2023-03

Impacts of shifting phenology on boundary layer dynamics in North America in the CESM

Version	Published version
Citation (published version):	X. Li, T. Ault, A.D. Richardson, C.M. Carrillo, D.M. Lawrence, D. Lombardozzi, S. Frolking, D.A. Herrera, M. Moon. 2023. "Impacts of shifting phenology on boundary layer dynamics in North America in the CESM" Agricultural and Forest Meteorology, Volume 330, pp.109286-109286. https://doi.org/10.1016/j.agrformet.2022.109286

Agricultural and Forest Meteorology 330 (2023) 109286

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Impacts of shifting phenology on boundary layer dynamics in North America in the CESM

Xiaolu Li [a,*], Toby Ault [a], Andrew D. Richardson [b,c], Carlos M. Carrillo [a], David M. Lawrence [d], Danica Lombardozzi [d], Steve Frolking [e], Dimitris A. Herrera [f], Minkyu Moon [g]

[a] Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY 14850, United States
[b] School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, AZ 86011, United States
[c] Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, AZ 86011, United States
[d] National Center for Atmospheric Research, Boulder, CO 80302, United States
[e] Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824 United States
[f] Department of Geography & Sustainability, The University of Tennessee-Knoxville, Knoxville, TN 37996-0925, United States
[g] Department of Earth and Environment, Boston University, Boston, MA 02215, United States

ARTICLE INFO

Keywords:
Plant phenology
Land-atmosphere interaction
Land-atmosphere coupling
Community Earth System Model
Boundary layer

ABSTRACT

Plant phenology modulates water and energy exchanges between the biosphere and the atmosphere and therefore influences planetary boundary layer (PBL) dynamics. Here we conduct a modeling experiment using the Community Earth System Model version 2, where plant phenology is prescribed based on satellite climatology in the control experiment. We then shift the timing of vegetation green-up and senescence in North America by one month earlier and later and investigate how shifting phenology could influence land-atmosphere interactions. Altering plant phenology modifies boundary layer fluxes through both direct influences on evapotranspiration and absorbed solar radiation and indirect effects through changes in low cloud fraction. The prescribed shift in phenology has significant but different influences on PBL dynamics and land-atmosphere coupling in the spring and fall in the Great Plains and Eastern United States. In the spring, earlier plant phenology significantly decreases PBL height in the Great Plains by more than 100 m. In the autumn, the Great Plains experience a significant increase in PBL height of over 100 m in the early fall while Eastern US exhibits a significant increase in the late fall when prescribed senescence is shifted earlier. As shifts in plant phenology alone can cause significant changes in PBL conditions at the seasonal timescale in the Great Plains and Eastern US, our experiments can help infer the potential location and magnitude of phenology-induced changes and provide useful information for observation-based analysis and model evaluation.

1. Introduction

Simulating the climate system with Earth system models is an essential way to predict climate conditions in the future (IPCC, 2021). Simulating land-atmosphere interactions and coupling is critical to understanding and improving predictions of the Earth's climate and yet challenging due to the non-linear processes and complex feedback (Santanello et al., 2013). Therefore, the influence of soil moisture on land surface fluxes and precipitation has been investigated through a range of studies from local (e.g., Santanello et al., 2011; Dirmeyer et al., 2018) to global (e.g., Koster et al., 2004; Taylor et al., 2012) scales. Accurate representation of terrestrial plant phenology is also important for the accuracy of climate model simulations across models and spatial scales (e.g., Bounoua et al., 2000; Guillevic et al., 2002; Lawrence and Slingo, 2004; Rechid and Jacob, 2006; Barbu et al., 2011; McCarthy et al., 2012; Lorenz et al., 2013; Koster and Walker, 2015; Fox et al., 2018). Specifically, because plant phenophase changes modulate land-atmosphere coupling (e.g., Schwartz, 1992; Richardson et al., 2013), shifting phenology also changes land surface states and fluxes (e.g., Fitzjarrald et al., 2001; Guillevic et al., 2002; Levis and Bonan, 2004; Lorenz et al., 2013; Puma et al., 2013; Xu et al., 2020) and may therefore alter planetary boundary layer (PBL) dynamics.

Large disagreement exists between modeled and observed spring onset as well as growing season length (e.g., Richardson et al., 2012;

* Corresponding author.
E-mail address: xl552@cornell.edu (X. Li).

https://doi.org/10.1016/j.agrformet.2022.109286
Received 23 May 2022; Received in revised form 20 October 2022; Accepted 12 December 2022
Available online 31 December 2022

Mahowald et al., 2016; Scholze et al., 2017; Peano et al., 2021; Li et al., 2022). Peano et al. (2021) found a 0.6-month average delay globally in the timing of spring onset between land surface model simulations and remote sensing estimates. A range of model development efforts has been made to better represent plant phenology in land surface models, with a focus on drought/stress deciduous phenology (e.g., Dahlin et al., 2015; Kim et al., 2015; Birch et al., 2021) and data assimilation approaches (e.g., Sabater et al., 2008; Barbu et al., 2011; Albergel et al., 2017; Scholze et al., 2017; Fox et al., 2018). However, it is unclear how the delayed phenology in the current generation of models would influence the simulated land-atmosphere interactions, or how big the associated biases in land surface fluxes and PBL height might be.

Spring onset has been occurring earlier over the past few decades as seen in ground observations (e.g., Schwartz and Reiter, 2000; Parmesan and Yohe, 2003; Cook et al., 2012), indicator models (e.g., Jolly et al., 2005; Schwartz et al., 2006, 2013; Ault et al., 2015), and satellite imagery (e.g., White et al., 2009; Karkauskaite et al., 2017). A series of studies using the spring indices models find a 1.5 days per decade trend of earlier spring onset over the past few decades in the Northern Hemisphere and interannual variability as large as 60 days in spring onset timing (Schwartz et al., 2006, 2013; Ault et al., 2015). Although they disagree on the magnitude of the earlier trend, studies based on different species and scales agree that plant phenology is responding to the recent warming and other stresses (Parmesan and Yohe, 2003; Root et al., 2003). Autumn phenology is also changing due to variations in both spring phenology and environmental factors (Keenan and Richardson, 2015; Liu et al., 2016; Fu et al., 2018; Piao et al., 2019). As variations in the timing of plant phenophase would influence both land-atmosphere coupling and the carbon cycle (e.g., Schwartz, 1992; Richardson et al., 2013; Scholze et al., 2017), it is also critical to investigate how the advancing trends in plant phenology influence the other components of the Earth's system.

While plant phenology significantly influences land-atmosphere coupling, the explicit role of the timing of plant phenophase change has received relatively little attention. Because phenology is closely linked to its environment, it is hard to separate its influences from the environmental factors driving the changes in observational records (Findell et al., 2015; Green et al., 2017). Therefore, studies have used climate or weather models to conduct controlled experiments to explore phenology impacts on land surface states and land-atmosphere interactions (e.g., Guillevic et al., 2002; Levis and Bonan, 2004; Lorenz et al., 2013; Bali and Collins, 2015; Xu et al., 2020). These experiments mostly focus on the influence of the variations of or disagreement in the leaf area index (LAI) values (e.g., Bounoua et al., 2000; Lorenz et al., 2013; Puma et al., 2013) or the changes in both spring onset timing and growing season length (e.g., Xu et al., 2020). However, as large disagreements are present between modeled and observed phenology and plant phenology exhibits earlier trends across different measurements, it is critical to examine how the timing of plant phenophase change alone impacts land-atmosphere coupling.

Therefore, in this project, we conduct experiments using the Community Earth System Model (CESM) to explore how shifting plant phenology would influence land surface and atmospheric states, biosphere-to-atmosphere fluxes, and land-atmosphere coupling more generally. Shifting phenology would influence the timing of modeled plant activity such as photosynthesis and evapotranspiration, and therefore further influence surface albedo, latent and sensible heat fluxes to the atmosphere, and potentially humidity and cloud fraction in the lower atmosphere. Particularly, we focus on: (1) How would shifting phenology influence PBL dynamics in the CESM? (2) How do these influences vary seasonally?

