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North American rain-on-snow ablation climatology

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ABSTRACT: Rain-on-snow ablation events carry a relatively high risk for rapid snowmelt and runoff due to the combination of liquid precipitation and generally high turbulent fluxes into the snowpack. Determining the variability in rain-on-snow ablation is critical in describing local hydroclimate. This study uses a gridded observational snow dataset to examine spatiotemporal variations in North American rain-on-snow ablation over a 50 yr period. Here we show rain-on-snow ablation represents approximately 33 % of all ablation events in the eastern third of the continent, compared to <20 % in its interior. Rain-on-snow ablation was most frequent along the western and eastern coasts of the continent, with >10 events observed per year on average. A central band of enhanced event frequencies propagated meridionally during the calendar year, most prominently in the eastern half of the continent. Seasonal (September to August) event frequency from 1960–2009 significantly decreased by approximately 50 % across much of northern Quebec and in the southern Appalachians, while it significantly increased in portions of British Columbia and southeastern Quebec. Interannual variations in event frequency were primarily forced by variations in seasonal-scale snowfall and snow depth, and only moderately associated with variations in air temperatures.

KEY WORDS: Snow depth · Climate change · Snowmelt · Rain-on-snow · North America · Ablation

1. INTRODUCTION

Snow cover ablation is a primary control on regional hydrology in the middle and high latitudes, where a majority of runoff is associated with snowmelt processes (Barnett et al. 2005). Such snow-ablation-induced runoff can serve as critical water resources for downstream communities and ecosystems (Yarnell et al. 2010, Conner et al. 2016, Qin et al. 2020), but also pose a substantial risk in the form of flooding (Leathers et al. 1998, Pradhanang et al. 2013). From 1972 to 2006, snow ablation flooding resulted in over $3.3 billion in total losses in the USA, and had the largest spatial footprint for any flooding mechanism (Changnon 2008).

Snow ablation in North America occurs under a diversity of atmospheric mechanisms, including instances of high pressure overhead allowing increased shortwave radiation to reach the surface (Suriano 2019), the advection of warm and moist air during southerly flow regimes (Grundstein & Leathers 1998, 1999), and in association with both wet and dry synoptic weather types (Leathers et al. 2004). The occurrence of rain-on-snow (ROS) ablation has been widely studied due to the potential for rapid ablation that may result in excessive runoff and flooding, or even delayed drought conditions (e.g. Ye et al. 2008, Trubilowicz & Moore 2017, Moghadas et al. 2018, Qin et al. 2020). Liquid precipitation falling on top of the snowpack imparts substantial energy into the pack; the liquid precipitation itself transfers sensible heat, and there is the potential for latent heat exchange if the precipitation were to refreeze (Suriano & Leathers 2018). Additionally, large sensible and latent heat fluxes are typically transferred into the snowpack during ROS events from relatively warm air and dewpoint temperatures (Grundstein & Leathers 1998, 1999).

Research on ROS in North America has historically focused on the high-elevation regions in the Rocky,

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Cascade, and Sierra Mountain ranges due to the role snow-derived water resources play in the hydroclimatology of the western USA (McCabe et al. 2007, Mazurkiewicz et al. 2008, Jones & Perkins 2010, Guan et al. 2016, Musselman et al. 2018, Yan et al. 2019). With some exceptions, studies often focus on local scales associated with specific watersheds to yield the more tailored information for water resource managers. Only a select few studies have examined ROS across a larger scale for North America.

Li et al. (2019) evaluated the flooding impact of ROS using a hydrologic modeling technique reliant on orographically scaled data (Livneh et al. 2015), additionally identifying relative contributions to melt from different energy sources. ROS was noted as most frequent along the west and east US coasts, with peak frequency within the seasonal cycle in late fall and mid-winter east of 90° W longitude. However, the study restricts analysis to US regions with relatively large snowpack snow-water-equivalents, thus much of the US central plains and southeast are ignored. Cohen et al. (2015) similarly found ROS events, defined as rainfall onto a surface with a snow cover fraction of at least 0.5 using a reanalysis product, were generally most common during autumn (SON) and winter (DJF). In contrast, Wachowicz et al. (2020) indicate ROS events were most common in the spring across the northeastern USA. Utilizing a gridded snow depth observational dataset (Mote et al. 2018), Wachowicz et al. (2020) further determined that ROS events in DJF decreased along the US east coast, while increasing in frequency in northern New England and portions of southeastern Canada from 1960 to 2009.

While previous studies to date have explored the spatiotemporal variability of ROS occurrences across North America, the evaluation of specifically ROS ablation for the continent, using a consistent, long-term, observational dataset, has not yet been conducted; such data will yield critical insight into hydroclimatic variability. Examining ROS ablation, as opposed to only the occurrence of rainfall with snow cover present, allows events which may result in a hydrologic outcome (i.e. runoff) to be analyzed (e.g. McCabe et al. 2007), and represents more operationally beneficial information than ROS occurrence alone.

In this study, the frequency and magnitude of daily ROS ablation events are evaluated for North America using a quality-controlled gridded snow depth dataset over the period 1960–2009. Events with snow depth loss are the focus of this study, where such depth losses were shown to yield runoff during the vast majority of events (Suriano et al. 2020), with implications to society through potential flooding (Leathers et al. 1998), and/or excessive nutrient and pollution transport (Seybold et al. 2019). In contrast to previous work, ROS ablation frequency and trends are presented in the context of the percentage of all mechanisms of snow cover ablation. Furthermore, this study derives spatiotemporal trends in ROS ablation frequency, and associations with concurrent meteorological conditions forcing variability are quantified for much of North America.

2. MATERIALS AND METHODS

2.1. Observational data

Daily snow depth, snowfall, precipitation, and surface air temperature data were obtained for North America, north of 25° N, from the Daily Gridded North American Snow, Temperature, and Precipitation Dataset (Mote et al. 2018) for the period 1960–2009. A brief discussion of the dataset is included below, including details of station density, quality control efforts, and validation. For complete details, please consult Mote et al. (2018), Dyer & Mote (2006), Kluver et al. (2016), and Suriano & Leathers (2017).

