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RESEARCH ARTICLE

Long-term measurements of seasonal snowpacks indicate increases in mid-winter snowmelt and earlier snowpack disappearance in the northeastern U.S.

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Abstract

Snowpacks are changing in northeastern North America as the regional climate warms, yet the relative influence of changes in precipitation compared to changes in ablation on snowpacks is poorly understood. We use 56 years of weekly snow water equivalent (SWE) measurements from three locations within a study site which vary in elevation and aspect, paired with adjacent daily climate measurements, to investigate relationships between climate and snowpack onset, maximum, and disappearance. Maximum snowpack size and snowpack duration are shrinking at all sites, at rates ranging from 4.3 days/decade at the coldest site to 9.6 days/decade at the warmest site. The shorter snowpack duration at all sites results from an earlier snowpack disappearance, stemming largely from reduced winter maximum snowpack sizes. Trends in snowpack establishment dates vary, with the south-facing site showing a trend toward later establishment but the two north-facing sites showing no change. The date of the maximum snowpack size varies by aspect and elevation but is not changing at any site. Using a 0˚ C threshold for frozen vs. liquid precipitation, we only observed a decrease in the proportion of precipitation falling in frozen form at the warmer, south-facing site in the winter period. In contrast, the total weekly snowpack ablation in the winter period has been increasing at least marginally at each site, even at sites which do not show increases in thawing conditions. Ablation increases range from 0.4 cm/decade at the warmest site, to 1.4 and 1.2 cm/decade at the north-facing sites. The south-facing site shows only marginally significant trends in total winter ablation, which we interpret as being limited by the smaller snowpack at this site. Overall, we conclude that rising air temperatures are leading to warmer, more sensitive snowpacks and this change becomes evident before those temperatures lead to changes in precipitation form.

Environmental Data Initiative: Weekly Snow and Frost Measurements: https://doi.org/10.6073/pasta/5e1c5cb3aae2391cda9ca3ab4487046c Vapor Pressure Measurements: https://doi.org/10.6073/pasta/c3a8d64d96a3dbb8edebf1c9f23bcd5f Daily Temperatures: https://doi.org/10.6073/pasta/e55086211f64b6ba71e667ca46018f2d Daily Precipitation: https://doi.org/10.6073/pasta/780d9eabe5e0e40fcb1ab44a34210e38 Daily Solar Radiation: https://doi.org/10.6073/pasta/a74f21929fc66d7b99f9cc343e575177.

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Introduction

The loss of seasonal snow cover is a key indicator of climate change across the Northern Hemisphere [1]. In northeastern United States, the size and duration of snowpacks have decreased as the climate warms [2,3] and are projected to continue to decline under a range of emissions scenarios [4,5]. These trends have implications for natural and human systems [6], including impacts on groundwater recharge and water supply [7], soil properties [8], forest productivity [9], wildlife mobility and competition [10–12], and winter recreation and tourism [2,13,14]. For some processes the length of the snowpack season matters more than the size of the snowpack (e.g., soil freezing [15]). Other concerns depend more on the overall size of the snowpack (e.g., groundwater recharge [16]), and some are impacted by both snow depth and duration (e.g., winter tourism [13]).

The onset of the seasonal snowpack begins when temperatures favor snowfall over liquid precipitation, and land surface conditions allow for net snow accumulation [17]. In the northeastern U.S., air temperatures in November have not changed significantly, whereas December is among the months showing the greatest warming [3,18], yet paradoxically the start date of the continuous snow cover does not appear to have changed appreciably [3,19]. Current climate projections under various emissions scenarios predict that future warming in this period will result in later snowpack onset dates [4], yet this snowpack characteristic appears somewhat resilient to climate changes to date [3,4,19].

When the snowpack develops early in the season, it insulates the soil by altering both convective heat transfer from air temperature and radiative energy transfer through changes in albedo [20]. Thus, the duration of the snow-covered season can affect the yearly heat balance of the soil [15], with attendant effects on temperature-dependent soil processes like respiration [21,22] and nitrogen cycling [23,24]. Lack of snow also exposes soils to cold winter air, increasing susceptibility to soil frost formation [15,25]. Soil frost has cascading effects on forest ecosystems, such as changes in hydrologic flowpaths [26,27], soil and litter decomposer communities [28–30], and both below- and aboveground productivity [9,31].

The characteristics of the snowmelt season integrate conditions over a wider range of months than the snowpack onset period. Spring snowmelt, culminating in snowpack disappearance, is dependent on both springtime weather to drive melting [32], as well as the depth of the snowpack at the beginning of the snowmelt period [15], which reflects the balance between accumulation and melting over the winter months [33]. Atmospheric conditions, such as precipitation phase and the surface energy budget influence snowpack longevity in the spring [32,34]. Snowmelt initiation timing reflects the overall cold storage of the snowpack (the amount of energy required to "ripen" the snowpack), which is a function of snowpack temperature and water content [35]. When snowmelt starts earlier in the year, it tends to happen more slowly [33,36], which has implications for water resources [37], the timing of stream runoff [38], and growing season soil moisture [15]. In addition, earlier snow disappearance can allow soils to warm earlier [15,39], altering rates of soil microbial activity [24] and above- and belowground respiration in spring [40].

Determining trends in midwinter snowpack size and temperature, in addition to changing spring climate conditions, is therefore essential for understanding how declining seasonal snow cover impacts forest ecosystems in the subsequent growing season. The midwinter period, when the snowpack is generally accumulating [32], may ultimately govern the characteristics of spring snowmelt through the mass and overall cold content of the snowpack [33,35,39]. Snowpack mass and cold content may each be sensitive to different climatic drivers, such as midwinter thaws [36], precipitation form or amount [14,41], or radiation balance [34]. In the northeastern U.S., midwinter thaw temperatures are increasing [2,42], and are projected to continue [4]. Precipitation volume is also increasing on an annual basis [43], while the proportion falling as snow is diminishing at sites in the region [41,44].

The northeastern U.S. lacks a region-wide snow monitoring network that can match long-term measurements of snowpack mass dynamics with high-quality, co-located weather data to elucidate relationships between climate and snowpack characteristics important to ecosystems and people [2], such as the SNOTEL network managed by the U.S. Natural Resource Conservation Service in the western U.S. [32,33]. Recent contributions toward addressing this deficiency in the northeastern U.S. have used snow depth to represent the historical snowpack [3,42], remote sensing to depict snowpack depth and duration [45–47] or shorter historical snow water equivalent (SWE) records combined with modeling [4,48,49]. Our study advances this body of work by utilizing weekly, long-term measurements of SWE from three nearby sites that vary along a climate gradient, as well as co-located precipitation and air temperature measurements. This allows us the opportunity to assess the relative roles of any changes in precipitation as compared with changes in weekly net snowpack ablation in our understanding of the changing snowpacks in our region.

