

## Seasonal Asymmetry of Diurnal Warming in China and Its Impacts on Vegetation Activity (Postprint)

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### Abstract

Based on meteorological data from 1982-2015, linear trend analysis and GIS spatial analysis methods were employed to analyze the spatiotemporal patterns of seasonal day-night warming in China over the past 34 years; combined with GIMMS-NDVI 3g remote sensing data and vegetation zoning data, partial correlation analysis was used to investigate the response of vegetation in different vegetation zones to seasonal asymmetric warming. The results show that: (1) Over the past 34 years, day-night temperatures in China have exhibited a universally extremely significant upward trend; day-night warming demonstrates asymmetric characteristics in all seasons, and this asymmetric feature shows obvious seasonal differences, with daytime warming rates being 1.49 times, 0.98 times, 0.73 times, and 1.69 times the nighttime warming rates in spring, summer, autumn, and winter, respectively; (2) The response of vegetation in different zones to seasonal day-night asymmetric warming varies: compared with nighttime warming, daytime warming has a greater impact on vegetation activity and affects a wider area; day-night warming in spring and winter has a broader influence range on vegetation activity, and day-night warming in spring and autumn generally plays a promoting role in the increase of vegetation NDVI; (3) Seasonally asymmetric day-night warming has different effects on vegetation activity in different zones, and the degree of this impact varies significantly with seasons. By analyzing the seasonal variation trends of day-night warming in China and its impacts on different vegetation types, this study helps to deepen our understanding of the effects of seasonal day-night asymmetric warming on terrestrial vegetation dynamics in China against the backdrop of global climate change.

## Full Text

### Preamble

#### Asymmetric Seasonal Variability in Day- and Night-time Warming and Their Effects on Vegetation Activity in China

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### Abstract

This study examines asymmetric variations in day- and night-time warming using least squares linear regression analysis, and characterizes the differential effects of seasonally asymmetric warming on vegetation activities in China using a second-order partial correlation method. Based on normalized difference vegetation index (NDVI), vegetation type, and meteorological data from 1982 to 2015, the following results were obtained: (1) China experienced a significant trend of day- and night-time warming across all seasons during the study period. Day- and night-time warming rates were seasonally asymmetric: the daytime warming rate in spring, summer, autumn, and winter was 1.49, 0.98, 0.73, and 1.69 times higher, respectively, than that at night. (2) Daytime warming had a significantly greater and more extensive impact on vegetation than night-time warming. The areas affected by asymmetric seasonal warming in spring and winter were larger than those in summer and autumn. (3) Different vegetation types responded differently to seasonal asymmetry in day- and night-time warming, and the degree of response varied distinctly between seasons. This analysis of seasonal variations in day- and night-time warming and its impacts on different vegetation types directly contributes to our understanding of the local and regional effects of warming on terrestrial vegetation in China within the context of global climate change.

**Keywords:** Day- and night-time warming; asymmetric variability; vegetation activity; climate change; China

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### Introduction

Vegetation serves as the primary carrier of material cycling and energy flow in the Earth system, playing an irreplaceable role in regulating global carbon

balance, reducing greenhouse gas concentrations, and maintaining climate stability [1-2]. The normalized difference vegetation index (NDVI) is a commonly used indicator for monitoring and indicating changes in vegetation activity and productivity [3-5]. Many physiological and ecological characteristics of vegetation, such as photosynthetic capacity, growth cycle duration, and community dynamics, are sensitive to climate change [6-7]. Consequently, research on vegetation dynamics and their responses to climatic factors has become a key issue in global change studies [8-9].

Increasing evidence indicates that global climate warming exhibits widespread diurnal and seasonal asymmetry, characterized by inconsistent warming rates between day and night and across seasons [10-12]. Most regions globally show faster night-time warming than daytime warming [10], while mid- to high-latitude regions in the Northern Hemisphere commonly exhibit faster summer warming than in spring and autumn [12]. Since most plant photosynthesis occurs during the day while respiration continues throughout the entire day, differences in day- and night-time warming rates inevitably exert important influences on vegetation carbon uptake and consumption [13-15]. Moreover, vegetation responses to temperature vary across seasons [15-17]. In temperate regions, phenological characteristics and photosynthetic properties of vegetation show distinct seasonal cycles, making it essential to study the relationship between diurnal asymmetric warming and vegetation dynamics at the seasonal scale to clarify warming effects on vegetation under global change.

