Changes to rainfall, snowfall, and runoff events during the autumn–winter transition in the Rocky Mountains of North America

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ABSTRACT

In cold conditions, early winter precipitation occurs as snowfall and contributes to the accumulating seasonal snowpack. In a warming climate, precipitation may occur as rainfall in mountainous areas. Detecting changes during seasonal transitions is difficult because these may encompass changes in timing, magnitude and phase, which may not be consistent between vears. In this study, a sampling window from September to December is used to assess trends in magnitude, frequency and duration (of rainfall, snowfall and runoff events) in 127 climate stations and 128 watersheds with more than 30 years of record across the Rocky Mountains of North America. Rainfall events have increasing frequencies and durations, and magnitude trends are predominantly increasing at mid-latitude and mid-elevation. Snowfall events have the largest numbers of significant trends, with both increasing and decreasing trends in each of magnitude, frequency and duration. Snowfall events have decreasing frequencies and durations in the northern low-elevation sites and increasing frequencies and durations at the southern high-elevation sites. Trends in runoff events are less common than for rainfall and snowfall but are greater than expected by chance, and show similar frequency and duration patterns to snowfall trends. Snowfall and runoff events are decreasing in frequency and duration north of Wyoming and increasing to the south. Snowfall magnitude is generally decreasing to the north and increasing to the south, with runoff magnitude trends showing the reverse.

RÉSUMÉ

Dans les environnements froids, les précipitations au début de l'hiver sont constituées de chutes de neige qui contribuent à l'accumulation de la couche neigeuse hivernale. Dû au réchauffement climatique, ces précipitations peuvent devenir des chutes de pluie dans les régions montagneuses. Déterminer les variations pendant les périodes de transitions entre les saisons est difficile; ces variations, qui ne sont pas consistantes d'une année à l'autre, incluent la date d'occurrence, la quantité de précipitation, et la phase (neige ou pluie). Dans cette étude, une fenêtre d'échantillonnage de septembre à décembre est utilisée pour évaluer les tendances des quantités, des fréquences d'occurrence et des durées associées aux chutes de pluie et chutes de neige, et aux évènements de ruissellement dans 127 stations météorologiques et 128 bassins versants, sur plus de 30 années de données aux travers des Rocheuses d'Amérique du Nord. Les chutes de pluie ont été de plus en plus fréquentes, et leur durée et quantité ont une tendance principalement à la hausse dans les latitudes et altitudes moyennes. Les chutes de neige ont le plus grand nombre de tendances significatives avec à la fois des tendances à la hausse et à la basse pour leurs quantités, fréquences et durées. Au nord, la fréquence et la durée de ces évènements baissent sur les sites de basse altitude mais elles augmentent sur les sites de haute altitude dans le sud. Pendant la période considérée, les évènements de ruissellement ont des tendances plus faibles que les chutes de pluie et de neige, mais sont plus importantes que seul le hasard pourrait prévoir et sont similaires en fréquence et en durée aux tendances des chutes de neige. Les évènements de ruissellement et les chutes de neige décroissent en fréquence et durée dans les régions qui sont situées plus au nord du Wyoming et ils accroissent plus au sud. Pour les chutes de neige, leur quantité est généralement en déclin dans le nord mais elle s'accroit dans le sud alors que la quantité des évènements de ruissellement montre des tendances opposées.

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Introduction

In a warmer and wetter climate, will Rocky Mountain watersheds show increased streamflows or increased occurrences of large streamflows in early winter, because precipitation falls as rain instead of snow? While mountains occupy only a small area of North America, they produce a disproportionate fraction of available water (Bales et al. 2006; Viviroli et al. 2007; Wrzesien et al. 2018). Leith and Whitfield (1998) observed changes in early autumn flows in the Similkameen River in British Columbia. Autumn flooding in Arizona in 1993 resulted from a series of storms with high rainfalls with repeated accumulation and melting of snow and rain-on-snow events (House and Hirschboeck 1997). Similar results were reported by Whitfield and Cannon (2000), indicating that increases in flow events during autumn occur widely in western Canada. Rood et al. (2008) demonstrated the presence of similar autumn events in the Rocky Mountains of Alberta, as shown in Figure 1, where

two recent years have autumn runoff events. These events suggest that as autumn air temperatures increase in mountainous areas, this causes the freezing elevation to increase, and therefore a larger fraction of a given basin would be expected to have rain and rain-on-snow events and such events would therefore increase in frequency over time (Knowles and Cayan 2004).

