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LETTER

Snowmelt control on spring hydrology declines as the vernal window lengthens

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Abstract

The vernal window, or the winter-to-spring transition, is a key period for seasonally snow-covered, forested ecosystems. The events that open and close the vernal window shape the unique characteristics of spring hydrology that, in turn, influence both terrestrial and aquatic ecosystem processes. Few studies have examined how climate change will alter the vernal window and thereby impact basic hydrology during this transitional period. We project that over the 21st century the vernal window will lengthen by +15 to +28 d in northeastern North America. Loss of snow cover under a high climate forcing scenario eliminates the vernal window across 59% of the study domain, removing snow's influence on spring runoff in those areas. Spring runoff timing where the vernal window lengthens but does not disappear becomes similar to the southern, snow-free region where precipitation drives winter runoff, indicating a fundamental change in the hydrologic character of northeastern forests.

1. Introduction

The vernal window encompasses a time when neither a snowpack nor a closed forest canopy is present, allowing for direct inputs of solar radiation to soils and water bodies [1–4]. Both the loss of seasonal snow cover and shifts in the timing of spring snowmelt that denote the start of the vernal window are well-known impacts of climate change [5–8]. Prior studies have also documented the advancement of phenological events such as budburst [9], which demarcates the end of the vernal window. While both snowmelt and budburst are occurring earlier in the year, rates of change in these phenomena are not equivalent, with snowmelt timing advancing faster than canopy greenup [10]. In a warming climate, this asynchrony may elongate the vernal window, but the rates of change in these two phenomena are rarely investigated simultaneously.

Because the vernal window occurs during a dynamic period of snowpack disappearance and canopy greenup, it contains a series of dramatic hydrologic transitions that exert control over the hydrologic character of the system throughout spring and into the growing season [2, 6–9]. At the start of the vernal window, snowmelt rapidly releases a reservoir of water that affects soil moisture, groundwater recharge, baseflow, runoff, nutrient export, and the hydrologic connectivity of soils to streams [10]. The emergence of buds and leaves in deciduous vegetation at the end of the vernal window also exerts controls on ecosystem water balance as evapotranspiration becomes a significant hydrologic flux [11]. Like the start and end of the vernal window, hydrologic transitions that occur within it are also known to be changing, such that peak spring discharge and runoff center of volume have advanced earlier in the year in keeping with earlier snowmelt [6, 7, 12, 13].

Here we present the first analysis of how the vernal window length will change over the 21st century in northeastern North America, utilizing a modeling framework to assess shifts in both the opening and closing of the vernal window as well as hydrologic fluxes within the window. We find that climate change will lengthen both the entire vernal window and shift the timing of key spring transitions such

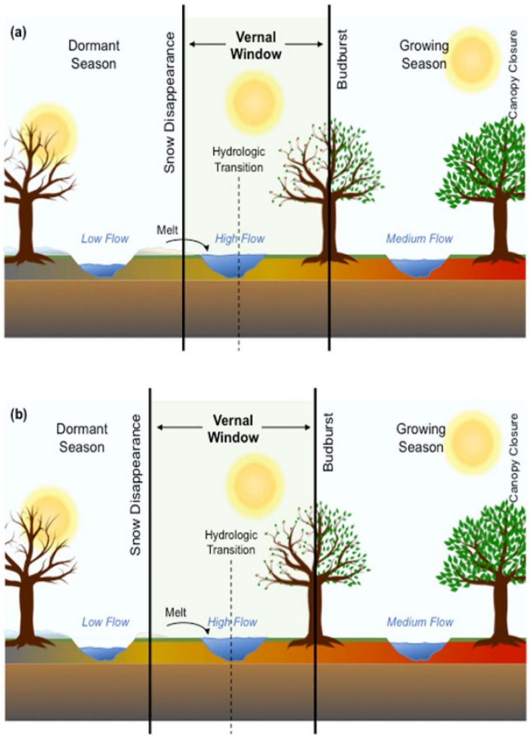

Figure 1. Conceptual model of the historical vernal window. The vernal window (A) starts with snow disappearance and ends with budburst and leaf-out of the forest canopy. The timing of both the start and end of the vernal window drive the timing of the spring hydrograph, which transitions from low flow during the dormant season to high flow within the vernal window period. As the vernal window lengthens due to climate change (B), the timing of snow disappearance and budburst advance to earlier days of the year, but at different rates. This leads to an overall lengthening of the vernal window. Spring high flows also occur earlier, with implications for ecosystem hydrology.

as hydrologic export, resulting in novel impacts on ecosystem function (figure 1). Northeastern North America (figure 2) serves as a model system for seasonally snow-covered areas that globally extend from 40–60°N [14], suggesting potential vernal window and hydrologic changes can be expected elsewhere.