This paper describes 56 years of snowpack changes using three different locations along a climate gradient at a site in the northeastern U.S. Using daily weather data from the site, we ask to what degree are reported changes in snowpack characteristics in the region due to changes in precipitation compared with increases in snowpack ablation.

Methods

Study site

This study was conducted at the Hubbard Brook Experimental Forest (HBEF) in New Hampshire, USA (43˚ 56' N 71˚ 45' W; Fig 1). The HBEF is administered by the USDA Forest Service and is described in detail in Holmes and Likens (2016) [50]. The data used in this analysis have all been collected as a part of the USDA Forest Service's hydrometeorological research program and are publicly available. The HBEF climate is cool and continental with summer

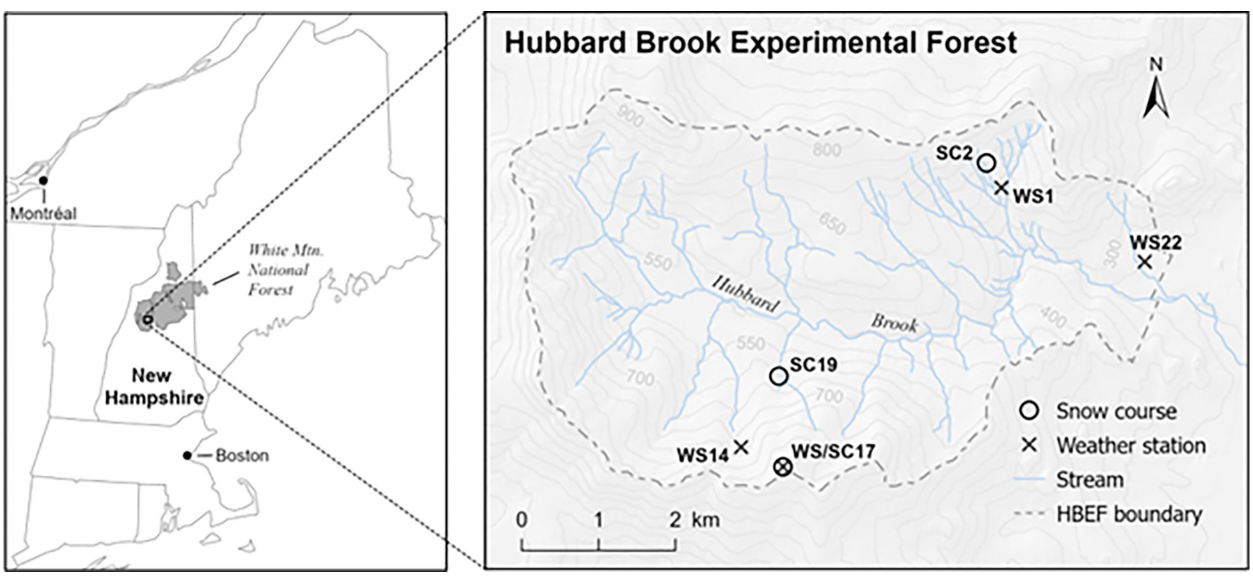

Fig 1. Map of the hubbard brook experimental forest. The panel on the left places the HBEF within the northeastern United States, and the panel on the right shows the locations of the snow courses and weather stations used in this analysis. All map layers are published and available at https://hubbardbrook.org/data-catalog/. Specific layers are cited in the [S1 Methods].

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temperatures averaging 18˚ C in July and winter temperatures averaging -8˚ C in January. Snowpacks vary year to year, but historically begin developing by December and persisting into April [49]. The vegetation is primarily mature, second-growth forests, with the northern hardwoods sugar maple (*Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.), and yellow birch (*Betula alleghaniensis* Britt.) dominant at low and mid-elevations and the conifers red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* (L.) Mill.)) dominant at higher elevations [51].

Snowpack measurements and derived variables

The USDA Forest Service maintains a network of snow courses distributed throughout the HBEF where weekly snowpack depth and SWE measurements are taken using a Federal snow sampling tube (Rickly Hydrological Company, Columbus, OH, United States) along a transect consisting of 10 measurements spaced 2 m apart [52]. Three snow courses were selected for this study because they have the longest records (>50 years) and represent a range of elevations and aspects (Fig 1). Snow course (SC) 2 has a southerly aspect and an elevation of 555 meters. Snow courses 19 (SC19) and 17 (SC17) both have northerly aspects and elevations of 600 m and 898 m, respectively. The three sites thus lie along a general climate gradient from warmer to colder, driven by a change in aspect from south to north and by an increase in elevation. In this study, the highest of the three snow measurement sites is located in a spruce-fir dominated stand, while the lower two sites are in northern hardwoods. We used SWE (instead of depth) as the central metric for calculating snowpack characteristics because decreases in SWE represent net snowpack losses through ablation, whereas depth measurements are affected both by ablation and settling of the snowpack.

Using the weekly SWE measurements, we calculated the dates of snowpack onset and disappearance for each season. Snowpack onset was defined as the date when SWE first reached a 6 cm threshold. This threshold was chosen because it both represents the snowpack size observed to be sufficient to decouple soil temperatures from air temperatures at our site [15, S1 Fig, S2 Methods], and allows us to avoid uncertainties in historical measurement protocols for early season, possibly intermittent, snow events. The last week of recorded SWE was used to define the end of the seasonal snowpack, and the duration of snowpack was calculated as the number of days between snowpack onset and snowpack disappearance (Table 1).

Overall snowpack size was defined as the maximum SWE for the season, and we recorded the date when the maximum was reached. Following Harpold and Brooks [32], we define *winter* as the period of snowpack accumulation from December 1 to the median date of maximum SWE for each snow course over the period of record and we define *spring* as the period of snowpack disappearance following the median date of maximum SWE through the median date of last recorded snow for each snow course. We used December 1 as the winter starting point because it is the beginning of meteorological winter. Thus, each snow course has slightly different time periods for both *winter* and *spring* (Table 1).

Finally, we calculated snowpack reductions during *winter* by identifying weeks within these time periods where the weekly SWE measurement was lower than the previous week. In these cases, a weekly net loss was calculated by subtracting the current week SWE from the previous week SWE. The precision of our weekly loss calculation is limited by two factors. First, there are instances where ablation events are buffered by snow events, such that instances of water loss are obscured. Second, there are instances under smaller snowpacks where water losses are more severe at the colder sites simply because there is more water available in the relatively larger snowpacks.