Available variables are interpolated from individual observation stations from the Cooperative Observer Program (Department of Commerce 2003) in the USA and from the Meteorological Service of Canada (Braaten 1996) onto a 1°, latitude by longitude grid using the Spheremap spatial interpolation procedure (Willmott et al. 1984). Spheremap leverages a modified Shephard's inverse-distance algorithm for projecting onto a spherical lattice. Station density for the gridded dataset has been shown to vary over space and time (Dyer & Mote 2006, Kluver et al. 2016), thus a variable search radius is used. A maximum of the nearest 25 stations within 100 km are used in generating the interpolated value for a grid cell. Should there be 5 or fewer stations within 100 km of the grid cell center, only those stations are used. Further, if no stations are located within a 100 km radius, the search radius is set to the nearest observation (Kluver et al. 2016). Station density from 1960–2009 is reported in Fig. 1. In the USA, stations are geographically distributed across the country, with density increasing particularly along the east and west coasts after 1948 and slowly declining after reaching a peak in 1970 (Kluver et al. 2016). Daily snow depth observations are available across much of Canada starting in 1960, whereas prior to this, they were concentrated

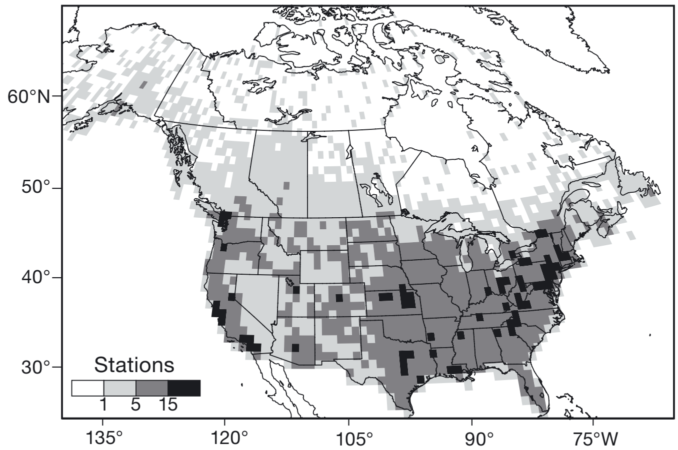

Fig. 1. Observation station density (stations per grid cell) of the Daily Gridded North American Snow, Temperature, and Precipitation Dataset (Mote et al. 2018) over the 1960–2009 study period

in western British Columbia and along the US–Canada border (Dyer & Mote 2006).

Quality control was initially conducted prior to interpolation following the procedure of Robinson (1989). Additionally quality control was performed following the procedure of Suriano & Leathers (2017) due to the potential for the interpolation scheme to artificially increase or decrease grid cell snow depth between successive days due to station reporting irregularities (Mote et al. 2018). This potential could result in false ablation or accumulation events being identified. Locations with varying topographic relief were identified as being particularly prone to this issue (Suriano & Leathers 2017). Kluver et al. (2016) performed a validation assessment on the gridded dataset. Compared to other observations, the dataset has a negative bias that is particularly apparent in regions with large topographical variability. This is attributed partially to the interpolation method that smooths higher-frequency signals, typically associated with higher elevation stations, with multiple station observations, and to the inconsistent geographic locations of the stations used by the gridded dataset and those of the validation (Kluver et al. 2016). While additional quality control greatly limits the potential for erroneous ablation, caution should be taken particularly when examining ablation events in regions with large topographic variability, such as the Rocky and Cascade mountain ranges. This study focuses most on the region east of the Rocky Mountains, therefore no additional measures were taken to account for the topographical limitations of the dataset.

While the termination of the dataset in 2009 inhibits analysis of the most recent events, the consistent use of cooperative observation sites and long-term data record is conducive for climatological analyses, making it advantageous for this application over other products such as the Snow Data Assimilation System (https://nsidc.org/data/g02158). The consistent use of a single observational dataset, with proper quality control, allows for the well known potential biases in snow data (Kunkel et al. 2007) to be appropriately accounted for, and brings greater confidence to the resulting analysis.

2.2. Definition of ROS ablation

Here, ROS ablation is defined as an inter-diurnal snow depth decrease of at least 1.0 cm in an individual grid cell, only during instances when the average daily temperature on the day of the event exceeds 0°C, when at least 0.01 cm of precipitation is observed, and when there was not more than 2.54 cm of snowfall on the previous day. The 1.0 cm snow depth loss threshold is used to aid in the validity of snow depth change being a proxy for ablation (Suriano & Leathers 2017, Suriano 2019, Wachowicz et al. 2020). The use of inter-diurnal snow depth changes less than 1.0 cm would increase the likelihood that an event is not grounded in meteorological plausibility and is just the result of interpolation- and/or station-reporting-based erroneous signals (Suriano & Leathers 2017). Such small events may also not be linked to snowmelt, for example the case where liquid precipitation only percolates the top few centimeters of the snowpack, changing the characteristics and depth of the snowpack, but not resulting in melt. By removing instances of less than 1.0 cm of snow depth loss, there is an increased focus on the evaluation of only days with a hydrologic outcome (McCabe et al. 2007), compared to just occurrences of liquid precipitation onto snow.

Isolating days with average temperatures greater than 0°C serves 2 purposes: (1) indicating liquid precipitation as opposed to snowfall (Wachowicz et al. 2020), and (2) assuming the level of snowpack maturity (Dyer & Mote 2007). The snowpack can be assumed to be relatively isothermal and mature when surface air temperatures are greater than 0°C, and thus snowpack compression is relatively minimal (Dyer & Mote 2007). Further, snowpack compression is most prominent immediately following accumulation, thus removal of events where snowfall in excess of 2.54 cm is observed on the previous day aids in the removal of events forced by compression (Suriano & Leathers 2018).

Multiple values of these thresholds were initially considered based on an evaluation of the literature (McCabe et al. 2007, Mazurkiewicz et al. 2008, Pradhanang et al. 2013, Freudiger et al. 2014, Wachowicz et al. 2020). For the reasons outlined above, the chosen definition yielded higher confidence that the change in snow depth was grounded in ablation, not compression or other non-physical processes, while ensuring sufficient frequency of events were available for analysis, particularly in the under-studied continental interior regions where the inclusion of a higher precipitation threshold greatly reduces event frequency.

