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Continuous advance in the onset of vegetation green-up in the Northern Hemisphere, during hiatuses in spring warming

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Previous studies have documented substantial advancing trends in the onset date of vegetation green-up (VGD) during the 1980s and 1990s over the Northern Hemisphere, while later studies based on data from the spaceborne advanced very high-resolution radiometer (AVHRR) have reported this trend stalled during the warming hiatus from the late 1990s to early 2010s. However, there is uncertainty in this finding of a hiatus in VGD advance due to the identification of quality issues associated with the data from AVHRR. Using the high-quality data from the Moderate Resolution Imaging Spectroradiometer, we show VGD significantly advanced despite the warming hiatus due to the high sensitivity of VGD to temperature and the magnitude of VGD advance over 2000–2021 (2.5–2.6 days decade⁻¹, $P < 0.01$) is close to that over 1982–1999 or 1982–2002 with intensive warming, which suggests caution be exercised in the inference of climate warming based on advances in spring phenology.

npj Climate and Atmospheric Science (2023)6:7; <https://doi.org/10.1038/s41612-023-00343-0>

The onset date of vegetation green-up (VGD) is widely used as an indicator of ecosystem response to climate change, due to its sensitivity to warming and its role in a variety of ecosystem and climate system processes^{1–3}. While analyses of in situ and satellite observation data show substantial and widespread advances in VGD associated with global warming during the 1980s and 1990s^{4,5}, recent satellite-based studies have reported a stall in these advances from the late 1990s to the early 2010s^{6,7}, due to a warming hiatus^{8,9}. However, this reported halt in VGD advance could be open to question, given that the analyses were based on the normalized difference vegetation index (NDVI) data derived from the advanced very high-resolution radiometer (AVHRR) sensor (AVHRR NDVI_{3g,v1})¹⁰ that has quality issues¹¹ and has produced estimates of interannual changes in VGD since the early 2000s that differ substantially from those derived from other high-quality satellite products, such as NDVI data derived from moderate resolution imaging spectroradiometer (MODIS) and SPOT VEGETATION^{12,13}.

Furthermore, questions may be asked concerning the attribution of this reported stall in VGD advance to a warming hiatus, given that the hiatus was based on the annual mean air temperature^{8,9}, whereas the interannual changes in VGD were driven by the temperature of a given period (mostly from two weeks to two months) preceding the VGD (pre-VGD temperature)¹⁴ and that warming hiatus of annual mean temperature may not necessarily reflect a stall in warming of pre-VGD temperature. In addition, the warming hiatus might have ended as a result of accelerated warming since 2015¹⁵. However, it is not known whether there was an accelerated increase in pre-VGD temperature. If the temporal changes of pre-VGD temperature were similar to those of mean annual temperatures, there might be a turning point in the trend of pre-VGD temperature.

In this study, we used the high-quality MODIS NDVI dataset and climate data from the European Centre for Medium-Range Weather Forecasts Reanalysis v5-Land (ERA5-Land) dataset to test for hiatuses in warming of pre-VGD temperature and VGD

advance at mid- and upper-latitudes (30–75°N) of the northern hemisphere (NH), between the late 1990s and early 2010s. Here, we used both the threshold- and inflection point-based methods^{13,16} to determine VGD from annual NDVI trajectories (see Supplementary Methods for details). Then, we tested for turning points in the temporal trends in pre-VGD temperature and VGD to confirm acceleration in warming of the pre-VGD temperature following warming hiatus periods and identified associated VGD responses.

Of the 12 different periods between the late 1990s and early 2010s, during which previous studies identified a hiatus in warming of annual mean temperature^{8,9,15}, we found evidence for increases in pre-VGD temperature averaged over the NH (for details, see Supplementary Methods) over the single period of 2001–2014 (1.0°C decade⁻¹, $P < 0.05$), while in eight of the remaining 11 periods with hiatuses in warming of pre-VGD temperature, there were advances in VGD (2.2–4.0 days decade⁻¹; $P < 0.05$) determined by the threshold-based method (Fig. 1a). The VGD determined by the inflection point-based showed similar changes (Supplementary Fig. 1a). In the following results, we report changes in VGD and associated pre-VGD temperature for the threshold-based method unless specifically stated.