2. Material and methods

2.1. Experimental design

We use a coupled land-atmosphere component configuration (the 'F2000Climo' component set) of the Community Earth System Model version 2 (CESM2). In this configuration, CESM2 is forced with climatological ocean conditions and non-evolving glaciers. We use the 1995–2005 climatological sea surface temperature and sea ice boundary dataset (Hurrell et al., 2008) to be consistent with the year 2000 initial conditions. The atmospheric component of CESM2, the Community Atmosphere Model version 6 (CAM6; Neale et al., 2010) has 32 vertical layers and is set to a 1° horizontal resolution with the finite-volume dynamical core. The land component of CESM2, the Community Terrestrial Systems Model version 5.0 (CTSM5.0; Lawrence et al., 2019) uses a satellite phenology (SP) mode to specify leaf area index (LAI), stem area index (SAI), and vegetation height and modulates plant phenology in the control experiment. LAI and SAI are calculated based on MODIS MCD15A2 version 5 8-day LAI composites from 2003 to 2015 (Lawrence and Chase, 2007) and the canopy height of tree plant functional types (PFTs) is derived from the ICESat canopy height mapping (Simard et al., 2011). The monthly averaged phenology data is then interpolated into daily when the model runs. To test changing phenology, we then shift plant phenology for the full growing season (e.g., both onset and offset) in North America (Fig. 1a) one month earlier or one month later for the shifted phenology experiments (see Fig. 1b for a demonstration of LAI shifts and Fig. S1 for PFT area weights).

We first run 40-year global simulations of control and shifted phenology experiments for early and late North American phenology. Because phenology-induced changes at the interannual timescale are not statistically significant in the original 40-year simulations, we run additional independent simulations of 70 years with slightly different initial conditions to eliminate the possibility that this non-significance is due to insufficient simulation length. We discard the first 10 years of each simulation for spin-up and adopt and combine the later 90 years for comparison.

2.2. Methods

We analyze changes in planetary boundary layer (PBL) dynamics including PBL height and energy and water fluxes between the shifted phenology and control simulations. We also compare the surface energy balance from the three runs. Because these are satellite phenology runs, biogeochemical cycles in CTSM are not enabled, so we cannot evaluate the influences on vegetation growth or the carbon cycle. We use the two-sample *t*-test to compare the difference between the experiments. We also adopt a 5% significance level and adjust for false discovery by recalculating the significance level to control the expectation of falsely rejected hypotheses (Benjamini and Hochberg, 1995).

2.3. Energy versus moisture control on land-atmosphere coupling

We also adopt the critical soil moisture (Denissen et al., 2020; 2022) framework to test the limiting factor of land-atmosphere coupling in the simulations. We calculate Kendall's rank correlations between monthly total evapotranspiration (ET, canopy evaporation + canopy transpiration + ground evaporation, equals latent heat flux in CTSM) and surface temperature/soil moisture for each month with a mean temperature over 283 K. We use soil moisture in the top 10 cm of soil, as it measures the soil moisture available to plants, and remove the seasonal cycle in each variable by subtracting the monthly mean over all simulation years. We then calculate the difference between temperature and soil moisture correlations with ET [i.e. corr(ET,T) - corr(ET,SM)] and use the correlation difference to determine when land surface changes from energy-limited to soil moisture-limited states.

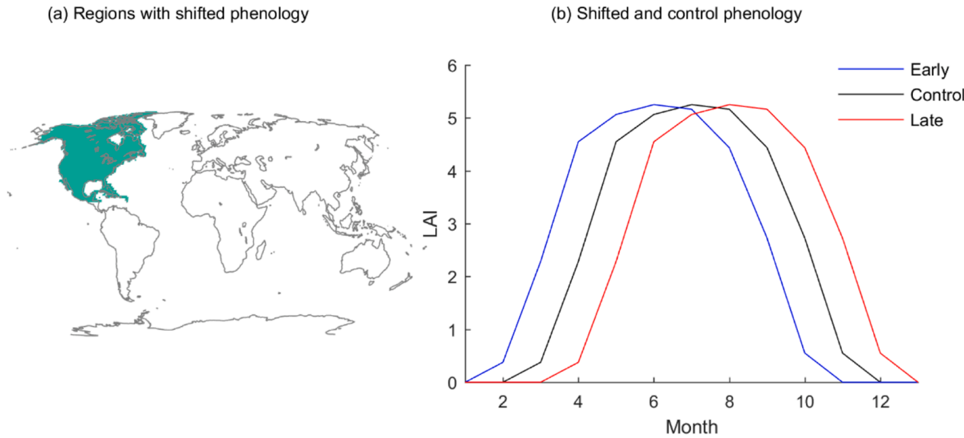

Fig. 1. (a) Regions where plant phenology is shifted in the experiments (North America) and (b) demonstration of leaf area index (LAI) shifts of one plant functional type (PFT) at an illustrative grid point. LAI, stem area index (SAI), and vegetation height of each PFT are shifted at each grid cell.

3. Results

Shifting plant phenology influences both absorbed solar radiation and evapotranspiration and therefore has the potential to modify PBL states and fluxes. As our focus is on how phenology influences land-atmosphere coupling in the PBL, here we first analyze phenology-induced changes in PBL states and fluxes such as land surface temperature, latent and sensible heat fluxes, and radiation. We then characterize the impacts of varying phenology on PBL height. We also show the limiting factors of evapotranspiration, when the land changes from energy-limited to moisture-limited states, and how shifting phenology modifies that transition. We then demonstrate changes in surface energy balances in the Great Plains and Eastern United States where the most significant changes are present.

3.1. Changes in PBL conditions and dynamics

Land surface states and fluxes within the boundary layer exhibit significant changes at the seasonal scale in response to the shifted phenology. Latent heat fluxes (LE) increase in the spring and decrease in the fall when the growing season is shifted earlier (Fig. S2ef). Over North America, LE is on average 1.3 W/m^2 higher in the spring and 1.8 W/m^2 lower in the fall in the early phenology vs. control simulations while 1.8 W/m^2 higher in the spring and 1.5 W/m^2 lower in the fall in the control vs. late phenology experiments (Fig. S2f). The largest changes in LE are present over the Great Plains and Eastern US, with significant increases of more than 20 W/m^2 in the Great Plains and Pacific coast in the spring and around 20 W/m^2 decreases in the fall in the Great Plains and Eastern US in the earlier phenology experiments (different from zero at $p < 0.05$; Fig. S3). Sensible heat fluxes (H) show opposite and smaller changes than LE. The difference between the early phenology and control runs over North America is -0.8 W/m^2 in the spring and 1.3 W/m^2 in the fall and a difference of -1.4 W/m^2 in the spring and 1 W/m^2 in the fall is present between the control and late phenology simulations (Fig. S2h). Spatially, H can be more than 15 W/m^2 lower in earlier phenology runs over the Great Plains and part of Eastern US in the spring and more than 10 W/m^2 higher in the fall (Fig. S4). Notably, H can be on average 2 W/m^2 significantly higher around the Hudson Bay regions in both spring and fall in the early phenology simulation than in both the control and late phenology runs (Fig. S4). At annual to interannual scales, LE and H mostly show small and non-significant changes except for a few regions in the Northern Great Plains or around the Hudson Bay (Fig. S5a-f).

Along with changes in latent heat fluxes and evapotranspiration from the land surface, there are also significant changes in low cloud fraction and convective precipitation rate at the seasonal timescale (Figs. 2 and S6). Significantly higher vertically-integrated low cloud fraction is present over the Great Plains in the early spring and in Eastern US in the late spring in earlier phenology simulations while both regions show significantly lower low cloud fraction in the fall in earlier phenology runs (Fig. 2). On average, the low cloud fraction is 1.4% higher in the spring and 1.9% lower in the fall over North America in the early vs. control and control vs. late phenology comparisons (Fig. S2ij). Convective precipitation rate also increases significantly in the spring and decrease in the fall over the Great Plains in earlier phenology runs (Fig. S6). At the interannual timescales, changes in vertically-integrated low cloud fraction are small and non-significant except for a significant but small increase in the early vs. late phenology experiments around the Hudson Bay (Fig. S7a-c). Convective precipitation rate only exhibits small and mostly non-significant changes at the interannual timescale (Fig. S7d-f). Meanwhile, only small and mostly non-significant changes are present in vertically-integrated mid and high cloud fractions as well as large-scale precipitation rate, which suggests that synoptic weather patterns dominate these variables.

Changes in other components of the energy balance are consistent with the changes in land surface states and fluxes. Net solar flux decreases significantly in the spring in earlier phenology runs over the Great Plains and increases significantly in the fall in Eastern US partially due to the changes in shortwave cloud forcing, though early melting of snowpack in regions around the Hudson Bay causes net solar flux at the surface to increase in the earlier phenology experiments in both spring and fall (Fig. S8). The same pattern is observed at the top of the atmosphere (Fig. S9). Except for the Hudson Bay regions, only small and non-significant differences are present at the interannual timescales (Fig. S5g-l). In regions around the Hudson Bay, water equivalent snow depth also decreases significantly in the earlier phenology runs in the spring due to early melting (Fig. S10).