Previous studies by domestic and international scholars have investigated seasonal effects of day- and night-time warming on vegetation activity at macro scales using meteorological station data and satellite observations, though findings vary. Shen et al. [18] found that summer daytime warming benefits vegetation growth on the Tibetan Plateau, while night-time warming in the same season has negative effects. Tan et al. [7] analyzed vegetation responses to asymmetric day- and night-time warming across mid- to high-latitude Northern Hemisphere regions, revealing that night-time warming benefits vegetation growth in spring and summer, while autumn night-time warming negatively affects most regions. Wu et al. [19] similarly demonstrated that diurnal warming in different seasons differentially affects photosynthetic capacity across the Northern Hemisphere mid- to high latitudes. Despite these efforts using remote sensing and meteorological data to analyze seasonal response characteristics of Northern Hemisphere vegetation to diurnal warming [7, 18-19], a comprehensive understanding of how seasonal asymmetric day- and night-time warming affects vegetation activity remains lacking. Further research combining remote sensing and meteorological data with experimental warming studies is needed to explore these effects.

China, located in eastern Eurasia and strongly influenced by eastern monsoon and northwest arid climates, represents one of the most sensitive and complex regions to global climate change [20]. Climate change impacts on China's vegetation dynamics are significant [21-22]. With vast territory, diverse topography,

and substantial variations in hydrothermal conditions, regional differences in vegetation response to climate change are pronounced across China, making it suitable for large-scale studies on vegetation-climate relationships using long-term datasets [1, 23]. Based on this understanding, this study utilizes nearly 34 years of meteorological and satellite remote sensing observations, combined with linear regression and spatial analysis, to analyze seasonal trends in day- and night-time warming across China and its effects on different vegetation types, aiming to enhance understanding of how seasonal asymmetric warming influences terrestrial vegetation dynamics in China under global climate change.

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## 1. Remote Sensing Data

The NDVI data used in this study were obtained from the third-generation GIMMS-NDVI3g dataset produced by NASA's Global Inventory Modeling and Mapping Studies group, provided by the NASA Ames Ecological Forecasting Laboratory (<http://ecocast.arc.nasa.gov/data/pub/gimms/3g.v1/>). This dataset currently represents the longest time series of NDVI data and has been widely applied in large-scale vegetation dynamic studies [24-25], net primary productivity assessment [26], and biomass estimation [4]. The dataset has a spatial resolution of  $1/12^\circ$ , a temporal resolution of 15 days, and covers the period 1982-2015.

During data processing, the maximum value compositing method was applied to reconstruct monthly NDVI values across China to further eliminate interference from clouds and atmospheric noise [21]. Since NDVI values in low vegetation cover areas are significantly affected by underlying surfaces, areas with multi-year average NDVI values greater than 0.1 were defined as vegetation regions, following relevant studies [1, 25].

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## 2. Meteorological Data

Monthly extreme maximum temperature (Tmax), extreme minimum temperature (Tmin), and precipitation data for China from 1982-2015 were obtained from the China Meteorological Data Sharing Service Network's monthly surface climate dataset. The Inverse Distance Weighted (IDW) method was used to interpolate meteorological factors spatially, with ArcGIS 10.2 employed to obtain raster images covering the entire study area [24]. Following relevant studies [27], March-May, June-August, September-November, and December-February were defined as spring, summer, autumn, and winter, respectively, with seasonal means calculated for each climate variable.