The spatial variation of snow cover in the Rocky Mountains is highly variable and has decreased, particularly in October and November (Karl et al. 1993). Over the past 100 years, annual total precipitation and snowfall north of 55°N in North America have increased, as has the fraction falling as liquid (Groisman and Easterling 1994). Karl et al. (1993) showed that air temperature variations explained up to 78% of the variance in regional snow cover and decreases in snow cover during winter, and that the variance of the ratio of snow to total precipitation has more than doubled. In the United States, autumn precipitation has increased (Small et al. 2010).





Figure 1. Examples of climate-driven shifts in streamflow in the Bow River at Banff (after Rood et al. 2008).

December-to-February snowfall in Canada increased in the period between 1915 and 1992 (Brown and Goodison (1996), although mountainous regions were poorly represented. Groisman et al. (1994a) reported a global retreat in snow cover extent in the northern hemisphere in the second half of the hydrologic year (April to September). After 1970, the retreat in the snow cover paralleled changes in the influence of snow cover on the radiative balance (Groisman et al. 1994b).

The accumulation of snow water equivalent (SWE) is affected by variability in the cool-season climate. The variability of SWE is affected by both temperature and precipitation, with strong spatial discontinuities; temperature is more important in New Mexico and precipitation more important in Idaho and Colorado (Cayan 1996). Snow is the largest component of surface water storage in most basins in western North America, and the number of melt events during winter has increased (Mote et al. 2005); the largest increases have occurred in the warmest mountain areas. The spatial patterns and elevational dependence of trends are climatic, as trends in the north follow precipitation trends whereas trends in the south are more complicated (Mote et al. 2005). In the Columbia Basin, Hamlet and Lettenmaier (1999) showed earlier spring peak flows and smaller flows in the April-September period, with increased winter flows. High-elevation regions in the Rocky Mountains are relatively insensitive to temperature trends, and trends in snowpack are connected to trends in precipitation (Hamlet et al. 2005).

Many global climate models project warmer and wetter conditions over the Rocky Mountains. A shift in future winter precipitation towards rain, with decreased snow packs, is widely forecast (Trenberth et al. 2003; Knowles et al. 2006; Nolin and Daly 2006; Barnett et al. 2008). In the western United States and Canada, warming has already produced strong decreases in winter snow accumulation and spring snowmelt over much of the affected area regardless of precipitation change (Hamlet and Lettenmaier 1999; Adam et al. 2009; MacDonald et al. 2011, 2012; Kienzle et al. 2012). Decreased snowpacks are projected to produce decreases in warm-season runoff in many mid- to high-latitude areas where precipitation changes are either moderately positive or negative in the future projections (Dierauer et al. 2018, 2019). Changes in snowpacks and the timing of snowmelt-derived runoff are largest near the boundaries of the areas that currently experience substantial snowfall (Mote 2006). The September 2013 storm and flood event in Colorado was a case where rainfall replaced snowmelt as the dominant peak (Kampf and Lefsky 2016).

Büntgen and Krusic (2018) call for alternative methods to study autumn ecology. Detecting changes in autumn events is difficult using methods that rely on central-limit theory since the differences over time are not in the mean value of any single variable but include phase shifts (ie between rain and snow), and the timing of resulting runoff. Leith and Whitfield (1998) demonstrated that while changes in autumn streamflow between two decades for short time periods could be large on average, they were not statistically significant. In the first decade of their analysis autumn flow events did not occur, while in the second decade autumn events occurred only in some years so much of the second decade was the same as in the first. In such a situation, it is difficult to detect a difference statistically, despite it being visually obvious. Basically, the first decade was 'all off' while the second was 'some on - some off', and therefore distribution-based or rank-based testing, such as the Mann-Whitney test used by Leith and Whitfield (1998), was unable to detect a difference.

Additionally, the timing and duration of autumn runoff events are highly variable, much more so than spring snowmelt and rain-on-snow events that have a substantial memory and are linked to seasonal patterns, and so recur at similar points in the year (Barry 2008). Autumn events are driven predominantly by weather systems, rather than seasonal climate patterns, and so cannot be detected at monthly, seasonal or annual time steps. Changes in autumn, and winter, runoff patterns and amounts can also affect the centre of volume of the hydrograph without there being any actual change in the timing of the snowmelt peak (Whitfield 2013).