Changes in surface temperature are also significant at the seasonal scale due to the combined influences of land surface states and fluxes within the boundary layer in response to the shifted phenology. In the spring, the surface temperature is significantly lower in the Great Plains and part of Eastern US when plant phenology is earlier (Fig. 3). Compared to the late phenology simulations, the spring surface temperature is 2 K lower in the control run and more than 3 K lower in the early phenology run over the Great Plains (different from zero at $p < 0.05$; Fig. 3). However, positive changes in temperature are also associated with earlier phenology in regions around the Hudson Bay. In the fall, a warmer surface temperature is present across North America with earlier phenology simulations, with 2 K warming in the Great Plains in the early fall and 1.5 K warming in Eastern US in the late fall for the early-control comparison. Compared to the control simulation, the early phenology experiment is 0.18 K cooler in the spring and 0.23 K warmer in the fall while the late phenology run is 0.19 K warmer in the spring

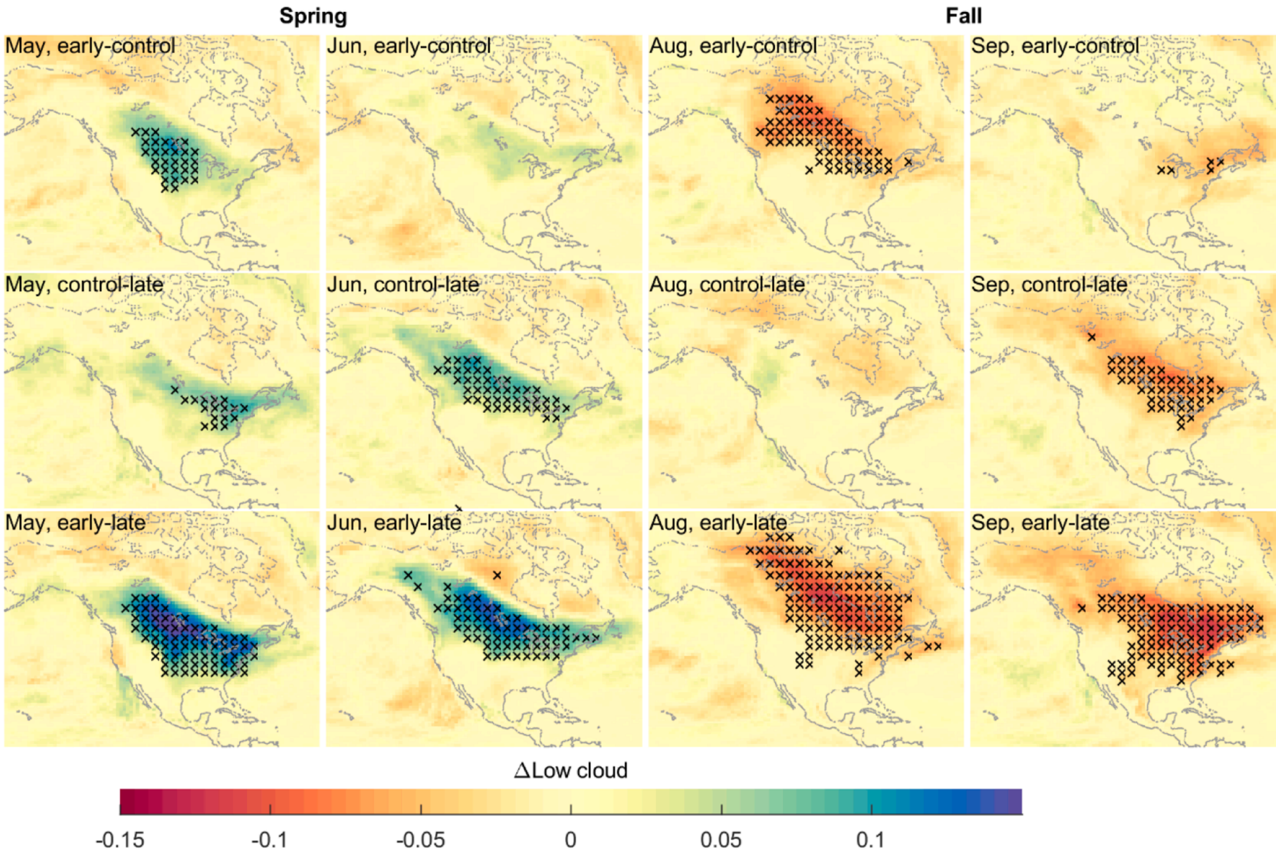

Fig. 2. Monthly differences in vertically-integrated low cloud fraction (Low cloud) between the three simulations. Grid points with a significant difference after false positive adjustment are marked with black crosses. First row: maps showing low cloud fraction differences between the early phenology run and the control experiment in May, June, August, and September in North America. Second row: maps showing low cloud fraction differences between the control run and the late phenology experiment in May, June, August, and September. Third row: maps showing low cloud fraction differences between the early phenology run and the late phenology experiment in May, June, August, and September.

and 0.14 K cooler in the fall in North America (Fig. S2d). Note because plant phenology is prescribed in the experiments, these changes in surface temperature do not trigger further changes in phenology that might be expected as a result of temperature changes. Interannual changes between simulations are small and non-significant, except for some of the permafrost region northwest of the Hudson Bay in the early vs. late phenology comparison (Fig. S7g-i). Seasonal changes at the surface also influence temperature in the upper layers of the atmosphere, though significant changes are only present below 700hPa (see Fig. S11 for 850hPa). Seasonal amplitude of temperature variation decreases as the height increases (Fig. S12) and the spatial pattern is consistent with surface temperature below 700hPa. At or above 700hPa, mostly small and non-significant changes are present between simulations, and the spatial patterns differ from surface temperature as they experience more impacts from large-scale circulations.

Changes in plant phenology also modify relative humidity (RH) variability in and near the surface layer. Relative humidity exhibits decreasing seasonal amplitude as the height increases (Fig. S13). Over North America, at the surface level, RH is close to 90% in the winter and gradually decreases to around 75% in the summer as the temperature rises and the growing season starts (Fig. S13i). When phenology is shifted earlier, RH is 0.6% and 0.8% higher in the early-control and control-late phenology runs in the spring, respectively, and 1.3% and 1% lower in the fall. These change to 0.7% and 0.9% at 850hPa in the spring and −1.2% and −1% in the fall and 0.12% and 0.03% at 700hPa in the spring and −0.14% and −0.32% in the fall (Fig. S13fhj). The spatial pattern of RH differences is similar to those of latent heat fluxes. In the earlier phenology simulations, the Great Plains and Eastern US exhibit a significant increase in surface RH in the spring and a significant decrease in surface RH in the fall (Fig. S14). At or above 700hPa, mostly small and non-significant changes are present, even in the transition seasons (Fig. S15). Therefore, in addition to small interannual changes, little changes in RH are present at or above 700hPa.

3.2. PBL heights

In North America where we directly shift plant phenology, planetary boundary layer heights change significantly at seasonal scales, but exhibit small and mostly non-significant changes annually (Figs. 4, S2ab, and S7j-l). In the spring, earlier leaf-out causes PBL height in the Great Plains to drop more than 100 m (different from zero at $p < 0.05$; Fig. 4). Fall PBL height significantly increases by more than 100 m when senescence is earlier in the Great Plains in the early fall and in Eastern US in the late fall (different from zero at $p < 0.05$). Summer and winter exhibit smaller changes except for an increase in PBL height in earlier phenology runs during the summer in the permafrost region around the Hudson Bay, especially in the early versus late phenology comparison. Over North America, PBL height is on average 6.6 m lower in earlier phenology simulations (i.e., early vs. control, control vs. late, and early vs. late) in the spring and early summer and 5.3 m higher in the fall (Fig. S2b). Notably, changes in PBL height have larger variations in the spring but last longer in the fall. Significant changes in PBL heights are only present in North America where we have shifted phenology. At the interannual timescale, the changes in spring and fall cancel out and PBL heights show no large or significant changes in and outside North America, except for regions northwest of the Hudson Bay (Fig. S7j-l).

