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Regional Differences in High Elevation Snowpack Decline Along the North American Rocky Mountains

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ABSTRACT

The Rocky Mountains (RM) provide the ‘water towers’ for western North America, with deep winter snowpack accumulations that melt to contribute flows for the extensively utilised Columbia, Colorado, Saskatchewan, Missouri and Rio Grande River systems. With climate change, winter and spring warming are increasing seasonal and elevational rain versus snow proportions and altering the annual patterns of snowpack accumulation and melt. Prior studies have reported declines in snowpack extent or water content, especially on an index date, April 1. These declines could reflect reductions in the total annual snowpacks or earlier transitions to snowmelt. To resolve these influences, we assessed daily snowpack patterns at 314 snow pillow stations in the higher elevations along the 2500 km transboundary RM corridor, over three decades from 1991 to 2020. We found regional differentiation, with little change in the maximum snow water equivalent (SWE_{max}) or its timing (Day_{max}) in the most-northerly, Canadian RM region (BC, AB); slight declines in the Northern US (ID, MT, WY) and Central US (UT, CO); and major declines in the Southern US (AZ, NM; average ΔSWE_{max} : $-2\%/yr$; ΔDay_{max} : $-0.75\%/yr$). With compound influences of declining SWE_{max} and earlier Day_{max} , the April 1 SWE (SWE_{Apr1}) was more responsive, with progressive decline at some Northern US and Central US stations, and steep decline in the Southern US region (ΔSWE_{Apr1} : $-6.5\%/yr$). Due to these compound influences, we recommend that future analyses include snowpack maxima and seasonality as well as April 1 measures, since that precedes the peak snowpack for higher elevation and northern sites, but follows the peak for lower and southern sites, confounding trend comparisons. Thus, higher elevation RM snowpacks are declining but with considerable latitudinal variation, displaying slight change in magnitude and seasonality in the northern regions, and greater change southward. These patterns contrast with some other climate change patterns that display increasing responsivity with higher latitude.

1 | Introduction

The Rocky Mountains (RM) provide the largest mountain system in North America and extend relatively continuously from western Canada southward through the western United States. The mountains intercept moisture systems especially originating from the Pacific Ocean, resulting in extensive snow

fall and snowpack accumulation through the winter months (Bales et al. 2006; Li et al. 2017). The snowpacks subsequently melt through the spring and summer supporting the ‘nival’, or snowmelt-dominated river flow regimes that provide primary water sources for human uses and hydropower generation and support the region’s richest natural ecosystems (Hauer et al. 2016; Immerzeel et al. 2020; Qin et al. 2020; Rood et al. 2008).

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The deep RM snowpacks provide massive seasonal water storages and are regarded as North America's 'water towers' (Immerzeel et al. 2020; Viviroli et al. 2007). The RM create the Continental Divide and provide the headwater regions for some of North America's most extensively utilised river systems. These include the Columbia and Colorado Rivers that flow west to the Pacific Ocean, the Mackenzie and Saskatchewan systems that flow northward to the Arctic Ocean, and the Missouri and Rio Grande River systems that drain southeastward to the Gulf of Mexico and Atlantic Ocean. These river systems have been extensively dammed for water storage and flow regulation and commonly flow from wetter mountain zones down through water-scarce arid and semi-arid regions, where river water is extensively diverted for irrigation and other human uses (Bales et al. 2006). Climate change is altering precipitation patterns while warming is increasing aridity, compounding the challenges from increasing water demand in these river basins that include some of North America's fastest-growing cities, including Calgary, Denver, Salt Lake City and Phoenix (Christensen et al. 2004; Gottlieb and Mankin 2024; Overpeck and Udall 2020).

River flows integrate the patterns of precipitation and snowpack accumulation and melt through their full watersheds. Through the RM region, annual river flows have been gradually declining and there have been greater changes in the flow seasonality (Clow 2010; Christensen et al. 2004; Rood et al. 2008; Stewart et al. 2005; St. Jacques et al. 2010). Winter flows are increasing (Rood et al. 2008), reflecting progressive warming that increases the seasonal and elevational rain versus snow proportion (Berghuijs et al. 2014; Whitfield and Shook 2020), and winter melting, which can be increased with rain-on-snow events (Knowles et al. 2006; McCabe et al. 2007). Subsequently, the spring freshet is earlier, reflecting spring warming and earlier snowmelt (McCabe and Clark 2005; Rood et al. 2008; Stewart et al. 2005). Consistent historical changes in flow seasonality across multiple RM rivers (Philipsen et al. 2018; Rood et al. 2005; Stewart 2009) reflect regional warming and broad-scale changes in the patterns of snowpack accumulation and melt (Barnett et al. 2005; Stewart et al. 2005). The empirical patterns are consistent with hydroclimatic modelling that project changes in amount, distribution and persistence of mountain snowpacks (Adam et al. 2009; Barnett et al. 2005; Gottlieb and Mankin 2024; Huning and AghaKouchak 2018; Shepherd et al. 2010).

Analyses of historical snowpacks have commonly reported reductions in the extent of coverage or water content at sites sampled on April 1 (Brown and Robinson 2011; Hamlet et al. 2005; Mote 2006; Mote et al. 2018; Pierce et al. 2008). This date has been regarded as approximating the snowpack peak (Bohr and Aguado 2001), although it is recognised that snowpack accumulations continue at some higher elevation sites (Harpold et al. 2012; Kapnick and Hall 2012). With the progressive spring-time warming and the earlier freshet, the question arises of whether historical snowpack declines on April 1 reflect declines in the total winter snowpack or changes in snow melt seasonality (Montoya et al. 2014). To resolve the two factors, we analysed historical daily snowpacks along the full international RM corridor. We assessed data from the network of SNOTEL (snow telemetry) or snow pillow stations that record the accumulating

water mass or snow water equivalent (SWE) through the winter season (Barnett et al. 2005; Knowles et al. 2006; Kapnick and Hall 2012; McCabe et al. 2007; MacDonald et al. 2011). We focused on the higher elevation snow stations, since these provide snow melt through the mid- to late summer when river flows are lower while water demands for irrigation and other human uses are higher. This is also a vulnerable interval for the river ecology, since low flows result in water warming and lower dissolved oxygen that stress fish and the aquatic ecosystems (Wieder et al. 2022), and lower river levels reduce water infiltration into the alluvial aquifers that support phreatophytic riparian woodlands (Phelan et al. 2022; Rood et al. 2008; Stewart 2009).

Following from the historical RM river flow regimes and prior analyses of RM snowpack patterns, we investigated four hypotheses.

1. Accompanying increases in the winter rain versus snow proportion, there would be a progressive decline in the historical RM snowpacks, with declining trends in the annual maximum winter snowpacks (SWE_{max}).
2. Due to spring warming, the day of the maximum snowpack (Day_{max}), which represents the transition from net snow accumulation to melt, would be progressively earlier.
3. Reflecting the combination of declining snowpack and earlier snowmelt, the April 1 snowpacks (SWE_{Apr1}) would display steeper decline rates than the SWE_{max} .
4. There would be geographic differentiation, and since climate warming has increased with higher latitude (Deutsch et al. 2008; Roots 1989; Solomon et al. 2007), the snowpack decline could be greater in more northerly regions.

2 | Methods

2.1 | Study Area and Snowpack Data

We compared snowpack patterns in the RM of two Canadian provinces and seven American states ('jurisdictions') grouped into four regions: (1) Canada, including British Columbia (BC) and Alberta (AB); (2) the Northern US (United States) region of Idaho (ID), Montana (MT), and Wyoming (WY); (3) the Central US region of Utah (UT) and Colorado (CO); and (4) the Southern US region of Arizona (AZ) and New Mexico (NM). For the analyses and presentations, the groups, jurisdictions and locations are sequenced from north to south and then from west to east.