Table 1. Datasets and definitions of derived variables used in this study.

Datasets	Source
Snowpack	USDA Forest Service, Northern Research Station. 2023a. Hubbard Brook Experimental Forest: Weekly Snow and Frost Measurements, 1955—present ver 18. Environmental Data Initiative. [52]
Daily temperature	USDA Forest Service, Northern Research Station. 2024a. Hubbard Brook Experimental Forest: Daily Temperature Record, 1955—present ver 13. Environmental Data Initiative. [53]
Daily precipitation	USDA Forest Service, Northern Research Station. 2024b. Hubbard Brook Experimental Forest: Daily Precipitation Rain Gage Measurements, 1956—present ver 21. Environmental Data Initiative. [58]
Daily vapor pressure	USDA Forest Service, Northern Research Station. 2023b. Hubbard Brook Experimental Forest (USDA Forest Service): Vapor Pressure Measurements, 1966—present ver 10. Environmental Data Initiative. [56]
Solar radiation	USDA Forest Service, Northern Research Station. 2024c. Hubbard Brook Experimental Forest: Daily Solar Radiation Measurements, 1959—present ver 13. Environmental Data Initiative. [62]
Snowpack Derived Variables	
	Definition
Onset (day of year)	The date at which the snowpack first reaches 6cm SWE [15]
Last SWE (day of year)	The date of the last recorded SWE of the season
Duration (days)	The number of days between onset and Last SWE each season
Winter	The period between Dec 1 and the median date of maximum SWE at each site (see Table 1 for dates) [32]
Spring	The period between the median date of maximum SWE and the median date of last SWE at each site (see Table 1 for dates) [32]
Snowpack reduction (cm)	The difference in SWE between weeks when a subsequent week showed a lower SWE than the previous week
Climate Derived Variables	
Average daily temperature (˚ C)	The daily average temperature derived from the nearest weather station and adjusted by a lapse rate of -0.0065˚C per meter of elevation gain [54]
Thawing degree days (TDD)	The cumulative sum of average daily temperatures at each site exceeding a 0˚ C threshold [19]
Condensation Degree Days (CDD)	The cumulative sum of the differences between the estimated snow surface temperature and the dewpoint temperature when the snow surface temperature was colder than the dewpoint temperature (see methods)
Total Precipitation (mm)	The sum of daily precipitation amounts at the nearest weather station
SNOW (mm)	The sum of daily precipitation that fell on days with daily average temperatures at or below 0˚ C [59]
SNOW/Precip	The fraction of the daily precipitation that fell on days with daily average temperatures below 0˚ C [61]

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Climate measurements and derived variables

Long-term meteorological data from nearby weather stations within the HBEF were used to calculate variables describing climate conditions expected to influence the energy budget of a snowpack (Fig 1). For temperature variables, we used the nearest weather station with a temperature record that matched the snow record in duration and adjusted the daily average temperature [53] up or down using a lapse rate of 0.0065˚C/m [54]. For SC2, the nearest station was weather station 1, located 77 m downslope and with a similar aspect. For SC19 and SC17, we used weather station 14, which was 132 m higher than SC19 and 166 m lower than SC17, with a similar aspect. For each site we used daily average temperatures to also calculate a thawing degree days metric (TDD, defined as the cumulative sum of average daily temperatures exceeding a 0˚ C threshold).

In order to estimate conditions of latent heat transfer to the snowpack, we calculated a condensation degree-day (CDD) metric, which was based on an estimate of snow surface temperature and the modeled dewpoint temperature. Dewpoint temperature was modeled for the entire record at weather stations 1 and 14 using a random forest model [55] trained on observed dewpoint temperature at station 22 between 1981 and 2023, with mean daily, minimum daily, and diurnal range in air temperature as independent variables. The dewpoint temperature at station 22 was calculated using the daily average temperature and relative humidity measurements [56] (Fig 1), using the Bolton (1980) equations [57]. The random forest model prediction versus observations had a relationship of predicted = 0.95*observed+0.1 (R^2 = 0.95) and a mean absolute error = 1.8˚C. The model was then used with weather stations 1 and 14 to predict the mean daily dewpoint at those stations over their observation record. We assumed the snow surface temperature was equal to the daily average air temperature when air temperature was less than or equal to 0˚ C, and 0˚ C when the air temperature was above freezing, and then compared this surface temperature estimate with the dewpoint temperature. In instances where the estimated snow surface temperature was less than the dewpoint temperature, the condensation degrees for the day were calculated as the difference. In instances where the estimated snow surface temperature was greater than the dewpoint temperature, we assumed that there was no latent heat transfer into the snowpack. The CDD metrics for the analyses were cumulative sums of the daily values over the time periods in question.

For precipitation variables, we paired each snow course with the nearest weather station with a long-term daily precipitation record. We paired SC2 with weather station 1, SC19 with weather station 14, and SC 17 with weather station 17 [58]. We then matched daily precipitation values with adjusted daily average air temperatures to partition precipitation that fell during freezing air temperatures (which we called SNOW) [59]. We realize this oversimplifies the range of temperatures at which precipitation can occur as snow, which can vary between -2 and 2˚C [60] and also does not allow for mixed precipitation. Because we are concerned primarily with snowpack SWE and thus heat transfers to the snowpack, a 0˚C threshold was deemed suitable. We report both total precipitation and the fraction falling as SNOW [61].

To capture trends in solar radiation, we used long-term solar radiation data [62] from weather station 22 at US Forest Service headquarters (Fig 1). We assumed that the trend in solar radiation at station 22 was indicative of the trend at all sites, even though they would have different total insolation due to their different topographic settings.

Methods and instrumentation for all snow and climate data are described in the metadata for each published dataset.

Assessing trends in the snowpack and drivers of change

Temporal trends in snowpack and climate variables were tested for significance ($\alpha <= 0.05$) using the Kendall correlation in the *cor.test()* function in R, with instances where $\alpha <= 0.1$ and >0.05 reported and treated as marginally significant. Linear slopes associated with those trends were estimated using the Sen robust estimation technique [63]. This approach uses the median of a set of slopes generated from each unique pair of data points in the time series. Correlations between snowpack and climate variables were quantified to provide insight into whether reductions in snowpack could be due to changes in inputs (i.e., precipitation amount, precipitation phase), or changes in other variables such as solar radiation, air temperature, and dewpoint temperature that affect ablation. Data analyses were conducted using R version 4.3.1 [64]. The strength of the relationships between two snowpack descriptors (maximum SWE and last recorded snow per season) and climate variables or antecedent snowpack variables were described using a Spearman rank correlation as implemented with the *cor.test()* function.