In addition to defining ROS ablation, this study also defines non-ROS ablation for comparative purposes in determining the proportion of ablation events that are ROS in nature. Non-ROS ablation is defined as the inter-diurnal decrease in snow depth of at least 1.0 cm during instances when the maximum daily temperature during the event exceeds 0°C (Suriano 2019), there is no snowfall in excess of 2.54 cm on the day preceding the event (Suriano & Leathers 2018), and there is no precipitation. The primary difference in the definitions of ROS and non-ROS ablation is the inclusion/omission of the precipitation term. Given these definitions, ROS ablation here may not necessarily account for freezing rain events.

2.3. Study design

The frequency and magnitude of ROS ablation and non-ROS ablation events were calculated from daily events at each 1° grid cell within the domain monthly and for the September through August snow season, hereafter designated as seasonal. Standard statistics are initially presented (Section 3.1), followed by results on spatiotemporal variability and trends (Section 3.2), and physical forcing mechanisms (Section 3.3). The coefficient of variation in Section 3.1 was calculated based on the magnitude of ablation from individual events, not monthly or seasonal averages. The proportion of ROS ablation events from all ablation events, represented as a percentage, was calculated for the entire 1960–2009 period as the frequency of ROS ablation events divided by the sum of the frequency of ROS and non-ROS ablation events. Temporal trends (Section 3.2) were evaluated using Sen's slope estimate and statistical significance determined using the Mann-Kendall test. In aiding the determination of forcing mechanisms driving ROS ablation variability (Section 3.3), meteorological variables of snow depth, snowfall, temperature maximum and minimum, and precipitation were regressed against ROS ablation frequency. Variables were detrended seasonal values for the period 1960–2009. All tests were conducted in SPSS v. 26.

3. RESULTS

3.1. ROS ablation spatial variability

Mean seasonal ROS ablation frequency from 1960 to 2009 was spatially heterogeneous across North America, with a maximum frequency in the Pacific Coast Ranges exceeding 30.0 events yr^{-1}, and relative minima less than 2.0 events yr^{-1} in much of the continent's interior and south of 40° N latitude (Fig. 2a). In eastern North America (i.e. northeast USA, southeast

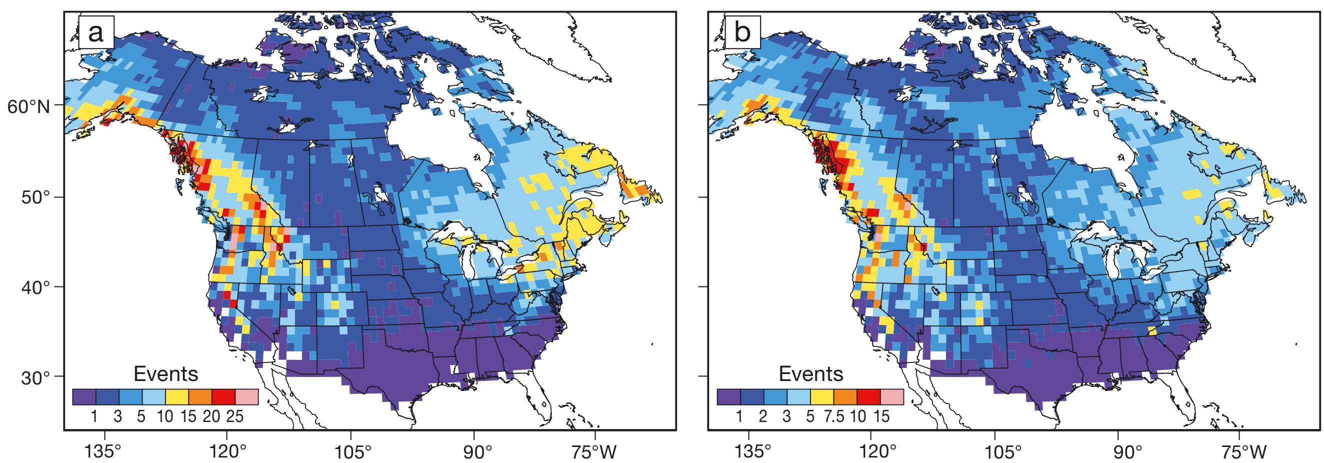

Fig. 2. (a) Average seasonal (September to August) ROS ablation event frequency from 1960–2009 and (b) SD of seasonal (September to August) ROS ablation frequency, in events. Warm tones denote greater frequency

Canada), ROS ablation was relatively frequent, with approximately 5 to 15 events yr^{-1}. As the threshold for ROS ablation magnitude was increased (2.5, 5.0, 10.0 cm ablation), a similar seasonal spatial distribution persisted (not shown). Seasonal variability is apparent across much of the western regions of the domain, with an SD of seasonal (September to August) ROS ablation frequency of less than 1.0 south of 35° N, between 1.0 and 2.0 through the North American plains, and then greater than 3 events yr^{-1} in the northeast USA and eastern Canada (Fig. 2b).

Within the seasonal cycle, a band of relatively higher frequencies of ROS ablation was observed through the study domain as the availability of snow and meteorological conditions suitable for ROS ablation varied. The central band of enhanced ROS ablation frequencies was most prominent in the eastern half of the continent, advancing south from September through January to approximately 41° N, before retreating north from February to June (Fig. 3). Across the Great Lakes region into New England and southeastern Canada, the largest average frequency