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### 3. Vegetation Zoning Data

Vegetation zoning data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences. Based on the 1:1,000,000 China Vegetation Atlas, this dataset divides China into eight distinct vegetation regions with relatively consistent internal vegetation composition. Accordingly, this study classified Chinese vegetation into eight major zones: temperate grassland region (R1), temperate desert region (R2), alpine vegetation region of the Tibetan Plateau (R3), cold temperate coniferous forest region (R4), deciduous broad-leaved forest region (R5), subtropical evergreen broad-leaved forest region (R6), mixed deciduous broad-leaved forest region (R7), and tropical monsoon rainforest (R8).

[Figure 1: see original paper] Spatial distribution of studied sub-regions across China

Since most vegetation ceases growth in winter except for subtropical/tropical vegetation and some artificial vegetation, winter diurnal temperature trends and correlations with NDVI were only analyzed for the subtropical evergreen broad-leaved forest region (R6) and tropical monsoon rainforest (R7) in winter.

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#### 1. Linear Trend Analysis

At both regional and pixel scales, least squares linear regression was performed between diurnal temperatures and corresponding years to characterize temperature trends. Linear regression coefficients were tested for significance using t-tests, with  $P < 0.05$  indicating significant trends and  $P < 0.01$  indicating highly significant trends. Pixel-by-pixel calculations of seasonal day- and night-time temperature change rates were conducted to analyze spatiotemporal patterns across China's vegetated areas.

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#### 2. Partial Correlation Analysis

Partial correlation analysis can eliminate interference from other variables to study the effects of asymmetric day- and night-time warming on vegetation dynamics. This study employed pixel-based spatial analysis to calculate second-order partial correlation coefficients between seasonal NDVI and  $T_{max}/T_{min}$  while controlling for precipitation. T-tests were used for significance testing, with  $P < 0.05$  indicating significant correlation and  $P < 0.01$  indicating highly significant correlation.

## 1. Regional Scale

Linear regression analysis revealed significant upward trends in day- and night-time temperatures across all seasons from 1982-2015. The warming rate was fastest in winter ( $0.61^{\circ}\text{C}/10\text{a}$ ) and spring ( $0.49^{\circ}\text{C}/10\text{a}$ ), and slowest in summer ( $0.35^{\circ}\text{C}/10\text{a}$ ) and autumn ( $0.29^{\circ}\text{C}/10\text{a}$ ). Comparing day- and night-time warming rates, winter and spring Tmax increased at rates 1.69 and 1.49 times faster than Tmin, respectively, while autumn and summer Tmax increased at 0.73 and 0.98 times the Tmin rate, respectively. Thus, diurnal warming showed asymmetric patterns in all seasons, with pronounced seasonal differences: daytime warming exceeded night-time warming in spring and winter, while night-time warming exceeded daytime warming in autumn and summer.

Due to substantial differences in latitude, longitude, and location across vegetation zones, diurnal warming trends varied significantly by region and season. Analysis of different vegetation zones revealed distinct asymmetric patterns: in spring, zones R1, R3, R5, and R7 showed faster daytime warming, while R2, R4, and R8 showed faster night-time warming; in summer, R1, R3, R4, and R8 exhibited faster daytime warming; in autumn, R1, R3, R5, and R7 showed faster daytime warming; and in winter, R1, R3, R4, and R6 showed faster daytime warming. All vegetation zones demonstrated seasonal asymmetry in diurnal warming, but the pattern varied significantly among zones.

Statistics of trends in seasonal Tmax/Tmin at regional scale ( $^{\circ}\text{C}/\text{a}$ )

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## 2. Pixel Scale

While spatial averages characterize overall temperature trends, they may mask opposite trends in different regions due to spatial heterogeneity in temperature changes [21, 27]. Therefore, this study applied least squares linear regression models pixel-by-pixel to calculate diurnal warming trends and performed significance tests.

**Spring:** Most areas of China showed rising diurnal temperatures, with approximately 68.36% of the country exhibiting significant upward trends, primarily located in northern Xinjiang, the central Inner Mongolia Plateau, the North China Plain, and southeastern coastal regions. Significant decreasing trends were rare, covering only 0.21% of China, mainly in western Xinjiang.