Historical daily SWEs were obtained for BC (<https://governmentofbc.maps.arcgis.com/apps/webappviewer/index.html?id=c15768bf73494f5da04b1aac6793bd2e>), AB (<https://rivers.alberta.ca/>) and the US states (<https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/water/snowsurvey/>). The Canadian RM is generally lower in elevation, and two northern Canadian snow pillow stations were less than 5500 ft. (1676 m), while the others were greater than 6000 ft. (1829 m). For the US, all snow pillow stations required two criteria: historical records exceeding 30 years in duration and elevations above 6000 ft. This resulted in the analysed stations,

with names, numbers, jurisdictions, regions, latitudes, longitudes, elevations and durations provided in the archived data set (<https://doi.org/10.5061/dryad.5qfttdzj4>), along with the average snowpack measures and trend statistics for each station, as follows.

2.2 | Snowpack Analyses—Magnitude and Seasonality

From the historical daily data, three measures were derived for each snow station for each snow year, which extended from 1 October to 30 June.

1. The maximum SWE value of that year (SWE_{\max}).
2. The day of the SWE_{\max} (Day_{\max}), which provided an index of snowpack seasonality, was selected. In cases of multiple maximal values, the first day was selected.
3. The April 1 snowpack (SWE_{Apr1}) is the SWE value on that index date.

The yearly values for the three measures were derived from the full data sequence for each station and similar statistical analyses were undertaken for two data series: (1) the three-decade interval from 1991 through 2020, which provided a consistent comparison across the stations; and (2) the full records to 2020, which had substantial variation in record duration across the stations. The outcomes were very similar between the two analyses, and we primarily present the results from the reference three-decade analysis, since a focus was the comparison of patterns across the different geographical regions. In the Results, we provide some comparisons between the two time series.

For statistical treatment, the snowpacks usually completely melt through the summers at the studied snow stations, which avoided the complexity of carry-forward of snow across years. Consequently, the yearly values were treated as independent measures, although it is recognised that multiple-year hydroclimate patterns exist, especially correlated with the Pacific Decadal Oscillation (PDO; Mantua et al. 1997; McCabe and Dettinger 2002; Pederson et al. 2013; Rood et al. 2005; St. Jacques et al. 2010). Descriptive statistics were derived for each of the three snowpack measures for each snow station, including means and other measures that are provided in the archived data file (<https://doi.org/10.5061/dryad.5qfttdzj4>).

Temporal trend analyses were undertaken for each measure at each station. This involved bivariate correlations with IBM SPSS Statistics 28 (IBM, Armonk, NY, USA), with three statistics: the parametric Pearson Product r , and two non-parametric rank-order tests, Kendall's τ -b and Spearman ρ . The non-parametric tests provided almost identical statistical outcomes and only the Kendall's τ -b results are presented. The Pearson r and Kendall's τ -b outcomes were also very consistent (Figure 1), and we emphasise one or the other, depending on the type of comparison, as reported. For correlations and other statistical outcomes, we considered three thresholds: 'trend' (t), $p < 0.1$; 'significant' (*), $p < 0.05$; and 'highly significant' (**), $p < 0.01$.

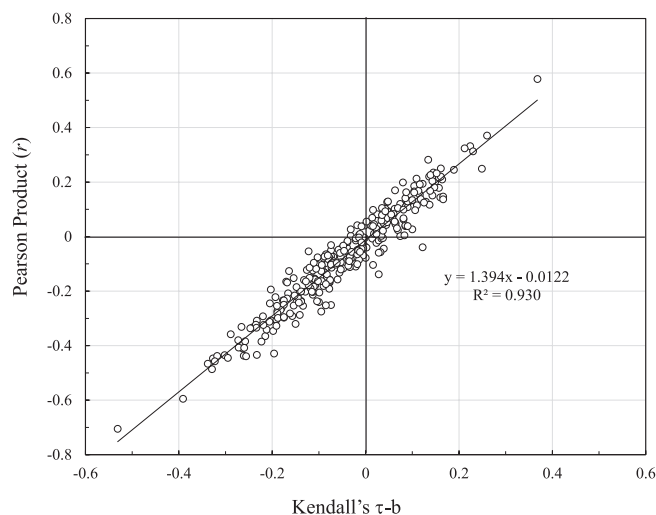


FIGURE 1 | The relationship between two bivariate correlations, the Pearson Product r and the non-parametric Kendall τ -b, for the SWE_{\max} of 314 high elevation North American Rocky Mountain snow stations over a 30-year period, from 1991 to 2020.

To further characterise the temporal changes, we undertook regressions for each measure for each snow station. These involved linear and polynomial regressions (quadratic and then higher-order), and we selected the simplest function that provided a near-maximal coefficient of determination (R^2); linear regression was generally sufficient. From these regressions, the nature of the change was assessed using the slope (b) as increasing (+ve value) or decreasing (–ve value). Subsequently, the numbers of stations with increasing versus decreasing changes were determined for each RM region or jurisdiction, and the χ^2 (Chi-square) test assessed deviation from an expected, random 50:50 distribution. The change rates (Δ) represented the magnitudes of change, calculated as the regression slope (b) divided by the mean value for each measure for each station. For visualisation with mapping, change rates were categorised as 1 (magnitude < 1), 2 (1 to 1.99), 3 (2 to 2.99) or 4 (> 3).

2.3 | Geographical Patterns

Mean measures of the individual snow stations were plotted by latitude (x-axis) and regression analyses revealed correlative patterns. The simplest function that provided a near-maximal coefficient of determination (R^2) was selected, commencing with linear and subsequently quadratic equations. To compare the distributions in the seasonal patterns of the Day_{\max} change rates (ΔDay_{\max} , days/decade) across the jurisdictions, we provide violin plots with a kernel density estimator.

To visualise the geographical patterns in the snowpack measures, the snow stations were mapped with QGIS 3.22 (Q Geographic Information System, Open Source Geospatial Foundation Project, <http://qgis.org>). Following the non-parametric Kendall's τ -b correlation analysis, each station was represented with a symbol to display apparent increases (Δ) or decreases (∇) in the measure based on the regression slope, with the symbol size representing the apparent magnitude of change, and symbol colour and intensity indicating direction and statistical significance for

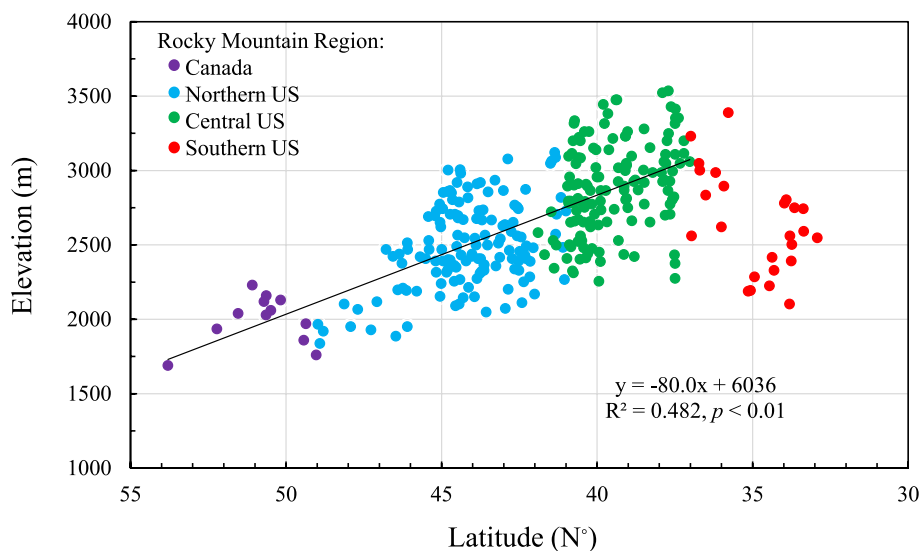


FIGURE 2 | The relationship between the latitude and elevation for the analysed snow stations, with colours representing the four Rocky Mountain regions studied. With the discontinuous distribution, the southerly stations of NM and AZ were not included in the regression.

individual stations. Combined results by jurisdiction were plotted with pie charts to represent the change direction (colour) and levels of statistical significance (intensity).