Analysis of the corrected Akaike information criterion (AIC_C) to test for turning points in pre-VGD temperature over the NH between 2000 and 2021 showed better estimation using a linear regression model than a piecewise model (see Supplementary Methods). Similarly, a *t*-test indicated that the turning point of the pre-VGD temperature trend estimated by piecewise regression was not significant ($P = 0.25$). Hence, there was no turning point in the pre-VGD temperature averaged over the NH during 2000–2021. Likewise, we found no evidence for turning points in the average pre-VGD temperature over Eurasia (AIC_C; *t*-test $P = 0.39$) or North America (AIC_C; *t*-test $P = 0.54$) (Supplementary Table 1). Consistently, we identified turning points in pre-VGD temperature for 3.7% (AIC_C; Fig. 2a) and 7.3% (*t*-test $P < 0.05$; Supplementary Fig. 2a) of the NH area. Similarly, we found no

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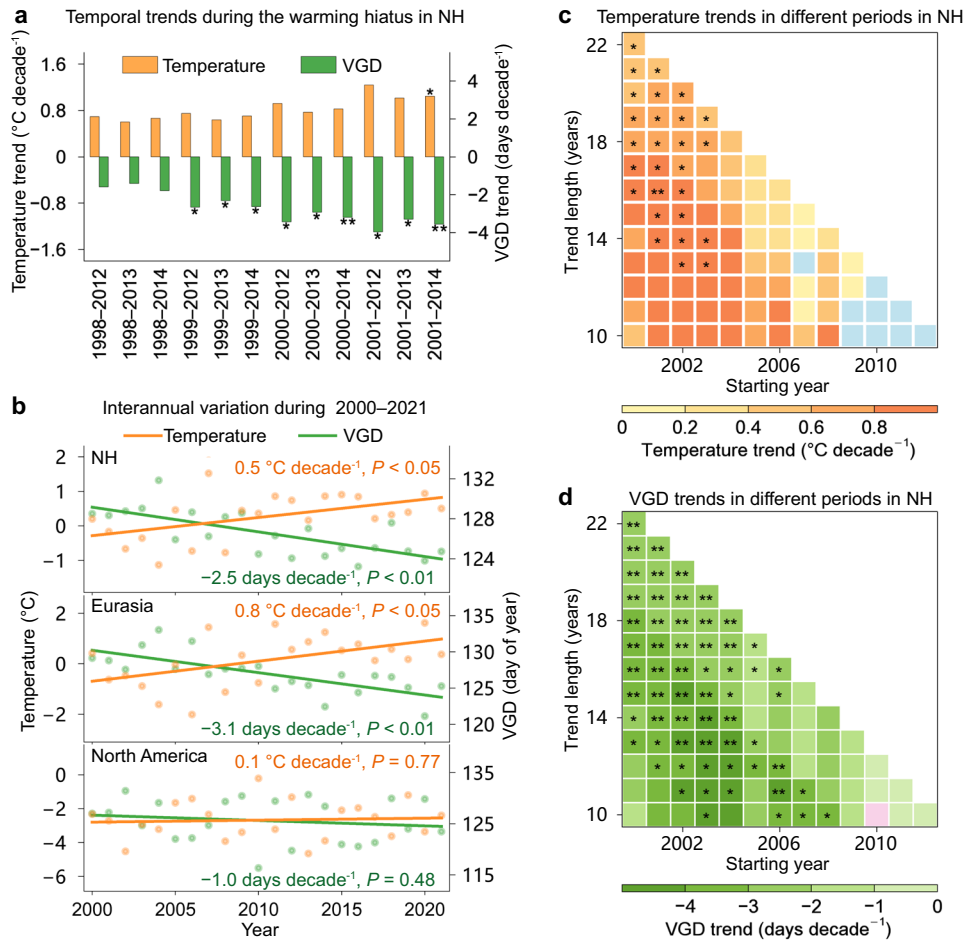


Fig. 1 Temporal trend in onset date of vegetation green-up (VGD) and mean temperature in the period preceding VGD (pre-VGD temperature) at hemisphere and continental scales. Temporal trends in pre-VGD temperature and VGD averaged over the mid- and upper-latitudes (30–75°N) of the Northern Hemisphere (NH) during the warming hiatuses reported in previous studies (**a**), over the NH, Eurasia, and North America, respectively, during 2000–2021 (**b**), and over the NH during the periods of different lengths starting between 2000 and 2012 (**c**, **d**). Positive and negative trends in VGD indicate delay and advance, respectively. * $P < 0.05$ and ** $P < 0.01$. VGD is determined by the threshold-based method (see Supplementary Methods) as the first date when NDVI increases by 20% of the annual amplitude in the ascending period of the annual NDVI trajectory. VGD was derived from MODIS NDVI since 2000 and from AVHRR NDVI3g.v1 in 1998 and 1999 (see Supplementary Methods).

evidence for turning points of average VGD over the NH (AIC_C; t -test $P = 0.26$), Eurasia (AIC_C; t -test $P = 0.48$), or North America (AIC_C; t -test $P = 0.40$) (Supplementary Table 1) and identified turning points in VGD for 6.7% (AIC_C; Fig. 2b) and 11.0% (t -test $P < 0.05$; Supplementary Fig. 2b) of the NH area. The VGD determined by the inflection point-based method also produced results supporting the lack of turning point in the trends of pre-VGD temperature and VGD (Supplementary Table 1 and Supplementary Fig. 3a–d).