2. Methods

We use the locally constructed analogs [15] (LOCA) climate dataset for the period 1980–2099 to drive two models simulating key vernal window events in northeastern North America: a hydrologic model and a phenology model, both of which are described below. The LOCA climate dataset is comprised of 29 GCMs with daily precipitation, and minimum and maximum temperature statistically downscaled to 1/16th degree (supplementary materials and methods and table S1 (available online at https://stacks.iop.org/ERL/15/114040/mmedia)). All 29 models and two forcing scenarios (lower, RCP4.5 [16], and higher, RCP8.5 [17]) are used to drive both models. In our findings we report the unweighted ensemble mean and standard deviation of simulation results for each of three key vernal window events: snow disappearance, budburst, and spring runoff center-of-volume (R-COV). We identify portions of the study region that, due to the loss of seasonal snowpack (figures 2(A), (B)), lose their vernal window over the 21st century (figures 2(E), (F)). To better understand the implications of a disappearing vernal window on hydrology in forested ecosystems, we compare changes in the spring runoff characteristics in the regions that retain their vernal window to those that lose it, accounting for the change in those contrasting areas over time.

2.1. Hydrologic model

Snow disappearance date and runoff center of volume (R-COV) are modeled with the University of New Hampshire Water Balance Model, WBM [18, 19]. WBM is a process-based, modular, gridded hydrologic model that simulates spatially and temporally varying water volume; it is amongst the earliest developed [20] global hydrologic models (GHMs) and can be scaled to any study domain. WBM represents all major land surface components of the hydrological cycle, and tracks fluxes between the atmosphere, above-ground water storages (e.g. snowpack), soil, vegetation, groundwater, and runoff. A digitized river network connects grid cells, enabling simulation of flow through river and groundwater systems. Full documentation is provided in [18] and [19]; here we provide details on an update to the snow water equivalent simulation methods. Runoff as simulated by WBM has been used and validated extensively in studies of the northeastern US (*e.g.* [21], [22], *and references therein*) and in global studies that encompass other seasonally-snow covered forested regions from 40–60°N [18, 19, 23, 24]; additional runoff validation is given here in supplementary table S3.

As described in [18] and [19], WBM takes daily precipitation and temperature inputs and determines internally if the precipitation falls as snowfall or rain based on temperature thresholds of -1 °C for snowfall and 1 °C for snowmelt. Snow water equivalent is the balance between snowfall and snowmelt. For this study, a modification has been made to account for the impact of large orographic gradients on snowfall and snowmelt. The elevation distribution of each model grid cell is calculated from a 30 meter digital elevation model, resulting in binned elevation categories of vertical bands (bin size = 250 m elevation change). A temperature lapse rate of -6.4 °C km^{-1} is applied to the mean daily temperature at the reference elevation for each binned elevation category, resulting in an adjusted mean temperature