Table 2. Median lengths (in days) and trends over time in the timing of: Snowpack duration, snowpack onset, day of maximum snow water equivalent, and day of the last recorded snow, as well as the maximum SWE for the year, at three sites that vary in aspect and elevation at Hubbard Brook from the winter of 1968 through the winter of 2023.

	SC 2			SC 19			SC 17		
	value	trend	p	value	trend	p	value	trend	p
Median duration (days)	**84**	**-0.96**	**< 0.001**	**97**	**-0.647**	**0.007**	**119**	**-0.43**	**0.033**
Day of Onset	**35 (Jan 4)**	**0.58**	**0.007**	36 (Jan 5)	n.t.	0.117	32 (Jan 1)	n.t.	0.129
Day of maximum SWE	95 (Mar 3)	n.t.	0.400	113 (Mar 21)	n.t.	0.87	115 (Mar 23)	n.t.	0.191
Day of last snowpack	**128 (Apr 5)**	**-0.25**	**0.008**	**138 (Apr 15)**	**-0.29**	**0.003**	**153 (May 1)**	**-0.17**	**0.035**
Max SWE (cm)	**15.85**	**-0.14**	**0.012**	**21.55**	**-0.18**	**0.003**	**25.00**	**-0.26**	**< 0.001**

Variables are described in Table 1. Trends are reported in instances when the p-value <0.05. Instances with no statistically significant trend are indicated with an n.t.

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Results

The duration of the snowpack at all three sites varied by landscape position and across the long-term record (Table 2, Fig 2). The south-facing site (SC2), which had a median snowpack duration of 84 days, shows a shortening of snowpack duration of 9.6 days/decade ($p < 0.01$). The highest, coldest site (SC17), whose median snowpack duration was 119 days, is shortening at a rate of 4.3 days/decade ($p = 0.03$). Median snowpack duration and change over time at the middle site (SC19) were between the low- and high-elevation sites, occurring for a median of 97 days and shortening at a rate of 6.5 days/decade ($p < 0.01$). Changes in snowpack duration at the two north-facing sites (SC19 and SC17) are due to changes in the date of last recorded snow, while changes in snowpack duration at the south-facing site (SC2) are due to changes in dates of both onset and last recorded snow (Table 2). The rates of change reported are slightly conservative because of rare instances later in the record where a 6 cm snowpack onset was not reached during that year. These years (2016 at all three locations and 2006 at SC2) were excluded from the snowpack duration analysis. Like snowpack duration, the seasonal maximum amount SWE has decreased significantly over time at all three sites (Table 2, Fig 3), with declines over the 56-year record of 7.8, 10.1, and 14.6 cm for snowcourses 2, 19, and 17, respectively. However, the date on which the snowpack reaches the maximum has not changed over time at any of the sites. (Table 2, Fig 2).

All three sites show increasing average temperatures in the winter period, with rates of increase of 0.3–0.4˚C/decade, and no changes in total amount of precipitation in this period (Table 3; Fig 4A–4F). Only the south-facing site (SC2) shows trends in climate variables associated with crossing the freezing threshold, however, with an increase in TDD of 2.9˚C/decade and a 3% decrease per decade in the proportion of snow to total precipitation (Table 3, Fig 4A–4C). The two north-facing sites do not show any increases in thawing conditions (TDD, CDD), nor changes in the form of precipitation. All temperature-related meteorological variables tested were strongly correlated with the maximum snowpack size (Table 3).

Cumulative snowpack losses during *winter* increased over time at SC19 and SC17 ($p < 0.01$, Fig 5A, Table 3), while increases in cumulative snowpack losses were only marginally significant at SC2 ($p = 0.06$). The rates of loss in this period varied from 0.4 cm/decade at SC2, 1.4 cm/decade at SC19, and 1.2 cm/decade at SC17. Losses at both SC19 and SC17 increased because both the number of loss events per *winter* period increased (Fig 5B) and the total volume of loss per event increased (Fig 5C). The average size of a weekly snowpack loss increased by 0.27 cm/decade at SC19 ($p<0.001$) and 0.19 cm/decade at SC17 ($p = 0.02$) and did not show a change at SC2. The number of weekly net losses per *winter* period increased at

