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Declining North American Snow Cover Ablation Frequency

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Abstract

At a continental scale, trends in aggregate ablation frequency inform changes in snow cover extent, however the variability and trends in the frequency and magnitude of snow ablation events at regional scales are less well understood. Determining such variability is critical in describing regional hydroclimate, where snow ablation can influence streamflow, soil moisture, and groundwater supplies. This study uses a gridded dataset of United States and Canadian snow ablation events derived from 1960-2009 surface observations to examine spatial and temporal variations of snow ablation frequency. Here we show a relatively narrow band of peak ablation frequency seasonally advances and recedes over North America, forced by variations in snow depth and meteorological conditions suitable for ablation. Particularly in more moist regions away from the continent's interior, hydrologically-relevant ablation events of at least 10.0 cm occur on an approximately yearly basis. Collectively, ablation events became significantly less frequent with time, where events specifically in the Appalachians and in Great Lakes regions declined by as much as 75% over the 50-year period. Decreases in ablation frequency across the study region are primarily driven by significant decreases in snow cover, inhibiting the potential for ablation to occur due to a lack of sufficiently deep snowpacks. These results point to important snow cover related changes in the hydrologic cycle in a warming climate and highlight specific areas of interest where more localized analysis of ablation trends and forcing mechanisms would be appropriate.

Keywords: snowmelt, climate change, Appalachians, snow season, snow hydrology, snowfall

1.0 Introduction

Snow cover and its ablation are major components of the hydrologic cycle in most areas of North America where ephemeral snow cover occurs. Specifically, the ablation of snow cover influences important hydrologic variables such as streamflow, soil moisture, ground water and lake levels (Leathers et al. 1998; Barnett et al 2005; Graybeal and Leathers 2006). Snow ablation has also been shown to be important in severe snowmelt-induced flooding episodes across the continent (Leathers et al. 1998; Graybeal and Leathers 2006; Musselman et al. 2017; Wachowicz et al. 2020). In recent decades, maximum snow depth and snow mass in North America have significantly decreased (Kunkel et al. 2016; Mudrky et al. 2020), while trends in snowfall totals are regionally variable (Kluver et al. 2017). Snow cover extent (SCE) over North America however, has increased during autumn and early winter (Brown 2000; Allchin and Déry 2019), with a coincident decrease in North American SCE during the spring (Frei and Robinson 1999; Mudryk et al. 2020). Thus, a seasonal shift in SCE is indicated with the snow cover season beginning earlier in the autumn and ending earlier in the spring across the continent (Rupp et al. 2013; Kunkel et al. 2016). Snow cover ablation events, spatially averaged for North America, exhibited a similar seasonal shift in the 20th century, with an increase and decrease in March and May ablation events, respectfully, indicating an earlier onset of ablation across the continent (Dyer and Mote 2007).

The temporal variability and trends of observed North American ablation events have been examined at a large-scale by prior studies (e.g. Dyer and Mote 2007), however relatively little attention has been given to their spatial extent. A comprehensive analysis of historical variability and trends in ablation would provide critical context for understanding projected changes to North American snow cover and runoff in the 21st-century (Brutel-Vuilment et al.

2013; Demaria et al. 2016; McCrary and Mearns 2019). As such, this study focused its efforts on spatially examining trends in ablation frequency from 1960-2009. This research uses a gridded snow dataset (Mote et al. 2018), updated from previous versions (Dyer and Mote 2007; Kluver et al. 2017), to spatially investigate continental- and regional-scale ablation events and their 50-year trends for the period 1960–2009. Despite the termination point of 2009, this dataset provides sufficient scope for this climatological application, and offers distinct advantages over other available products with more recent end dates (see Methodology). This work differs from previous research (Dyer and Mote 2007) in that it develops the statistical distribution of ablation events' frequencies and magnitudes spatially across the continent. In addition, trends in ablation events at regional spatial scales are quantified and discussed. Given the ubiquitous influence of snow cover ablation on hydrologic variables, and the possible negative influence of changes in their seasonal cycle on agricultural concerns (Qin et al. 2020), disruption of biogeochemical cycles during flushing events (Sadro et al. 2018), and snowmelt flooding (Leathers et al. 1998; Graybeal and Leathers 2006), a comprehensive understanding of ablation is of great importance for resolving snow cover / hydrologic cycle associations in a warming climate. Specific research objectives of this study are to:

1) Develop a snow ablation climatology from 1960-2009, focusing on inter- and intra-annual snow ablation frequency,
2) Quantify the long-term linear trends in snow ablation frequency spatially, and
3) Examine possible forcing mechanisms of snow ablation frequency variability and trends.

2.0 Methodology

2.1 Snow data

Daily data were obtained from a quality-controlled dataset of gridded snow depth, snowfall, precipitation, and temperature over North America (Mote et al. 2018); Data are presently available at the National Snow and Ice Data Center (https://nsidc.org/data/g10021). In the generation of the dataset (Mote et al. 2018) daily surface observations from the United States' Cooperative Observer Network (U.S. Department of Commerce 2003) and the Meteorological Service of Canada (Braaten 1996) were subjected to quality control procedures (Robinson 1988), and then interpolated onto a 1-degree grid via Spheremap spatial interpolation procedure from the University of Delaware (Willmott et al. 1984; Dyer and Mote 2006). The interpolated fields were also subjected to additional quality control (Suriano and Leathers 2017), validated (Kluver et al. 2017), and used in a number of recent studies (Dyer and Mote 2007; Suriano and Leathers 2018; Suriano 2019; Wachowicz et al. 2020).

While the daily data begin in 1900 with coverage from approximately 25°N – 82°N, this study restricts analysis to 1960-2009 and south of 51°N (Figure 1). North of 51°N, surface observation station density declines rapidly in the dataset, and the likelihood a gridded observation is based primarily on interpolation increases (Kluver et al. 2017). For the remaining domain (south of 51°N), prior to the 1960 snow season (September-August), data availability is not necessarily consistent across the entire domain, thus starting in September of 1959 allows for high confidence in the data, and a sufficiently long period of time to develop a climatology over a large spatial domain. The termination of the dataset in 2009 is a limitation and is further discussed in section 4.4. However, this dataset is advantageous over other snow depth products such as the National Weather Service's National Operational Hydrologic Remote Sensing Center Snow Data Assimilation System due to its length of record, use in similar studies (Dyer and Mote 2007; Suriano and Leathers 2017), and its consistent use of Cooperative Observer Network observations in the United States. Despite its current termination point, the observational dataset and this study provide valuable information on the spatiotemporal variability and forcing mechanisms of trends in snow ablation events.