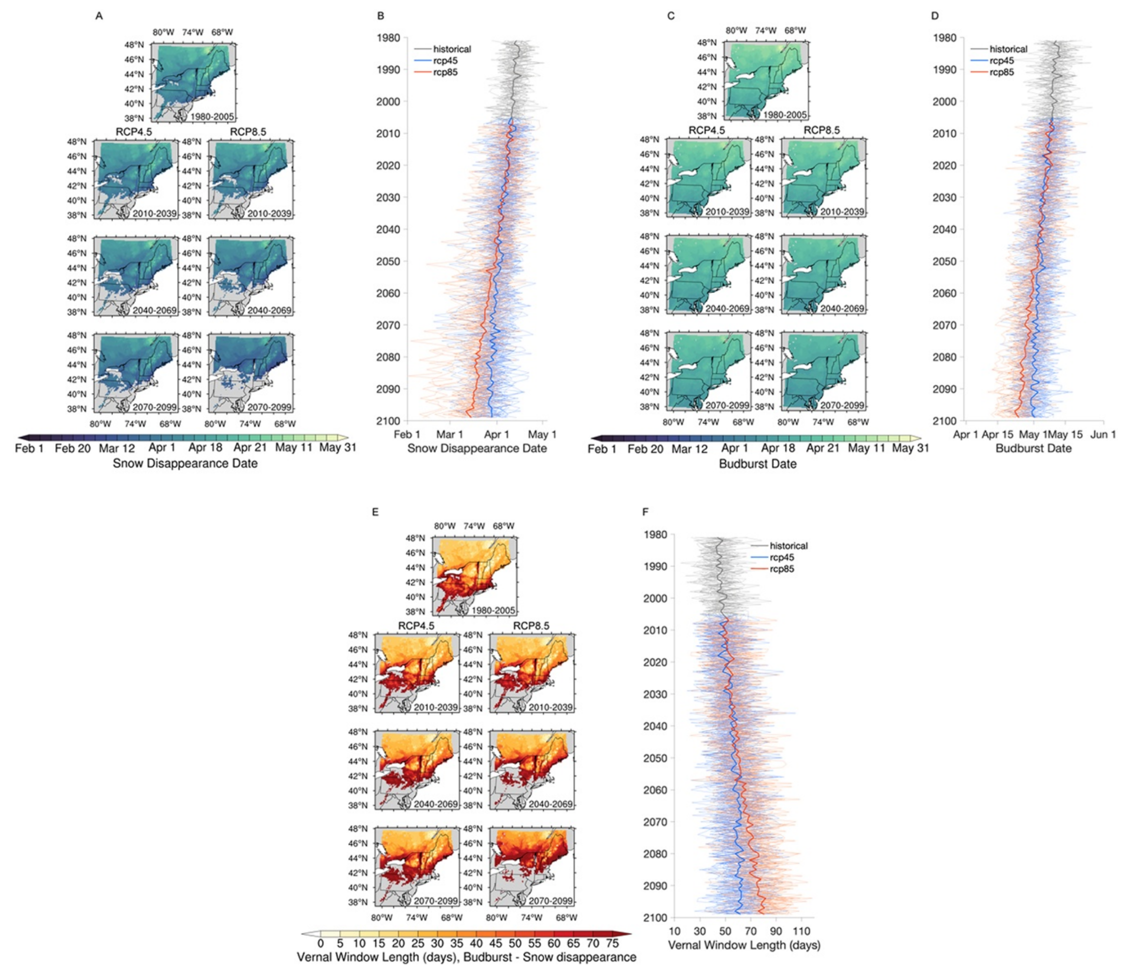

Figure 2. Simulated time series of the beginning, end, and length of the vernal window. Ensemble mean of (A) snow disappearance date for lower (left column) and higher (right column) forcing scenarios, RCP4.5 and RCP8.5, respectively. (B) Individual ensemble (thin lines) and ensemble mean (thick lines) of snow disappearance date for historical (grey), lower (blue) and higher (red) forcing scenarios. Same as (A), (B) but for (C), (D) budburst date and (E), (F) vernal window length (in days).

for the portion of each grid cell in each elevation category.

2.2. Snow disappearance

Here we define snow disappearance as the date by which <0.1 mm WBM-simulated snow water equivalent (SWE) remains, and no additional SWE is accumulated until the next winter season. We applied a mask to each simulated 30 year climatology (early 2010–2039, mid- 2040-2069, and late-century 2070–2099) ensemble mean (i.e. figure 2) that excluded grid cells where more than 50% of years in the specified time slice had fewer than 20 d when snow water equivalent was greater than 30 mm. Modeled SWE is validated against historical (1950–2013) SWE observations at 1034 stations (supplementary figure S1) by driving WBM with the gridded reanalysis climate product used to statistically downscale the LOCA daily temperature and precipitation projections [25]. While the ideal validation metric would be the day of year on which snow disappears, most snow observational records within our study domain are weekly to biweekly, obscuring the exact day on which snow cover was lost. Comparison of historically-simulated SWE disappearance date trends to the few observational SWE sites with daily observations show that, for the overlapping observational and simulation period of 1990–2005, both the model and the observations show no significant trend (see supplementary materials §3.1 for details).

