This provides a basis for further research on spring phenological responses to regional climate change and offers case studies for investigating how different vegetation types respond to global asymmetric warming.

1. Study Area Overview

The study area encompasses the Mongolian Plateau region, including all of Mongolia and China's Inner Mongolia Autonomous Region [Figure 1: see original paper], covering approximately 2.7$×10^{6}$ km^2. The terrain slopes from west to east, with mountainous areas in the northwest, vast Gobi desert in the southwest, and endless hilly grasslands in the central and eastern regions, with an average elevation of 1580 m. The plateau is located in central Asia, bounded by the Greater Khingan Mountains in Heilongjiang Province to the east, extending westward to the Altai Mountains in Xinjiang Uygur Autonomous Region, north to the Sayan and Yablonovy ranges, and south to the Yinshan Mountains. Surrounded by mountains and far from oceans, it forms a closed inland plateau [**?**].

The Mongolian Plateau has a typical arid and semi-arid climate, with long, cold winters and hot, dry summers. Temperatures are highest in the southwestern Gobi desert region and lowest in northern Mongolia and northeastern Inner Mongolia. Precipitation distribution is opposite to temperature, with the highest annual totals (300–400 mm) in the north and northeast, and the lowest (<100 mm) in the southwest [**?**]. The plateau's unique geography and climate support diverse vegetation types, transitioning from northeast to southwest as forest (northern Sayan Range, northern Khentei Mountains, and Greater Khingan region), grassland (central and northwestern Mongolia), Gobi desert (southwestern Mongolia and Inner Mongolia), and sparse vegetation (southwestern Inner Mongolia). Cropland and shrubland are mainly distributed in central-eastern Inner Mongolia [**?**].

2. Data and Methods

2.1 Data Sources

2.1.1 Vegetation Index Data NDVI and EVI data were obtained from MOD13C1 products via the NASA AppEEARS platform (https://appeears.earthdatacloud.nasa.gov/), with temporal resolution of 16 days and spatial resolution of 0.05° (approximately 5.6 km). Given that vegetation is dormant or snow-covered in winter across most of the study area, data from days 90–200 (approximately early April to mid-July) were selected for analysis [**?**]. To minimize impacts from non-vegetated areas like Gobi and desert with extremely low vegetation cover, regions with multi-year average NDVI < 0.1 were designated as "non-vegetated areas" and excluded from analysis [?].

2.1.2 Vegetation Type and Elevation Data Vegetation type data were derived from MCD12Q1 products and elevation data from the Geospatial Data Cloud. After projection transformation, clipping, and resampling, raster data with 5.6 km spatial resolution matching the NDVI data were obtained. Original vegetation classification categories were merged to produce five vegetation types: forest, grassland, shrubland, cropland, and sparse vegetation, for analyzing differential responses of SOS to temperature across vegetation types.

2.1.3 Meteorological Data Meteorological data were obtained from the Institute of Geography and Geoecology, Mongolian Academy of Sciences, and China Meteorological Data Network (http://data.cma.cn/), including monthly maximum temperature, minimum temperature, and precipitation from 94 stations (46 in Mongolia and 48 in Inner Mongolia). Kriging interpolation was applied in ArcGIS to generate meteorological raster images with consistent projection and pixel size to the NDVI data. Based on previous research and regional conditions, the 6-month period before the multi-year average SOS (November–April) was defined as the pre-season, representing the non-growing season [?]. Masking and clipping were used to extract monthly maximum temperature (daytime temperature), minimum temperature (nighttime temperature), and precipitation raster images for the Mongolian Plateau.

2.2 Methods

2.2.1 Smoothing and Reconstruction of NDVI and EVI Data To reduce impacts from clouds, atmosphere, and solar zenith angle, the Harmonic Analysis of Time Series (HANTS) method was used to smooth the 90–200 day NDVI data as a function of time. HANTS considers both vegetation growth cycles and data characteristics, accurately reflecting periodic variations in time series curves and widely applied in phenological studies [?]. The core of the HANTS algorithm combines least squares with Fourier transform, proposed by Roerink et al. in 2000, expressed as:

$$y_i = A_0 + \sum_{j=1}^{N} A_j \sin(\omega_j t_i + \phi_j) + \varepsilon_i$$

where y_i is the fitted NDVI value; A_0 is the remainder term for harmonics with equal frequency; A_j is the amplitude of each harmonic; $\omega_j = 2\pi j/N$ is the frequency; ϕ_j is the initial phase; N is the time series length; and ε_i is the residual term.