2.2 Snow ablation definition

With the snow data containing no information on snow water equivalent, prior work has defined a decrease in snow depth as snow ablation (Grundstein and Leathers 1998; Dyer and Mote 2007; Leathers et al. 2004; Suriano and Leathers 2018; Suriano 2019). This study similarly defined a snow ablation event as an inter-diurnal snow depth decrease within an individual grid cell, only for days when the maximum daily temperature on the second day of an associated event exceeds 0 °C. Under conditions when the maximum daily temperature exceeds 0 °C, the portion of snow depth decrease attributable to snow compaction/compression is minimized (Dyer and Mote 2007). With temperatures above freezing, it can be assumed the snowpack is relatively isothermal and mature, removing the effect of compaction/compression as effectively as possible (Dyer and Mote 2007; Suriano and Leathers 2017). Other work further suggests such a definition of snow ablation does carry hydrologic implications, despite not directly measuring snow water equivalent. More than 75% of 1960-2009 snow depth decrease events resulted in an increase in river discharge in two different mid-latitude watersheds at a 3-day lag, the Susquehanna and Wabash River basins (Suriano et al. 2019a).

Other processes such as sublimation, wind erosion, and measurement errors may also influence the depth of the snowpack beyond melt and compaction. Over large temporal scales, sublimation can be considerable, however over a single event the effect is minimal (Déry and Yau 2002) and is not directly accounted for in this study. Similarly, effects of drifting snow are not incorporated into the analysis; it is standard measurement practice to take snow observations in areas where wind effects and drifting are minimized (U.S. Department of Commerce 2013). Non-physical processes related to measurement can also alter snow depth change without being associated with ablation or melt, including variations in the time of observation (Kunkel et al. 2007). Different observation times for stations in close geographic proximity may result in an interpolated daily snow depth change within a grid cell to not be grounded in meteorological processes. However, this impact should be minimally impactful due to the additional quality control measures (Suriano and Leathers 2017).

2.3 Generating an ablation climatology

Snow ablation is examined across the individual grid cells of the studied domain during the September – August snow seasons of 1960-2009. Similar to previous studies (e.g. Suriano and Leathers 2018), only snow ablation events greater than 2.54 cm are analyzed. This is done to restrict analysis to more hydrologically significant events (Grundstein and Leathers 1998) and decrease the likelihood non-physically-based events are erroneously examined. It is standard measurement practice in the United States Cooperative Observer Network to round snow depth observations to the nearest inch, with 0.5 inches representing the first non-trace value. Thus, the minimum non-trace depth measure is 1.0 inches (i.e. 2.54 cm) and would represent an observable ablation value for the purposes of this study.

Daily ablation events are aggregated into monthly and seasonal values by grid cell, and standard statistics including median, coefficient of variation, and maximum are calculated. Additionally, ablation event frequency is calculated monthly and seasonally across the grid cells of the domain at multiple ablation magnitude thresholds: 2.54 cm, 5.0 cm, 10.0 cm, and 25.0 cm, corresponding to small, moderate, large, and extreme ablation, respectively. These thresholds are chosen based on the distribution of the event's magnitudes, and the convenience of using rounded bins. Trends in snow ablation frequency are calculated using Sen's slope estimate, and significance determined using the non-parametric Mann-Kendall test.

To aid in determining possible forcing mechanisms of any apparent trends in ablation event frequency, this study additionally examines snowfall, snow depth, and temperature variations over the study period. Trends in these variables are calculated using the techniques noted above and are then correlated to the trends in ablation events across the study region using Spearman's rank order correlation.

3.0 Results

3.1 Spatial snow ablation climatology

Median ablation event magnitude, defined as an inter-diurnal decrease in snow depth when maximum temperatures exceed 0°C (see Methodology), from 1960-2009 was 4.4 cm for the study region. Much of the continent's interior exhibited smaller event magnitudes, while relative maxima corresponded to regions of higher elevation and greater seasonal snowfall (Figure 2a). Along the Gulf Coast, large (> 10.0 cm event^{-1}) median ablation values were observed. All ablation events in this region were manually inspected using the gridded dataset and daily weather maps to ensure events were meteorologically and physically plausible. Further details are presented in the following section (4.1) and is supported by an examination of coefficients of variation (Figure 2b). Maximum daily ablation magnitudes (Figure 2c) were noted in regions of high elevation and generally high snowfall totals, with multiple regions seeing a maximum daily ablation greater than 70 cm.

For all ablation events (magnitudes $\geq$ 2.54cm), regions of higher seasonal frequency of ablation corresponded to those with greater snowfall receipt. The prominent lake-effect snow regions to the lee of the Great Lakes, higher elevation regions in the Appalachians and Rockies, and regions in southeastern Canada subjected to a high frequency of snowfall-producing mid-latitude cyclone tracks (Klein 1957; Guo et al. 2017), all exhibited a relatively high ablation frequency in excess of 20 events year^{-1} (Figure 3a). For the remaining bins of progressively larger ablation magnitudes ($\geq$ 5.0 cm, $\geq$ 10.0 cm, $\geq$ 25.0 cm; Figures 3b-d), the frequency of ablation events followed a similar spatial pattern to that of ablation events greater than 2.54 cm, but with diminishing yearly values.

Across much of the Great Plains, Midwest and Mid-Atlantic of the United States, an ablation event in excess of 10.0 cm would be considered be a 5-year event, occurring approximately once every five years or with a 20% chance of occurring any given year (Figure 3c). In the Northeast sector of the domain (i.e. northeast United States and southeastern Canada), a 10.0 cm or greater event is far more frequent, with a recurrence interval of less than one year. In contrast, in the southern United States, many regions experienced no ablation events of at least 10 cm, with those that did only experiencing one event over the 50-year period.

Approximately half of the grid cells in the domain experienced a daily ablation event of at least 25.0 cm between 1960-2009 (Figure 3d). In the regions of relative maxima (southeastern maritime Canada, high elevation regions to the west), events of at least 25.0 cm have a recurrence interval of approximately 2.2 years. If one were to assume a 10:1 snow to liquid water ratio of the snowpack, and the entirety of such snow ablation were to runoff, a 25.0 cm ablation event in a single mid-latitude grid cell would release approximately 235 million cubic meters of water.

Our analysis of monthly ablation events revealed a band of relatively higher snow ablation event frequencies traversed the domain as availability of snow and meteorological conditions suitable for ablation varied with the seasonal cycle of incoming shortwave radiation. The band of enhanced ablation frequencies advanced south from October through January to approximately 41°N, before retreating north from February-May (Figure 4a-f). March and April experienced the largest average frequency of ablation events, where approximately 5-9 ablation events occurred each month across the Great Lakes region into New England (Figure 4d, 4e). Ablation event frequencies in the months of June – November can be found in the Supplementary Material (Figure S1).

3.2 Trends in snow ablation

Seasonally, ablation frequency averaged across the entire domain significantly decreased by 0.02 events year^{-1} ($p < 0.001$; not shown) from 1960-2009, however, trends were spatially heterogeneous (Figure 5a). In the southern Appalachians, ablation events significantly declined in frequency ($p < 0.050$) by 0.06 to 0.17 events year^{-1}, representing in some cases more than a 75% reduction in the number of ablation events when a linear fit is applied over the 50 years. Similarly, portions of southwest Ontario, north of Lake Superior, exhibited significant declines in ablation frequency, on the order of 0.10-0.25 fewer events year^{-1} ($p < 0.050$).