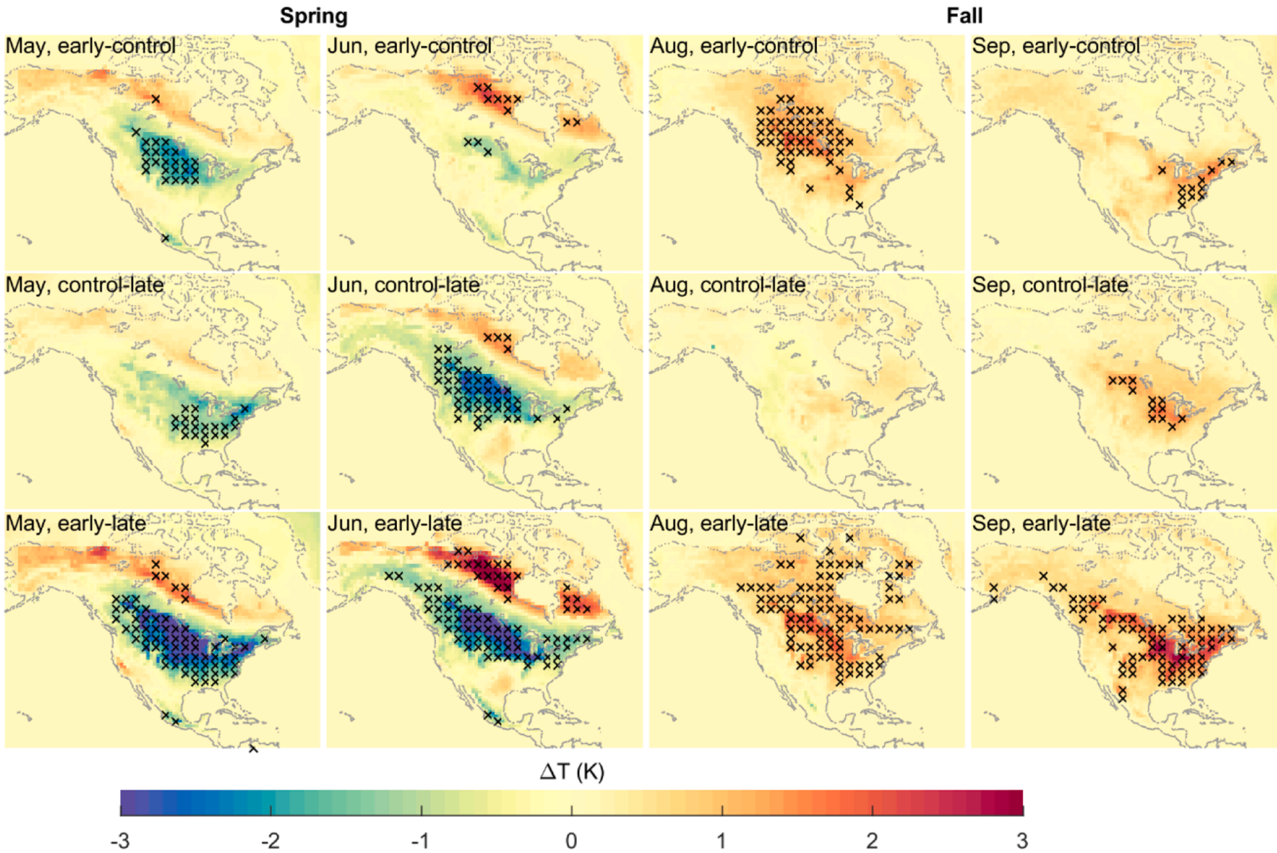

Fig. 3. Monthly differences in surface temperature (T, radiative, unit: K) between the three simulations. Grid points with a significant difference after false positive adjustment are marked with black crosses. First row: maps showing surface temperature differences between the early phenology run and the control experiment in May, June, August, and September in North America. Second row: maps showing surface temperature differences between the control run and the late phenology experiment in May, June, August, and September. Third row: maps showing surface temperature differences between the early phenology run and the late phenology experiment in May, June, August, and September.

3.3. Energy and moisture control over the land surface

The timing when the land surface changes from energy-limited states to moisture-limited states differs geographically and between simulations (Fig. 5). Temperature dominates evapotranspiration at the beginning of the growing season (Fig. S16). As plants emerge and canopy transpiration and evaporation increase, soil moisture becomes more limiting and starts to control evapotranspiration (Fig. S17). The Great Plains is mostly moisture-controlled (Fig. 5ghi) and the change from an energy-limited to a moisture-limited state happens early (April or earlier) in the year (Fig. 5abc). Regions at mid-latitudes and in Eastern US enter moisture-limited states in June or even later (Fig. 5abc) and the land surface in half or more of the growing season is temperature-controlled in Eastern US (Fig. 5ghi). Changes in transition timing between simulations are relatively small (Fig. 5def). When plant phenology is shifted earlier, more arid regions like the Great Plains and some locations in Alaska enter the moisture-controlled state earlier while more humid places like Northeastern US changes into the moisture-controlled state later possibly due to the decreased surface temperature (Fig. 5def). We also note, even though significant seasonal changes are present in evapotranspiration, changes in soil moisture are small and mostly non-significant possibly due to decreased surface temperature and increased convective precipitation (Fig. S18).

3.4. Changes in surface energy balance

Surface energy fluxes are also examined to investigate why the Great Plains and Eastern US exhibit the most significant phenology-derived changes and why their seasonal patterns differ (Fig. 6). Earlier spring onset in the early vs. control and control vs. late phenology simulations increases evapotranspiration and causes latent heat fluxes to increase and net shortwave radiation to decrease in the spring, resulting in a lower surface temperature and decreases in both sensible heat fluxes and net longwave radiation. The opposite occurs during the fall. Compared to the Great Plains, changes in energy balance start earlier and last longer into the fall season in the Eastern US, though the absolute amplitude of the variation is lower, especially in the spring. In addition, compared to changes in the spring, fall differences are usually smaller in their amplitude but last longer, especially in the Great Plains. Both the Bowen ratio and the amplitude of changes are larger over the Great Plains than in Eastern US. For Eastern US, the Bowen ratio exhibits a larger spring change in the late phenology simulation and a larger fall change in the early phenology simulation.

4. Discussion

Shifting terrestrial plant phenology influences PBL height and other land surface states and fluxes significantly and asymmetrically at seasonal timescales in CESM2. Studies have shown that an earlier leaf out and longer growing season length would cause more total net solar radiation and warmer land surface (Xu et al., 2020). However, our work shows that in an ideal experiment where influences of earlier spring may be offset by earlier fall and growing season length does not change, shifting plant phenology alone would not cause significant changes at the annual to interannual timescales except in the Hudson Bay region where earlier melting of snowpack is triggered. Shifts in autumn phenology correspond to spring phenology variability, but effects vary spatially (Keenan and Richardson, 2015; Liu et al., 2016; Fu et al., 2018;

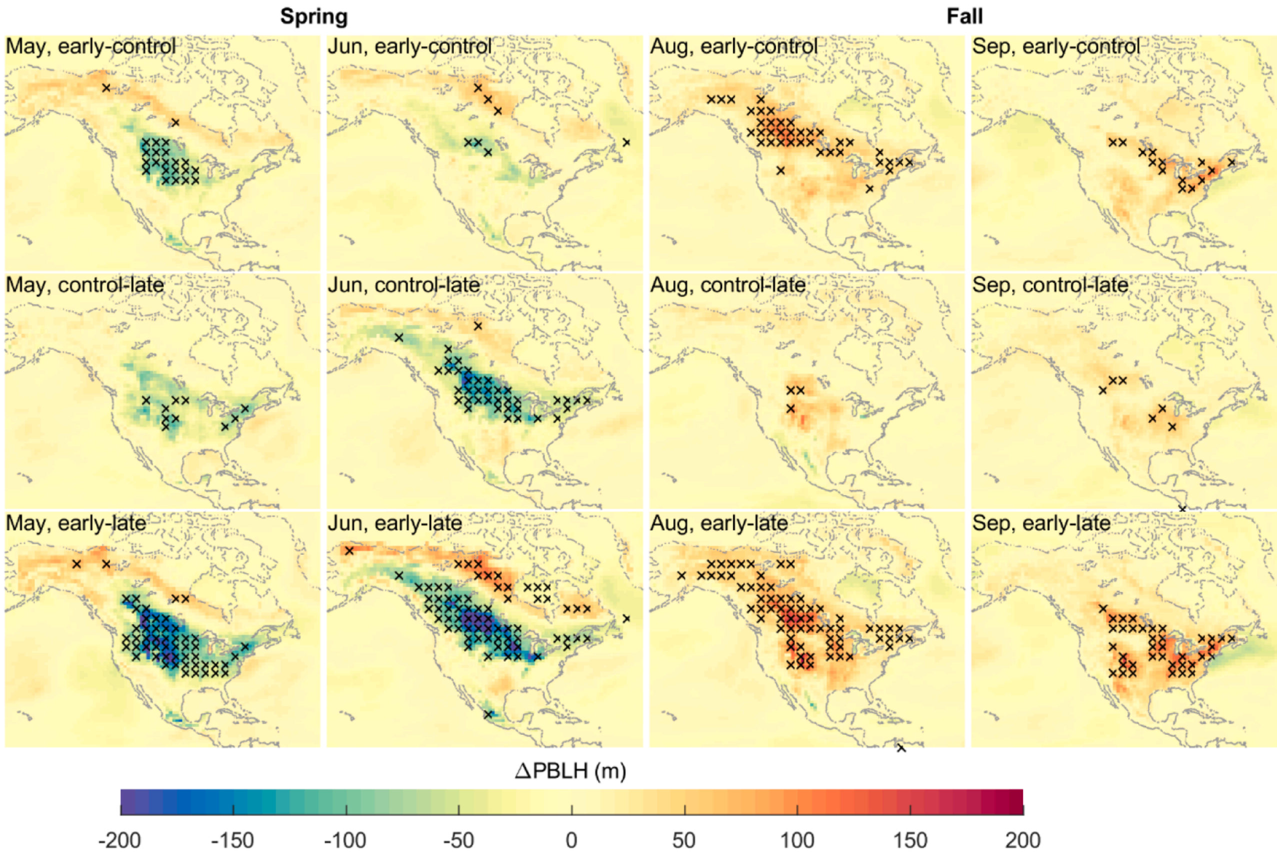

Fig. 4. Monthly differences in PBL height (PBLH, unit: m) between the three simulations. Grid points with a significant difference after false-positive adjustment are marked with black crosses. First row: PBL height differences between the early phenology and the control experiment in May, June, August, and September in North America. The second row shows PBL height differences between the control and the late phenology experiment in May, June, August, and September. Third row: maps showing PBL height differences between the early phenology and the late phenology experiment in May, June, August, and September.