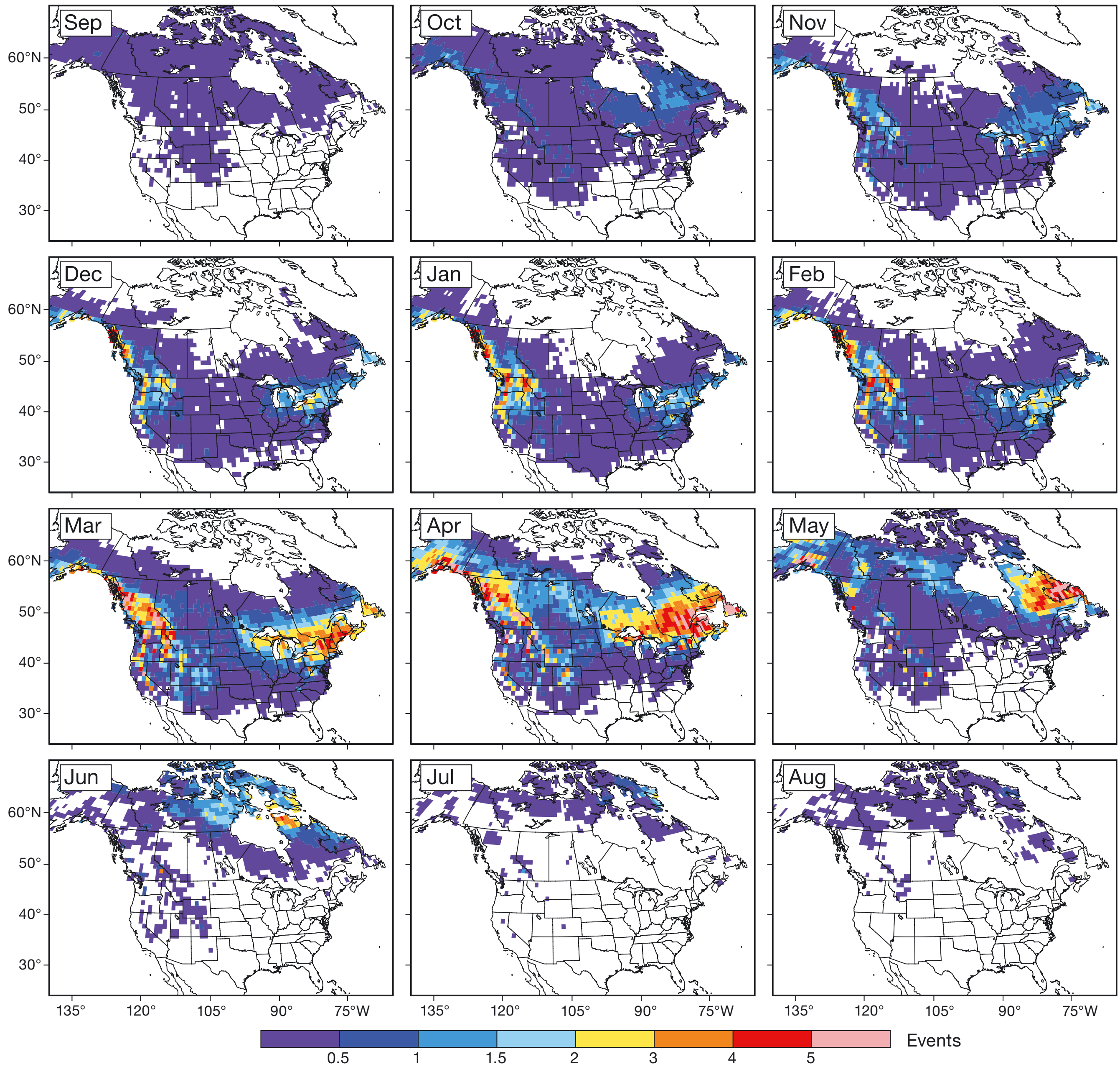

Fig. 3. Interannual average ROS ablation event frequency, 1960–2009, for September–August

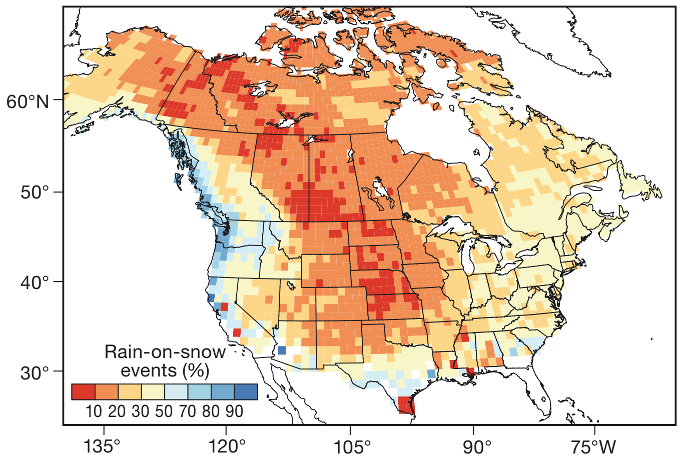

Fig. 4. Percentage of 1960–2009 ablation events classified as ROS for the September to August season

of ROS ablation was observed in March and April, where 2.0 to 6.0 ROS ablation events occurred each month. There was a clear increase in ROS ablation frequency during the meteorological spring (March, April, May) over much of the region east of the Rocky Mountains, likely due to the co-occurrence of sufficiently deep snowpacks and increased probability for liquid precipitation and warm air advection.

With respect to North America, ROS ablation represented approximately 22.7% of all ablation events within a given year. This value was greatest along the western coast, where ROS ablation represented 70 to 100% of ablation events (Fig. 4). In the east, ROS ablation represented approximately 33% of events, with <20% of events in the interior of the continent being considered ROS. The relatively high percentages observed along the southern Gulf Coast (~30 to 50%) were attributed to the low frequency of ablation events associated with infrequent snowfall yet a high frequency of ROS ablation-inducing meteorological conditions.

Across the study domain, average daily ROS ablation magnitude was 3.4 cm (standard deviation σ: 1.0 cm). This is approximately 22% greater than average daily non-ROS ablation magnitude. Examined spatially (Fig. 5a), average ROS ablation magnitude exhibited many similarities to the distribution of ROS ablation frequency, with relative maxima observed in northeastern North America and the Pacific Coast Ranges exceeding 4.0 cm per event. Much of the continent interior and plains exhibited average magnitudes of approximately 2.6 to 3.2 cm per event.

The large average magnitudes depicted along the Gulf Coast were likely due to the occurrence of a single ROS ablation event, where a recently accumulated snowpack rapidly ablated. Individual events here were manually inspected to confirm physical plausibility, and the mechanism was further supported by examination of the ROS ablation magnitude coefficient of variation (Fig. 5b). Very low coefficients (<10%) were observed in this region. Elsewhere, coefficients of variation were lowest in the interior, and increased to the west and east. Maximum coefficients are observed directly along the coasts. Maximum daily ROS ablation magnitudes exceeded 70 cm per event, and were observed primarily in northeastern North America and along the Pacific Coast, with some exceptions (Fig. 5c).