Within the seasonal cycle, significant trends in monthly ablation event frequency are apparent. Analysis was limited to the months of February, March, and April (Figure 5b-d), however ablation frequency trends for the remaining months can be found in the Supplementary Material (Figure_S2). Ablation event frequency in February significantly declined ($p < 0.050$) across much of the Appalachian region, with decreases in excess of 0.06 events year^{-1} (Figure

5b). In the central Appalachians, trends represented a reduction in ablation event frequency of over 70%, from approximately 3.5 events year^{-1} in the 1960s to less than 1 event year^{-1} in the 2000s. In March (Figure 5c), trends in ablation frequency were not as spatially coherent when compared to February. There are, however, some regions that standout including the increasing in event frequency in in the southern Canadian Plains (+ 0.06 events year^{-1}; $p < 0.050$) and the decreasing frequency in the Northeast U.S. (- 0.09 events year^{-1}; $p < 0.050$). By April, ablation events are predominately limited to higher latitudes, and significant trends were detected north of Lake Superior (Figure 5d). In this region, ablation event frequency decreased by as much as 0.16 events year^{-1} ($p < 0.001$), representing a decrease of approximately 67% from 1960-2009 when a linear fit is applied.

Examining the frequency of ablation events of different magnitudes, the largest trends are observed for the smallest ablation events, between 2.54 and 5.0 cm of snow depth loss (Figure 6a). Much of the study region exhibits decreases in ablation frequency of this magnitude, with large regions of significant declines observed in the Appalachians, in the northern US High Plains, and in the southern tier of Canada, similar to results in Figure 5a. For moderate ablation events (5.0 to 10.0cm), significant decreases in frequency persist in the Appalachian region, in areas north of the Great Lakes, and in the northern US High Plains, however the rate of decline is less than that of small ablation events, indicating smaller changes in moderate ablation frequency with time (Figure 6b). Regions of increasing moderate ablation event frequency are also noted in the Red River of the North (approx. 47.5°N, 97°W) and in the upper Mississippi River basins. Signals of the ablation of lake-effect snow to the lee of the Great Lakes are also apparent.

For large ablation events (10.0 to 25.0cm), regions of significant change are limited to only a small handful of homogeneous regions, including increasing frequencies in lake-effect regions of the Great Lakes basin, and decreasing frequencies in the central Appalachians, among others (Figure 6c). Extreme ablation events (greater than 25.0cm) exhibited significant trends in very few locations over the study period. Most notable was the relatively large increase in the southern Coast Mountains of British Columbia (Figure 6d).

3.3 Mechanisms forcing declining frequency

It is hypothesized that the frequency of days with snow cover are a primary forcing mechanism of variations and trends in ablation event frequency. Under this proposed mechanism, years with greater (fewer) days of snow cover would have more (fewer) days where snow ablation events are possible, leading to more (fewer) ablation events. To partially explain the observed general decrease in ablation frequency, snow cover days would have had to decline over the study period.

Results of this study support this hypothesis. For much of the domain, particularly east of the Rocky Mountains, the frequency of snow cover days declined by as much as 0.8 days year^{-1} (Figure 7a). A linear decrease of 0.8 days year^{-1} represents a reduction of over a month in snow cover days during the study period. Significant decreases in snow cover day frequency are observed in entire Appalachians region and along the eastern North American coast, in regions of the Midwest US, in the northern US High Plains, and north of Lake Superior. Within regions of topographic variation in the western US, both increasing and decreasing trends are observed (see section 4.4 for greater discussion). When the timeseries of annual snow cover frequency and ablation frequency are de-trended, the two variables are significantly correlated for nearly all of the study region (Figure 7b). In years with a greater frequency of ablation events, there are more days with snow cover ($r_s = 0.83, p < 0.001$).

In the Great Lakes region, while warming temperatures may increase the potential for ablation to occur, providing more favorable atmospheric conditions, the dominant control of temperature appears to be that warming limits the amount of snow and thus potential for ablation. During years with warmer surface air temperatures, snowfall, snow cover, and snow depth values were significantly smaller ($r_s = - 0.75$, $p < 0.001$), and thus the frequency of ablation was less. A similar relationship was noted in the Appalachian region where seasonally, especially in February/March, the decrease in ablation events was highly related to decreases in snow cover, snowfall, and snow depths. This is statistically related to an increase in maximum air temperatures throughout the winter months. Snow depths, snowfall totals, and maximum surface air temperatures were all significantly related to ablation frequency ($r_s = .83$, $p < 0.001$), ($r_s = .88$, $p < 0.001$), ($r_s = .38$, $p < 0.010$), respectively. Thus, the decrease in snowfall and snow depth leaves less snow to ablate during the spring months, resulting in significant decreases in ablation events across the Appalachian region, despite warmer surface temperatures being a favorable environment for ablation.

4.0 Discussion

4.1 Spatial snow ablation climatology

The large magnitude of median and maximum snow ablation events in the U.S. Gulf Coast region was unexpected given the region’s southerly location and generally warmer climate. As such, all ablation events in this region were manually inspected to ensure the detected events were meteorologically and physically plausible. In all cases, snowfall accumulations were observed and immediately followed by warm and humid air masses, creating the necessary conditions for rapid ablation. Many of these accumulations (and thus ablations) were large. For example, on February 12-13, 1960, snowfall totals of in excess of 22 cm were recorded in portions of the Gulf Coast. This was followed by a daily maximum temperature of over 12 °C and dewpoints above 9 °C, where nearly the entire snowpack was ablated. In many grid cells in this region, the February 1960 event was the only ablation event to exceed the 2.54 cm threshold necessary for analysis. Thus, the median ablation value is large, with very low coefficients of variation. In other grid cells of the Gulf Coast region, large median ablation magnitudes are noted with large coefficients of variation. In nearly all cases, this is indicating that a single large ablation event occurred along with a few relatively small ablation episodes.

Elsewhere across the domain, relative maxima of ablation magnitude tend to correspond to regions with higher snowfall amounts and/or in association with the potential for the co-occurrence of meteorological conditions suitable for large ablation. This is a logical association, as more snowfall will equate to a deeper snowpack, and a deeper snowpack creates the opportunity for a larger ablation event to potentially occur; a 10 cm ablation event cannot occur with a 9 cm deep snowpack. The higher frequencies of ablation events also are noted in similar regions with a greater magnitude. This too is expected as a deeper snowpack is able to "withstand" more ablation events prior to being depleted. Additionally, a deeper snowpack may persist longer into the spring months, enabling the ablation season to last longer, resulting in an increase in ablation frequency. While this study does not examine the meteorological characteristics associated with ablation events, nor differentiate their relative hydrologic impacts by atmospheric environment, much research has been conducted on these atmospheric conditions at regional scales in North America (Grundstein and Leathers 1998; Leathers et al. 1998; Leathers et al. 2004; Guan et al. 2016; Suriano & Leathers 2018; among others).