Over the period 2000–2021, average VGD across the NH advanced by 2.5 days decade⁻¹ ($P < 0.01$) and there was an increase of 0.5 °C decade⁻¹ in pre-VGD temperature ($P < 0.05$; Fig. 1b), despite a lack of significant trends in pre-VGD temperature and VGD since 2009 (Fig. 1c, d). The main contribution to the pre-VGD warming and VGD advance across the NH over this period was from Eurasia, where average pre-VGD temperature increased by 0.8 °C decade⁻¹ ($P < 0.05$) and VGD advanced by 3.1 days decade⁻¹ ($P < 0.01$; Fig. 1b). In contrast, there were no changes in average pre-VGD temperature or VGD in North America during the period 2000–2021 ($P > 0.05$; Fig. 1b). The VGD determined by the inflection point-based method showed similar temporal changes (Supplementary Fig. 1b–d).

These results indicate that changes in the pre-VGD temperature and VGD were continuous from 2000 to 2021, with warming pre-VGD temperature and advancing VGD recorded in most areas of the NH (Fig. 2c, d), where the temperature increased and VGD advanced in Eastern America, Alaska, western Canada and most areas of Eurasia, whereas the temperature cooled and VGD delayed in limited areas of Eastern Canada and Northern Europe. There were a similar spatial pattern of trends in pre-VGD temperature and VGD based on the inflection-based method (Supplementary Fig. 3e–f).

Consistent with previous reports of the stalling of advances in VGD and identification of hiatuses in warming across the NH between the late 1990s and early 2010s^{6,7} based on the AVHRR NDVI_{3g.v1} dataset, our analyses of this dataset showed similar results (Supplementary Fig. 4). However, our analyses of different sources of satellite data revealed evidence for continued advances in VGD throughout these periods (Fig. 1a and Supplementary Fig. 1a). Whereas the previous studies were based on analysis AVHRR NDVI_{3g.v1} data, for which quality issues have been identified for data collected post-2000¹¹, our analyses were based on high-quality MODIS NDVI data¹⁷ collected using a sensor that lacks the problems associated with the AVHRR sensor