3.2. Temporal variability

Multiple regions across the continent exhibited spatially homogeneous significant ($p < 0.05$) linear trends in ROS ablation frequency over the period 1960–2009 (Fig. 6). In northern Quebec, ROS ablation frequency declined by approximately 0.14 events yr^{-1}, representing a decrease in excess of 50% on a linear fit over the 50 yr period. Similar decreases of 0.07 to 0.12 events yr^{-1} were observed across broad sections of the Canadian Plains, including in southwestern Ontario, north of Lake Superior. In the southern Appalachians, seasonal ROS ablation events declined by 0.3 to 0.7 events per decade. While the magnitude of significant change is small, it represents a linear-fit decrease of over 60% in the southern Appalachians. Significant increases in ROS ablation frequency were observed in eastern maritime Canada, and along the Inside Passage of Alaska and in southern British Columbia, with trends of approximately 0.08 and 0.17 events yr^{-1} observed, respectively.

In the southern Appalachians, the seasonal trends in ROS ablation frequency were primarily driven by significant decreases in frequency during the months of February and March (Fig. 6c,d). In contrast, April exhibited large decreasing trends in frequency in southwestern Ontario and increasing trends in southeastern Quebec (Fig. 6e). In May, ROS ablation frequency significantly declined in much of the Canadian Plains and in northern Quebec, and increased in the Inside Passage of Alaska and in southern British Columbia (Fig. 6f). By June, ROS ablation was primarily restricted to the most northerly regions, and trends in frequency from 1960–2009 indicated decreases in regions of Newfoundland and Nunavut (Fig. 6g).

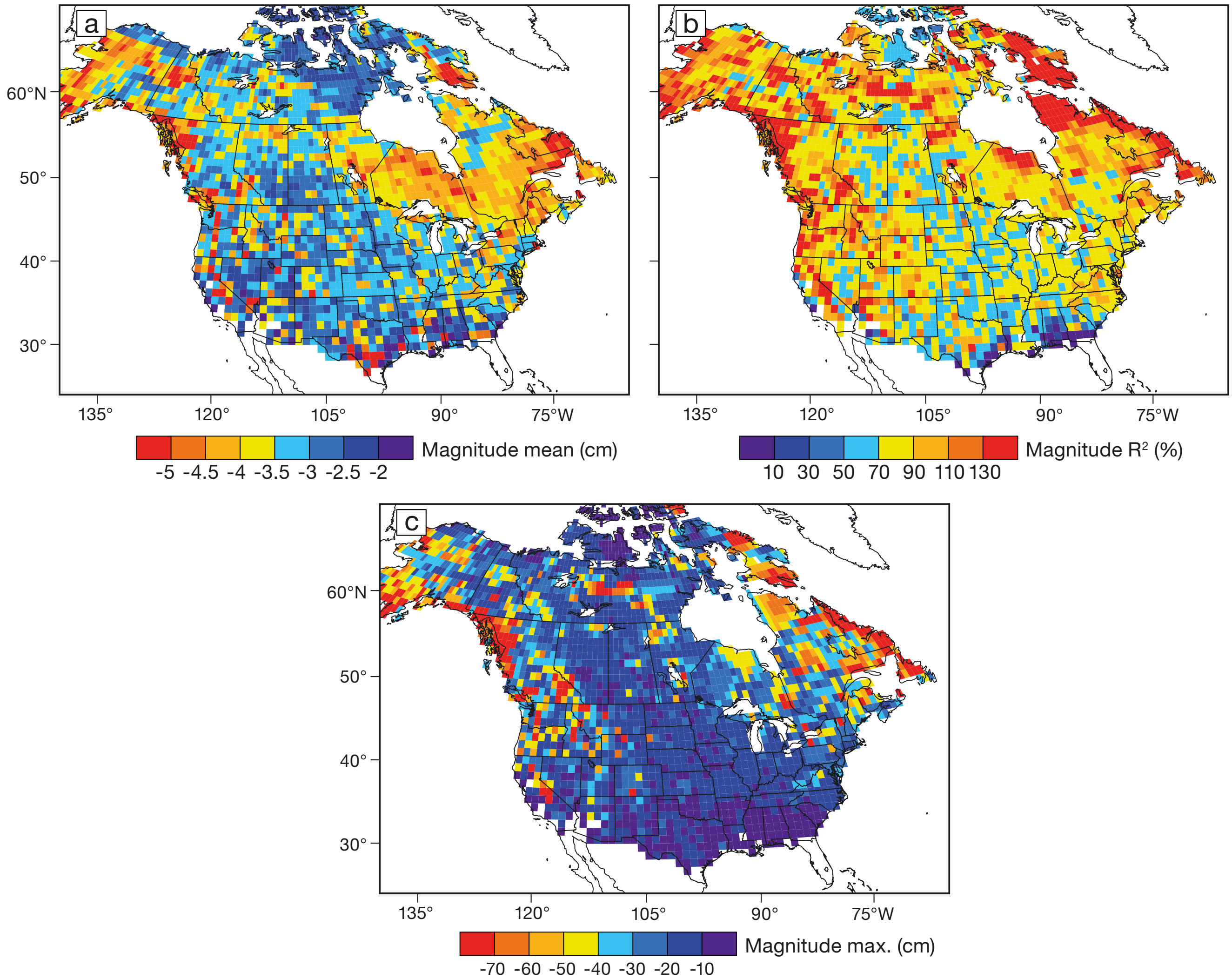

Fig. 5. Magnitude of 1960–2009 seasonal (September to August) ROS ablation: (a) average, (b) coefficient of variation, and (c) maximum

3.3. Mechanisms forcing ROS ablation variability

Snowfall was identified as the most important variable in determining ROS ablation frequency for the domain as a whole. Snow seasons (September to August) with an enhanced frequency of ROS ablation occurred during those with enhanced snowfall totals ($R = 0.69$, $p < 0.01$). Regionally, greater correlation coefficients were observed between snowfall totals and ROS ablation frequency in the eastern USA and along the west coast of North America, with lesser correlations in northern Canada (Fig. 7b). With additional snowfall, there is more snow available to be ablated during a potential ROS event. This is supported by regressions between ROS frequency and seasonal (September to August) snow depths, where enhanced snow depths were observed during periods with more ROS ablation events ($r_S = 0.31$, $p < 0.05$). This could be represented both as higher snowfall leading to greater snow depth at the end of the cold season (e.g. April) and thus a deeper snowpack that could generate more ablation events, and also as higher snowfalls during the winter (e.g. January) leading to greater opportunities for ablation prior to terminal ablation at the end of the snow season. Temperature maximums and minimums additionally explain a significant amount of variance in ROS ablation frequency for the continent ($r_S = -0.45$ and -0.32, respectively, $p < 0.05$) (Fig. 7c,d). With warmer temperatures, fewer ROS ablation events were observed at the seasonal scale. Domain wide, precipitation was also