The seasonal propagation of a band of relatively high frequency in ablation events, noted in this study, supports previous work (Dyer and Mote, 2007; Suriano and Leathers, 2017). This progression is likely the result of the frequency of ablation being controlled by both the availability of snow cover to be ablated, and the meteorological conditions capable of ablating. In January for instance, the band of peak ablation frequency is relatively narrow, as to its north, meteorological conditions that can ablate snow are not overly frequent. To its south, while conditions to melt snow are common, the snowpack itself is not deep enough to allow for a 2.54 cm ablation event to occur regularly. Thus, the band of higher ablation frequency moves northward as an increase in temperature and moisture conditions suitable for melting snow advances northward and the persistence of a minimally-deep snowpack retreats towards the polar region.

4.2 Trends in snow ablation

Decreasing trends in ablation frequency in the Appalachians are similar to those reported by Wachowicz et al. (2020) examining rain-on-snow ablation. They detect decreases in frequency during the winter (DJF) and spring (MAM) seasons in this region (Wachowicz et al. 2020). The decreases of ablation event frequency in the greater Great Lakes region, north of Lake Superior, observed here are most prominent during the month of April, corresponding to the typical end of the snow season in the Great Lakes basin. Such a decrease suggests that the snow season is shortening, with less snow available to be ablated by April. Examination of trends in snow cover from 1960-2009 in this region for the month of April (Figure S3) support this conclusion, with April snow cover significantly decreasing from 1960-2009.

This may carry substantial environmental and social implications to this region, particularly given the importance of snowmelt induced runoff to the annual hydrologic cycle of the Great Lakes watershed. In the Great Lakes basin, more than 50% of annual runoff comes from snowmelt (Barnett et al. 2005), where that snowmelt runoff is the dominant control of Great Lakes water levels during the spring and summer (Quinn 2002). As such, an earlier end to the snow season with fewer April snowmelt runoff events may affect the supply of hydroelectric power generation through increased variability within the hydrologic season (Vicuna et al. 2008) while also negatively influencing various ecological habitats within the basin (Barry et al. 2004; Fracz and Chow-Fraser 2013). Increased flooding caused by earlier snowmelt, coupled with the potential for ice-jamming in the cold season, is an additional potential complication. Conversely, fewer ablation events may lessen the risk of snowmelt-inducing flooding, limiting direct flood damages while also potentially reducing the occurrence of large influxes of excessive nutrients and pollution entering waterways noted during ablation events.

When trends in event frequency are broken down into different magnitudes, small ablation events (2.54 to 5.0 cm) appear to dominate the overall trend signal. Small ablation events are broadly decreasing in frequency. This could be derived in changes in snow cover limiting the number of days with sufficient snow depth for ablation to occur (see next section), or perhaps an indication that fewer small events are occurring in favor of more relatively larger events. The latter hypothesis does not seem likely for most regions, based on examination of event frequencies in the moderate, large, and extreme magnitude bins (see Figure 6b-d). The exception is in select river basins of the US Great Plains and Midwest, where decreases in small ablation events (both statistically significant and not statistically significant) occur simultaneously with significant increases in moderate and/or large ablation events. This is supported by the examination of annual trends in ablation magnitude (not shown), where in these regions (Red River of the North, Upper Mississippi, and Souris River basins), ablation magnitude significantly increased by approximately 0.03-0.1 cm event^{-1} year^{-1}. A mechanism driving this potential shift in ablation magnitude towards more frequent larger events remains unclear but may be associated with the combination of more suitable atmospheric conditions for large, but infrequent, snowfalls, coupled with the potential for rapid ablation thereafter. A more localized study in these regions would be appropriate.

4.3 Mechanisms forcing declining frequency

Snow cover and snow mass have broadly decreased across the continent in recent decades (Mudryk et al. 2020). This conclusion is supported by analysis in this study which indicated days with snow cover have significantly declined across much of the study region. With a declining snowpack, less snow would be available for an ablation event to occur, and the snowpack may be 'exhausted' earlier in the spring months, effectively limiting the seasonal total of ablation events. Furthermore, fewer days of snow cover would equal fewer opportunities for ablation. The broadly observed decrease in ablation frequency in this study supports this prior result.

The region of declining ablation frequency in southwest Ontario is associated with decreasing snow cover and snow depth across this region, where the average seasonal snow depth declined by approximately 0.19-0.51 cm yr^{-1} (~60%) from 1960-2009 (Suriano et al. 2019b). Trends in snow depth in this region can explain over 50% of the variance in ablation frequency trends. Furthermore, the decline in snow depth, thus ablation frequency, is closely tied to the general increase in temperature observed across the region (Suriano et al. 2019b). Other research discusses the possibility of decreasing frequency of snowfall-producing synoptic types as a different, but related, explanation to observed decreases in snow depth in south-central Canada, including north of Lake Superior (Dyer and Mote 2006; Isard et al. 2000).

In the Appalachian region, it is likely that the decrease in snow cover is driving the decrease in ablation frequency, with less snow available for ablation. Warming winter maximum temperatures across the region are linked to the decrease in both snowfall, snow depth, and snow cover, although this was not comprehensively investigated here and is the subject of a different forthcoming manuscript. Other research has explored the role of shifting precipitation phase during the cold season as a possible mechanism driving snowfall decreases. Winter temperature increases led to increases in the rain/snow precipitation ratio, resulting in more precipitation falling as rain than as snow and reducing snowfall totals (Feng and Hu 2007; Notaro et al. 2014; Knowles 2015; Suriano and Leathers 2016).

4.4 Limitations

Much work has been done examining the characteristics and variability of snow ablation in the mountainous regions of North America. While variability in results exist, a majority of studies have noted that snow cover, snow depths, and/or ablation events have declined in frequency over time, driven by a warming global climate (McCabe et al., 2007; Mazurkiewicz et al., 2008; Jones & Perkins, 2010) including during the most recent data where this study does not provide temporal coverage (Guan et al., 2016; Yan et al., 2019). While the results of this study indicate many of these similar mountainous regions exhibit decreases in snow cover (Figure 7; S3) and snow ablation frequency (Figure 5, S2) from 1960-2009, it warrants acknowledging the role scale plays in the confidence in such conclusions in these environments. Similarly, it should be noted that while regions corresponding to higher elevation tend to have a greater magnitude of ablation, it can not necessarily be presumed that this feature is exclusively the result of higher snow depths and a greater potential for larger ablation. Suriano and Leathers (2017) demonstrated that in grid cells with a high degree of topographic variability, variations in the consistency of observation station reporting practices can greatly alter ablation magnitudes. For instance, a high elevation station with a deep snow pack reporting one day, then not reporting next, may create an artificial ablation event within an interpolated grid cell with a mixture of high and low elevation stations. While quality control has greatly mitigated this effect from being included in the analysis (Suriano and Leathers 2017), care should be taken when comparing ablation results along the Rockies, Cascades, and Sierras, to regions with less variable topography. As a result, the authors focused their attention primarily to the regions east of the Rocky Mountains. Additional limitations of the dataset are discussed at length in Kluver et al. (2017) and Suriano and Leathers (2017).

