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Non-uniform time-lag effects of terrestrial vegetation responses to asymmetric warming

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A B S T R A C T

The immediate effects of asymmetric warming (i.e., day- and night-time warming) on terrestrial ecosystems have been well documented, but the time-lag effects remain poorly understood. In this paper, we investigated the global inter-annual hysteretic responses of vegetation to asymmetric warming over the period of 1982–2013. The net primary production (NPP) was employed as the indicator of vegetation growth, and accumulated monthly average daily maximum temperature and minimum temperature (ATmax and ATmin) were used to reflect the asymmetric warming condition. Additionally, partial correlation analyses were conducted to examine the correlations between NPP and ATmax/ATmin on a monthly scale. Furthermore, the best time lags that ATmax/ATmin had on NPP and the optimal correlations between ATmax/ATmin and NPP were analyzed by time-lag analyses. The results showed that (i) vegetation responded to the asymmetric warming with near 12-month delays at a global scale, and vegetation exhibited larger lags in responding to recent warming over temperature-limited areas or semiarid and subhumid regions compared to other places; (ii) compared with ATmin, ATmax had longer time-lag effects on biomes over mid-high latitudes (45 °N–90 °N, 23 °S–60 °S) and high altitudes (i.e., the Tibetan Plateau and the Brazil Plateau) and smaller delay impacts on biomes in other regions; (iii) with hysteretic impacts considered, ATmax correlated positively with vegetation in temperature-limited areas and negatively in heat-sufficient and water-deficit places, and the reverse was mostly true for ATmin. These phenomena may be associated with the intrinsic differences in the mechanisms that day- and night-time temperatures have on vegetation growth. Our paper gives new insights into the non-uniform responses of the terrestrial ecosystem to asymmetric warming. Looking ahead, terrestrial ecosystem models are highly recommended to incorporate such non-uniform time-lag impacts and distinguished correlations so as to improve their performances in future work.

1. Introduction

Plant is one of the most important natural correspondents of the air, water, soil and other natural elements and it plays a crucial role in the terrestrial carbon cycle. While, being disable to generate heat, green plants have to depend on ambient temperature as thermal energy to modulate the inner biogeochemical processes (Foote and Schaedle, 1976) and further regulate the plant architecture and biomass (Patel and Franklin, 2009). This natural instinct makes temperature be one of the most significant factors that controls plant growth and development.

The last 30 years have witnessed a greater warming trend existing in the daily minimum temperature (Tmin) rather than in the daily maximum temperature (Tmax) (IPCC, 2014; Xia et al., 2014), what's known as asymmetric warming (Peng et al., 2013). This asymmetry in warming is bound to generate non-uniform effects on vegetation (Peng et al., 2013; Tan et al., 2014; Xia et al., 2014), because Tmin appears at night time, and it accounts for the night-time temperature or warming and strongly affects the plant dark autotrophic respiration; while Tmax appears at day time, and it accounts for the day-time temperature or warming and greatly influences both plant day-time photosynthesis and respiration. With increasing global warming temperature, this asymmetry is projected to be enhanced in future decades (Hansen et al., 2010; IPCC, 2014), which urges the studies of the impacts of such non-uniform warming exhibited on terrestrial vegetation growth.

Sensitivities of vegetation to asymmetric warming have been well documented in recent studies. For instance, Peng et al. (2013) reported that in the Northern Hemisphere (NH), Tmax positively correlates with boreal biomes in wet and cool boreal ecosystems but negatively correlates with dry temperate biomes, while Tmin is negatively correlated

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with boreal vegetation and behaves complexly over dry temperate regions. Tan et al. (2014) and Wu et al. (2016) found that seasonal divergences exist in the vegetation responses to Tmax and/or Tmin: Tmax significantly and positively associates with the growth of vegetation over vast boreal NH in spring, summer and autumn; on the contrary, Tmax is negatively related with the vegetation growth in temperate dry ecosystems, typically during summer; the positive effects of Tmin on vegetation growth are exhibited in spring and summer, particularly over most temperate regions, whereas there are pervasive distributions of negative correlations between Tmin and autumn normalized difference vegetation index (NDVI). Additionally, Shen et al. (2016) discovered that Tmin has stronger impacts on the vegetation green-up data and summer greenness of the vegetation over the Tibetan Plateau than Tmax does. These aforementioned studies recognized the significance of non-uniform responses of vegetation to asymmetric warming; however, they mainly focused on the instantaneous effects of asymmetric warming on vegetation growth. Through the regulation of plant phenology (Mulder et al., 2016; Richardson et al., 2010) and alteration of soil nutrient and moisture availabilities (Hill and Ghr, 2011; Iii, 1983; Sherry et al., 2008; Wan et al., 2005), the antecedent climate may also exert indirect effects on terrestrial ecosystems (Xia et al., 2014), known as time-lag effects. However, few studies have considered such time-lag effects in exploring the impacts of asymmetric warming on vegetation growth.