Piao et al., 2019). Therefore, it is critical to consider the independent as well as aggregate impacts of shifts in spring and fall phenology when examining the influence of phenology on land-atmosphere coupling and other components of the Earth's system.

Modifying plant phenology influences both land surface states and fluxes directly through changing the Bowen ratio and indirectly through changes in low cloud fraction (Fig. 7). While studies using observations as well as land surface models similar to or different from CTSM5.0 have also suggested that changing plant phenology impacts surface energy balance and Bowen ratio (e.g., Bounoua et al., 2000; Fitzjarrald et al., 2001; Guillevic et al., 2002; Levis and Bonan, 2004; Puma et al., 2013; Bali and Collins, 2015; Green et al., 2017), our study highlights that changes in low cloud fraction can also be important due to their impacts on both shortwave cloud forcing and convective precipitation. Earlier phenology in the spring decreases the Bowen ratio through increasing evapotranspiration, decreasing surface temperature, and changing the energy distribution between sensible and latent heat fluxes, as well as increases low cloud fraction and therefore increases reflected shortwave solar radiation by clouds and increases convective precipitation rate, further causing surface temperature and net solar radiation to decrease (Fig. 7). As surface temperature decreases and convective precipitation increases, even though significant increases in canopy evapotranspiration and latent heat flux are present, changes in soil moisture can be small if the growing season length or maximum LAI value remains unchanged, especially in the top soil layers. These processes can further cause changes in PBL height and structure, triggering changes in atmospheric circulation. Though phenology-induced changes in large-scale circulations are not significant in our experiments due to the constant growing season length and maximum LAI value, other studies have shown that phenology can influence cloud fraction and precipitation significantly in regions with relatively high vegetation coverage including the Great Plains and Eastern US (Van Heerwaarden et al., 2009; Findell et al., 2011; Xu et al., 2020). Although there are large uncertainties in cloud simulations in climate models, the potential negative feedback loop caused by phenological changes through changes in cloud fraction and reflected shortwave solar radiation can be critical to understanding the future climate.

Our study also reveals large potential influences of snow-melt timing in the permafrost regions around the Hudson Bay associated with variability in the timing of plant phenophase change. Studies have found large permafrost degradation risks in the coastal regions of the Hudson Bay under future climate scenarios, but models disagree on the magnitude of changes (e.g., Gough and Leung, 2002; Gagnon and Gough, 2005; Zhang, 2013). Our experiments suggest that, in addition to a direct influence of the warming temperatures, changes in plant phenology may further accelerate the process by modifying land surface fluxes and cloud fraction. In addition, changes in plant phenology may occur at different rates from variation in snow melting/accumulation (e.g., Creed et al., 2015; Contosta et al., 2017; Grogan et al., 2020), resulting in complex feedback and uncertainties in assessing phenology impacts on land-atmosphere coupling. Therefore, controlled experiments using climate models can be a useful way to understand these feedback and uncertainties.

Influences of phenology shifts depend on both the location of the region and the season of interest. Aside from the Hudson Bay, our experiments show that the Great Plains and Eastern US experience the largest influences from changes in plant phenology, but the amplitude and duration of the impacts are different between the two regions and

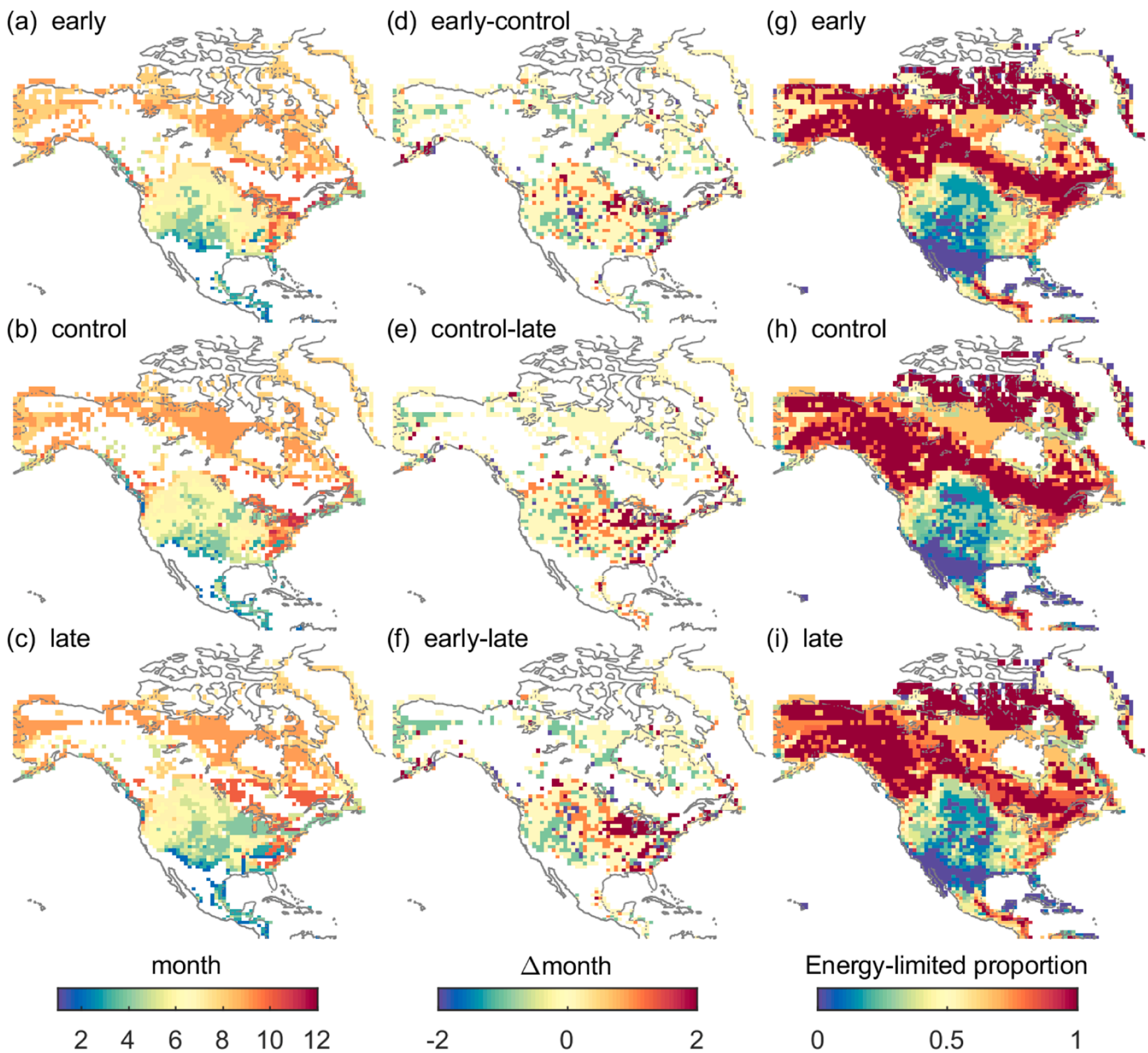

Fig. 5. Energy and moisture control over the land surface. (a-c) The month when the land surface changes into a soil moisture-controlled state from a temperature-controlled state. (d-f) Differences between simulations in when the land surface changes into a soil moisture-controlled state from a temperature-controlled state. (g-i) Proportion of the year when the land surface is controlled by temperature rather than soil moisture.