Previous work has shown that autumn flow events are intermittent and their timing is irregular. Many studies of flow events have focused on their magnitude, but frequency and duration are important attributes that are as likely to change. In this study, the changes that have occurred in rainfall, snowfall, and streamflows in the Rocky Mountains of North America are examined. Within this domain, the interest is in changes in precipitation phase and storage/runoff to increase the understanding of autumn processes, which in turn strongly affect the attributes at larger temporal scales (eg April 1 SWE; summer low flows). The hypotheses are that, as a result of warming,

1. The relative frequency, magnitude and duration of autumn events are changing.

- 2. There are more/larger/longer autumn events in the south than in the north.
- 3. There are fewer/smaller/shorter autumn events at higher elevations.

Methods

The domain of this study is the North American Rocky Mountains, as shown in Figure 2a. Climate and hydrometric stations in this study are from the same spatial domain and were selected from independent networks. Daily precipitation records were obtained for 127 climate stations in the Rocky Mountains; this included 102 stations from the US National Climate Data Center (NCDC) and 25 from Environment Canada (Figure 2b; Table 1 provides the details by state and province). These stations record rainfall and snowfall separately and events that were greater than 10 mm as water were isolated for the autumn period from 1 September to 31 December. The threshold of 10 mm was selected to denote heavy precipitation, as was done by Peterson et al. (2002) and Klein Tank and Können (2003). From these the annual number of events (frequency), the autumn maximum event and the duration of all such events (total number of days in flow events) were extracted.

Daily streamflow records from 128 hydrometric stations which are considered suitable for climate studies within the Rocky Mountains from New Mexico to Northern British Columbia were used (Figure 2c). These were either Hydro-Climatic Data Network (HCDN; in the US) or Reference Hydrologic Basin Network (RHBN; in Canada) or suitable for possible inclusion in a Reference Hydrologic Network ('RHN-like'; in Canada). See Whitfield et al. (2012) for a description of the specific criteria for RHNs. The 'RHN-like' stations in Canada are included since many of the gauging stations in the Canadian Cordillera are natural streamflow and unregulated, and were not originally included in the RHBN



Figure 2. The study area and the sampled sites: (a) satellite image of western North America, (b) locations of the 127 climate stations, and (c) location of the 128 hydrometric stations. Solid symbols indicate the hydrometric stations are part of a reference hydrologic network (RHN), and open circles indicate stations that are considered RHN-like.

Table 1. Distribution between states and provinces of climate and hydrometric stations including Reference Hydrologic Network (RHN) sites and RHN-like hydrometric stations.

Province		Climate stations (#)	Elevation (m)		Hydrometric gauges		Area (km ²)		Elevation (m)	
State			min	max	RHN	RHN-like	min	max	min	max
Alberta	AB	11	927	1580	8	11	21	9765	936	1706
British Columbia	BC	14	450	1323	12	29	9	15600	491	1364
Washington	WA	3	579	775						
Idaho	ID	0			33		57	35094	396	2257
Montana	MT	35	639	2030	13		29	30549	627	1983
Wyoming	WY	23	1143	2399	11		24	10813	2181	2839
Colorado	CO	19	1186	2763	8		94	749	1970	2790
Utah	UT	22	1240	1925	1		63		2549	
New Mexico	NM	0			2		1217	25200	1916	2062

because of concerns about over-representation of this region from a national perspective. The 'RHN-like' stations have continuous records, natural flows (no regulation) and minimal changes in land use within their basins, and are suitable for trend studies (Burn et al. 2012).

For each climate station there were time series of the annual number of events, the magnitude of the largest annual event, and the total durations of both rainfall and snow events. For each hydrometric station there were similar time series. Trends were determined for the period of record for each station, which consisted of a minimum of 30 years of record between 1950 and 2011. One of the challenges of this type of analysis is that record length may affect results. While a common period where all stations have data has considerable merit, the decision to use the period of record provided the greatest quantity of data available for detecting change; comparing rates of change between stations using records of different lengths is not appropriate.