**Summer:** Similar to spring, 67.20% of China showed significant upward trends in Tmax, concentrated in northern Xinjiang, eastern Qinghai-Tibet Plateau, central-western Inner Mongolia Plateau, southern North China Plain, and most southern regions. Significant decreasing trends accounted for only 0.05% of the study area.

**Autumn:** Areas with significant upward trends covered 41.31% of the study area, mainly in the northwestern region, northern Northeast Plain, western

North China Plain, and eastern and southern coastal areas. Significant decreasing trends occupied only 0.22%, concentrated in northwestern Heilongjiang.

**Winter:** Significant upward trends covered 73.16% of the study area, distributed in the eastern Qinghai-Tibet Plateau, northern Northeast Plain, western North China Plain, and eastern and southern coastal regions. Significant decreasing trends comprised merely 0.03% of the study area.

[Figure 2: see original paper] Spatial patterns of warming rate of Tmax and Tmin in spring

[Figure 3: see original paper] Spatial patterns of warming rate of Tmax and Tmin in summer

[Figure 4: see original paper] Spatial patterns of warming rate of Tmax and Tmin in autumn

[Figure 5: see original paper] Spatial patterns of warming rate of Tmax and Tmin in winter

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## 1. Regional Scale

At the regional scale, second-order partial correlation coefficients between NDVI and diurnal temperatures were positive across all seasons. Spring and winter NDVI showed significant positive correlations with Tmax ( $P < 0.05$ ), while correlations with Tmin were not significant in any season. This indicates that daytime warming has a greater impact on vegetation activity than night-time warming in China, with spring and winter daytime warming exerting more widespread effects.

Since different vegetation types have distinct biological characteristics that may lead to varied responses to climate change [1, 3-4, 28], this study calculated partial correlation coefficients between NDVI and diurnal warming for each vegetation zone. Results showed that seasonal asymmetric diurnal warming affected different vegetation types to varying degrees. In spring, vegetation in zones R1, R2, R4, R5, R6, and R7 showed weak correlations with Tmax, while R3 showed significant positive correlation. In summer, R1 and R3 showed significant positive correlations with Tmax, whereas R2 showed significant negative correlation. In autumn, R1, R3, and R4 showed significant positive correlations with Tmax. In winter, R6 and R7 vegetation showed significant positive correlations with both Tmax and Tmin.

Seasonal partial correlation coefficients of NDVI and Tmax/Tmin at regional scale

## 2. Pixel Scale

To understand spatial patterns of vegetation-climate relationships across seasons, pixel-scale partial correlation coefficients were calculated between NDVI and diurnal temperatures.

**Spring:** Significant correlations covered 37.51% of the study area, with 85.90% showing positive correlations, mainly in the eastern Qinghai-Tibet Plateau, Greater Khingan Mountains, and Northeast Plain. Significant negative correlations accounted for only 0.98%, distributed in southern Shanxi's Guanzhong Basin and northwestern Xinjiang. The positive response of most Chinese vegetation to spring temperature increases likely relates to advanced growing seasons [29]. Notably, areas showing significant positive correlations with Tmax far exceeded those with Tmin, possibly because daytime warming more effectively advances leaf expansion and green-up dates [30].

**Summer:** Significant correlations covered 60.05% of the study area, with 50.56% showing positive correlations, distributed in the Greater Khingan Mountains, eastern Northeast China, northeastern Tibet, and southern China. Significant negative correlations comprised 4.43%, located in central-eastern Qinghai-Tibet Plateau, central Yunnan Plateau, and Northeast Plain. Compared to spring, fewer areas showed significant positive correlations, possibly because summer daytime temperatures in most regions already approach optimal levels for vegetation growth, reducing sensitivity to further daytime warming [31]. Daytime warming may reduce water availability, potentially explaining negative correlations in some areas [18].

**Autumn:** Significant correlations covered 64.23% of the study area, with 63.30% showing positive correlations, mainly in western Xinjiang, the Sichuan Basin, and northern Northeast China. Significant negative correlations accounted for 1.55%, sporadically distributed in the eastern coastal zone. Compared to spring, fewer areas showed positive responses to daytime warming, likely because autumn vegetation photosynthesis duration and productivity are less temperature-sensitive than in spring [32].