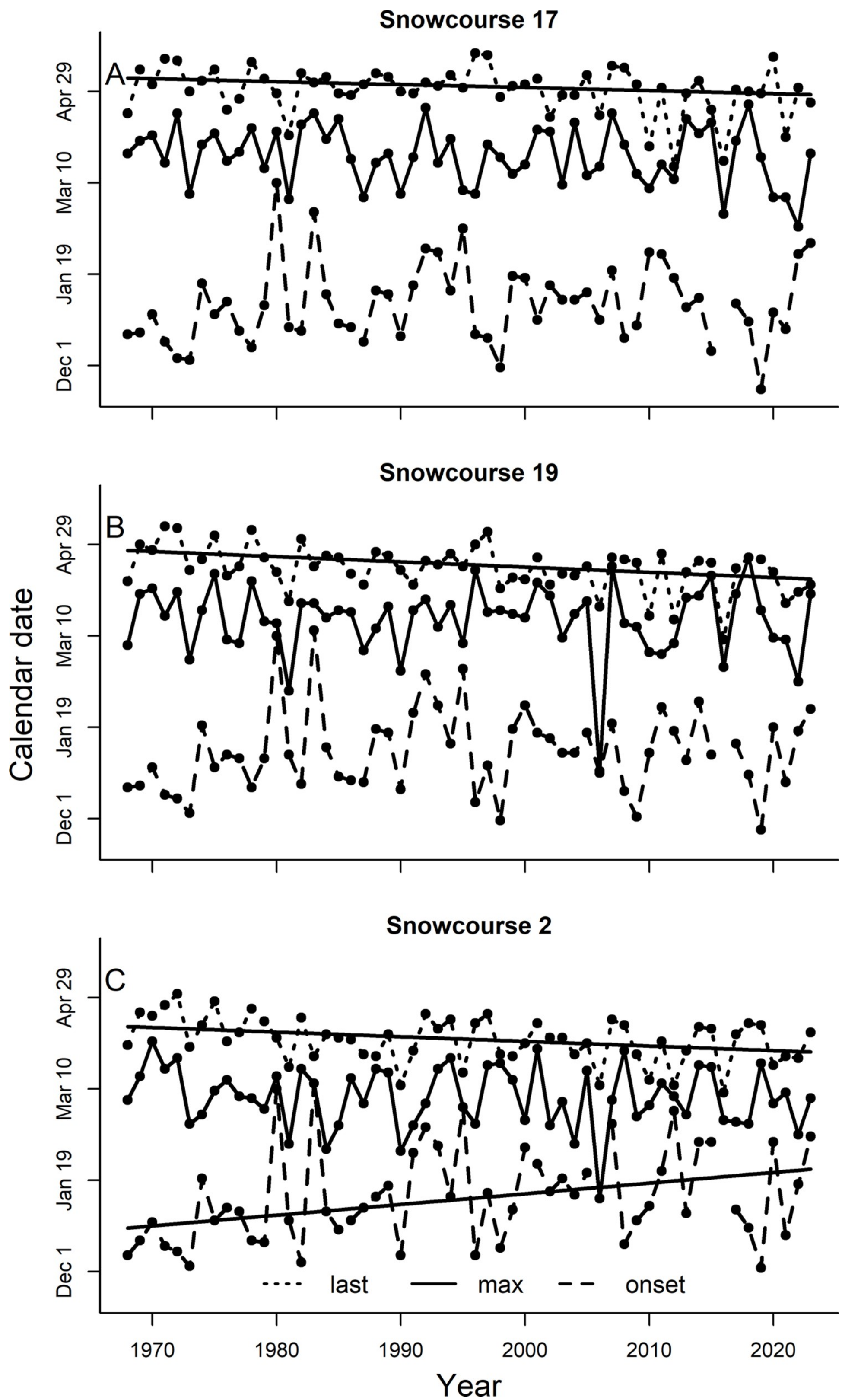

Fig 2. Dates of major snowpack milestones. In each panel the lower line is the onset date (when the snowpack reached 6 cm of snow water equivalent). The middle line is the date the snowpack reached its maximum, and the top

line indicates the date of the last recorded snow. Solid lines through the data indicate significant trends at p< = 0.05. Slopes and precise p-values are found in Table 2. Panel A corresponds to snowcourse (SC)17, which faces north at 898 meters in elevation. Panel B corresponds to SC19, which faces north at 600 meters, and panel C corresponds to SC2, which faces south at 555 meters.

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least marginally at all three sites (0.2 events/decade at SC19 (p = 0.021), 0.47 events/decade at SC17 (p < 0.001), and 0.2 events/decade at SC2 (p = 0.076). However, cumulative weekly snowpack losses during *winter* were not consistently correlated with annual maximum SWE across the three sites (Table 3).

In spring, the annual date of last recorded snow occurred earlier at all three sites (Table 1; Fig 2) and is advancing at rates of 2.5 (SC2), 2.9 (SC19), and 1.7 (SC17) cm/decade at the three sites. The proportion of precipitation falling as snow did not change at any site in this time (Table 4). Temperature-related environmental variables (average air temperature, TDD, CDD, and snow/total precipitation) were generally correlated with the date of last-recorded snow (Table 4), but of these only CDD showed any change over time and at only one site. Since the direction of this change is indicative of less thawing pressure from latent heat transfer, we do not see any environmental changes in the *spring* period that would increase snowmelt pressures. Solar radiation was not correlated with the date of last snow at any of the sites (S1 Table). In contrast to the environmental variables, annual maximum SWE was both highly correlated with the last recorded snow date and decreasing over time (Table 4), indicating its primary importance in explaining the shortening of the spring period.

Discussion

Snowpack duration and amount have clearly declined at our study site. Declines in snowpack duration were largely due to earlier snowpack disappearance in spring, consistent with other regional observations [3,19], while a change in snowpack onset was only evident at the south-facing site. These results reinforce recent observations in the region by Murray et al. (2021), [3] who measured snow covered days with no SWE threshold and found a consistent yet non-significant trend of declining snow cover [3], and Burakowski et al (2022), who predicted

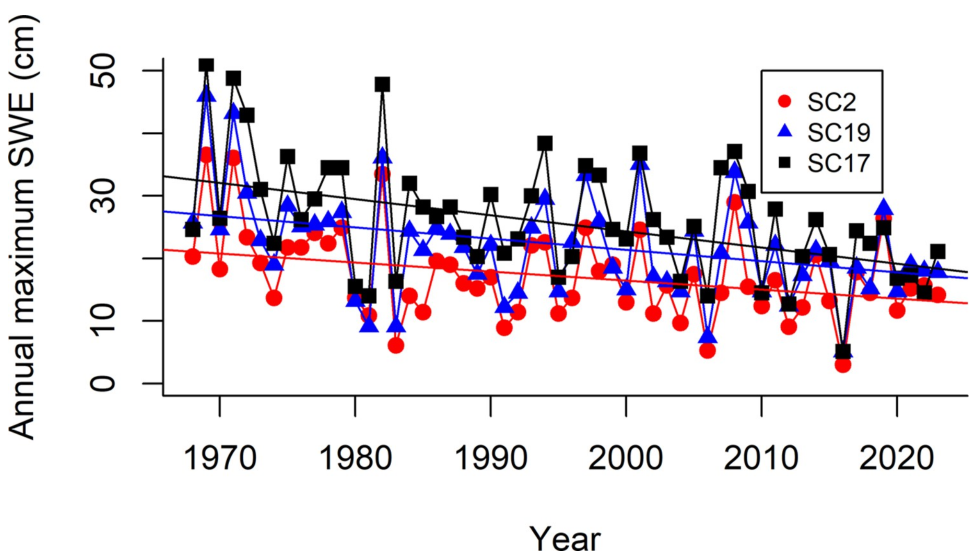

Fig 3. Annual maximum snowpack size (SWE) from three snowcourses (SC) which vary by elevation and aspect. Solid lines indicate significant trends at p< = 0.05. Slopes and precise p values are found in Table 2.

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Table 3. Environmental conditions in the *winter* timeperiod at each location, showing any changes over time and correlations between each variable and the maximum size of the snowpack (SWE).