2.4 | Multifactor Modelling

The similar outcomes between the Pearson Product r and non-parametric correlations, and the sufficiency of linear regressions for individual factors supported a linear regression approach for multifactor analyses. Consequently, to consider the influences from combined geographical factors, forward-stepwise linear regression was undertaken with Automatic Linear Modelling (IBM SPSS 28). The three predictive factors were the latitude, elevation, and longitude of each snow station. Modelling was undertaken separately for the three snowpack measures and for their change rates as targets: SWE_{max} , ΔSWE_{max} , Day_{max} , ΔDay_{max} , SWE_{Apr1} , ΔSWE_{Apr1} . This modelling commences with the most influential factor and additional factors are included that correspond with residuals, with the Akaike Information Criterion applied for model selection. Data treatments including transformations and outlier exclusions were explored but had minor influences on the model accuracies and consequently, direct models were selected.

3 | Results

3.1 | Latitudinal Patterns

The 314 snow pillow stations were located over 24.7° latitude, extending from east-central BC, about 2500 km southeastward through the American Rocky Mountain (RM) regions to southwestern NM. The delineation of the 'Rocky Mountains' has varied, and our study included some disjunct mountain ranges in southern UT, central AZ, and flanking the AZ-NM border. These extended the latitudinal range but are lower in elevation and somewhat separate from of the more continuous core of the RM corridor (Figure 2).

In the Canadian regions of BC and AB, there were only 4 and 8 snow stations, respectively, with 30-year records. In contrast, high elevation stations with three-decade records were abundant across the three US RM regions, and especially for the Northern US and Central US (Figure 2).

There is an elevation \times latitude trade-off along the RM corridor, with higher mountains in the US than in the Canadian RM (Figure 2). Consequently, the snow stations in Canada were lowest in elevation (altitude), and as the latitude decreased, the snow stations analysed in this study, which were the highest in the respective areas, were located at progressively higher elevations (Figure 2).

The three snowpack measures displayed significant variation with latitude, but with considerable variability along the latitudinal corridor, across and within the RM regions (Figure 3). The SWE_{max} displayed a somewhat progressive decline with snow station latitude, and this was especially evident with the lower snowpacks in the Southern US region (Figure 3A). This region included snow stations from the separate and lower mountain ranges situated in the arid regions of southern AZ and NM, and these stations displayed similar SWE_{max} values to those along the more continuous RM corridor.

The variability in SWE_{max} was greater for the RM regions other than the Southern US (Figure 3A). This was not significantly correlated with the variation in elevation, such as across the Northern US snow stations ($r=0.077$, not significant, not displayed).

Along the RM corridor, the snowpack seasonality varied with latitude, with the day of maximum SWE (Day_{max}) differing by about 2 months (Figure 3B). The Day_{max} was substantially earlier in the Southern US, especially for the mountain ranges of southern AZ and near the AZ-NM border, below $\sim 35^\circ N$ (Figure 3B). There was a steeper increase in the Day_{max} from $35^\circ N$ to $40^\circ N$ and then the response flattened, especially by $45^\circ N$ (Figure 3B).

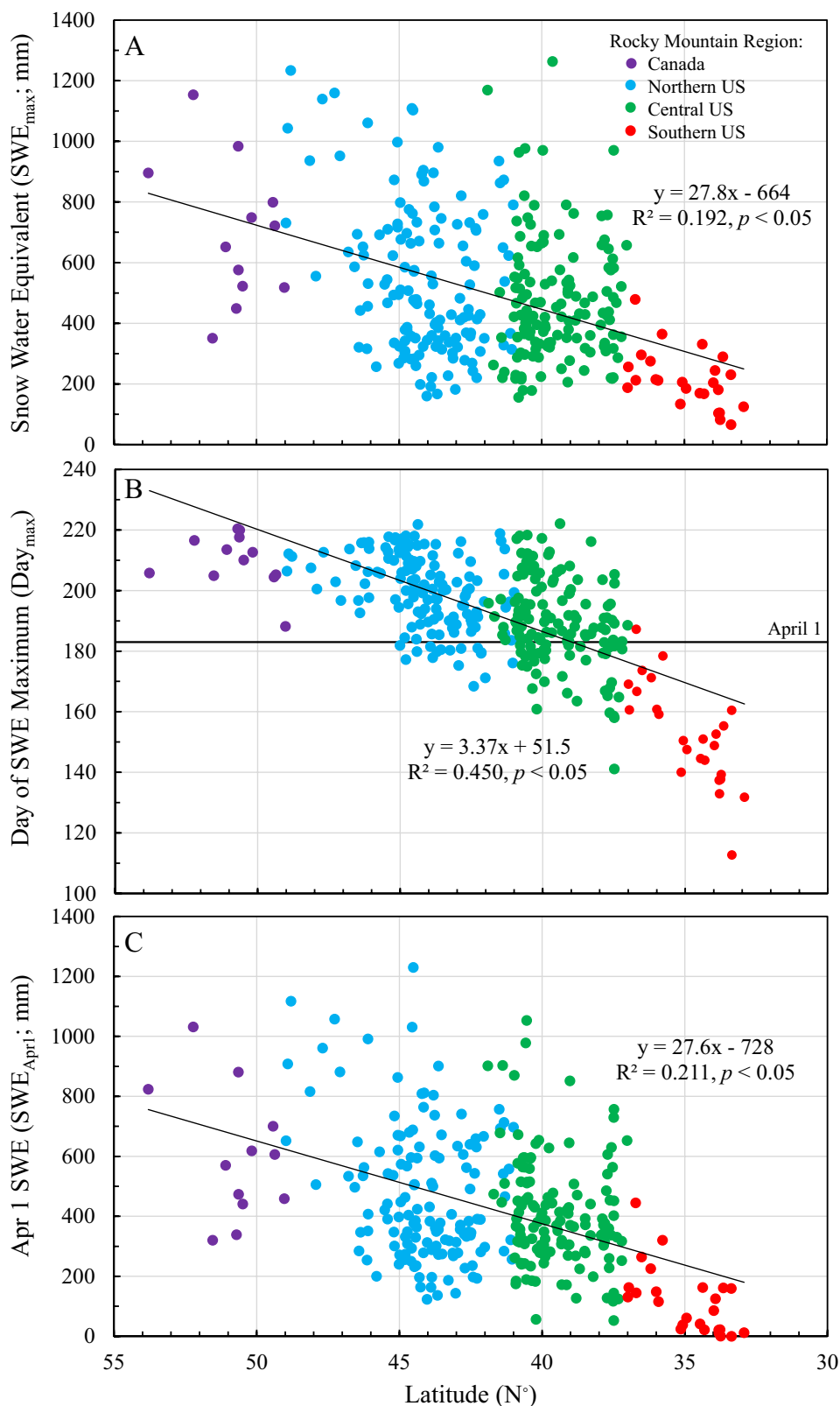


FIGURE 3 | The relationship between Rocky Mountain snow station latitude and the maximum snow water equivalent (SWE_{max} , A); the snow year day of the SWE_{max} (Day_{max} , B); and the Apr 1 SWE (SWE_{Apr1} , C). Average values for each station from 1991 to 2020 are shown.

For the Canadian, Northern US, and Central US regions, there was variation up to a common upper limit of ~day 220 or May 7 (Figure 3B). This would be associated with the rapidly lengthening days, especially for the northern regions, and increasing

insolation that could contribute to this common seasonal limit for the transition from snow accumulation to melt. That late limit was more than a month after April 1 (day 183), which has often provided the reference date for snowpack analyses (Figure 3B).

Consequently, April 1 assessments would considerably underrepresent the maximal snowpack accumulation in the Canadian and the Northern US, and Central US regions.

Conversely, for the Southern US, the Day_{max} was a month or more before April 1 (Figure 3B). There would consequently be substantial snowmelt before April 1. This would also underrepresent the maximum snowpack, but for the opposite reason to the underestimation for many snow stations in the other RM regions.