2.3. Phenology model

Budburst, which indicates the start of the vernal window closing, is simulated using the thermal time model within the open source phenor modeling suite [26]. We use Phenocam data from [27] to parameterize the phenor thermal time model; this dataset represents a quality-controlled, peer-reviewed subset of all available Phenocam Network (https://phenocam.sr.unh.edu/) observations within the study domain. By comparing the Phenocam plant function type descriptions to the MODIS MCD12Q1-derived IGBP land cover categories [28], we find that these Phenocam observations are representative of the vegetation and land cover of the region, with some small exceptions. Of the 58 available phenocam sites from [27] within the study domain, 43 sites identify deciduous broadleaf as the primary plant functional type, and 16 of these sites have evergreen needleleaf listed as the secondary plant functional type (figure S2). 63.5% of the study domain is classified as deciduous broadleaf or mixed forest by the MODIS MCD12Q1 land cover product [28]; we consider these 43 sites to be representative of the study domain vegetation on average. We used the historical temperature data to which the LOCA climate data were downscaled [25] along with MODIS 3 d transition dates at the 43 sites to optimize the thermal time model of budburst date within phenor. We recognize that this does not represent the other land cover types (representing 10.3% of the domain); further research is needed on urban and developed land and cropland land cover types in this region. The results of model calibration are shown in figure S4.

2.4. Vernal window duration

Vernal window onset is defined as the date after November 1 on which modeled SWE is less than 0.1 mm and does not become positive again until the following snow season. Vernal window closure is the day of year when budburst occurs. Vernal window length is calculated as the number of days between snow disappearance and budburst. Grid cells in which there are fewer than 20 d with SWE >30 mm are considered to have no vernal window, as snow cover is insufficient to calculate a snow disappearance date. For the purpose of calculating regional averages consistently across all metrics (figure 2 and table 1), model grid cells with fewer than 20 d with SWE >30 mm are assigned a vernal window onset date of January 1 in order to estimate region-wide snow disappearance dates. In this way, snow-free grid cells are assigned the longest possible vernal window, rather than assigning a '0', which artificially shortens the regionally averaged vernal window length as snow-free grid cells are dropped from the regional average and it becomes more heavily weighted by colder grid cells. For grid cells that lack seasonal snow cover, vernal window duration is therefore the number of days between January 1 and budburst. Since the vernal window duration is a function of SWE disappearance date and budburst date, we rely on the model validations of those metrics as validation for simulating the vernal window.

2.5. Precipitation, snowmelt, and runoff center-of-volume

To assess how a lengthening and disappearing vernal window impacts spring hydrology, we track the spring runoff center of volume (R-COV; defined as the 50th percentile of cumulative runoff from Nov. 1 through May 31), over time in our simulation results, following the methods of [1]. Similarly, we define the precipitation center of volume as the 50th percentile of cumulative precipitation from Nov. 1 through May 31, and the snowmelt center of volume as the 50th percentile of cumulative snowmelt from Nov. 1 through May 31. These precipitation and snowmelt metrics are used to evaluate the relative importance of snowmelt versus precipitation in controlling runoff, as described below in §3.2.

2.6. Statistical analysis

We used generalized least squares regression to both determine trends in vernal window transition dates and to compare differences in the rates of change in vernal window events. The trend analysis encompassed both the historical period and two climate forcing scenarios. Univariate statistical models evaluated trends over time in snow disappearance, R-COV, and budburst. For multiple regression models, dependent variables were day of year at which two vernal window events occurred (snow disappearance and budburst; snow disappearance and R-COV; or R-COV and budburst). Independent variables were year crossed with a covariate indicating vernal window event type (snow disappearance, budburst, or R-COV). We considered rates of change, i.e. modeled slopes, to be statistically significantly different if $p < 0.05$. Using the *nlme* package [29] in R 3.5.2 [30], we compared statistical models that included variety of autocorrelation and variance structures, using the multi-model inference statistic Akaike's Information Criteria to choose the model with the best overall fit [31]. Model fits that did not improve with the addition of autocorrelation or variance structure were assumed to meet the assumptions of linear regression [32].

Multiple linear regression of R-COV to identify the relative importance and explanatory power of snowmelt COV and rainfall COV was done using the R *relaimpo* package version 2.2–3 [33]. Confidence intervals were estimated using bootstrapping with 1000 iterations, and the relative importance was calculated using the Lindeman, Merenda, and Gold (LMG) method. Results are summarized in table S4.