	SC2		SC 19		SC 17	
	ρ	**trend**	**ρ**	**trend**	**ρ**	**trend**
Tave (˚C)	**-0.44**	**0.04**	**-0.51**	**0.03**	**-0.43**	**0.03**
p-value	**<0.001**	**0.001**	**< 0.001**	**0.004**	**< 0.001**	**0.004**
TDD	**-0.56**	**0.29**	**-0.59**	n.t.	**-0.44**	n.t.
p-value	**<0.001**	**0.047**	**< 0.001**	0.340	**< 0.001**	1
CDD	**-0.47**	n.t	**-0.46**	n.t.	**-0.40**	n.t.
p-value	**< 0.001**	0.243	**< 0.001**	0.81	**0.002**	0.960
Precip (mm)	0.23	n.t.	**0.36**	n.t.	**0.39**	n.t.
p-value	0.081	0.347	**0.007**	0.882	**0.003**	0.344
SNOW/total precip	**0.48**	**-0.003**	**0.44**	n.t.	**0.41**	n.t.
p-value	**< 0.001**	**0.018**	**<0.001**	0.516	**0.002**	0.48
Cumulative snowpack loss (cm)	n.s.	0.04	**0.29**	**0.14**	n.s.	**0.12**
p-value	0.167	0.062	**0.029**	**< 0.001**	0.555	**0.001**

Cumulative snowpack loss is the sum of the net weekly melts. Other variables are described in Table 1. Trends are reported in instances when the p-value <0.1, with instances of p-value< = 0.05 in bold. Instances with no statistically significant correlation are indicated with an n.s. and instances with no significant trend are indicated with an n.t.

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near-term declining snow cover relative to a 1980–2005 baseline under different emissions scenarios [4]. More broadly, Vincent et al (2015) observed declines in snowpack duration at sites across Canada, with most sites showing declines in the spring period [65]. While the dates of snowpack disappearance were highly correlated with the air temperature derived variables (mean air temperature, TDD, CDD) during the spring period, these variables have not changed over time in this period, nor has the proportion of precipitation falling as snow. This strongly suggests that the earlier snowpack disappearance dates we report here are best explained by declines in maximum SWE, which reflect winter processes and not spring conditions.

The changes in snowpack onset and duration are consistent with other observations in the region. Previous studies have used different thresholds for delineating the start of the snowpack season, including the beginning of a continuous snowpack [3,19] and a 3 cm SWE threshold [4]. None of them have shown a change in the timing of snowpack onset, despite early winter warming both historically [3,18] and under projected climate change [4]. Our relatively large threshold for snowpack onset was chosen for its significance in decoupling soil temperatures from air temperature [66,67], and thus relevance to questions related to soil frost [9,20,68]. The onset date using our definition of 6 cm SWE is trending later into the winter at the south-facing site but not at either north-facing site, suggesting that aspect may be important in the sensitivity of this metric. Onset occurs at a time of year when direct radiation is at a minimum, but still differs greatly by aspect, so perhaps either the effect of radiation on the early snowpack or radiation-driven differences in antecedent soil temperatures contribute to aspect-related differences in snowpack onset timing. Our somewhat counterintuitive observation that winter melts are more clearly increasing on the north-facing sites, combined with the later onset of the snowpack only at the south-facing site, suggests to us that early season snow events on the south-facing site are melting out before they have the chance to accumulate to a size where we can perceive snowpack responsiveness to climate. The influence of aspect on snowpack onset deserves further study as changes in the timing of early snowpack development strongly affects soil temperatures [66].

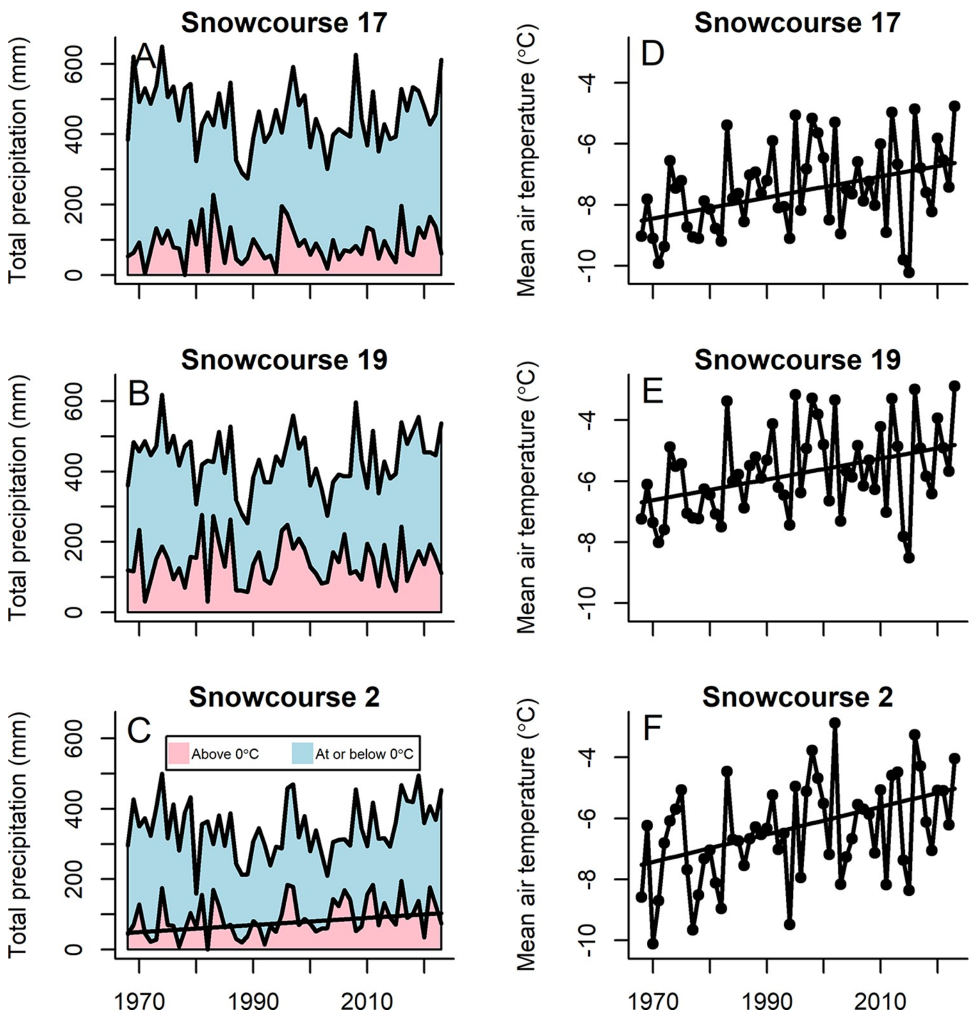

Fig 4. Trends in total precipitation in the *winter* period, separated by volume that fell on days above freezing, or days at or below freezing. Panels d-f show the average temperatures at each site in this period.