Over the latitudinal range, the April 1 snowpacks (SWE_{Apr1}, Figure 3C) displayed a similar pattern as the snowpack maxima (SWE_{max}, Figure 3A). For both measures, the latitudinal variation accounted for about 20% of the variation across the snow stations (the R² values), with more substantial variation within the RM groups other than the Southern US. The two SWE regression lines were parallel, with common slopes of 28 mm/°N, and the SWE_{Apr1} line was shifted downward by 64 mm (Figure 3A vs. 3C).

The linear trends in SWE_{max} and SWE_{Apr1} were relatively consistent across the latitudinal range, and consequently the proportional reduction was greater for the Southern US region (Figure 3). Some of the AZ and southern NM stations had nearly complete snow melt by the April 1 assessment (Figure 3C).

Thus, the underrepresentation of the annual snowpack with the April 1 measurement is proportionally higher for locations with shallower snowpacks and with earlier snowmelt.

3.2 | Historical Trends—Maximum Winter Snowpack (ΔSWE_{max})

An emphasis of this study was the investigation of regionalization in temporal trends in the maximum yearly snowpacks (SWE_{max}). There were 314 total snow stations, and of these, about two-thirds (63%) displayed negative correlation coefficients, suggesting decreases from 1991 to 2020; this proportion exceeded a random distribution (Table 1). The geographical pattern is mapped in Figure 4, revealing a stronger decline in SWE_{max} values in southern regions. This is demonstrated by the increased numbers of red triangles that indicate significant temporal trends and the larger triangles that indicate greater Δ in magnitude. Both changes were more common in the southern states, especially in NM (Figure 4).

The SWE_{max} outcomes are grouped by jurisdiction in Table 1, confirming the geographical pattern. None of the Canadian snow stations displayed significant trends, and only a few individual stations in the Northern US region displayed significant trends (Table 1). Within the Central US region, only 1% of the

TABLE 1 | Statistical analyses for historical trends of (1) maximum yearly snow water equivalent (ΔSWE_{max}), (2) day of the snow maximum (ΔDay_{max}), and (3) snow water equivalent on April 1 (ΔSWE_{Apr1}) for 314 high elevation snow stations in nine jurisdictions along the North American Rocky Mountains from 1991 to 2020.

Region Jurisdiction	Canada		Northern US			Central US		Southern US		Total
	BC	AB	ID	MT	WY	UT	CO	AZ	NM	9
Station total (<i>n</i>)	4	8	31	41	68	72	65	12	13	314
ΔSWE _{max}										
% Stns with declining SWE _{max}	25.0	62.5	48.4	43.9	44.1	76.4	75.4	100	100	63.06
χ ² (↑ vs. ↓)			0.032	0.434	0.941	20.1	16.8	12.0	13.0	22.3
<i>p</i>			0.858	0.610	0.332	0.000	0.000	0.000	0.000	0.000
Significant cases ^a	0	0	0	0	3	1	6	2	8	32
ΔDay _{max}										
% Stns with earlier Day _{max}	0.0	25.0	77.4	73.1	72.1	88.9	89.2	100	100	80.3
χ ² (earlier vs. later)			9.32	8.81	13.2	43.6	40.0	12.0	13.0	129.8
<i>p</i>			0.002	0.003	0.000	0.000	0.000	0.000	0.000	0.000
Significant cases ^a	1	0	5	3	3	10	18	10	11	89
ΔSWE _{Apr1}										
% Stns with declining SWE _{Apr1}	25.0	50.0	32.3	29.3	36.7	73.6	67.7	100	100	55.1
χ ² (↑ vs. ↓)			3.90	7.05	4.77	16.1	8.14	12.0	13.0	4.291
<i>p</i>			0.048	0.008	0.029	0.000	0.004	0.000	0.000	0.038
Significant cases ^a	0	0	0	1	3	1	3	9	7	35

Note: There were too few stations in the Canadian provinces for the χ² test, and for the US jurisdictions, statistically significant results (*p* < 0.05) are in bold.

^aSignificant cases: the number of stations with significant trends (– or +, *p* < 0.05) based on Kendall's τ-b correlations.

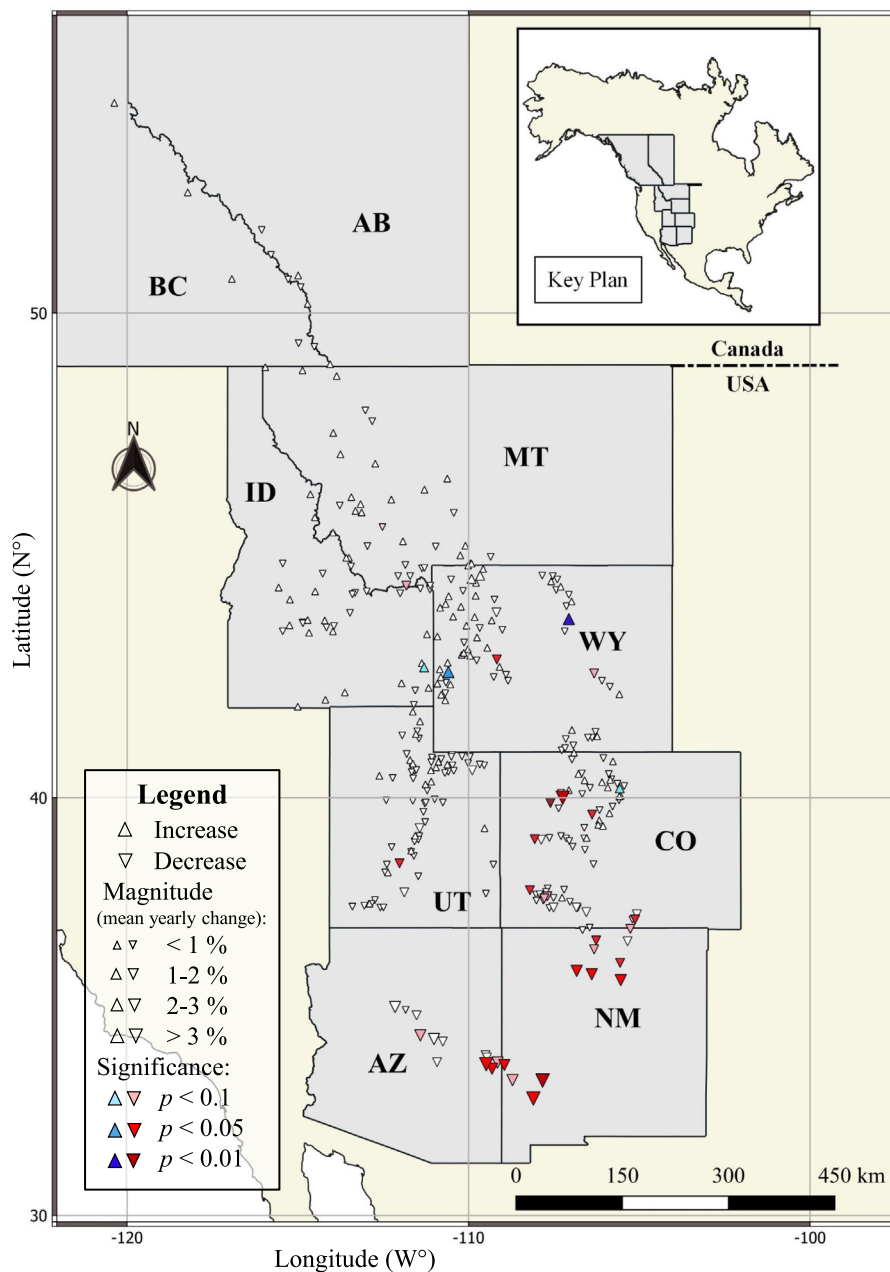


FIGURE 4 | A map of the Rocky Mountain snow pillow stations studied from 1991 to 2020. The symbols show increases (Δ) or decreases (∇) in the historical maximum snow water equivalents (SWE_{max}) using the Kendall's τ -b analysis. The symbol colour indicates direction of change and statistical significance, and the symbol size represents the magnitude of change.

stations displayed significant trends in UT, while 9% of the stations in CO displayed any significant trends (Table 1). For the Southern US, there was also an apparent longitudinal pattern, with 17% of snow stations in AZ revealing a significant SWE_{max} decline, while 62% of stations in NM displayed significant declines (Table 1).