2.2.2 Cumulative NDVI Logistic Curve Curvature Extreme Method After HANTS smoothing, the logistic function was used to fit the cumulative

NDVI data. Curve curvature (K) was calculated to extract the start of growing season pixel by pixel, with the date (day of year) corresponding to maximum curvature defined as SOS:

$$y(x) = \frac{c}{1 + e^{a+bx}} + d$$

$$K = \frac{|y''(x)|}{[1 + y'(x)^2]^{3/2}}$$

where $y(x)$ is the cumulative NDVI on Julian day x; d is the background NDVI; c is the difference between maximum cumulative NDVI and background; a and b are fitting parameters; K represents the angle of the unit tangent vector along the differentiable curve; and s is the simulated unit length.

2.2.3 Dynamic Threshold Method The dynamic threshold method was applied to EVI data for phenology extraction. A sixth-order polynomial was fitted to determine the SOS threshold based on annual change rates and multi-year average seasonal change rates, then used to retrieve the date. The sixth-order polynomial, proposed by [**?**], well approximates filtered curves and enables pixel-by-pixel calculation, offering advantages for fitting entire growing season curves. Calculations were performed in three steps: (1) Compute multi-year average EVI ($\overline{EVI_t}$) and change rates (EVI_{ratio}); (2) Determine SOS threshold by selecting the median of maximum EVI_{ratio} values from the first half of the year; (3) Fit annual EVI data pixel-by-pixel using the sixth-order polynomial, with SOS defined as the date when the fitted curve first reaches the threshold.

$$EVI_{ratio} = \frac{EVI_{t+1} - EVI_t}{\overline{EVI_{t+1}} - \overline{EVI_t}}$$

$$EVI = k_n x^n + k_{n-1} x^{n-1} + \cdots + k_1 x + k_0$$

where x is Julian day; n is polynomial degree (6 in this study); and k_n are least squares regression coefficients.

2.2.4 Linear Regression Analysis Pixel-scale linear regression was used to analyze spatiotemporal trends in SOS, maximum temperature, minimum temperature, and precipitation on the Mongolian Plateau [**?**]:

$$b = \frac{n \sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n \sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2}$$

where b is the trend slope (annual change rate) for temperature or precipitation; positive slopes indicate increasing temperature/precipitation (delayed

SOS), while negative slopes indicate decreasing values (advanced SOS); x_i is the temperature or precipitation in year i; y_i is SOS or cumulative pre-season precipitation; and n is the number of study years.

2.2.5 Partial Correlation Analysis Partial correlation analysis was used to examine relationships between SOS and pre-season maximum temperature, minimum temperature, and precipitation, further investigating dynamic vegetation responses and asymmetric diurnal warming effects. When three variables are correlated, this method excludes the influence of one variable to analyze the correlation between the other two [**?**]:

$$r_{xy\cdot z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1 - r_{xz}^2)(1 - r_{yz}^2)}}$$

where r_{xy} is the correlation coefficient between variables x and y; $r_{xy\cdot z}$ is the partial correlation between x and y excluding z; and r_{xz}, r_{yz} are correlation coefficients. Specifically, $r_{yT_{max}\cdot T_{min},P}$ represents the partial correlation between maximum temperature and SOS excluding minimum temperature and precipitation; $r_{yT_{min}\cdot T_{max},P}$ represents the partial correlation between minimum temperature and SOS; and $r_{yP\cdot T_{max},T_{min}}$ represents the partial correlation between precipitation and SOS. Significance was tested using t-tests, with $P < 0.05$ indicating significant correlation.