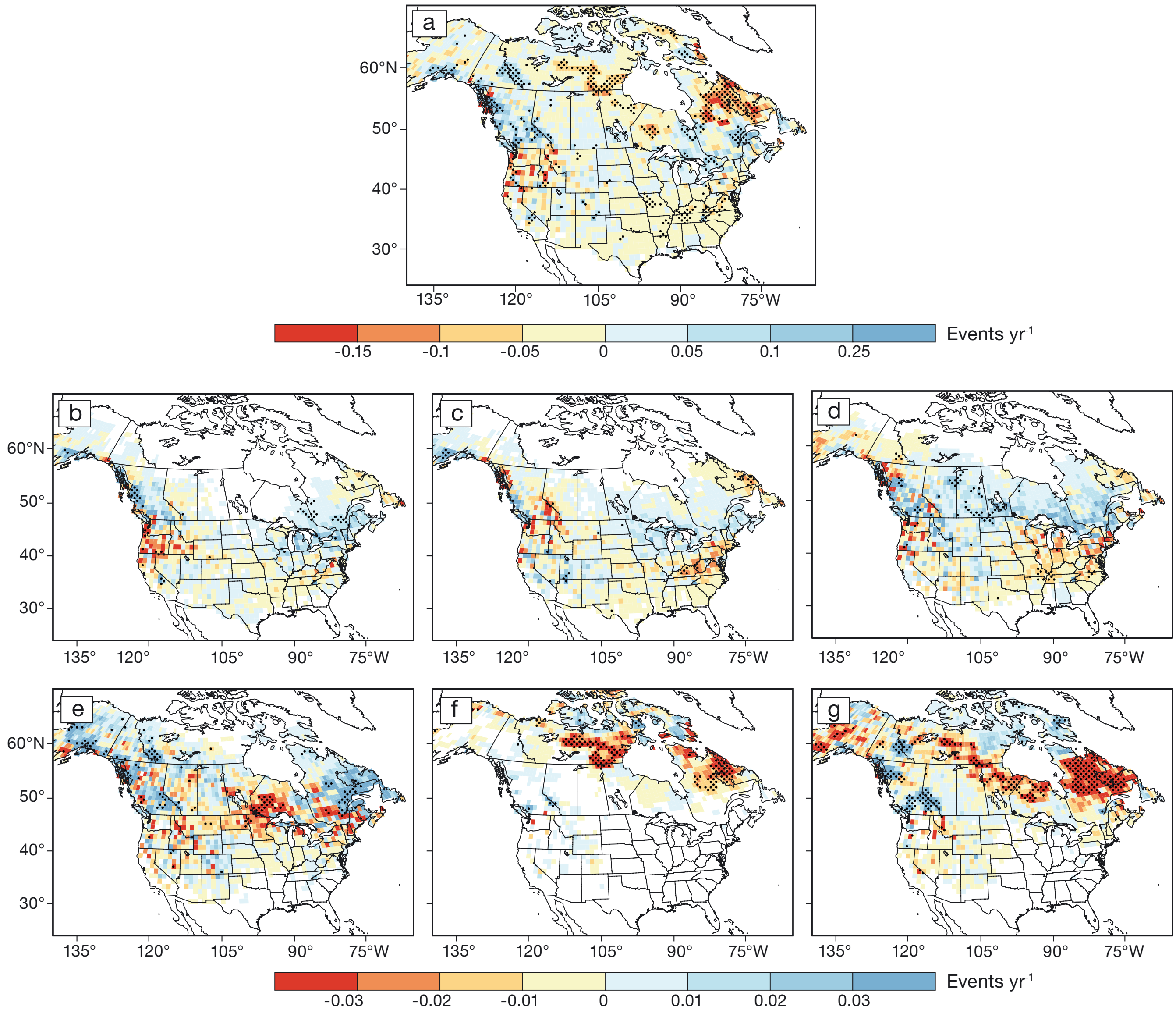

Fig. 6. Linear trend in 1960–2009 ROS ablation event frequency for (a) the September to August snow season, (b) January, (c) February, (d) March, (e) April, (f) May, and (g) June. Black stippling: statistically significant trends ($p < 0.05$)

significantly correlated to ROS ablation event frequency ($r_S = 0.36$, $p < 0.05$), such that a greater frequency of ROS is noted in seasons with greater precipitation. This is a logical association given the ROS ablation definition requiring precipitation; thus seasons with more precipitation increase the potential for a ROS ablation event to occur. Spatially, this correlation is strongest over much of the mountain west, across a SW-to-NE region spanning from portions of the Upper Midwest into the Great Lakes basin, and onward into eastern Newfoundland (Fig. 7e).

4. DISCUSSION

4.1. Spatial variability

The spatial variability in the frequency of ROS ablation events is similar to that shown in recent studies, with a greater frequency of events in coastal and mountainous regions where locations are subjected to greater snowfall and increased potential for liquid precipitation events during the snow cover season (Cohen et al. 2015, Li et al. 2019). Here however, we include analysis in the continental interior and more