between seasons. Studies have identified these regions as "hot spots" for land-atmosphere coupling (e.g., Koster et al., 2004; Findell et al., 2011; Bali and Collins, 2015; Williams and Torn, 2015). Particularly, Eastern US exhibits relatively weak land-atmosphere coupling in soil moisture-based analysis (e.g., Koster et al., 2004), but vegetation can alter evapotranspiration and modify land-atmosphere coupling strength (Findell et al., 2011; Williams and Torn, 2015). Our results also show that while earlier plant phenology shifts increase canopy evapotranspiration and cause moisture control over land-atmosphere coupling to increase in arid regions, the combined cloud and temperature feedback may further enhance temperature control in regions with abundant soil moisture. Although the overall influence of phenology shifts is small at the interannual timescale, at seasonal timescales, changes in phenology alone can have large and significant impacts on land surface fluxes. In addition, while phenology is set to a specific (pre-defined) function in SP mode, the rate at which spring "green up" occurs in real plants is likely to be sensitive to the variations in local weather conditions during this stage of plant phenophase. It is therefore possible that as-of-yet-undiscovered feedback can enable plants to modify PBL dynamics and in return to further influence LAI (e.g., accelerate leaf emergence) in the spring. As a large disagreement is present between plant phenology simulated by land surface models and derived from observational records (e.g., Scholze et al., 2017; Peano et al., 2021; Li et al., 2022) and the influences of changes in spring phenology on the variability of autumn phenology and growing season length are uncertain (e.g., Keenan and Richardson, 2015; Liu et al., 2016; Piao et al., 2019), it is important to study these seasonal scale influences as well.

Controlled experiments using Earth system models allow us to separate phenology impacts due to plant phenophase change alone from the changes induced by phenology responding to its environment. That is, phenology changes as a response to the changing climate, and these changes further alter PBL conditions and land-atmosphere coupling. Conducting controlled experiments allows us to separate the roles of different processes like phenology shifts and the feedback loop induced by phenological changes in land-atmosphere coupling. However, as models differ in the processes they include and their parameterization, the feedback can be model-specific and experiments evolving more models and more experimental settings need to be done to explore the

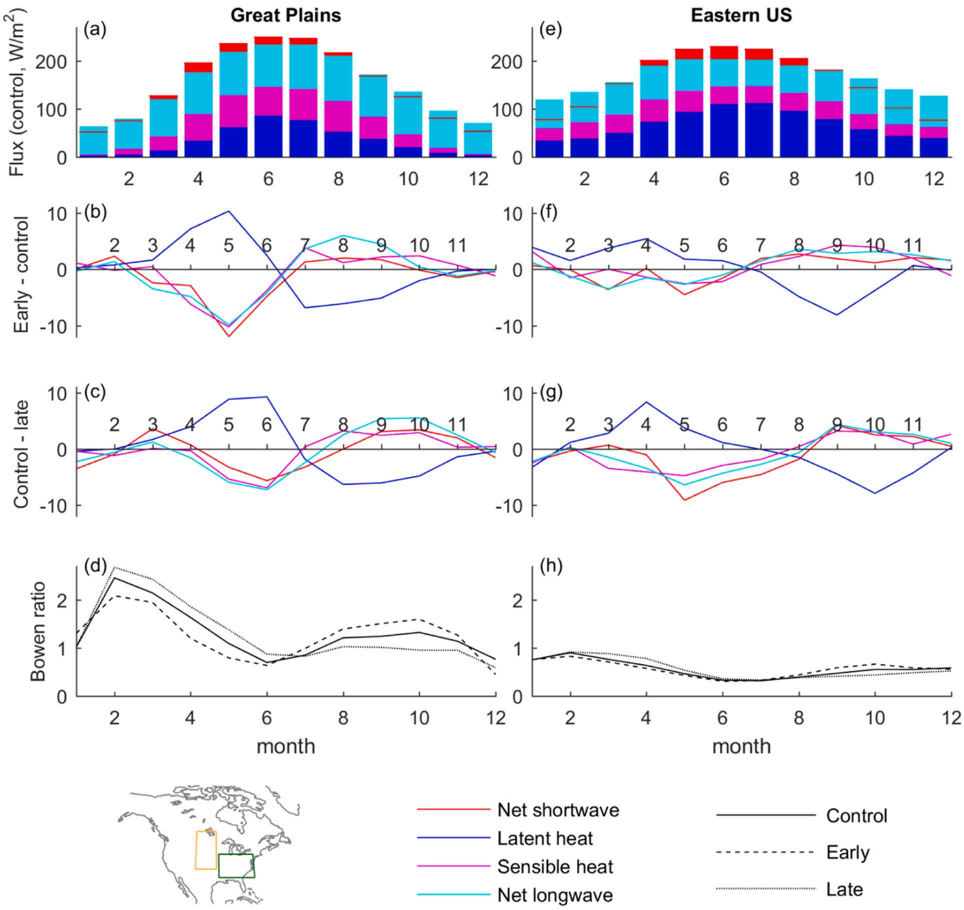

Fig. 6. Mean and differences of surface energy fluxes averaged over regions showing the largest and most significant changes in the Great Plains (shown by the orange box on the map) and Eastern US (green box). (a) and (e): Stacked bar diagram showing the balance between net shortwave radiation at the surface (red, starts from zero) and the sum of surface latent heat fluxes (blue, starts from zero), surface sensible heat fluxes (magenta, stacked), and net longwave radiation at the surface (cyan, stacked) in the control simulation in (a) the Great Plains and (e) Eastern US. (b), (c), (f), and (g): Differences between the surface energy fluxes in the early vs. control and control vs. late phenology simulations (unit: W/m2). (d) and (h): Monthly mean Bowen ratio in the three simulations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

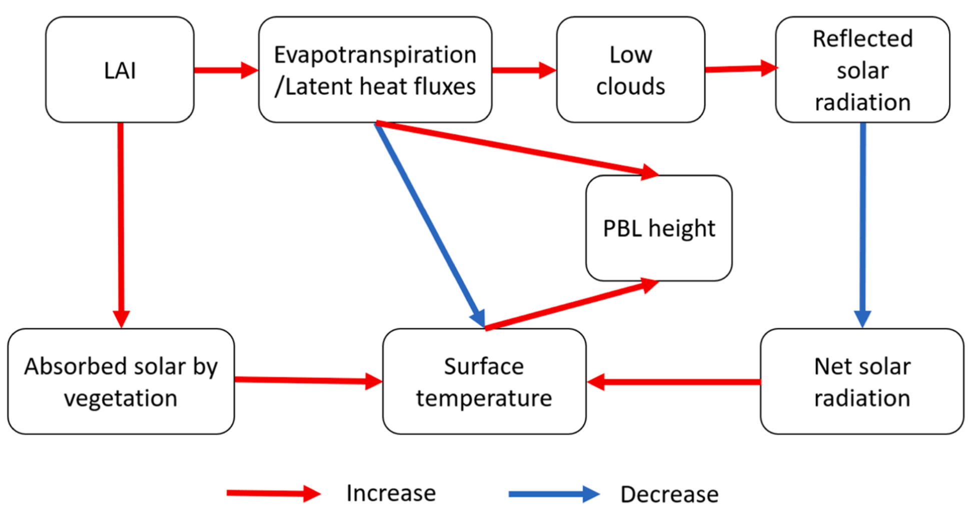

Fig. 7. Conceptual diagram showing the relationships between key PBL states and fluxes.

full scope of phenology-induced changes in land-atmosphere interactions. Our experiments are therefore a first step towards characterizing the PBL response, and additional simulations with more dynamic or more responsive plant phenology would help further refine the regional responses and feedback of the biogeochemical processes. As spring onset timing is advancing (Schwartz et al., 2013; Ault et al., 2015) and models vary in their phenology simulations (Peano et al., 2021), investigating and disentangling phenology influences on land-atmosphere interactions is critical for understanding future climate changes. Our work also shows statistically significant changes at the seasonal timescale due to variations in the timing of plant phenophase change alone, and similar changes are anticipated in the observations as well when phenology varies (e.g., Green et al., 2017; Rey-Sanchez et al., 2021). Therefore, this work may also help identify regions where large changes in the PBL due to phenology variability may occur and the processes that dominate the changes.