3. Results and Analysis

3.1 Spatiotemporal Patterns of Maximum Temperature, Minimum Temperature, and Precipitation

From 2001 to 2020, both maximum and minimum temperatures during the 6-month pre-season showed increasing trends across the Mongolian Plateau, while precipitation decreased to some extent. Maximum temperature increased at an average rate of 0.7 °C per decade, minimum temperature at 0.3 °C per decade, and precipitation decreased at 3.2 mm per decade. The warming trend differed significantly between maximum and minimum temperatures, with maximum temperature warming 2.3 times faster than minimum temperature, indicating increasing diurnal temperature ranges.

Spatially, most areas showed overall warming trends for both maximum and minimum temperatures. Maximum temperature increased across 98.8% of the region, with decreasing trends in only 1.2% of the area, primarily in Chen Barag Banner, Hulunbuir City, Inner Mongolia [Figure 2: see original paper]. Minimum temperature increased across 85.9% of the region, with decreases in 14.1% of the area, mainly in southwestern Inner Mongolia, western Hangai Mountains, and northern Khentei Mountains in Mongolia. Thus, asymmetric diurnal warming patterns also varied spatially, with different warming rates across specific regions. Precipitation showed clear latitudinal zonation, increasing across most of Inner Mongolia south of 45°N, particularly in central and eastern areas, while decreasing across most of Mongolia north of 45°N, with only small areas showing increases.

3.2 Response of Green-up Date to Maximum Temperature, Minimum Temperature, and Precipitation

The average SOS on the Mongolian Plateau occurred on day 128 (range: 110–140), with 92.8% of the region concentrated between days 125–135 (early May). SOS showed a clear east-west gradient, with earliest green-up (before day 110) in the eastern Greater Khingan Mountains and latest (around mid-May, day 140) in the Hangai Mountains of northwestern Mongolia [Figure 3: see original paper]. This spatial pattern is consistent with findings by [**?**] and [**?**].

Pixel-based partial correlation analysis revealed clear spatial heterogeneity in SOS responses to maximum temperature, minimum temperature, and precipitation. Approximately 54.1% of the region showed negative correlations between SOS and maximum temperature, with 17.1% being significant ($P < 0.05$), concentrated in the Sayan Range, eastern Khentei Mountains, and Xilingol Grassland of Inner Mongolia. Only 12.7% showed significant positive correlations, scattered in northern Hangai Mountains, western Khentei Mountains, Hulunbuir Grassland, Ordos Plateau's Mu Us Sandy Land, and Hetao Plain. In contrast, 57.5% of the region showed negative correlations between SOS and minimum temperature, with 20.1% being significant—higher than for maximum temperature. Significant positive correlations covered 11.8% of the region, mainly in northern Hangai Mountains and eastern Hulunbuir Grassland, showing nearly opposite distribution to maximum temperature correlations [Figure 4: see original paper].

The 6-month pre-season showed the strongest effects of maximum and minimum temperatures on SOS, covering 59.7% of the study area. Overall, diurnal warming advanced SOS across most regions, likely due to widespread advancement of the growing season from temperature increases. Notably, areas with significant negative correlations between SOS and minimum temperature far exceeded those for maximum temperature, indicating that nighttime warming more readily advances SOS.

Correlation analysis between SOS and precipitation showed that 58.9% of the region had negative correlations, with 20.6% being significant, concentrated in southeastern Sayan Range, eastern Khentei Mountains, and Xilingol Grassland of Inner Mongolia. Significant positive correlations covered 11.8% of the region, mainly in northern Hangai Mountains and eastern Hulunbuir Grassland. About 49.1% of the region showed precipitation effects concentrated in the 3–4 months before SOS. Precipitation had stronger advancing effects on SOS, demonstrating that in this arid/semi-arid ecosystem, precipitation is the primary limiting factor for vegetation growth.

Different vegetation types showed varying responses [Figure 5: see original paper]. All vegetation types showed strong overall negative correlations between SOS and minimum temperature, indicating nighttime warming more effectively advanced green-up. Forest and grassland showed stronger negative correlations with minimum temperature than maximum temperature, with forest having the highest proportion of significant pixels (25.5%), suggesting nighttime warming particularly advances forest SOS, possibly due to forests being distributed at higher latitudes and elevations where nighttime warming reduces frost risk. In contrast, shrubland, cropland, and sparse vegetation showed stronger negative correlations with maximum temperature, with cropland showing 20.8% significant negative correlation with maximum temperature, indicating daytime warming more strongly advances SOS in these types.