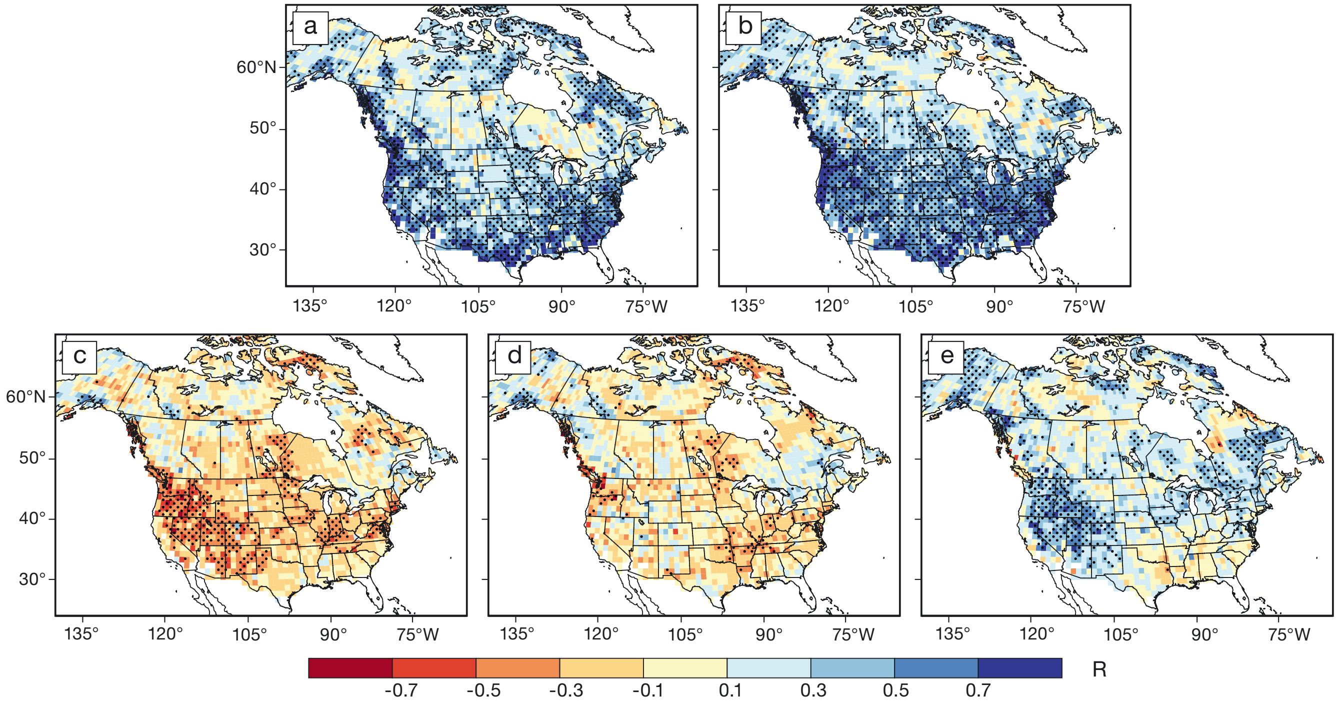

Fig. 7. Pearson's correlation coefficient (R) between 1960–2009 seasonal ROS ablation frequency and (a) snow depth, (b) snowfall, (c) maximum temperature, (d) minimum temperatures, and (e) precipitation. Black stippling: significant trends ($p < 0.05$)

southerly locations that while often ignored in the literature (e.g. Li et al. 2019), experience relatively frequent ROS ablation events that can cause localized relevance to day-to-day operations, including damage to infrastructure during extreme events (e.g. DiLiberto 2019). Even representing typically <20% of all ablation events, ROS ablation events in these areas are worth evaluating. While infrequent in the Great Plains, ROS ablation can still be hazardous, as evident by the March 2019 flooding event which resulted in approximately $6.2 billion (2020 dollars) in losses across the central Great Plains in the USA (DiLiberto 2019). Results of this study also detect features of a seasonally migrating band of peak ROS ablation frequencies in eastern North America, which is similar to other snow cover- and snow ablation-based climatologies (Dyer & Mote 2007, Suriano & Leathers 2017, Suriano et al. 2021).

The spatial distribution of ROS ablation events during the winter months is similar to that described by Cohen et al. (2015); however, here ROS ablation exhibits a higher relative frequency during the spring, similar to the conclusions of Wachowicz et al. (2020) for the eastern USA. Over the northeast region, a similar domain to that of Wachowicz et al. (2020), this study detected approximately 8.0 ROS ablation events per September to August season. This falls below the D1 ablation definition value of approximately 14 events (defined as air temperature >0°C, snow depth loss >0 cm, and precipitation >0 cm) used by Wachowicz et al. (2020), but greater than their most strict definition, D4 (air temperature >0°C, snow depth loss >1 cm, and precipitation >1 cm), of approximately 5 events. Given the differences in ROS ablation definition, some variation is expected, but values here fall within their stated range (Wachowicz et al. 2020). Alignment of our spatiotemporal results with recent studies in the literature using different methodological approaches builds greater confidence that the novel contributions presented with respect to the percent contribution of ablation due to ROS, the seasonal cycle of ROS events, and results presented in Sections 3.2 and 3.3 are robust and grounded in physical meteorological conditions.

4.2. Temporal trends

Significant trends in ROS ablation frequency are generally more pronounced here than in Cohen et al. (2015), with multiple homogeneous regions exhibiting linear increases or decreases in frequency over the 50 yr period. We attribute the detection of greater linear trends in ROS ablation frequency here, compared to other studies in the literature, to differences in definitions of ROS ablation and the use of an observational dataset over reanalysis product. In the western USA, we detect both increases and decreases in ROS ablation frequency, similar to McCabe et al. (2007), albeit at a coarser resolution here than the individual observational stations used in the previous study. In the eastern USA, the direction of trend in ROS ablation event frequency is similar to that of Wachowicz et al. (2020), with decreasing trends in the southern and central portions of the northeast in meteorological spring and winter, and increasing trends in meteorological winter in the northern portions of the northeast.

Specific to eastern Canada, ROS ablation frequency increases during the months of January through April, but decreases in May. Such a dipole of trends during the snow season suggests the snow season and/or meteorological conditions that support ROS ablation may be changing. Previous research examining the snow season has indicated a general shortening with time, with snow cover decreasing significantly during the spring months (Frei & Robinson 1999, Mudryk et al. 2020). Reductions in spring snow cover, particularly late spring, could lead to insufficient snow depths for ROS ablation to occur. In contrast, previous research in the nearby Great Lakes region has suggested the conditions suitable for ablation have become more common over the last 50 yr, with increases in the frequency of weather types with warmer and more moist conditions, and wind/sky conditions more favorable for enhanced turbulent energy fluxes (Suriano & Leathers 2021). Reduction of late-spring snow cover, when coupled with more favorable atmospheric conditions for ablation, could drive an increased frequency of late-winter and early-spring ROS ablation at the expense of late-spring events.

4.3. Mechanisms forcing ROS ablation variability

In most cases, a higher frequency of seasonal ROS ablation was associated with seasons of enhanced snow depth and snowfall, and seasons with cooler temperatures. The negative association between temperature and ROS frequency, also replicated by Pradhanang et al. (2013) specifically in New York State, is likely further exemplifying the association with snowfall and snow depth. Cooler temperatures resulted in enhanced snow totals, and thus a greater potential for ROS to occur — pending the meteorological conditions.