3. Results

3.1. Climate change lengthens the vernal window

We find that both the onset (snow disappearance; figures 2(A), (B)) and closing (budburst; figures 2(C), (D)) of the vernal window have shifted to an earlier day of year over the historical period (1980–2005) and will continue this earlier shift through the late 21st century (2070–2099). In addition, the date at which the vernal window opens changes more rapidly than the date at which it closes (table 1). Historically, the snow disappearance date has shifted at a significantly faster rate than budburst

Table 1. Vernal window transitions and vernal window length through the 21st century. For each time period, the first row gives the average date (or length for the vernal window (VW) length), with the standard deviation in parentheses, of each of the four metrics assessed. The second row gives the trend in days per decade over the time period. A negative trend in snow disappearance, R-COV, and budburst indicates that the date is shifting earlier. A positive trend in vernal window length indicates the vernal window is getting longer. Asterisks indicate trend p-values (* p < 0.01, ** p < 0.001). Snow Disappearance dates are only given for the portion of the study region that retains a winter snow cover, while all other metrics are given for the entire region. Note that this leads to a longer VW Length reported than the difference between the Snow Disappearance and Budburst dates.

		Snow Disappearance	R-COV	Budburst	VW Length
			Historical		
1980–2005	Date	April 13 (6.4)	March 19 (14)	May 10 (4.9)	46 (11)
	Trend	−1.7**	−2.8*	−1.0*	1.6
			Low Forcing (RCP 4.5)		
Early 2010–2039	Date	April 6 (7.9)	March 12 (15)	May 6 (5.3)	51.9 (12)
	Trend	−2.5**	−1.3	−1.4**	3.1**
Mid 2040–2069	Date	April 1 (9.1)	March 7 (15)	May 3 (5.6)	58.2 (13)
	Trend	−2.0**	−2.0**	−0.87**	2.3**
Late 2070–2099	Date	March 29 (9.6)	March 6 (14)	May 1 (5.3)	60.6 (13)
	Trend	−1*	−0.71	−0.53	0.92
Full 2006–2099	Date	April 2 (8.8)	March 9 (15)	May 4 (6)	56.7 (13)
	Trend	−1.6**	−1.2**	−0.95**	1.5**
			High Forcing (RCP 8.5)		
Early 2010–2039	Date	April 6 (8)	March 12 (14)	May 6 (5)	53.2 (13)
	Trend	−2.2**	−1.6	−1.4**	1.9**
Mid 2040–2069	Date	March 28 (9.8)	March 5 (14)	May 1 (5.4)	61.8 (13)
	Trend	−3.4**	−2.6**	−2.2**	3.4**
Late 2070–2099	Date	March 19 (11)	February 29 (14)	April 26 (5.4)	73.6 (14)
	Trend	−3.0**	−1.9*	−1.6**	4.0**
Full 2006–2099	Date	March 29 (9.5)	March 6 (14)	May 2 (5.9)	62.5 (13)
	Trend	−3.1**	−2.0**	−1.7**	3.3**

($p = 0.0003$), advancing by −1.7 d per decade as compared to a shift of only −1.0 d per decade for budburst. In the future, snow disappearance continues to advance significantly more rapidly than budburst date ($p < 0.0001$ in differences between the rates of change between snow disappearance and budburst for both low and high forcing scenarios). By late century, the snow disappearance date shifts earlier by a total of −15 (low forcing) to −25 (high forcing) days, or an average of −1.6 (low emission) to −3.1 (high forcing) days per decade over the region where a snow cover was maintained through the entire 21st century. It is notable that some portions of the study domain will no longer have any snow cover through the winter by late century; here, we define the presence of snow cover in grid cell as at least 20 simulated days with SWE > 30 mm. Assigning a 'snow disappearance' date of January 1 to this portion of the domain that has no winter snow cover each year, the full regional average of snow disappearance advances by −26 (low forcing) to −42 (high forcing) days. Budburst date shifts earlier by only −9 (low forcing) to −14 (high forcing) days, which is −1.0 (low forcing) to −1.7 (high forcing) days per decade by late century (2070–2099).

Differential rates of change between the two events that mark the start and end of the vernal window results in an overall lengthening of this period of +15 to +28 d from historical to late century time periods (figures 2(E), (F)). We find that historically, from 1980 to 2005, the vernal window lengthened at a rate of +1.6 d per decade. While this historical trend continues at a similar rate under low forcing (+1.5 d per decade from 2010 to 2099), we find an increased rate of change (+3.3 d per decade from 2010 to 2099) in the high forcing scenario. Notably, the vernal window length begins to stabilize at the end of the century in the low forcing scenario, gaining only +0.92 d per decade from 2070–2099. This is in contrast to the high forcing scenario, in which the vernal window gains +4.0 d per decade in the late part of the century.