As a further investigation, the snow stations were grouped by jurisdiction and the proportions with positive versus negative correlation coefficients for temporal SWE_{max} patterns were assessed using the χ^2 test. As revealed in Table 1 and Figure 5, there were more snow stations in UT, CO, AZ and NM with

significant correlations, supporting a greater snowpack decline southward.

3.3 | Snowpack Seasonality (ΔDay_{max})

Our hypothesis was that the day of the maximum SWE (Day_{max}) would be progressively earlier due to the winter and spring warming. This was supported for the US jurisdictions, again with stronger patterns of decline southward (Figures 6 and 7). The snow stations in the Southern US RM states of AZ and NM all displayed negative slopes in ΔDay_{max} , with

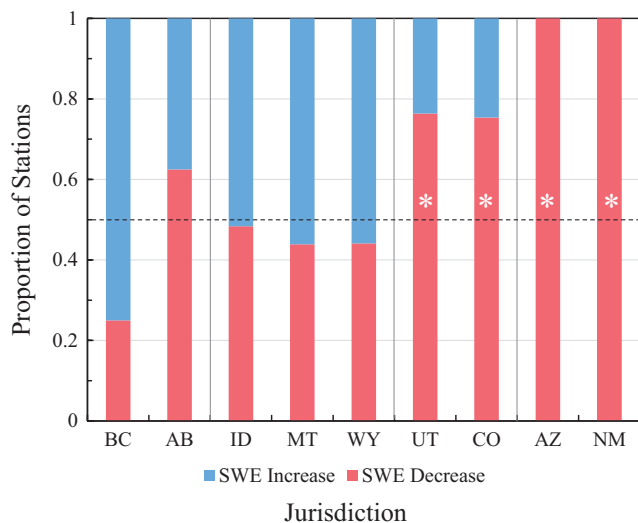


FIGURE 5 | The proportions of snow stations in each jurisdiction showing an increase (blue) or decrease (red) in SWE_{max} across the 30-year study period (1991–2020) for each Rocky Mountain snow station based on the Kendall's τ -b correlation. An “*” indicates a significant deviation between the proportions from random assortment based on χ^2 results ($p < 0.05$).

21 of the 25 stations displaying significantly earlier Day_{max} (Table 1). Almost 90% of the Central US RM stations had negative slopes, with significant ΔDay_{max} declines in 28 of the 137 sites. Extending the pattern, about three-quarters of the Northern US stations displayed negative ΔDay_{max} slopes, with 11 of the 139 individual stations providing significant changes (Table 1). In contrast, there was little evidence for earlier Day_{max} in the Canadian RM, with more stations providing positive than negative slopes in ΔDay_{max} , including two stations with apparently significant patterns (1 $p < 0.1$ and 1 $p < 0.05$; Table 1, Figures 6 and 7).

3.4 | April 1 Snowpack (ΔSWE_{Apr1})

Along the latitudinal RM corridor, similar regional patterns were displayed for the ΔSWE_{Apr1} (Figure 8) as were observed for the ΔSWE_{max} (Figure 4, Table 1). The AZ and NM sites of the Southern US region all displayed negative slopes in ΔSWE_{Apr1} , with most of the individual sites displaying significant trends (16 of 25; Table 1). Those southern sites also displayed the greatest magnitude of decline (Table 2, Figure 8). Extending northward, lower proportions of the Central US than Southern US stations displayed negative slopes in ΔSWE_{max} (Table 1). Only four of the Central US stations individually displayed significant declines, and the overall decline rates were about one-tenth of those in the Southern US (Table 2).

Extending further northward, fewer than one-half of stations in the Northern US displayed negative or declining slopes in ΔSWE_{max} (Table 1). For the Canadian RM, there were no significant changes for SWE_{Apr1} at individual stations and similar proportions of stations with apparent decline versus increase in SWE_{Apr1} over the study period (Figure 8, Table 1).

3.5 | Extending the Historical Record

Our emphasis was the comparison of snowpack trends across the RM corridor and for consistency, a common record interval was required. The 30-year record was chosen due to the shorter durations for the Canadian snow stations. Most of the American stations had longer periods of records, with some stations up to 55 years, and the overall average duration was 39.8 years ($SD = 4.34$). Similar analyses were undertaken for the full records as well as for the common 30-year record, with comparisons for SWE_{max} and ΔSWE_{max} provided in Figure 9.

Across the snow stations, the 30-year and full record average measures were very similar, and the SWE_{max} correspondence was almost complete (99.9%, Figure 9A). The slope was 0.99, with the intercept set at the 0,0 origin, reflecting a minimal decline in SWE_{max} in the recent interval. Similarly, the Day_{max} was tightly correlated (100.0% correspondence) and had a unit slope and origin intercept (0.999; not presented). Thus, the 30-year record provided average snowpack measures that were closely correlated with the longer historical records.

The comparison in the ΔSWE_{max} is provided in Figure 9B. As shown, there was about two-thirds correspondence (68%), and the regression approximated a unit slope with origin intercept. This revealed about one-third (32%) unassociated variation, which would reflect multiple influences, as will be discussed.

There was greater deviation for the snow stations that displayed increased rates of decline (Figure 9B, lower left). The decline rates were steeper with the 30-year record than with the full record, resulting in these lowest data points positioned below the regression line. These represented stations in the Southern US, consistent with the prior pattern of greater snowpack decline in AZ and NM, and this further indicates that the snowpack decline was steeper in the recent decades. The ΔDay_{max} were more consistent between the 30-year record and the full record, with 79.5% correspondence and linear regression that extended from the origin (0.0 ; $\Delta Day_{max30} = \Delta Day_{maxFull} \times 1.403$). This significant slope indicates that the rate of advancement in the transition to net snow melt for these higher elevation RM stations was more rapid in the past 30 years than for the average over the longer-term records, which averaged 40 years.

3.6 | Geographical Influences: Multi-Factor Modelling

The multi-factor modelling with forward-stepwise linear regression confirmed the primary importance of latitude (Table 3). This geographical factor provided the strongest predictor for each of the three snowpack measures (Table 3), consistent with the patterns displayed in Figure 2, with SWE_{max} , Day_{max} and SWE_{Apr1} declining with lower latitude. Elevation provided a secondary factor, with reduced SWE_{max} and SWE_{Apr1} , and earlier Day_{max} at lower elevations. Of the snowpack measures, Day_{max} was most strongly associated with the geographical location, with latitude and elevation combining to account for 82% of the variation across the RM corridor (Table 3). Longitude was also somewhat influential (Table 3), with decreased SWE_{max} and SWE_{Apr1} eastward.