Only in a select few locations (portions of Alaska, eastern Quebec, and along the western border of Canada's Northwest Territories) were significant positive correlations detected between ROS frequency and temperature (i.e. warmer temperatures yield more ROS events). While snow variables collectively explain more variance in ROS frequency on the whole, notable regions where temperatures played a more critical role include much of the western USA, portions of the Appalachians, and pockets of the central Canadian plains.

The primarily negative correlations between temperature, both maximum and minimum temperature, and ROS ablation frequency highlights 2 competing effects when evaluating ROS ablation. First, from the perspective of the meteorological or atmospheric conditions of the ROS ablation definition, colder air temperatures should decrease the potential for liquid precipitation to occur, and thus have the potential to decrease the frequency at which ROS ablation could occur. Second, from the perspective of the snowpack, colder conditions could also result in more snowfall and a thicker snowpack, thus increasing the potential for more ROS ablation events. Here, evidence suggests the snowpack perspective is more influential at the scales analyzed, with colder conditions being associated with more ROS ablation. This mirrors other research examining large-scale ablation conditions that found the interannual or interseasonal frequency of ablation is more closely related to snow characteristics than the variability of meteorological conditions suitable for ablation (Suriano 2019, Suriano et al. 2021).

Other studies have evaluated ROS ablation forcing mechanisms at smaller temporal scales on an event-by-event basis. They found fluxes of sensible and latent heat play a large role in ROS events, but that for many regions, net radiation is also a critical factor (Li et al. 2019, Suriano 2019). Our focus here on seasonal scale processes does not invalidate these findings, but rather acknowledges that large scale conditions are necessary for these smaller-scale events to occur. Other studies examining snow ablation, not necessarily ROS, observed similar features in forcing mechanisms. Studies in the Great Lakes basin indicate snow depth and snowfall are more dominant forcing mechanisms of ablation frequency in the region than temperature (Suriano 2019, Suriano et al. 2019); however, these studies further emphasize the importance of key synoptic-scale weather patterns in governing ablation frequency over time.

Further changes in ROS ablation across North America for the remainder of the 21st century will likely be closely connected to any potential changes in snowfall associated with warming atmospheric conditions. As atmospheric conditions warm during the cold season, there is an increased probability that more snowfall will initially occur associated with greater saturation vapor pressures in below-freezing atmospheric columns, but then result in more rainfall at the expense of snowfall with time once the column cannot support frozen hydrometeors as often (Krasting et al. 2013). This would result in the potential for a change point in snowfall, and thus ablation, to occur by 2025–2040, where the additional snowfall attributed to the greater saturated vapor pressures is overwhelmed by the reduction in snowfall in favor of more rainfall (Suriano & Leathers 2016). On a broad seasonal scale, more rain and less snow will limit the depth of the snowpack that could develop, and thus reduce the number of ablation events, ROS or otherwise, that could occur. However, there is a potential seasonal component that needs to be acknowledged.

Depending on the specific location, the projection for more rainfall at the expense of snowfall is not evenly distributed during the cold season, resulting in a net shortening of the snow season in late autumn and early spring (Krasting et al. 2013, among others). In the autumn, rainfall instead of snowfall would likely not alter the frequency of ROS ablation substantially beyond the broad seasonal-scale impact noted previously; the additional rainfall would likely not be falling onto an existing snowpack in autumn. But in the late winter and spring months, additional rainfall instead of snowfall could increase the frequency of ROS ablation events, with liquid precipitation occurring during a period when snow cover is typically present. This would not necessarily further change the total frequency of events beyond the broad seasonal-scale impact discussed above, but rather change when ROS events typically occur. This potential change is not overly apparent within the domain-wide observations, but in specific regions, such as in southwestern Ontario and southern Manitoba, significant increases in ROS ablation frequency in March are co-occurring with significant decreases in April.

There has been limited research to date exploring model projections of ROS ablation for the remainder of the 21st century. Jeong & Sushama (2018) explored possible ROS outcomes for the period 2041–2070, driven by RCP4.5 and 8.5 emission scenarios, and noted a decrease in snow-covered days in the projections. Their findings indicated ROS may increase across much of Canada in association with enhanced rainfall frequency, while decreasing in the eastern USA in spring associated with a diminished snowpack. Li et al. (2019) also detected a decrease in the frequency of ROS for much of the eastern USA, coupled with a change towards earlier events within the seasonal cycle, when evaluated with a +2°C scenario. With snowfall being a critical component of the ROS ablation potential, changes in the timing or magnitude of that snowfall will impact the potential for ROS ablation.

5. CONCLUSIONS

Four primary conclusions are drawn from this spatiotemporal analysis of ROS ablation events from 1960–2009 in North America:

(1) ROS ablation events occur throughout the year, with a latitudinally oriented band of peak event frequencies advancing and retreating south and north, respectively, in association with the seasonal cycle of the meteorological conditions capable of rainfall and snowmelt, and the presence of snow cover. The pronounced presence of ROS ablation events in spring indicates the importance of monthly analyses over exclusively interannual research foci.

(2) ROS ablation events represent approximately 33% of all ablation events in eastern and Atlantic coastal North America, compared to less than 20% in the interior plains and greater than 70% directly along the Pacific Coast. This highlights the need for regional-based analyses and management strategies.

(3) Regression analysis detects statistically significant linear trends in ROS ablation frequency in multiple homogenously clustered regions. ROS ablation frequency decreased in northern Quebec and in the southern Appalachians, and increased in southeastern Quebec and in British Columbia. Increases in January to April events, coupled with decreases in May in eastern Canada, suggest a shortening of the snow season, with the snowpack being depleted earlier in the year over time.

(4) While convention suggests warming temperatures will play a critical role in shaping ROS ablation frequency in a warming climate, the results here suggest the warming temperature signal is still mixed, and warming temperatures are more closely connected to the potential occurrence of snowfall, than that of the meteorological conditions necessary for snow ablation. Warming temperatures increase the potential for the liquid precipitation necessary for ROS ablation, but also then limit the persistence of the snowpack to be ablated. As such, snowfall amounts are determined to be the dominant control on ROS ablation frequency for the continent during the study period.

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