5. Conclusion

Shifting the timing of plant phenology modifies land surface states and fluxes as well as planetary boundary layer height significantly at seasonal timescales. Earlier spring phenology decreases PBL height significantly by more than 100 m in the Great Plains while earlier fall phenology increases PBL height in the Great Plains in the early fall and in Eastern US in the late fall by over 100 m. Earlier phenology in the spring decreases the Bowen ratio through increasing evapotranspiration and latent heat fluxes and decreasing surface temperature and sensible heat fluxes. Earlier green-up also increases low cloud fraction and therefore increases reflected shortwave solar radiation and convective precipitation rate, further causing surface temperature and net solar radiation to decrease. The combined Bowen ratio and cloud feedback increases moisture control over land-atmosphere coupling in arid regions but enhances temperature control in regions with abundant soil moisture. The opposite occurs during the fall. Controlled experiments using Earth system models provide an approach to separate roles of phenology-related processes in land-atmosphere coupling. Without changes in growing season length or overall leaf coverage, phenology-induced influences on land surface and PBL conditions are small at annual to interannual timescales except in the Hudson Bay region, but they are still significant at seasonal scales over the Great Plains and Eastern United States. Significant future changes in phenology are anticipated due to climate change, but the large biases between simulated and observed plant phenology at present-day induce considerable uncertainty in the simulation of the coupled system. As shifts in plant phenology alone can cause significant changes in PBL conditions at the seasonal timescale, our experiments can further help infer where the most significant changes are expected and provide useful information for observation-based analysis and intercomparison between model simulations and observations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work is supported by the National Science Foundation Macrosystems Biology award [grant numbers DEB-1702551, DEB-1702697, DEB-2017815] and the National Science Foundation Career Award [grant number AGS-1751535]. The authors would like to thank Mr. Jim Le Moine, Dr. Adam M. Young, and Dr. Mark A. Friedl for their helpful comments and feedback during the development of this project. We also thank the reviewers for their helpful and constructive comments, which greatly helped in improving this manuscript. We acknowledge high-performance computing support from Cheyenne (doi:10.5065/D6RX99HX) provided by NCAR's Computational and Information Systems Laboratory.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2022.109286.

References

Albergel, C., Munier, S., Leroux, D.J., Dewaele, H., Fairbairn, D., Barbu, A.L., Calvet, J.C., 2017. Sequential assimilation of satellite-derived vegetation and soil moisture products using SURFEX_v8. 0: LDAS-Monde assessment over the Euro-Mediterranean area. Geosci. Model Dev. 10 (10), 3889–3912.

Ault, T.R., Schwartz, M.D., Zurita-Milla, R., Weltzin, J.F., Betancourt, J.L., 2015. Trends and natural variability of spring onset in the coterminous United States as evaluated by a new gridded dataset of spring indices. J. Clim. 28 (21), 8363–8378.

Bali, M., Collins, D., 2015. Contribution of phenology and soil moisture to atmospheric variability in ECHAM5/JSBACH model. Clim. Dyn. 45 (9), 2329–2336.

Barbu, A.L., Calvet, J.C., Mahfouf, J.F., Albergel, C., Lafont, S., 2011. Assimilation of Soil Wetness Index and Leaf Area Index into the ISBA-A-gs land surface model: grassland case study. Biogeosciences 8 (7), 1971–1986.

Benjamini, Y., Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J. R. Stat. Soc. Ser. B 57 (1), 289–300.

Birch, L., Schwalm, C.R., Natali, S., Lombardozzi, D., Keppel-Aleks, G., Watts, J., Rogers, B.M., 2021. Addressing biases in Arctic–boreal carbon cycling in the Community Land Model Version 5. Geosci. Model Dev. 14 (6), 3361–3382.

Bounoua, L., Collatz, G.J., Los, S.O., Sellers, P.J., Dazlich, D.A., Tucker, C.J., Randall, D. A., 2000. Sensitivity of climate to changes in NDVI. J. Clim. 13 (13), 2277–2292.

Denissen, J.M., Teuling, A.J., Reichstein, M., Orth, R., 2020. Critical soil moisture derived from satellite observations over Europe. J. Geophys. Res. 125 (6) e2019JD031672.

Denissen, J., Teuling, A.J., Pitman, A.J., Koirala, S., Migliavacca, M., Li, W., Orth, R., 2022. Widespread shift from ecosystem energy to water limitation with climate change. Nat. Clim. Change 12 (7), 677–684.

Contosta, A.R., Adolph, A., Burchsted, D., Burakowski, E., Green, M., Guerra, D., Wollheim, W., 2017. A longer vernal window: the role of winter coldness and snowpack in driving spring transitions and lags. Glob. Change Biol. 23 (4), 1610–1625.

Cook, B.I., Wolkovich, E.M., Davies, T.J., Ault, T.R., Betancourt, J.L., Allen, J.M., Travers, S.E., 2012. Sensitivity of spring phenology to warming across temporal and spatial climate gradients in two independent databases. Ecosystems 15 (8), 1283–1294.

Creed, I.F., Hwang, T., Lutz, B., Way, D., 2015. Climate warming causes intensification of the hydrological cycle, resulting in changes to the vernal and autumnal windows in a northern temperate forest. Hydrol. Process. 29 (16), 3519–3534.

Dahlin, K.M., Fisher, R.A., Lawrence, P.J., 2015. Environmental drivers of drought deciduous phenology in the Community Land Model. Biogeosciences 12 (16), 5061–5074.

Dirmeyer, P.A., Chen, L., Wu, J., Shin, C.S., Huang, B., Cash, B.A., Lawrence, D.M., 2018. Verification of land–atmosphere coupling in forecast models, reanalyses, and land surface models using flux site observations. J. Hydrometeorol. 19 (2), 375–392.

Findell, K.L., Gentine, P., Lintner, B.R., Kerr, C., 2011. Probability of afternoon precipitation in eastern United States and Mexico enhanced by high evaporation. Nat. Geosci. 4 (7), 434–439.

Findell, K.L., Gentine, P., Lintner, B.R., Guillod, B.P., 2015. Data length requirements for observational estimates of land–atmosphere coupling strength. J. Hydrometeorol. 16 (4), 1615–1635.

Fitzjarrald, D.R., Acevedo, O.C., Moore, K.E., 2001. Climatic consequences of leaf presence in the eastern United States. J. Clim. 14 (4), 598–614.

Fox, A.M., Hoar, T.J., Anderson, J.L., Arellano, A.F., Smith, W.K., Litvak, M.E., Moore, D. J., 2018. Evaluation of a data assimilation system for land surface models using CLM4. 5. J. Adv. Model Earth Syst. 10 (10), 2471–2494.

Fu, Y., He, H.S., Zhao, J., Larsen, D.R., Zhang, H., Sunde, M.G., Duan, S., 2018. Climate and spring phenology effects on autumn phenology in the Greater Khingan Mountains, Northeastern China. Remote Sens. 10 (3), 449.

Gagnon, A.S., Gough, W.A., 2005. Climate change scenarios for the Hudson Bay region: an intermodel comparison. Clim. Change 69 (2), 269–297.

Gough, W.A., Leung, A., 2002. Nature and fate of Hudson Bay permafrost. Reg. Environ. Change 2 (4), 177–184.

Green, J.K., Konings, A.G., Alemohammad, S.H., Berry, J., Entekhabi, D., Kolassa, J., Gentine, P., 2017. Regionally strong feedbacks between the atmosphere and terrestrial biosphere. Nat. Geosci. 10 (6), 410–414.

Grogan, D.S., Burakowski, E.A., Contosta, A.R., 2020. Snowmelt control on spring hydrology declines as the vernal window lengthens. Environ. Res. Lett. 15 (11), 114040.

Guillevic, P., Koster, R.D., Suarez, M.J., Bounoua, L., Collatz, G.J., Los, S.O., Mahanama, S.P.P., 2002. Influence of the interannual variability of vegetation on the surface energy balance—a global sensitivity study. J. Hydrometeorol. 3 (6), 617–629.

Hurrell, J.W., Hack, J.J., Shea, D., Caron, J.M., Rosinski, J., 2008. A new sea surface temperature and sea ice boundary dataset for the Community Atmosphere Model. J. Clim. 21 (19), 5145–5153.

IPCC. (2021). Climate change 2021: the physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change, Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger et al. (eds.). Cambridge University Press. In Press.

Jolly, W.M., Nemani, R., Running, S.W., 2005. A generalized, bioclimatic index to predict foliar phenology in response to climate. Glob. Change Biol. 11 (4), 619–632.

Karkauskaite, P., Tagesson, T., Fensholt, R., 2017. Evaluation of the plant phenology index (ppi), ndvi and evi for start-of-season trend analysis of the northern hemisphere boreal zone. Remote Sens. 9 (5), 485.