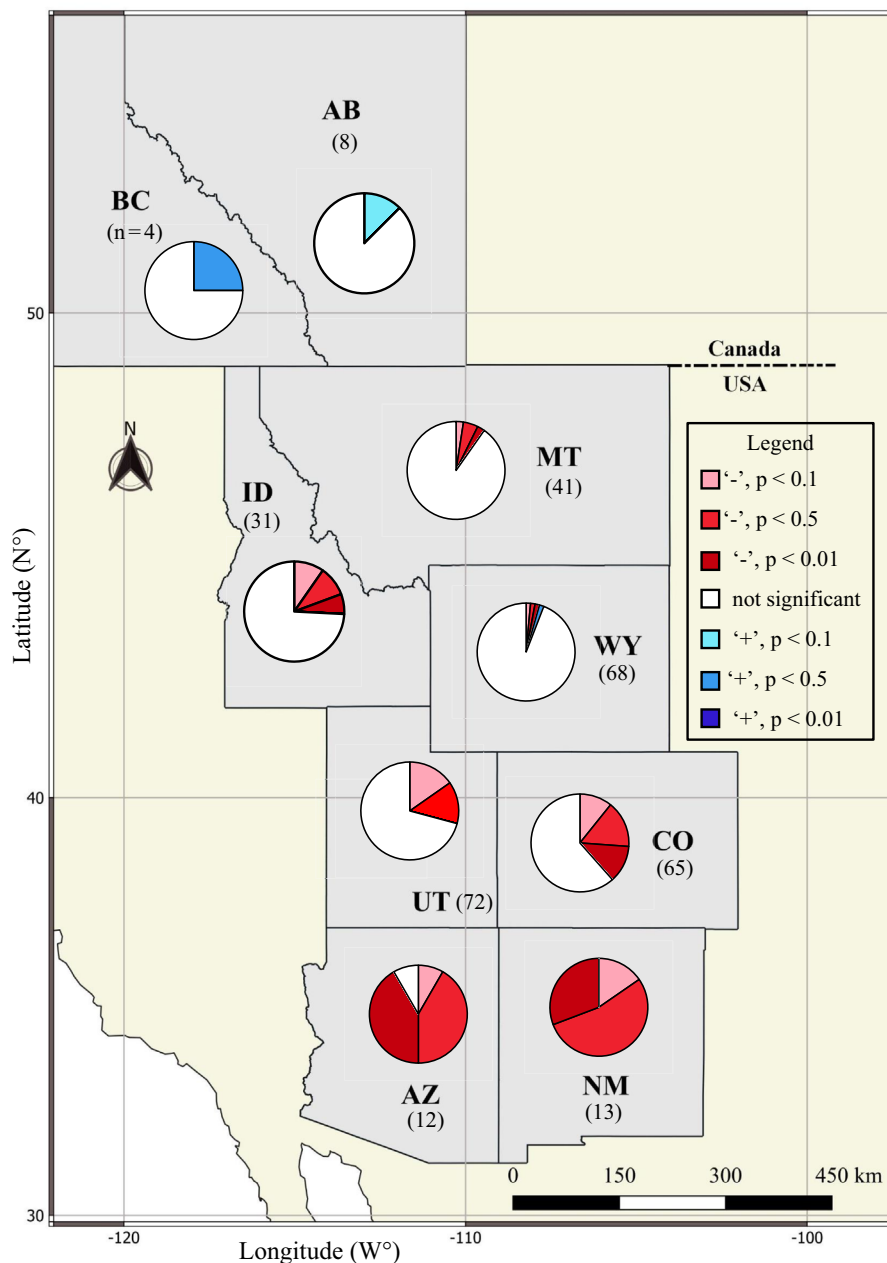


FIGURE 6 | A map with the proportion of Rocky Mountain snow stations in each jurisdiction displaying no, positive (blue) or negative (red) correlations for change in Day_{max} of SWE_{max} from 1991 to 2020.

Latitude was even more influential for the decline rates of all three snowpack measures (Table 3). This was responsible for almost all of the model accuracy for the change rates to provide $\Delta\text{SWE}_{\text{max}}$ and $\Delta\text{Day}_{\text{max}}$. The negative $\Delta\text{SWE}_{\text{Apr1}}$ was primarily associated with latitude, but elevation provided a moderate further influence (Table 3). With that secondary influence, the accuracy of the $\Delta\text{SWE}_{\text{Apr1}}$ model was about one-half, while the $\Delta\text{SWE}_{\text{max}}$ and $\Delta\text{Day}_{\text{max}}$ models accounted for about one-third of the observed variation over the RM corridor. It is notable that the multi-factor modelling, and particularly the influence of latitude, provided higher accuracy for the change rate measures of $\Delta\text{SWE}_{\text{max}}$ and $\Delta\text{SWE}_{\text{Apr1}}$ than

for the average SWE_{max} and SWE_{Apr1} measures (Table 3). This was not the case for $\Delta\text{Day}_{\text{max}}$ which was less effectively modelled than Day_{max} (Table 3).

4 | Discussion

We undertook this study to expand the analyses of historical snowpacks in the RM, which provide the ‘water towers’ of western North America (Immerzeel et al. 2020; Viviroli et al. 2007). Prior studies have primarily assessed snowpacks on April 1 as an index for the total water storage (Bohr and Aguado 2001)

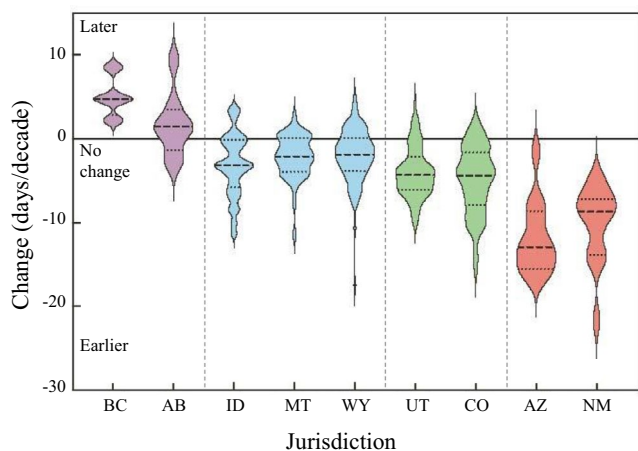


FIGURE 7 | The distribution of the $\Delta\text{Day}_{\text{max}}$ during the 30-year study period for each of the Rocky Mountain jurisdictions.

but a decline in snowpack or snow cover on April 1 could reflect changes in the snowmelt seasonality, rather than declining winter snowpack. To resolve these influences, we tested four hypotheses.

4.1 | Hypothesis Testing

Our first hypothesis was that there would be a progressive decline in the total yearly snowpack over time, which was assessed with the annual SWE_{max} . This hypothesis was supported for the overall RM corridor but with substantial latitudinal variation. There was a greater decline in the Southern US region, a moderate decline in the Central US, and a minimal decline in the Northern US and Canadian RM regions. This latitudinal pattern was displayed despite an opposing elevational pattern, with the Northern US sites being lower in elevation, and lower elevation sites could display higher sensitivity to recent climate change (Pepin et al. 2022; Sospedra-Alfonso et al. 2015).

Our second hypothesis was that due to spring warming with climate change there would be progressively earlier transitions to net snowmelt, which would be reflected by a progressive decline in Day_{max} , the day of the SWE_{max} . The overall results support this hypothesis and again reveal a strong latitudinal pattern. There was little change in the Day_{max} in Canada, and progressively earlier melting as latitude decreased southward across the American RM regions.

The earlier timing of snow melt is well established, and this leads to earlier spring runoff and river freshet (Adam et al. 2009; Barnett et al. 2005; Berghuijs et al. 2014; Cayan et al. 2001; Kapnick and Hall 2012; Rood et al. 2008; Stewart 2009). The earlier melt and increased springtime river flows result in reduced mid- to late summer river flows (Clow 2010; Knowles et al. 2006; Musselman et al. 2021; Philippsen et al. 2018; Rood et al. 2008). This imposes challenges for water management and for the river and riparian ecosystems since this is often an interval with warm and dry weather, when demands for irrigation and

hydropower increase. The lower river flows are vulnerable to warming temperatures, reduced dissolved oxygen, and reduced infiltration to recharge the alluvial groundwater that is essential for riparian woodlands in dry regions (Mote et al. 2005; Philippsen et al. 2018). For water resource management, the earlier timing of the snow melt season will compound the challenges from declining annual flows of some RM rivers (Rood et al. 2005, 2008).

Our third hypothesis was that the snowpack on April 1 (SWE_{Apr1}) would be declining due to the combination of those two patterns, decreasing total snowpack and earlier snow melt. This was observed and again with a predominant latitudinal pattern. There was a slight change in the Canadian RM region and an increasing change southward in the Northern US, Central US and then Southern US regions.

As predicted, the SWE_{Apr1} decline was greater than the decline in SWE_{max} , since it reflected the compound influences of snowpack decline and earlier snowmelt. These findings indicate that analyses of the April 1 snowpacks could inflate historical trends relative to the patterns in the annual RM snowpacks, which may be more accurately represented with the SWE_{max} . Relative to the underlying processes, both the SWE_{Apr1} and SWE_{max} would be reduced with winter snow melt events, including melt from rain on snow, which is probably increasing with winter warming (McCabe et al. 2007; Musselman et al. 2018).