3.2. Snowmelt replaced by rain as the primary controls on spring runoff

Since the vernal window onset is defined by snow disappearance, areas that lose winter snow cover due to climate change also lose their vernal window (figures 2(E), (F), grey areas, and figure 3(A)). Historically, 27% (±11%) of the study area had <20 d of simulated snow water equivalent <30 mm from Nov. 1 through May 31; this metric is used here to define seasonally snow-free areas. The snow-free and therefore vernal window-free region of the study area increases to 43% (±14%) under low forcing, and 59% (±16%) under high forcing scenarios (figure 3(A)). This loss of snow cover impacts not only the existence of a defined vernal window, but also notably alters the characteristics of spring hydrology as snowmelt typically drives the spring freshet, a pulse of freshwater that rapidly enters river systems near the opening of the vernal window. To assess how a lengthening and disappearing vernal window impacts spring hydrology, we track the spring runoff center of volume (R-COV. There is no significant trend in the LOCA-projected precipitation center of volume (COV), allowing for a controlled assessment of the impact of the vernal window; all changes in simulated R-COV here are caused by changes in temperature-driven snow dynamics, liquid versus solid precipitation, and evapotranspiration.

Like the start and end of the vernal window, we find that the spring R-COV date shifts earlier, with a rate of −1.2 (low forcing) to −2.0 (high forcing) days per decade over the 21st century (table 1). The vernal window-free portion of the study region has no change in R-COV, which is consistent with expectations based on a constant precipitation COV. An unexpected finding, however, is that despite retaining snow cover and a vernal window, spring hydrology in the most northerly and high-elevation parts of our study domain are no longer snowmelt-dominated by the late 21st century in the high forcing scenario (figure 3(C)); rather, the R-COV timing shifts closer to that of the vernal window-free region. Stated another way, even the portion of the domain that retains a snow cover has a change in spring hydrologic character toward a rainfall-dominated regime. Multiple linear regression analysis of region-wide R-COV as a function of snowmelt COV and rainfall COV (with rainfall defined as liquid precipitation) shows that, historically, snowmelt COV was relatively more important to spring freshet timing than rainfall COV (a scaled relative importance of 0.56 compared to 0.44). By late century, the relative importance of these two explanatory variables switches, with rainfall COV importance greater than snowmelt COV under both high and low forcing scenarios (figure 4(A)). Where a vernal window remains present, snowmelt COV retains its position as the more important of the two drivers, yet its relative importance is reduced from 0.68 historically to 0.60 (low forcing) and 0.56 (high forcing), while rainfall COV increases from 0.32 historically to 0.40 (low forcing) to 0.44 (high forcing) (figure 4(B)). Notably, the explanatory power of the combination of these two variables declines from 77% historically to 53% by late century (high forcing) in the vernal window present region, suggesting that additional mechanisms increase in their control over spring hydrology.

4. Discussion

This study is novel in demonstrating that snowmelt is occurring at a faster rate than budburst across the northeastern US, resulting in a longer vernal window both historically and in the future. The relative importance of factors that drive trends in snowmelt and budburst may account for some of this disparity. Warmer temperatures are largely responsible for advanced snowmelt timing, although solar radiation also plays a role, particularly in high elevation areas [34] or with earlier snowmelt onset [35]. By contrast, advancing phenological events such as budburst and leaf expansion are controlled by multiple interacting cues, including temperature and photoperiod [36], with photoperiod exerting a strong control over dormancy release in late successional forest species [37]. Thus, the vernal window may be lengthening because snow disappearance continues to advance earlier in the year as the climate warms while the physiological constraint of photoperiod limits the extent to which forest species can respond to warmer spring temperatures. One of the consequences of the lengthening vernal window is that spring runoff is advancing and becoming more closely tied to precipitation COV, as in snow-free regions. The hydrologic impacts of these phenomena are not well-understood within the northeastern US, as most prior research examining the effects of earlier spring snowmelt and runoff has occurred in more mountainous areas (e.g. *11, 12*). However [7], suggest that advances in the timing of peak spring flows and increases in winter rainfall together may result in reduced water storage and summer drought in the Northeast, which is consistent with impacts in other regions characterized by seasonal snow cover. While our study clearly demonstrates the declining role of snowmelt in driving spring hydrology, our results alone do not fully elucidate which mechanisms gain importance in influencing spring runoff timing. Our data show that the combined explanatory power of rainfall and snowmelt timing on spring runoff timing decreases over the 21st century. We hypothesize that a more ephemeral snowpack with more frequent mid-winter melt events would decouple snow disappearance dates from R-COV. This decoupling would not necessarily strengthen the relationship between runoff and rainfall timing, as in some cases rain-on-snow events cause mid-winter melts [38, 39]. In this way, ephemeral snowpack could explain the decrease in the combined explanatory power of both rainfall and precipitation on R-COV.