Precipitation effects also varied by vegetation type. Except for forest, which showed mainly positive correlations with precipitation, other vegetation types showed predominantly negative correlations, indicating precipitation advances SOS in all types except forest. These results demonstrate that asymmetric diurnal warming has generally positive advancing effects on SOS across the Mongolian Plateau, with nighttime minimum temperature increases having more significant advancing effects, particularly in forest regions.

4. Discussion

From 2001 to 2020, both daytime and nighttime pre-season temperatures on the Mongolian Plateau showed clear increasing trends, but with asymmetric warming rates and increasing diurnal temperature ranges, as daytime warming was 2.3 times faster than nighttime warming. This aligns with global asymmetric warming patterns [?]. Precipitation strongly influences this asymmetry through its close relationship with cloud cover and soil moisture [?]. Studies show that cloud cover, soil moisture, solar radiation, and atmospheric circulation may cause asymmetric warming, with increased cloud cover being a primary factor [?]. Clouds reduce daytime shortwave radiation reaching the surface, lowering maximum temperatures, while trapping longwave radiation at night, increasing minimum temperatures. However, the interaction mechanisms require further investigation.

In the arid/semi-arid Mongolian Plateau, precipitation is the main hydrothermal factor limiting vegetation growth. While diurnal warming generally advanced SOS, the mechanisms differ between daytime and nighttime warming. Nighttime warming advances SOS by reducing frost risk and low-temperature limitations [?], while also increasing effective soil water from ice and snow melt due to higher nighttime temperatures [?]. This provides adequate moisture for root uptake and earlier leaf expansion.

Daytime warming can delay SOS when temperatures exceed optimal thresholds for winter chilling requirements [?]. During the 3–4 months pre-season, daytime warming increases evapotranspiration, reducing soil moisture and partially or completely offsetting its advancing effects [?], consistent with findings in the Northern Hemisphere [?]. However, in cold, dry regions like the Tibetan Plateau, vegetation SOS is more closely related to minimum temperature increases [?], as higher minimum temperatures alleviate frost damage while maximum temperature increases may intensify cold stress.

Without ground observation data, we validated our results against previous studies. Our SOS values, calculated by averaging results from logistic curve curvature extreme and dynamic threshold methods, were consistent with published values for the Mongolian Plateau and surrounding regions . However, variations in phenological extraction methods, observation periods, and remote sensing data resolution cause some discrepancies among studies [?]. Therefore, our methods are suitable for analyzing spatiotemporal SOS variations on the Mongolian Plateau.

Vegetation phenological dynamics represent an integrated response to climate change, with temperature and precipitation being primary drivers. This study focused on these hydrothermal factors, but future research should consider other climatic factors (humidity, evaporation, sunshine duration) and anthropogenic influences. Additionally, vegetation responses to climate change often exhibit lag effects that vary across growth stages [?], affecting study accuracy. Future research should integrate multiple factors using controlled experiments and mathematical models to further clarify mechanisms of asymmetric diurnal warming effects on different vegetation phenologies.

5. Conclusions

Using 2001–2020 vegetation index data, monthly maximum/minimum temperature, and precipitation data, this study analyzed temperature and precipitation changes on the Mongolian Plateau and their impacts on SOS, yielding the following conclusions:

1) From 2001 to 2020, the pre-season maximum temperature warming rate was 2.3 times that of minimum temperature, showing clear diurnal asymmetry with spatial variations and increasing diurnal temperature ranges.
2) Vegetation SOS responses to asymmetric diurnal warming differed in pre-season length and spatial scale. The 6-month pre-season showed the strongest temperature effects, with minimum temperature having greater impact than maximum temperature, more widespread influence, and predominantly advancing effects.
3) Asymmetric diurnal warming had generally positive advancing effects on SOS across vegetation types. Daytime warming significantly affected shrubland, cropland, and sparse vegetation, while nighttime warming had stronger effects, particularly on forest regions.

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Note: Figure translations are in progress. See original paper for figures.

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