Procedures

Systems with regime shifts can show three types of change: smooth, abrupt or discontinuous (Scheffer and Carpenter 2003). Of particular interest here are those that are discontinuous, where the system flips between two regimes, often at different thresholds. Common statistical methods for detecting trends in magnitude cannot detect whether this type of regime shift has occurred. This is particularly true in the case of autumn flow events, as small differences in precipitation and/or temperature can result in autumns with or without events. Leith and Whitfield (1998) showed that despite a large difference in the mean autumn flows, the variability between and within years within individual decades meant that such changes were not statistically different using either parametric or nonparametric magnitude comparison techniques. An alternate way of assessing the question 'Is the system prone to regime shifts?' is demonstrated; trends in the frequencies and durations of events allow detection of changes in these attributes.

All analyses were done using R (R Development Core Team 2014). Determination of trends in magnitude used the Mann-Kendall test from the R package Kendall (McLeod 2015). This implementation of Mann-Kendall corrects for autocorrelation. Mann-Kendall trends in magnitude were considered significant if $p \leq 0.05$. Trends in frequency and duration were determined with logistic regression using the R package trend (Frei 2013). In logistic regression, an 'odds ratio' (the constant effect) near 1.0 indicates no change, a ratio greater than 1 indicates an increasing trend, and a ratio less than 1 indicates a decreasing trend. Only regression trends having p values \leq 0.05 were considered statistically significant.

Isolating runoff events

The approach to the analysis of autumn flow events was to create a series of autumn flow anomalies. To isolate the autumn flow events, the baseflow component of the record was estimated using the recursive Eckhardt filter (Eckhardt 2005, 2008, 2012). While Collischonn and Fan (2013) demonstrated a procedure for defining Eckhardt's filter parameters, fixed values for the filter parameters suitable for the Rocky Mountains suggested by Eckhardt (2012) avoid producing results that could be affected by differing filter parameters. Similar results were obtained using the 'backwards' filter of Collischonn and Fan (2013). One sample result for the Bow River at Banff in 2010 is shown in Figure 3. The observed daily flows and the estimated baseflows were differenced, and the resulting streamflow event series in the interval from day 244 to day 365 (\sim 1 September to 31 December) were

05BB001 - BOW RIVER AT BANFF [AB]



Figure 3. One example of the peak extraction technique. The grey shading indicates the baseflow estimated using Eckhardt's filter, and the solid line indicates the surface component. The green line indicates the period of the year which is considered to contain 'autumn events'; the number of events, the maximum magnitude (of the difference), and duration of events are determined from the difference between the green line and the estimated baseflow. In this example year, 2010, there were three events; the maximum was 55.1 m³/sec, and the total duration of events was 21 days.



Figure 4. Example results for the logistic regression for the number of autumn events (top row) and the total duration of events (bottom row) for 1910–2011 for 05BB001, the Bow River at Banff, Alberta, in the left column, and for 1952–2013 for 0223000, the Hams Fork below Pole Creek near Frontier Wyoming, in the right column.

retained for analyses. The differenced series was processed to count the number of peaks in the period and determine their magnitudes and durations. From these values, time series of the annual number of events, the magnitudes of the maximum autumn events, and the total durations of the events were extracted.

It is important to note that baseflow removal and peak detection are unrelated to methods such as peaks-over-threshold. Therefore, peak separation techniques required by these methods are not employed here. Sample results for the Bow River at Banff for 2010 (Figure 3) demonstrate the isolation of flow events. During the autumn, Rocky Mountain streamflows decline from the large peaks associated with summer snowmelt and rainfall. Thus, the autumn flows are mainly base flows, with a few, generally distinct peaks. The latter part of the 'autumn' time series actually occurs during the winter, ie when precipitation falls as snow, and when rivers are covered by ice. During the winter, barring melting events, there are no sources of surface runoff, and all flows are base flows, which are in recession. Winter peaks are due to melt events.

Results

In the presentation of results, the Bow River at Banff (station 05BB001) is used as an example, as it has the longest period of record among Canadian Rocky Mountain reference hydrometric sites (Whitfield and Pomeroy 2017). Typical results for the logistic regression for frequency and duration of autumn events for the period of record are for two cases shown in Figure 4. The results for the Bow River at Banff are non-significant. An example where the trends in frequency and duration were significant (station 9223000: Hams Fork below Pole Creek near Frontier Wyoming) is also shown.

The three hypotheses proposed above can be answered, with some qualifications:

Hypothesis 1: That the relative frequency, magnitude and duration of autumn events are changing.