As noted previously, the study period used here ends in 2009. This decision was based on the availability of data in the dataset determined to be the most advantageous for this study; the gridded snow dataset (Mote et al. 2018) does not currently have data from 2010 – present. While this prevents analysis during the most recent years, there are still substantial benefits to using this data product in providing the historical perspective necessary for assessing the climatological nature and long-term trends in snow ablation. The viability of other datasets was considered for this project; however the lack of a multi-decadal record eliminated most options. While the prospect of merging multiple datasets was considered to increase the study period closer to the present, this would have involved the merger of both observationally- and model-derived products, each with their own limitations and biases. Given the focus on long-term trends, this option introduced too much uncertainty associated with a potential step change skewing the results.

5.0 Conclusions

This study developed a spatial climatology of snow cover ablation events across North America to identify regions of interest concerning long-term trends in ablation event frequency. Using a 1° x 1° gridded snow dataset (Mote et al. 2018), the frequency and magnitude of snow ablation events was analyzed from 1960-2009 at monthly and seasonal (Sep-Aug) resolutions, where linear trends were evaluated.

We found during the snow season, a latitudinal-orientated band of enhanced ablation frequency developed across North America that was dependent upon the presence of snow cover and the occurrence of suitable meteorological conditions for melt. Snow ablation frequency significantly declined from 1960-2009 across the much of the study domain. Spatially coherent regions of interest included north of Lake Superior and in the central Appalachians, which both exhibited large decreases in seasonal ablation frequency that are most pronounced at the end of their respective snow seasons. When coupled with observed changes in snow cover, this provides further evidence of a shortening snow season in these North American regions. However, there appears to evidence of be competing signals in some regions, with warmer environments limiting snowpack depths and ablation potential, but also increasing the potential for fewer and larger ablation events to occur. Further research into these competing forcing mechanisms is warranted.

Decreases in ablation frequency in North America may decrease the frequency of snowmelt-induced flooding events, limiting loss of life and infrastructure damage. However, such changes will also influence the regional hydroclimate, potentially carrying ecological and water resource management implications.

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Data Availability

The snow data used in this study are publicly available at the National Snow and Ice Data Center, at https://doi.org/10.7265/N5028PQ3 (Mote et al. 2018).

Author Contributions

ZJS and DJL contributed to research design, data acquisition and analysis, and manuscript writing. TLM, GRH, TWE, LJW, and DAR contributed to data acquisition, and manuscript writing and revision. DJL, TLM, GRH, and DAR provided funding acquisition and project administration.

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Figure Captions

Figure 1. *Map of the study region used, with each 1° latitude-by-longitude grid cells analyzed shaded in grey.*

Figure 2 *(a) Median ablation event magnitude (cm), (b) coefficient of variation (%), and (c) maximum ablation event magnitude (cm) over 1960-2009 Sep-Aug seasons.*

Figure 3. *Yearly, Sep-Aug, frequency of seasonal ablation events, 1960-2009, for events with magnitudes (a) $\geq$ 2.54 cm, (b) $\geq$ 5.0 cm, (c) $\geq$ 10.0 cm, and (d) $\geq$ 25.0 cm. For reference, a value of 0.5 indicates one ablation events every two years, while a value of 0.1 indicates an ablation event every ten years.*

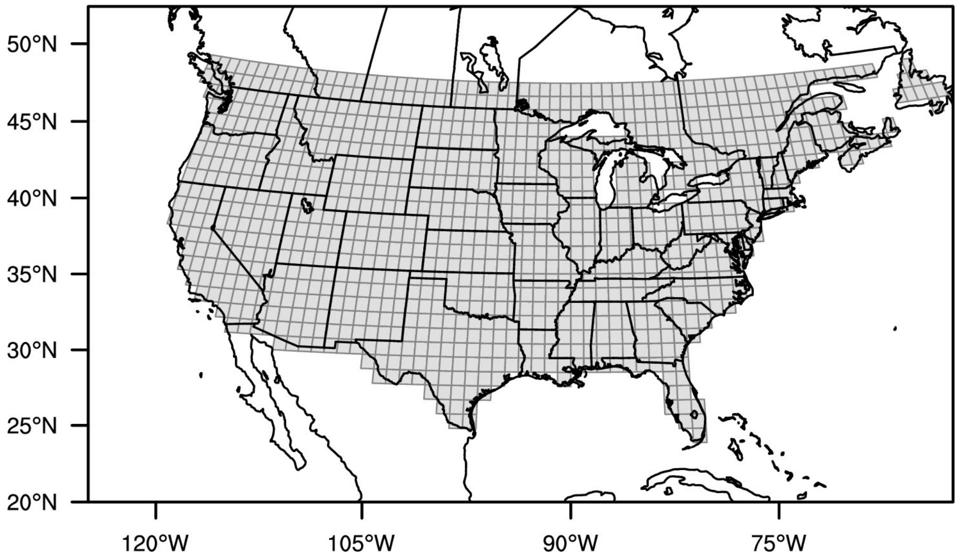
Figure 4. *Average ablation event frequency, in days, from 1960-2009 of magnitude $\geq$ 2.54 cm during the months of (a) December, (b) January, (c) February, (d) March, (e) April, and (f) May. Months of June – November can be found in the Supplementary Material (Figure S1).*

Figure 5. *Linear trends in ablation frequency from 1960-2009, reported in events per year, for (a) the Sep-Aug season, (b) February, (c) March, and (d) April. Hashed areas are statistically significant at the 95% confidence level. Months of May – January can be found in the Supplementary Material (Figure S2).*

Figure 6*. Interannual trend in ablation event frequency from 1960-2009, reported in events per year, for (a) small ablation events (2.54 – 5.0 cm), (b) moderate ablation events (5.0 – 10.0cm),*

(c) large ablation events (10.0 - 25.0 cm), and (d) extreme ablation events (25.0+ cm). Hashed areas are statistically significant at the 95% confidence level.

***Figure 7**. (a) Linear trend in the interannual frequency of snow cover days in days year^{-1}, and (b)* Spearman's rank order correlation coefficient between the frequency of snow cover days and ablation events from 1960-2009. *Hashed areas are statistically significant at the 95% confidence level.*