Keenan, T.F., Richardson, A.D., 2015. The timing of autumn senescence is affected by the timing of spring phenology: implications for predictive models. Glob. Change Biol. 21 (7), 2634–2641.
Kim, Y., Moorcroft, P.R., Aleinov, I., Puma, M.J., Kiang, N.Y., 2015. Variability of phenology and fluxes of water and carbon with observed and simulated soil moisture in the Ent Terrestrial Biosphere Model (Ent TBM version 1.0.1.0.0). Geosci. Model Dev. 8 (12), 3837–3865.
Koster, R.D., Dirmeyer, P.A., Guo, Z., Bonan, G., Chan, E., Cox, P., Yamada, T., 2004. Regions of strong coupling between soil moisture and precipitation. Science 305 (5687), 1138–1140.
Koster, R.D., Walker, G.K., 2015. Interactive vegetation phenology, soil moisture, and monthly temperature forecasts. J. Hydrometeorol. 16 (4), 1456–1465. https://doi.org/10.1175/JHM-D-14-0205.1.
Lawrence, P.J., Chase, T.N., 2007. Representing a new MODIS consistent land surface in the Community Land Model (CLM 3.0). J. Geophys. Res. 112 (G1).
Lawrence, D.M., Fisher, R.A., Koven, C.D., Oleson, K.W., Swenson, S.C., Bonan, G., Zeng, X., 2019. The Community Land Model version 5: description of new features, benchmarking, and impact of forcing uncertainty. J. Adv. Model Earth Syst. 11 (12), 4245–4287.
Lawrence, D.M., Slingo, J.M., 2004. An annual cycle of vegetation in a GCM. Part II: global impacts on climate and hydrology. Clim. Dyn. 22 (2), 107–122. https://doi.org/10.1007/s00382-003-0367-8.
Levis, S., Bonan, G.B., 2004. Simulating springtime temperature patterns in the community atmosphere model coupled to the community land model using prognostic leaf area. J. Clim. 17 (23), 4531–4540.
Li, X., Melaas, E., Carrillo, C.M., Ault, T., Richardson, A.D., Lawrence, P., Young, A.M., 2022. A comparison of land surface phenology in the Northern Hemisphere derived from satellite remote sensing and the Community Land Model. J. Hydrometeorol. 23 (6), 859–873.
Liu, Q., Fu, Y.H., Zhu, Z., Liu, Y., Liu, Z., Huang, M., Piao, S., 2016. Delayed autumn phenology in the Northern Hemisphere is related to change in both climate and spring phenology. Glob. Change Biol. 22 (11), 3702–3711.
Lorenz, R., Davin, E.L., Lawrence, D.M., Stöckli, R., Seneviratne, S.I., 2013. How important is vegetation phenology for European climate and heat waves? J. Clim. 26 (24), 10077–10100.
Mahowald, N., Lo, F., Zheng, Y., Harrison, L., Funk, C., Lombardozzi, D., Goodale, C., 2016. Projections of leaf area index in earth system models. Earth Syst. Dyn. 7 (1), 211–229.
McCarthy, M.P., Sanjay, J., Booth, B.B.B., Krishna Kumar, K., Betts, R.A, 2012. The influence of vegetation on the ITCZ and South Asian monsoon in HadCM3. Earth Syst. Dyn. 3 (1), 87–96.
Neale, R.B., Chen, C.C., Gettelman, A., Lauritzen, P.H., Park, S., Williamson, D.L., Marsh, D. (2010). Description of the NCAR community atmosphere model (CAM 5.0). NCAR Tech. Note NCAR/TN-486+ STR, 1(1), 1–12.
Parmesan, C., Yohe, G., 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421 (6918), 37–42.
Peano, D., Hemming, D., Materia, S., Delire, C., Fan, Y., Joetzjer, E., Zaehle, S., 2021. Plant phenology evaluation of CRESCENDO land surface models–Part 1: start and end of the growing season. Biogeosciences 18 (7), 2405–2428.
Piao, S., Liu, Q., Chen, A., Janssens, I.A., Fu, Y., Dai, J., Zhu, X., 2019. Plant phenology and global climate change: current progresses and challenges. Glob. Change Biol. 25 (6), 1922–1940.
Puma, M.J., Koster, R.D., Cook, B.I., 2013. Phenological versus meteorological controls on land-atmosphere water and carbon fluxes. J. Geophys. Res. 118 (1), 14–29.
Rechid, D., Jacob, D., 2006. Influence of monthly varying vegetation on the simulated climate in Europe. Meteorol. Z. 15 (1), 99–116. https://doi.org/10.1127/0941-2948/2006/0091.
Rey-Sanchez, C., Wharton, S., Vilà-Guerau de Arellano, J., Paw, U.K.T., Hemes, K.S., Fuentes, J.D., Baldocchi, D, 2021. Evaluation of atmospheric boundary layer height from wind profiling radar and slab models and its responses to seasonality of land cover, subsidence, and advection. J. Geophys. Res. 126 (7) e2020JD033775.
Richardson, A.D., Anderson, R.S., Arain, M.A., Barr, A.G., Bohrer, G., Chen, G., …, Xue, Y., 2012. Terrestrial biosphere models need better representation of vegetation phenology: results from the North American Carbon Program Site Synthesis. Glob. Change Biol. 18 (2), 566–584.
Richardson, A.D., Keenan, T.F., Migliavacca, M., Ryu, Y., Sonnentag, O., Toomey, M., 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. Agric. For. Meteorol. 169, 156–173.
Root, T.L., Price, J.T., Hall, K.R., Schneider, S.H., Rosenzweig, C., Pounds, J.A., 2003. Fingerprints of global warming on wild animals and plants. Nature 421 (6918), 57–60.
Sabater, J.M., Rüdiger, C., Calvet, J.C., Fritz, N., Jarlan, L., Kerr, Y., 2008. Joint assimilation of surface soil moisture and LAI observations into a land surface model. Agric. For. Meteorol. 148 (8–9), 1362–1373.
Santanello Jr, J.A., Peters-Lidard, C.D., Kumar, S.V, 2011. Diagnosing the sensitivity of local land–atmosphere coupling via the soil moisture–boundary layer interaction. J. Hydrometeorol. 12 (5), 766–786.
Santanello, J.A., Peters-Lidard, C.D., Kennedy, A., Kumar, S.V., 2013. Diagnosing the nature of land–atmosphere coupling: a case study of dry/wet extremes in the US southern Great Plains. J. Hydrometeorol. 14 (1), 3–24.
Scholze, M., Buchwitz, M., Dorigo, W., Guanter, L., Quegan, S., 2017. Reviews and syntheses: systematic Earth observations for use in terrestrial carbon cycle data assimilation systems. Biogeosciences 14 (14), 3401–3429.
Schwartz, M.D., 1992. Phenology and springtime surface-layer change. Mon. Weather Rev. 120 (11), 2570–2578.
Schwartz, M.D., Reiter, B.E., 2000. Changes in North American spring. Int. J. Climatol. 20 (8), 929–932.
Schwartz, M.D., Ahas, R., Aasa, A., 2006. Onset of spring starting earlier across the Northern Hemisphere. Glob. Change Biol. 12 (2), 343–351.
Schwartz, M.D., Ault, T.R., Betancourt, J.L., 2013. Spring onset variations and trends in the continental United States: past and regional assessment using temperature-based indices. Int. J. Climatol. 33 (13), 2917–2922.
Simard, M., Pinto, N., Fisher, J.B., Baccini, A., 2011. Mapping forest canopy height globally with spaceborne lidar. J. Geophys. Res. 116 (G4).
Taylor, C.M., de Jeu, R.A., Guichard, F., Harris, P.P., Dorigo, W.A., 2012. Afternoon rain more likely over drier soils. Nature 489 (7416), 423–426.
Van Heerwaarden, C.C., Vilà-Guerau de Arellano, J., Moene, A.F., Holtslag, A.A., 2009. Interactions between dry-air entrainment, surface evaporation and convective boundary-layer development. Q. J. R. Meteorol. Soc. 135 (642), 1277–1291.
Williams, I.N., Torn, M.S., 2015. Vegetation controls on surface heat flux partitioning, and land-atmosphere coupling. Geophys. Res. Lett. 42 (21), 9416–9424.
White, M.A., De Beurs, K.M., Didan, K., Inouye, D.W., Richardson, A.D., Jensen, O.P., O'keefe, J., Zhang, G., Nemani, R.R., Van Leeuwen, W.J.D., Brown, J.F., De Wit, A., Schaepman, M., Lin, X., Dettinger, M., Bailey, A.S., Kimball, J., Schwartz, M.D., Baldocchi, D.D., Lee, J.T., Lauenroth, W.K., 2009. Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982–2006. Glob. Change Biol. 15 (10), 2335–2359. https://doi.org/10.1111/j.1365-2486.2009. 01910.x.
Xu, X., Riley, W.J., Koven, C.D., Jia, G., Zhang, X., 2020. Earlier leaf-out warms air in the north. Nat. Clim. Change 10 (4), 370–375.
Zhang, Y., 2013. Spatio-temporal features of permafrost thaw projected from long-term high-resolution modeling for a region in the Hudson Bay Lowlands in Canada. J. Geophys. Res.: Earth Surf. 118 (2), 542–552.