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It is notable that the date by which the snowpacks reach their maximum size is showing no indication of getting earlier in the winter at any of the sites, so the spring snowmelt period is getting shorter, rather than shifting earlier. The winter is getting warmer and winter melts are increasing, but the snowpack appears to be accumulating, albeit to a smaller maximum, for the same amount of time. The spring period is getting shorter because there is a smaller amount of snow to melt. This trend toward increasing melts before the maximum SWE is consistent with observations from the western U.S., where widespread increases in melts before the date of maximum SWE have been observed [36]. Because this study utilized net snowpack changes on a weekly basis it is difficult to comment on snowmelt rates, but the increases in winter melts combined with the lower maximum SWE is consistent with observations from the west noting that, because declining snowpacks and increasing winter melts mean less snow is available at times of high energy availability, there has been a general slowing of snowmelt rates [69]. Our observation of decreasing seasonal snowpacks disappearing earlier in the year could result in changes to soil moisture and groundwater recharge, which experience their greatest seasonal input during the snowmelt season [70].

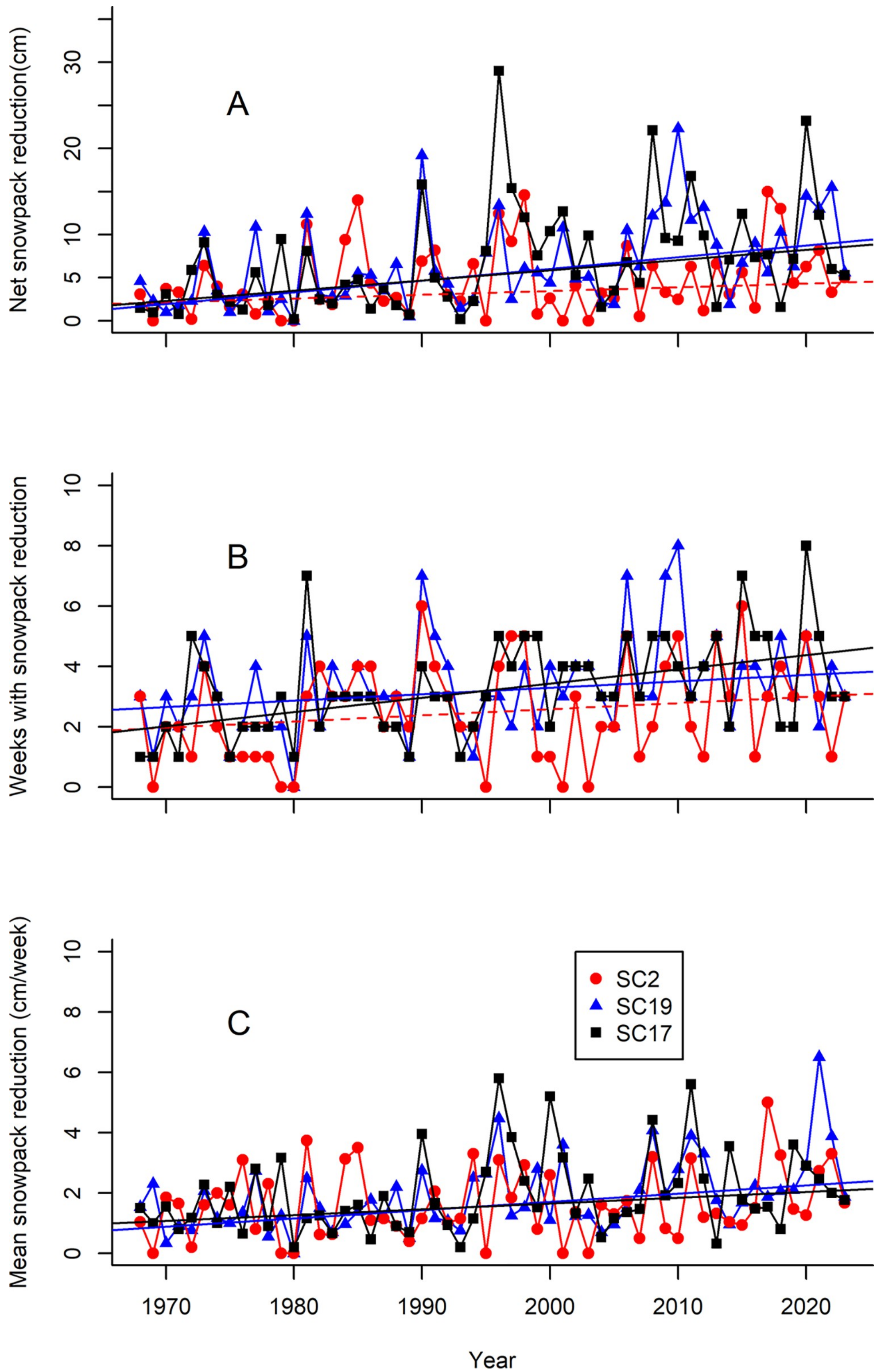

Fig 5. Total snowpack losses during winter (see Table 2) from three snow courses which vary in elevation and aspect. Solid lines indicate significant trends at $p<0.05$, dashed line indicates trend at $p<0.1$. Slopes and exact p-values are found in Table 3. Panel a shows the total net loss over the entire winter period. Panel b shows the number of weeks showing a net snowpack loss, and panel c shows the average size of the loss per each weekly loss.

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Table 4. Environmental conditions in the spring timeperiod (between the median date of maximum SWE and the median date of last-recorded snow) at each site paired with correlations between each variable and the date of last recorded snow.

	SC2		SC 19		SC 17	
	ρ	trend	ρ	trend	ρ	trend
Tave (˚C)	**-0.76**	n.t	**-0.64**	n.t.	**-0.48**	n.t.
p-value	< **0.001**	0.241	< **0.001**	0.611	< **0.001**	0.467
TDD	**-0.71**	n.t.	**-0.67**	n.t.	**-0.52**	n.t.
p-value	< **0.001**	0.493	< **0.001**	0.827	< **0.001**	0.329
CDD	**-0.67**	n.t.	**-0.60**	n.t.	**-0.50**	**-0.53**
p-value	< **0.001**	0.261	< **0.001**	0.661	< **0.001**	**0.045**
Precip (mm)	**0.3**	-0.59	n.s.	n.t.	n.s.	0.88
p-value	**0.026**	0.092	0.674	0.206	0.518	0.066
SNOW/total precip	**0.7**	n.t.	**0.31**	n.t.	0.24	n.t.
p-value	< **0.001**	0.534	**0.018**	0.369	0.078	0.727
Maximum SWE (cm)	**0.61**	**-0.14**	**0.63**	**-0.18**	**0.56**	**-0.26**
p-value	< **0.001**	**0.012**	< **0.001**	**0.003**	< **0.001**	< **0.001**

Trends are reported in instances when the p-value <0.1, with instances of p-value< = 0.05 in bold. Instances with no statistically significant correlation are indicated with an n.s. and instances with no significant trend are indicated with an n.t.