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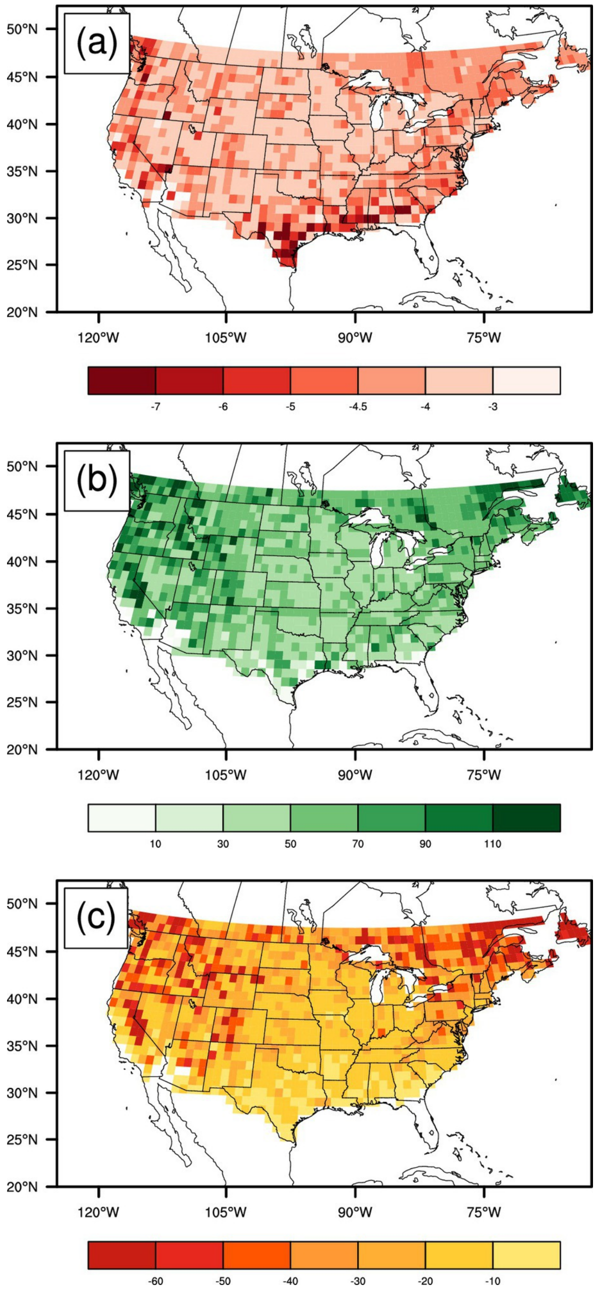

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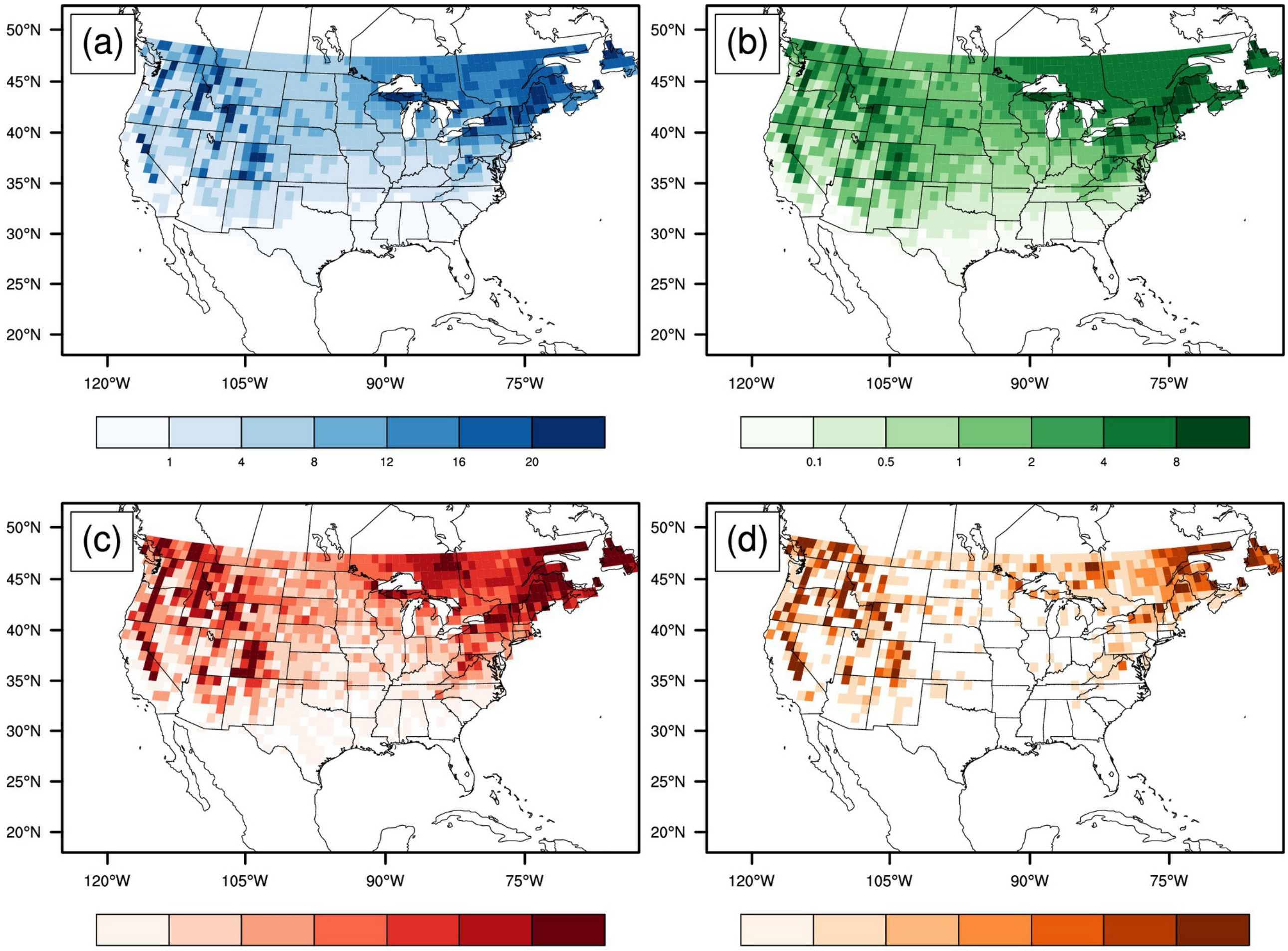

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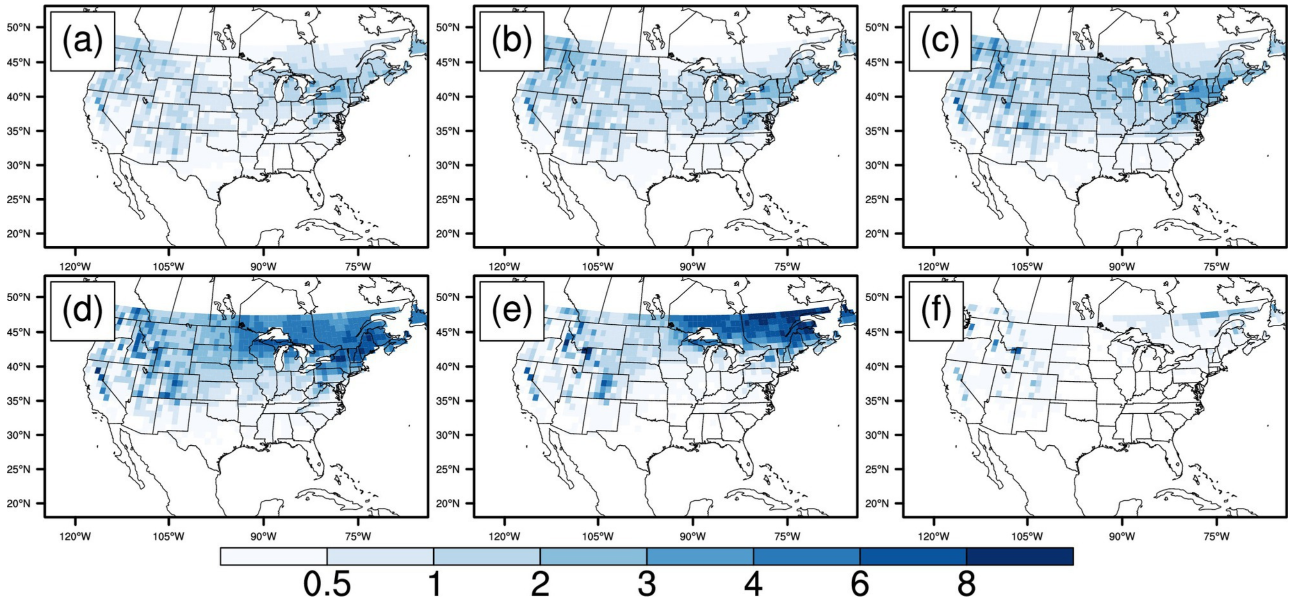