**Winter:** Significant correlations covered 27.12% of the study area, with 84.18% showing positive correlations, primarily in the Hanzhong Basin, Yunnan-Guizhou Plateau, and Jiangnan Hills. Significant negative correlations comprised only 0.87%. Night-time warming benefits vegetation growth in most areas, likely because temperature is the primary limiting factor in this season, and warming can enhance photosynthetic enzyme activity.

[Figure 6: see original paper] Spatial patterns of the partial correlation coefficients between spring NDVI and Tmax/Tmin

[Figure 7: see original paper] Spatial patterns of the partial correlation coefficients between summer NDVI and Tmax/Tmin

[Figure 8: see original paper] Spatial patterns of the partial correlation coefficients between autumn NDVI and Tmax/Tmin

[Figure 9: see original paper] Spatial patterns of the partial correlation coefficients between winter NDVI and Tmax/Tmin

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## 1. Conclusions

Based on 34 years (1982-2015) of meteorological and satellite remote sensing datasets, this study analyzed seasonal trends in diurnal warming and their effects on different vegetation types in China, reaching the following conclusions:

1. Day- and night-time temperatures in China showed significant upward trends across all seasons from 1982-2015, but warming rates varied substantially by season. Diurnal warming exhibited asymmetric patterns in all seasons, with pronounced seasonal differences: daytime warming exceeded night-time warming in spring and winter, while night-time warming exceeded daytime warming in autumn and summer.
  2. At the regional scale, NDVI showed positive correlations with diurnal warming in all seasons, with significant positive correlations in spring and winter for Tmax, but no significant correlations with Tmin. This indicates daytime warming has a greater impact on China's vegetation activity than night-time warming.
  3. At the pixel scale, areas where vegetation NDVI showed significant correlations with diurnal warming were more extensive in spring and winter, predominantly positive, indicating broader impacts of seasonal diurnal warming on vegetation activity during these seasons.
  4. Different vegetation zones in China showed distinct diurnal warming rates across seasons, and different vegetation types responded differently to asymmetric warming, with response degrees varying by season.
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## 2. Discussion

This study analyzed seasonal variations in diurnal temperatures across China and discussed vegetation responses using remote sensing and meteorological data. Vegetation responses to diurnal warming varied significantly by season. While most regions showed positive responses to temperature increases, areas negatively affected by warming existed in all seasons.

In regions where temperature is the primary limiting factor for vegetation growth, warming may promote NDVI increases by enhancing photosynthetic enzyme activity [33], improving soil nitrogen availability [34], and extending growing seasons [29]. In water-limited arid and semi-arid regions, daytime warming may negatively affect growth by increasing transpiration and accelerating soil water evaporation [35-36].

Although fewer areas showed significant correlations between NDVI and  $T_{min}$ , night-time warming can affect vegetation productivity through multiple pathways: increasing autorespiration rates, reducing soil water content, decreasing endosperm cell volume at maturity [38], and shortening grain-filling periods [39], all potentially reducing productivity. However, increased night-time respiration may also enhance next-day photosynthetic capacity through compensation effects [14, 40]. Notably, night-time warming can reduce frost damage frequency [41], enhance drought resistance [42], and regulate carbohydrate content in leaves [14], potentially benefiting productivity.

Vegetation dynamics are influenced by geographic factors (elevation, slope, aspect, surface roughness), cloud cover, solar radiation, and anthropogenic disturbances. Key controlling factors vary across regions due to differences in geographic conditions and human interference levels. Data availability limitations prevented comprehensive consideration of all factors affecting vegetation dynamics. Additionally, vegetation responses to climate factors often exhibit time lags, with lag durations varying across growth stages [43-44], potentially affecting result accuracy. Future studies should integrate multiple factors with controlled experiments or mathematical models to clarify mechanisms underlying seasonal asymmetric warming effects on different vegetation types.

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