Overall, there were many more stations showing trends that were statistically significant than would be expected by chance alone, as is summarized in Table 2. If changes were random, it would be expected that up to 5% of the sites would have significant trends by chance alone. Both increasing and decreasing trends

Table 2. Number and percentage of stations showing trends in frequency, maximum magnitude and duration of autumn events for rain, snow, and runoff for the study stations. The upper number is the number of stations with a significant trend, and the lower is the percentage of all stations.

	Rain		Sn	iow	Runoff		
	Increase	Decrease	Increase	Decrease	Increase	Decrease	
Frequency	10 7.0%	0	20	18 14 204	9 7 00/	10 7 80/	
Maximum	7.9% 8	2	13.7%	14.2%	7.0% 4	7.6 %	
Magnitude	6.3%	1.6%	11 .0 %	8.7 %	3.1%	3.1%	
Duration	12	0	20	16	7	5	
	9.4%	0.0%	15.7%	12 .6 %	5.5%	3.9%	

were observed and the results differ among variables and attributes. For autumn rainfall events, only the number of increasing trends in frequency, magnitude and duration exceeded those expected. There were no significant decreases in frequency and duration, and only two cases where magnitude decreased (Table 2). Autumn snowfall events had the greatest number of stations with significant trends; all attributes and trend directions exceeded the number expected by chance alone. Autumn runoff events had few significant trends in frequency, magnitude or duration; only trends in the frequency of events and increasing trends in duration exceeded the expected number. Trends in snowfall were more frequent (25.9% of cases) than trends in discharge (10.2%) or trends in rainfall (8.3%); trends in frequency were more frequent (17.5%) than those in duration (15.7%) or magnitude (11.2%).

Hypothesis 2: That there are more/larger/longer autumn events in the south than in the north; and Hypothesis 3: That there are fewer/smaller/shorter autumn events at higher elevations.

These hypotheses are linked by the assumption that relatively colder regions (ie at high elevations and latitudes) within the domain will experience fewer changes in precipitation phase (from snow to rain) and melting events. Within the domain of this study, the spatial locations of trends and the relationships with elevation help explain the observed trends in the figures that follow. The bias of site elevation with latitude is clear, stations in the south are at higher elevation than those in the north, reflecting the general elevation profile of the Rocky Mountains.

The spatial patterns of significant trends in the frequencies of autumn events are mapped in Figure 5. Only significant increasing rainfall frequency trends occur throughout the study area; no decreasing trends were detected (Figure 5a); increases in snowfall event frequency predominate in the south and west while decreases are found in the north and east of the domain (Figure 5b). Autumn runoff events appear to be increasing in the west and decreasing in the east.

The spatial patterns of trends in frequencies of autumn events (Figure 6) show significant increases in rainfall occurring at all elevations and latitudes



Figure 5. Spatial distribution of trends in the frequency of autumn events of (a) rain, (b) snowfall, and (c) runoff determined by logistic regression for >30 years of record. Statistically significant decreasing trends are shown in black, increasing in green, and not significant in grey. Symbols distinguish variables in the plots: rainfall (squares), snowfall (asterisks), and runoff (closed [Reference Hydrologic Network, RHN] and open [RHN-like] circles).



Figure 6. Trends in the frequency of autumn events of (a) rain, (b) snowfall, and (c) runoff determined by logistic regression for >30 years of record plotted against latitude and elevation. Statistically significant decreasing trends are shown in black, increasing in green, and non-significant in grey. Symbols distinguish variables in the plots: rainfall (squares), snowfall (asterisks), and runoff (closed [Reference Hydrologic Network, RHN] and open [RHN-like] circles).

(Figure 6a). Both increasing and decreasing snowfall frequencies occur south of 52°N, with decreasing trends being frequent at lower elevations and increasing trends at higher elevations, but not exclusively so (Figure 6b). Significant trends in runoff event frequency occur at all latitudes; at lower elevations the trends are generally increasing, while at high elevations decreasing trends are more common (Figure 6c).

The trends in magnitude of autumn rainfall, snowfall and runoff events are mapped in Figure 7, showing the predominance of significant trends of increasing magnitude in rainfall events (Figure 7a), the large number of trends in the magnitude of snowfall events (Figure 7b), and a small number of trends in runoff event magnitude (Figure 7c). There is no clear relationship between the occurrence of significant trends and either latitude or longitude. Significant trends of increasing rainfall magnitude occur between 40° and 48° N as well as above 900 m and below 2100 m (Figure 8a). Snowfall shows increasing and decreasing trends south of 48° N (Figure 8b); as in Figure 7b, snowfall event magnitude has increasing and decreasing trends which apparently



Figure 7. Spatial distribution of trends in the magnitude of autumn events of (a) rain, (b) snowfall, and (c) runoff determined by Mann–Kendall test for >30 years of record. Statistically significant decreasing trends are shown in red, increasing in blue, and non-significant in grey. Symbols distinguish variables in the plots: rainfall (squares), snowfall (asterisks), and runoff (closed [Reference Hydrologic Network, RHN] and open [RHN-like] circles).

overlap in spatial distribution and elevation. The number of significant autumn runoff events is small, so no spatial pattern or elevation pattern is evident.