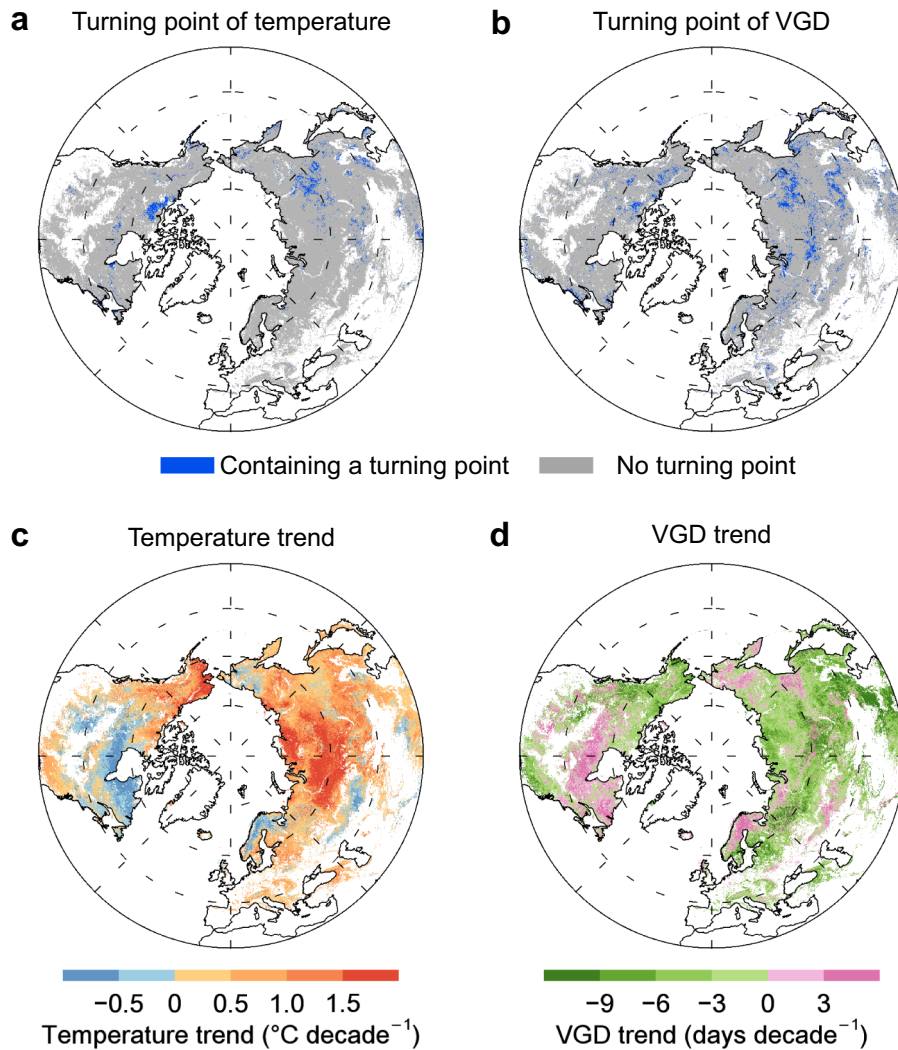


Fig. 2 Temporal trends in mean temperature in the period preceding VGD (pre-VGD temperature) and onset date of vegetation green-up (VGD). Blue pixels indicate turning points determined by the corrected Akaike information criterion (see Supplementary Methods) in **a** pre-VGD temperature and **b** VGD trends during 2000–2021. **c**, **d** Linear regression modeling of trends in pre-VGD temperature and VGD over the period 2000–2021. VGD is determined by the threshold-based method as the first date when NDVI increases by 20% of the annual amplitude in the ascending period of the annual NDVI trajectory.

(Supplementary Methods), leading to greater confidence. Moreover, our results showed that the continuous increases in pre-VGD temperature across the NH during the entire period 2000–2021 were associated with an increase in pre-VGD temperature since the early 2000s and small temperature trends during the 2010s (Fig. 1b, c and Supplementary Fig 1b, c), rather than accelerated warming following a warming hiatus between the late 1990s and early 2010s^{8,9}. In response to the pre-VGD temperature, we found a continuing advance in VGD, including most periods starting from the end of the 1990s, despite a lack of substantial warming of pre-VGD temperature in the corresponding period (Fig. 1 and Supplementary Fig. 1). The advancing rate of VGD (2.5–2.6 days decade⁻¹, Fig. 1b and Supplementary Fig. 1b) averaged over the NH during 2000–2021 is close to 1.9–2.8 days decade⁻¹ over 1982–1999 or 1982–2002 when there was intensive warming^{18,19}.

The phenology of vegetation in spring is particularly sensitive to changes in temperature, so small temperature increases may lead to substantial advances in VGD;²⁰ similarly, increases in precipitation that have been reported to advance spring phenology in some dry grasslands²¹ may explain the advances in VGD shown here. Research in some cold areas has shown that warming

outside the growing season may facilitate earlier fulfillment of chilling requirements, leading to earlier VGDs;²² indeed, our findings indicate that advances in spring phenology may not necessarily indicate overall climate warming, so we suggest caution be exercised in the inference of climate warming based on advances in spring phenology.

Nevertheless, our results show that spring temperature has continuously increased across the NH over the period 2000–2021, resulting in a continuous advancement of spring phenology that might have contributed to subsequent increases in spring gross primary production²³ and accelerated net carbon uptake²⁴ during the warming hiatus. It is likely that earlier spring green-up may increase the likelihood of summer drought effects, due to enhanced transpiration rates², that then reduce vegetation productivity²⁵. Our finding of advances in spring phenology during the warming hiatus also supports an increased risk of spring frost damage during ongoing global warming²⁶. Our results thus deepen understanding of spring phenology responses to recent climate change, especially during the warming hiatus that occurred between the late 1990s and early 2010s, with substantial implications for impacts on carbon-climate feedback.

SUMMARY OF MATERIALS AND METHODS

We determined VGD from the NDVI time series for the study period, extracted from the MOD13C1 Version 6 product, after the elimination of data recorded under the presence of snow, ice, clouds, and aerosols. The pre-VGD period with the strongest potential influence on VGD was defined as the period preceding the multi-year mean VGD, for which the absolute value of the partial correlation coefficient of mean temperature with VGD was maximized, while controlling for the effect of precipitation and radiation. Daily climatic data were obtained from the ERA5-Land dataset. Temporal changes in pre-VGD temperature and VGD were assessed using linear regression modeling. To test for turning points in the temporal trends of pre-VGD temperature and VGD, we compared linear and piecewise regression model predictions of pre-VGD temperature (or VGD), using the corrected Akaike information criterion and *t*-test, respectively. For further information see the Supplementary Methods.

DATA AVAILABILITY

All data used for this study are publicly available online.

CODE AVAILABILITY

The codes that support the findings of this study are available on request from the corresponding author.

Received: 30 September 2022; Accepted: 8 February 2023;

Published online: 17 February 2023

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ACKNOWLEDGEMENTS

This work was funded by the Fundamental Research Funds for the Central Universities.

AUTHOR CONTRIBUTIONS

M.S. designed research; N.J. and M.S. performed research; N.J. analyzed data; all the authors interpreted the results and wrote the paper.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41612-023-00343-0>.

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