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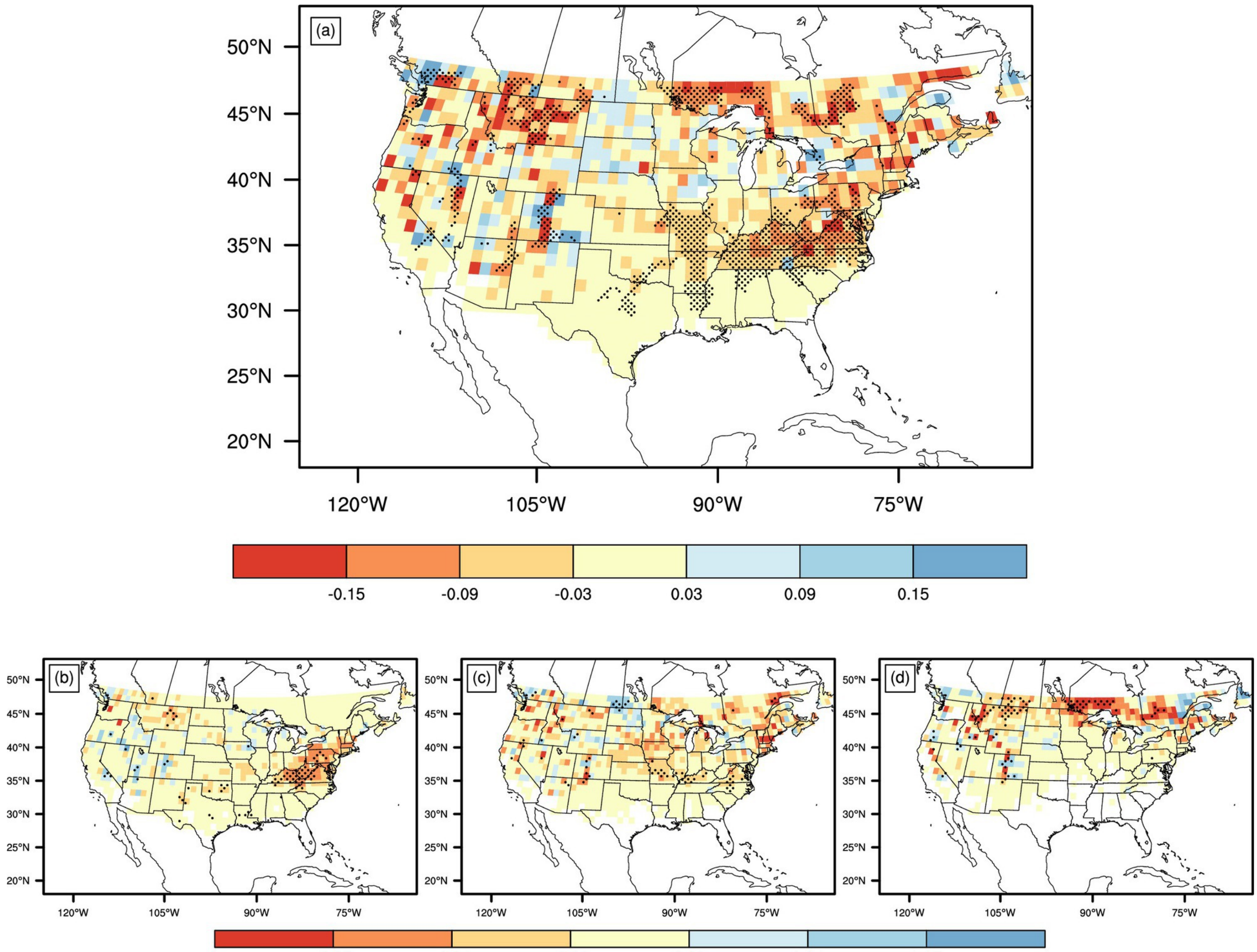

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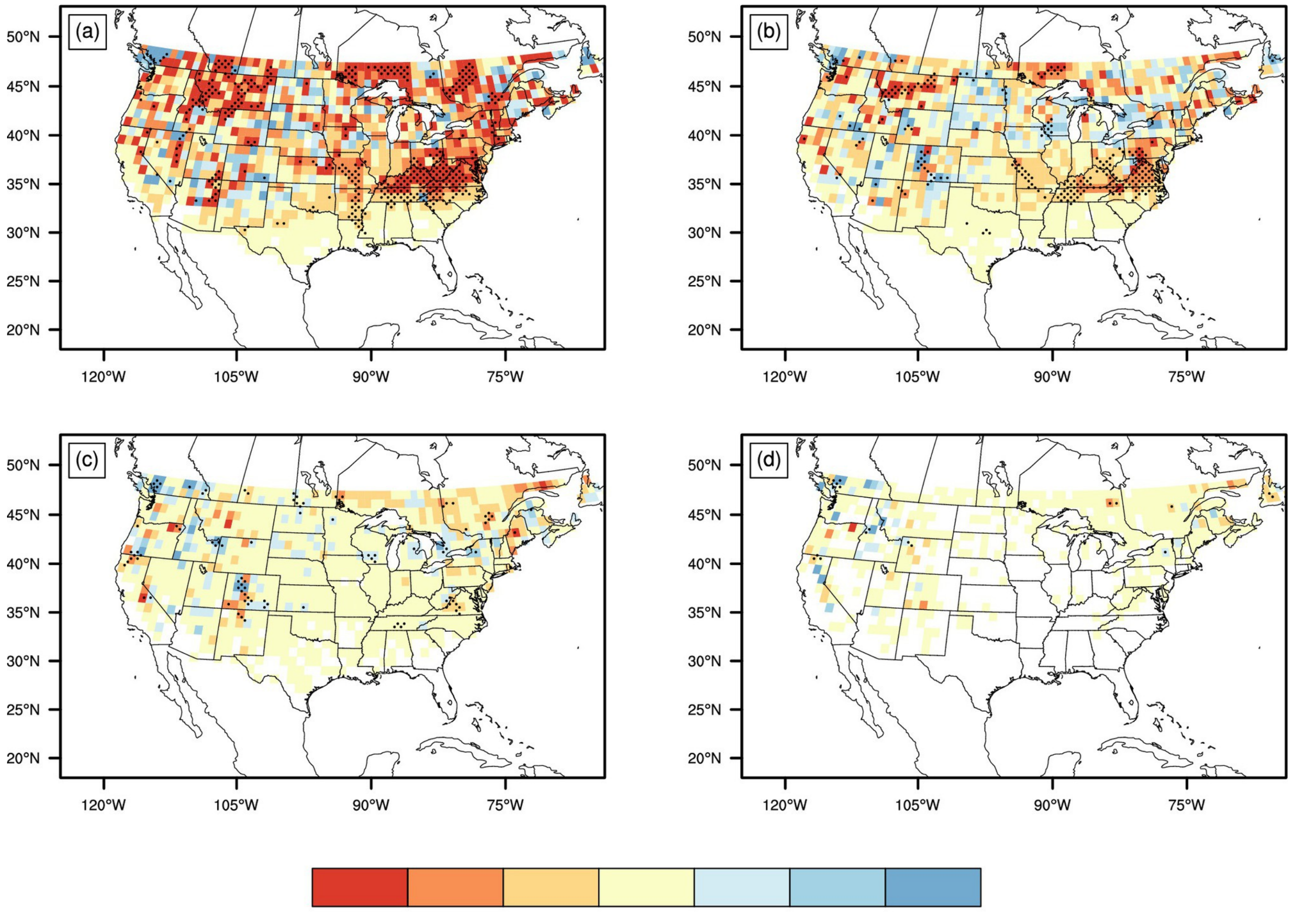