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The proportion of precipitation falling as snow in winter was strongly correlated with the overall maximum size of the snowpack but has only been changing over time at our south-facing location. Our two higher, north-facing sites have apparently remained cold enough that the fraction of winter precipitation falling below 0˚C remains about the same over time. Other authors have reported changes in precipitation type in our region [41,44], which can result in more rain-on-snow events and associated flooding [71]. Our results suggest a possible increase in rain-on-snow at the south-facing site only, yet because melting and maximum SWE declined at all three of the sites, rain-on-snow events do not seem to be the primary drivers of increased snow ablation events. It is important to note that our temperature threshold for rain/snow is a simplification of the complexities in precipitation form, but the lack of change in precipitation form and amount at two of the three sites suggests that changes in duration and size of snowpacks are not primarily explained by changes in precipitation inputs.

In contrast, there were clear increases in both the number of net snow ablation weeks and total amount of ablation over the winter period. Snowpack reductions could be a combination of melting and/or sublimation, but previous stable water isotope data from our site has suggested net condensation into the snowpack instead of net sublimation [72], so we interpret these trends to be primarily snowmelt driven. Surprisingly, total winter net weekly snowpack loss was only correlated with the maximum snowpack size at one of the sites (SC19), so the specific drivers explaining smaller snowpacks are unclear and cannot be attributed solely to the increase in winter snowpack losses. At the south-facing site, SC2, the net winter snowpack losses were often lower than the two north-facing sites and declined at a lower and only marginally significant rate over time (Fig 4). This disparity between aspects could reflect instances, typically in the early season, where the smaller snowpack at the south-facing site melted out completely while the deeper snowpacks at the north-facing sites were able to lose more water simply by virtue of their larger size. This dynamic can be seen in the numerous instances in Fig 5A where the north-facing sites show more cumulative melt. The occurrence and magnitude of snowmelt at the coldest site, SC17, is difficult to explain. This site showed increasing snowpack losses and a declining maximum SWE, but no significant correlation between the two and no significant changes over time of any other variable correlated with maximum SWE except mean temperature. Given that SC17 is located in a coniferous stand of trees and its decline in maximum SWE (14.6 cm decline over 56 years) is much greater than its increase in winter ablation (6.7 cm over 56 years) and we see no indication of changes in precipitation form or amount, we speculate that perhaps canopy interception of incoming snow may have increased at the coniferous site, given recent observations that spruce trees have expanded at the expense of birch trees at higher sites at the HBEF [51].

The fact that both mean temperatures and weekly snowpack reductions increased over time at both north-facing sites, yet there were no changes in metrics which would directly expose snowpacks to melt (TDD, CDD, and proportion of precipitation falling as snow) suggests that the snowpacks are warming and becoming more sensitive to latent and sensible heat inputs to the snowpack. If the observed decreases in solar radiation at our site are explained by cloud cover, this could also act to alter the energy budget of the snowpack by decreasing the radiative heating of the snowpack in the hours the sun is out, and limit nighttime cooling of the snowpack because cloud cover re-radiates long-wave radiation [73]. Winter snowpacks experience far more hours without direct radiation from the sun than with direct radiation inputs so cloud-driven decreases in radiation could be another factor warming the snowpacks. However, the frequency of our weekly net ablation measurements does not allow for the precision necessary to closely examine changes in relationships between melt and heat inputs. The best we can say is that the snowpack has been showing more ablation in the winter period, even in places where melt-inducing conditions are not increasing.

Weekly net changes in SWE combined with daily meteorological measurements do not allow for complete analysis of the energy budgets of a snowpack, especially when compared with the sub-daily data produced by snow monitoring installations such as the automated Snow Telemetry (SNOTEL) network of the American West [32,33]. However, decades of careful, weekly snowpack measurements combined with co-located weather data have allowed us to observe changes in snowpack behavior that are best explained by warming of the midwinter snowpack. The snowpack appears to be more responsive to thawing conditions, regardless of whether those conditions are increasing over time. This sensitivity shows itself most clearly at the colder sites with the larger snowpacks because they do not seem to cross the freezing temperature threshold more often but show both higher average losses per melt (Fig 5A) and more frequent melts. (Fig 5B). The increased sensitivity we observe is consistent with recent broad-scale findings by Gottlied and Mankin [1], who document a non-linear threshold response in snowpack sensitivity to temperatures at average climatological winter temperatures above -8˚C. We note that the mean Dec-Feb temperatures at our sites over the years of this study are -6.75˚C, -6.6˚C, and -8.5˚C for SC2, SC19, and SC17, respectively [53], suggesting that our sites experience the winter conditions that would make them increasingly sensitive to warming air temperatures.

Conclusion

Snowpack maximums and duration have both declined over our 56-year record of snowpack monitoring. The reduced snowpack duration is explained by a shorter spring snowmelt season at every site, stemming largely from lower snowpack maximums, and with a later-developing snowpack onset only evident at our south-facing location. The drivers of the decreased snowpack maximums are not entirely clear, as observed precipitation changes appear minor and total net snowpack ablation, despite clearly increasing over time, was not always correlated with the annual maximum snowpack size. The two locations which do not show increases in above freezing variables nevertheless show more frequent and more pronounced net weekly snowpack losses over the record, suggesting an increasing sensitivity of the snowpack to thawing conditions when they do occur. Warming temperatures appear to affect snowpack duration through alterations of their energy budget before those temperatures result in changes in precipitation form.

Supporting information

S1 Methods. Map layers.
(DOCX)

S2 Methods. Determination of snowpack SWE threshold for onset analysis.
(DOCX)

S1 Fig. The slope of the air/soil temperature relationship between measurements plotted against the average SWE for the December-February time period. Note that there are a few instances we would interpret as some coupling out around 10–12 cm SWE. We determined that this is too much snow to be useful as a snowpack development date, and since soil freezing is unlikely to occur under those conditions the weak relationship is of less interest than the stronger, more frequent coupling observed below the lower (6cm) threshold.
(TIF)

S1 Table. Trends in incoming solar radiation (mJ/m^2) during the two timeperiods analyzed in this study.
(DOCX)

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Writing – review & editing: Mark Green, John Campbell, Alix Contosta, Nina Lany, Amey Bailey.

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