Our fourth hypothesis was that there would be latitudinal patterns and since climate warming has increased with higher latitude (Deutsch et al. 2008; Roots 1989; Solomon et al. 2007), we expected that the declines in SWE_{max} , Day_{max} and SWE_{Apr1} could increase northward. This hypothesis was rejected, and the opposing pattern was prominent, with greater snowpack decline southward. The basis for this pattern deserves further exploration, including influences such as coordination with the El Niño southern oscillation (ENSO) and Pacific Decadal Oscillation (PDO) (Changnon et al. 1993; Cayan 1996; McCabe and Dettinger 2002; Rood et al. 2005). These provide climatic teleconnections with Pacific Ocean surface temperatures that may influence the north–south positioning of the ‘jet stream’, which delivers moist Pacific low-pressure systems to different RM regions, depending on its position (Changnon et al. 1993). This could provide one factor, and a better understanding of the underlying mechanisms would provide guidance relative to probable future water resource patterns and possible mitigation measures such as through dam and reservoir operations.

These findings support prior studies of RM snowpacks and provide further evidence relating to the historical influences from climate change on RM snowpack accumulation and melt. The observed latitudinal pattern was more prominent than recognised in some prior investigations, but there may be a bias in this study that included some disjunct mountain zones in the Southern US (Figure 4). Conversely, the snowpack changes were also displayed for the stations in northern NM that extended southward from the continuous RM corridor, supporting the primary latitudinal pattern.

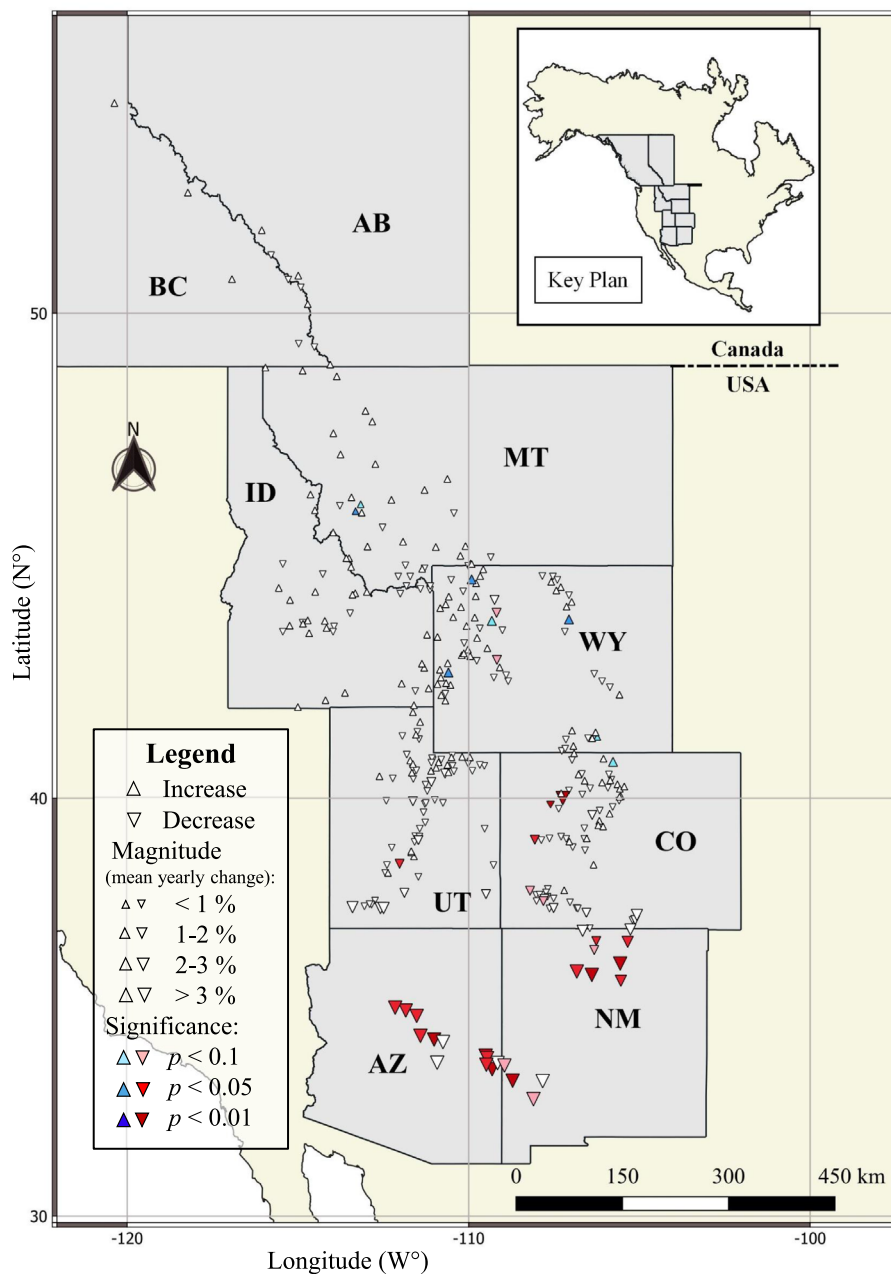


FIGURE 8 | A map of the North American snow pillow stations studied from 1991 to 2020. The symbols show increases (Δ) or decreases (∇) in April 1 snow water equivalents (SWE_{Apr1}) over the study period (Kendall's τ -b correlation, $p < 0.05$). The symbol colour indicates significant relationships, and the symbol size displays the magnitude of the observed change.

TABLE 2 | Mean rates of change for the maximum snow water equivalent (ΔSWE_{max}), day of SWE maximum (ΔDay_{max}), and SWE April 1 (ΔSWE_{Apr1}) for snow stations in nine jurisdictions along the North American Rocky Mountains from 1991 to 2020.

Region	Canada		Northern US			Central US		Southern US	
	BC	AB	ID	MT	WY	UT	CO	AZ	NM
Station total (n)	4	8	31	41	68	72	65	12	13
ΔSWE_{max} Mean (%/yr)	0.271	-0.139	0.076	-0.009	0.017	-0.338	-0.484	-2.019	-2.007
ΔDay_{max} Mean (%/yr)	0.239	0.0869	-0.157	-0.109	-0.107	-0.219	-0.261	-0.822	-0.678
ΔSWE_{Apr1} Mean (%/yr)	0.013	0.024	0.138	0.199	0.091	-0.444	-0.377	-8.003	-5.053