Recently, more and more studies have revealed that significant time-lag effects exist in the vegetation responses to antecedent temperature fluctuations. Braswell et al. (1997) revealed that the time lag of the vegetation responses to a warming temperature anomaly may reach up to 2 years. Potter et al. (1999) found a significant 1-year delay of annual net primary production (NPP) in response to temperature at middle to high latitudes. Wu et al. (2015) showed that plant growth over the mid-high latitudes is inclined to have simultaneous variations with temperature, whereas the vegetation at low latitudes may undergo one-month hysteresis impacts in responding to temperature. In addition, a large proportion of vegetation pixels over China exhibit a zero to one-month delay in response to temperature (Xu G. et al., 2014). These lines of evidence suggest that ecological plants may have strong interactions with previous temperature status. Therefore, it is necessary to consider the time-lag impacts when examining the associations between terrestrial vegetation and asymmetric warming.

The time-lag effects are defined here as the indirect impacts that antecedent asymmetric warming carries over a period time on present vegetation growth. The time-lag effect may come from the long-term tradeoff processes between plant growth and carbon (C) and/or nitrogen (N) availability (Vukićević et al., 2001; Zhang et al., 2016). The long-term turnover time of deep soil moisture to the surface is suggested to be another factor (Braswell et al., 1997; Zhang et al., 2016). The lagged mechanism possessed by plant biomes, which allow them to withstand soil moisture deficits over a period, is another possible reason (Vicente-Serrano et al., 2013). The photosynthesis and respiration acclimation mechanisms may also contribute to these time-lag impacts, as they enable the plant to adapt to elevated temperatures (Gunderson et al., 2000; Slot and Kitajima, 2015; Yamori et al., 2014). Finally, the time intervals of the plant assimilations being transported between leaves and rhizospheres may serve as inner mechanisms (Kuzyakov and Gavrichkova, 2010). Qualifying the hysteretic impacts of ambient temperature on vegetation variations and understanding the underling mechanisms can not only enrich our knowledge about the vegetation-climate interactions but also benefit the environmental management, because the policymakers can forewarn and take full measures to cope with the possible changes in the terrestrial ecosystem over a future period time. While there is still a blank in the spatial patterns for the time-lag effects of terrestrial vegetation responses to asymmetric warming at global scale, which greatly precludes a full understanding of the underling mechanisms behind time-lag effects and hinders policymakers from making the right strategies for environmental management. Therefore, it is urgent to ascertain the time-lag effects globally.

Most of the previous studies only included a point on a time scale, rather than a time range, when investigating the time-lag effects of ambient temperature on vegetation growth, which obscures the fact that the plants are likely to greatly respond to temperature on multiple scales. The calculation of the accumulated temperature (AT) may help to solve this problem. AT is the surplus or deficit of temperature with respect to a defined threshold and is given as an accumulation over a given period (i.e., month, season or year). Accumulations of the Tmax and Tmin can reflect the day- and/or night-time thermal condition available for green plants over the cumulative period that is required for green plants to complete growth transitions from one life stage to another, such as bud dormancy (Garcia-Mozo et al., 2000), leaf onset (Piao et al., 2015), flowering (Utsunomiya, 1992), maturity and yield (Macha et al., 2006). In addition, AT helps determine the plant stages and contributes to the spatial distribution patterns, dynamics and productivity of vegetation (Miller et al., 2001; Wang D. et al., 2014). Therefore, AT can be more sufficient for correlating to the vegetation growth, and it is necessary and important to consider the cumulative aspects of ambient temperature when seeking the interactive impacts between asymmetric warming and vegetation growth.

Although the mechanisms of how asymmetric warming affect vegetation have been well documented, little is known about the hysteretic impacts of asymmetric warming on vegetation. The terrestrial NPP estimated by remote sensing models has been widely applied to examine the interactions between vegetation growth and temperature (Anderegg et al., 2015; Nemani et al., 2003; Potter et al., 2012; Tan et al., 2014; Xia et al., 2014). In this paper, we used NPP as an indicator of vegetation activity, and the accumulated day- and night-time temperatures (ATmax and ATmin) as the representatives of the asymmetric day- and night-time warming. We attempted to validate how terrestrial vegetation responds to antecedent asymmetric warming. The time-lag effects include two crucial aspects – the time lags that antecedent warming has on vegetation growth and the correlations between them. In detail, we aimed to study:

1) The time lags of terrestrial vegetation in responding to asymmetric warming;
2) The correlations between vegetation growth and asymmetric warming at a specific lagged time.

We first obtained the global terrestrial NPP from 1982 to 2013 by applying the Carnegie-Ames-Stanford Approach (CASA) model, which was derived by a remotely sensed dataset-NDVI and meteorological datasets-monthly average temperature (TEM), monthly total precipitation (PRCP) and monthly incoming short wave solar radiation datasets (SOLAR). In addition, a calibration was made to CASA by modifying one key parameter, the maximum light use efficiency (ε_{max}), through the algorithm of modified least squares (MLS) (Zhu et al., 2006). Then, the linear partial correlation coefficients between NPP and ATmax/ATmin at a specific time lag (0–24 months) were calculated by employing partial correlation coefficient analyses. This was followed by quantifying the spatial patterns of the best time lags (BTL) that ATmax/ATmin had on NPP and the optimal partial correlation coefficients (R_{final}) between NPP and ATmax/ATmin through time-lag analyses. Finally, the BTL and R_{final} were further investigated in different climatic regions.

2. Materials and methods

2.1. Global datasets

2.1.1. Satellite-derived NDVI

NDVI is widely used to simulate terrestrial NPP (Nemani et al., 2003; Potter et al., 2012; Tucker and Sellers, 1986). The NDVI dataset