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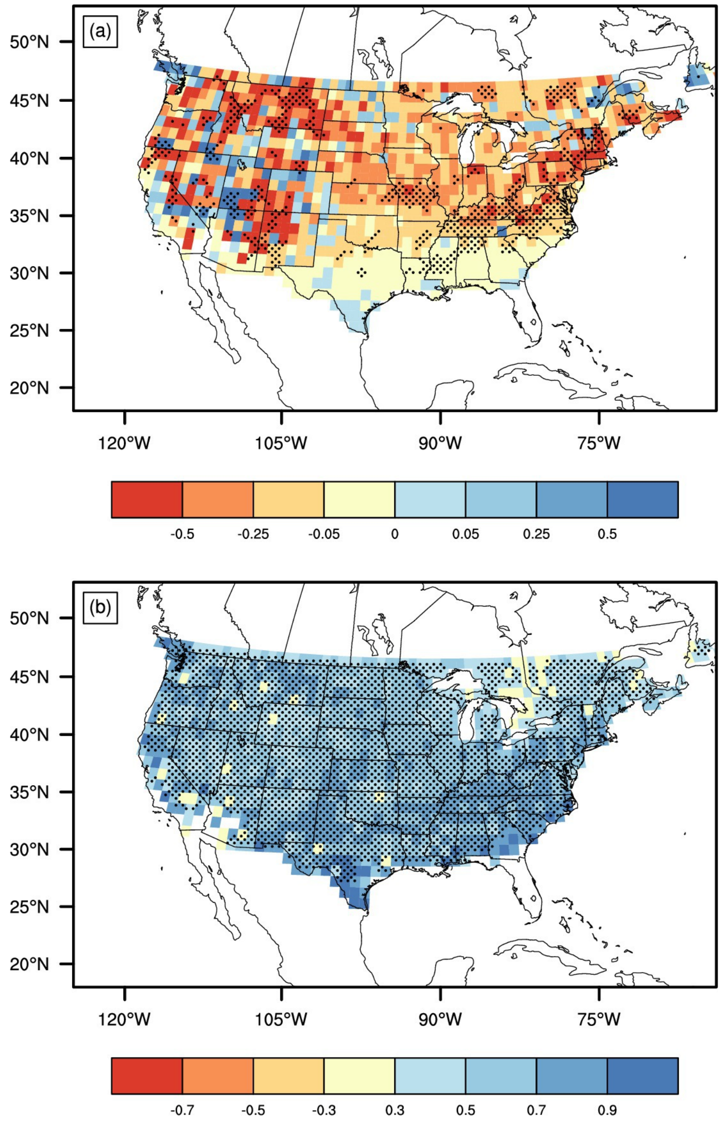

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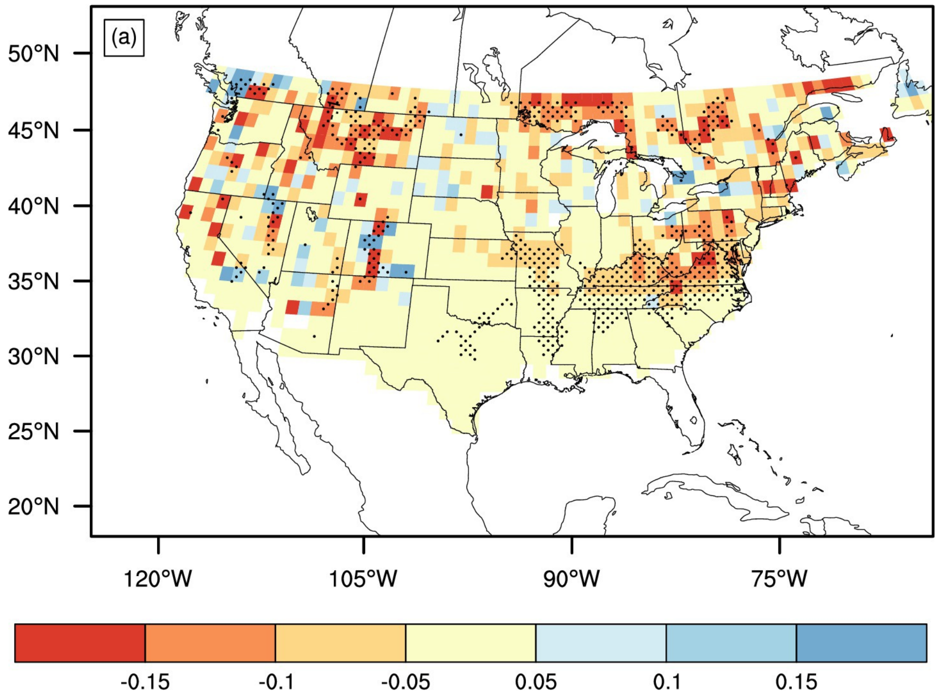

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Declining North American Snow Cover Ablation Events

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The interannual frequency of snow cover ablation events over North American is significantly related to the quantity of snowfall received during the cold season, in relation to warming atmospheric temperatures. From 1960-2009, the frequency of such ablation events has significantly changed across the continent, shown here, with fewer events occurring in the Appalachians, north of the Great Lakes, and along the front range in Montana with time.