Our results are based on modeled SWE, runoff, and budburst, and we acknowledge that uncertainties associated with each of these analyses influence our findings. For example, while the agreement between measured and modeled SWE is robust across most of the study domain (supplementary figure S2), there is heterogeneity in R^2 values across validation sites. Notably, simulated SWE underestimates observed SWE where lake-effect precipitation has a strong influence. This underestimation is to be expected since WBM, the model we used to simulate SWE, does not explicitly represent phenomena that lead to lake-effect

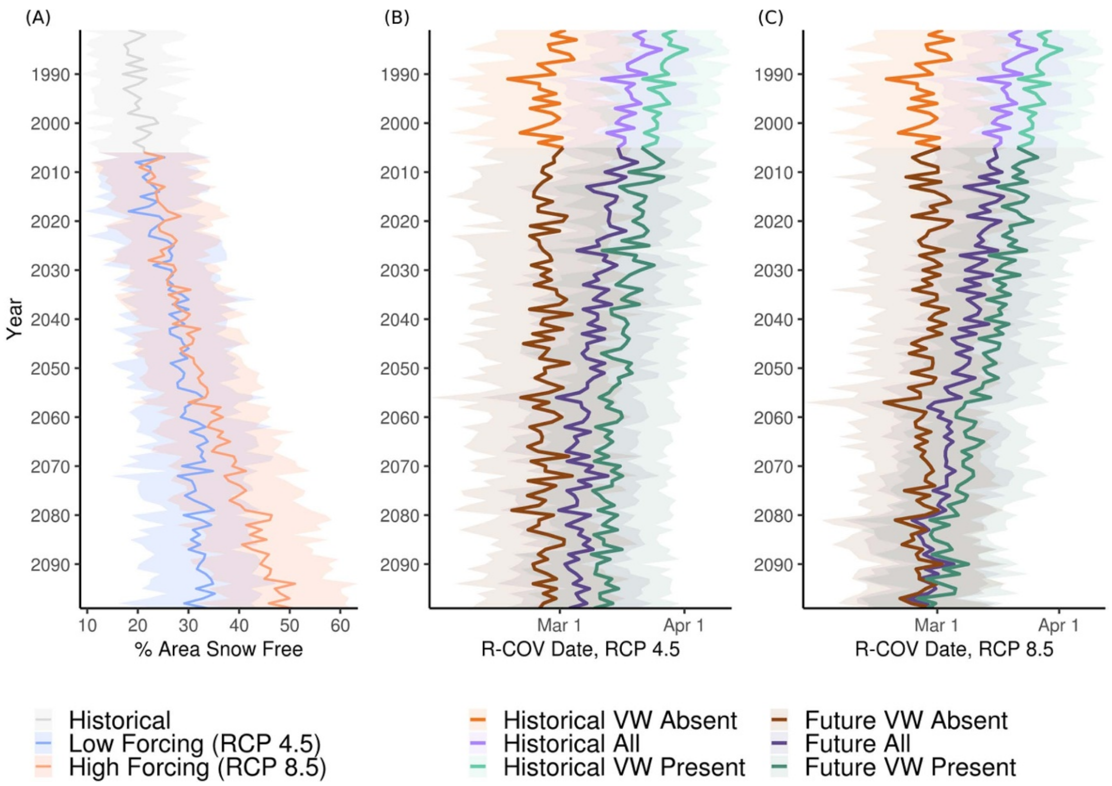

Figure 3. Spring runoff timing changes and converges between snow-free and snow-covered regions. Ensemble mean of (**A**) percent study area that is snow free for historical low forcing (RCP 4.5, blue) and high forcing (RCP 8.5, red), and R-COV date for (**B**) low forcing RCP 4.5, and (**C**) high forcing RCP 8.5. Standard deviations of the ensemble simulations are shown as shaded bands. R-COV date is presented for the vernal window-absent (orange), vernal-window present (turquoise) and entire (purple) region. As shown in panel (**A**), the percent of the study region accounted for in the vernal window-absent (VW-absent) versus vernal window-present (VW-present) areas changes over time.