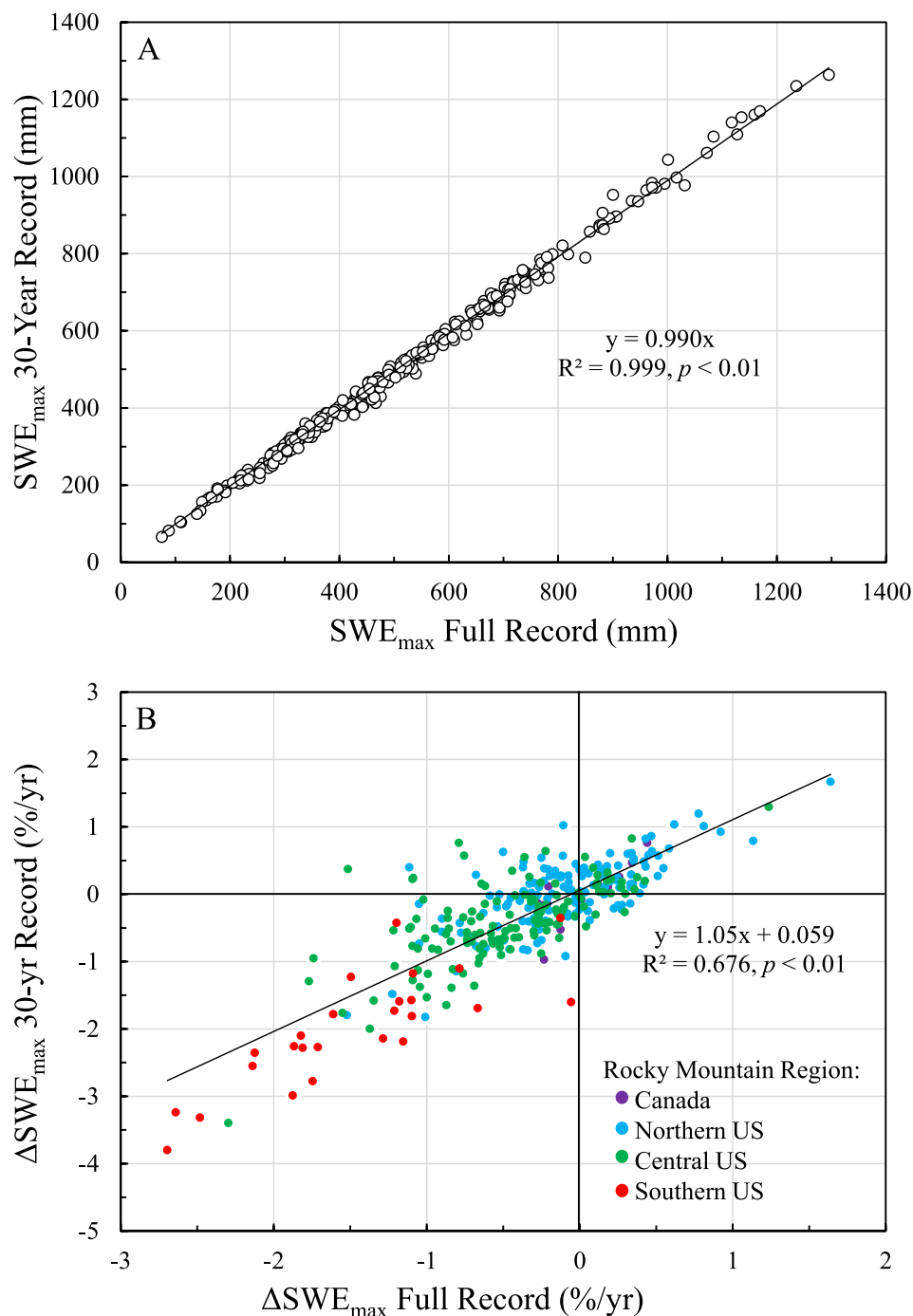


FIGURE 9 | The relationship between (A) the 30-year SWE_{max} record and the complete (full available interval) SWE_{max} for 314 Rocky Mountain snow station records, and (B) the 30-year ΔSWE_{max} record and the full record ΔSWE_{max} for 314 Rocky Mountain snow stations.

4.2 | Temporal Patterns

This study emphasised the three-decade interval from 1990 through 2020, a uniform interval that allowed comparisons across the full extent of the RM regions. This allowed inclusion of the Canadian region that has fewer and more recently installed snow stations. As described, the patterns from the shorter recent interval were generally consistent with analyses of the full SWE records, which extended back a half-century for some American snow stations (Figure 9). There were differences, and particularly stronger trends for the southern US in the recent 30-year

record, versus the longer full record. Thus, the latitudinal pattern was apparently amplified in the recent record.

Our findings extend the historical analyses of RM snow cover patterns, and the combined records display discontinuous patterns, rather than a progressive trend over the past century. This was recognised in the studies of April 1 SWE in the American RM regions by Mote (2006) and Mote et al. (2018). For the longer interval, there was a slight overall change from 1915 to 2000, but a low snow interval in the 1930s coincided with the extensive drought in western North America. The SWE_{Apr1}

TABLE 3 | Multi-factor, forward-stepwise linear regression models for snowpack measures and change rates (Δ) for high elevation snow pillow stations along the North American Rocky Mountain corridor from 1991 to 2020.

Measure	Geographical factor (Importance)			Accuracy (%)
	Latitude	Elevation	Longitude	
SWE _{max}	0.60	0.23	0.17	25.5
Δ SWE _{max}	0.96	0.04		34.3
Day _{max}	0.72	0.28		82.0
Δ Day _{max}	0.96	0.04		33.9
SWE _{Apr1}	0.61	0.25	0.14	27.3
Δ SWE _{Apr1}	0.74	0.16		48.2

declined from 1975 to 2000, which could have been associated with a PDO phase transition or other climatic variation, rather than a longer-term trend (McCabe and Dettinger 2002; Siler et al. 2019). Similar variations in historical trends have been detected for river flows from the RM, and we and others have recommended time series of two PDO cycles, around 80 years, to resolve progressive patterns with climate change, versus temporary patterns (Rood et al. 2005; St. Jacques et al. 2010).

4.3 | Contributing Factors

In addition to the geographical influences, there are also localised factors that impact snow accumulation and melt. Forest fires deplete forest canopies, affecting snow interception, redistribution, shading, and melt, and other processes (Tennant et al. 2017). Pathogen or disease outbreaks also impact the forest condition and snow patterns, with spatial scales ranging from small forest patches to widespread mortality of vulnerable tree species such as from the mountain pine beetle (Biederman et al. 2014).

Within the regional RM groupings, the elevational pattern is also complicated by the inclusion of snow stations on both sides of the Continental Divide and across different RM sub-ranges. While precipitation may display an orographic pattern of increase with elevation (Tennant et al. 2017), snow redistribution is extensive in the often-windy mountain zones. Snow is especially blown from the higher, treeless alpine zones and consequently the deepest snowpacks may occur in the forested subalpine band below the tree line (Cartwright et al. 2020; Clow et al. 2012). The forest types and tree lines vary along the RM corridor, further contributing to the elevational variation in SWE_{max}.

4.4 | Future Directions

Snow pillow stations provide site-specific records, but these are generally situated in accessible and non-hazardous locations, which may not reflect the broader RM snow patterns. There are often orographic patterns through the RM regions with increased precipitation and cooler temperatures with higher elevations, but as indicated, extensive redistribution can provide opposing geospatial influences. Snow accumulation and melt

modelling complement the field measurements, but some factors are important but uncertain, including sublimation (MacDonald et al. 2010).

Broader scale analyses of snow cover can be undertaken with aerial photography and even satellite imagery, but analyses of snow depth are more difficult. This can be assessed with differential airborne LiDAR, which maps surface topographies with and without snow, revealing snowpack accumulation (Cartwright et al. 2020). This method is advancing, and current applications assess reference zones that cover the applicable range of mountain zones relative to primary factors including elevation, slope, aspect and forest cover (Cartwright et al. 2020; Tennant et al. 2017), and field assessments investigate snowpack density as another variable. This could enable multivariate modelling for extrapolation across broader zones, and future applications will extend the analyses to watershed-scale RM snowpack patterns (Cartwright et al. 2020).

5 | Conclusion

This study was undertaken to explore historical trends in snowpacks along the Rocky Mountain (RM) corridor from western Canada southward to the southern United States. A common record interval was used and three measures were assessed. The April 1 SWE has been commonly considered in prior studies, and we included this and the maximum yearly SWE and its day of occurrence. As expected, we found an overall decline in these characteristics of the RM snowpacks, but the observed latitudinal pattern was opposed to our prediction. We expected increasing change with increasing latitude, which would be consistent with some other climate change measures and especially warming temperatures (Deutsch et al. 2008; Roots 1989; Solomon et al. 2007), which would influence the rain versus snow proportions, as well as the seasonal transition from snowpack accumulation to melt. In contrast, we found relatively minor changes in the snowpack patterns for the northern snow stations and increasing declines in SWE_{max} and SWE_{Apr1} in the southern stations, along with an earlier transition to snowpack melt, with declining Day_{max}. This geographical pattern is important for water resource management and suggests that changing RM snowpack resources could be more severe for the American southwest than for the northern RM regions that extend into Canada.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

A large Excel matrix is archived with Dryad, including all of 314 analysed stations (<https://doi.org/10.5061/dryad.5qfttdzj4>). This provides the station information, along with the three derived snowpack measures and their trend statistics for each station.

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