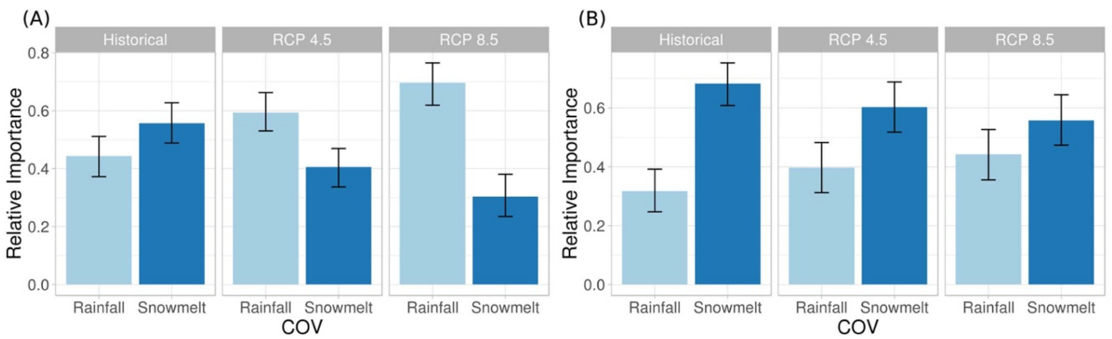

Figure 4. Rainfall becomes more important than snowmelt as a control on runoff timing. Multiple linear regression analyses of the relative importance of rainfall COV versus snowmelt COV for explaining R-COV are shown for (**A**) the full region and (**B**) the vernal window present region for historical, low forcing (RCP 4.5 late century (2070–2099), center column) and high forcing (RCP 8.5 late century (2070–2099), right column). Values are means of normalized relative importance values, with bars showing standard deviation.

snowfall, such as cold continental air masses moving across ice-free lake surfaces [40]. The phenology model parameters are optimized to represent deciduous broadleaf and mixed deciduous-coniferous forested ecosystems (see Methods); this parameterization likely does not capture the impact of climate change on cropland (4.1% of the study region), coniferous-dominated forests (0.6%), or urban areas (3.3%) [28], nor does the model simulate shifts in vegetation that may occur in the 21st century or the challenges that the decoupling of temperature and photoperiod may place on temperate tree species to adapt to climate change *in situ* [41]. In addition, coupled land-atmosphere models have already pointed toward the potential for a longer vernal window to damage plant tissues [42], thereby reducing evapotranspiration and impacting the ecosystem's water budget. A coupled land-atmosphere model with dynamic vegetation controls on phenology would help to disentangle complex land-atmosphere feedbacks related to soil moisture and vegetation state during the advancing, lengthening, and eventual disappearing vernal window. These types of further studies will be critical to understanding the impacts of shifting seasons in both northeastern North America and globally [43].

5. Conclusion

Here we have identified potentially large changes in the vernal window timing and length, as well as a shift in the hydrologic character of seasonally snow-covered northern forests by the end of the 21st century. Shifts in the timing of both the entire vernal window and key hydrologic transitions that occur within it carry implications for forest ecosystem function [7, 14, 42, 44, 45]. Snowmelt timing and its impact on soil moisture play important roles in forest productivity [46], disturbance [14], and drought resilience [42, 43, 47]. Soil water availability is one of the key drivers of inter-annual variability in forest productivity [48], and earlier snowmelt timing is known to decrease summer ecosystem productivity [49]. Changing hydrologic transition times will also likely impact aquatic ecosystem processes. The timing and frequency of high flow events, such as those caused by the rapid melting of a large snowpack, shape the metabolic processes within streams by scouring and burying biomass [50], mobilizing allochthonous carbon inputs [51], and flushing nutrients from snow reservoirs and soil pools [52]. These high flow events are also important to species-level phenology, as they impact the timing of migratory fish movements upstream [53], and the accompanying snowmelt driven low temperatures are required for spawning [54]. Future studies that focus on the ecological impacts of a lengthening and disappearing vernal window are critical to understand how ecosystem function will change in seasonally snow-covered northern forests.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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