All significant trends in the duration of rainfall events are increasing (Figure 9a). Similar to the frequency trends mapped in Figure 5b, the durations of snowfall events have increased in the south and decreased in the north (Figure 9b). The durations of autumn flow events have increased in the west and north but decreased in the east (Figure 9c). Significant increases in rainfall occur throughout the study domain; there are no sites that show a significant decrease in the duration of rainfall events (Figure 10a). Significant decreases in snowfall duration occur below 1500 m and at latitudes above 40°N; significant increasing durations of snowfall occur above 1200 m south of 45°N, and below 800 m north of 45°N (Figure 10b). Significant increasing durations of fall runoff events occur only north of 45°N and below 1000 m; significantly decreasing durations occur between 45°N and 50°N across a wide elevation band (Figure 10c).

Discussion

It is clear that the results presented show evidence of real changes in autumn events, but the results also are quite complicated as one might expect over the large spatial domain examined. Warming temperatures should favour rain over snowfall near the current freezing level; on the adjacent Prairies shifts from snowfall to rainfall during autumn have been reported (Mekis and Vincent 2011; Shook and Pomeroy 2012; Coles et al. 2017). Rain-on-snow events have become more prominent in other mountain regions where rain events were previously an infrequent contributor to peak flows (Vormoor et al. 2016; Rottler et al. 2019). Elevation is important. At low elevations, shifts from snowfall to rainfall result in increases in the frequencies and durations of autumn runoff events. At high elevations, and above the freezing level, snow accumulations often increase in frequencies and durations at higher elevations (Rasmussen et al. 2011). No two years contain the same weather patterns and antecedent conditions; time and space play a very large role in the observed streamflow series, and the present analysis is not amenable to simplification. For example, the freezing elevation during precipitation is influenced by the local temperature lapse rate, which has been shown to vary diurnally, seasonally and with location (windward vs lee side) in the Cascade Mountains (Minder et al. 2010). This variability would presumably hold true for the Rocky Mountains and should be the subject of future studies. Furthermore, air temperature alone is not sufficient to discriminate between rainfall and snowfall - the of the precipitation depends on phase the



Figure 8. Trends in the magnitude of autumn events of (a) rain, (b) snowfall, and (c) runoff determined by Mann–Kendall test for >30 years of record plotted against latitude and elevation. Statistically significant decreasing trends are shown in red, increasing in blue, and non-significant in grey. Symbols distinguish variables in the plots: rainfall (squares), snowfall (asterisks), and runoff (closed [Reference Hydrologic Network, RHN] and open [RHN-like] circles).

psychrometric energy balance of the hydrometeors (Harder and Pomeroy 2013).

The overall trend counts shown in Table 2 are consistent with expectations. Changes are most evident for snowfall events where the largest numbers of significant trends, both increasing and decreasing, were observed. Rainfall events were found to have mostly increasing trends, agreeing with a shift in winter precipitation towards rain (Trenberth et al. 2003). While the number of trends in the magnitude of autumn runoff events was greater than expected by chance alone, their number was far smaller than those for frequency or duration, or for rainfall and snowmelt magnitudes. This indicates that it will be easier to detect discontinuous regime changes by analyses of event counts rather than their magnitudes.

Spatial patterns are evident throughout the results presented here; there are differences between south and north, and interactions with elevation. Further relationships with orientation (slope, aspect) and location (leeward vs windward) may explain some trend variabilities. A climate station represents a point at a



Figure 9. Spatial distribution of trends in the duration of autumn events of (a) rain, (b) snowfall, and (c) runoff determined by logistic regression for >30 years of record. Statistically significant decreasing trends are shown in orange, increasing in brown, and non-significant in grey. Symbols distinguish variables in the plots: rainfall (squares), snowfall (asterisks), and runoff (closed [Reference Hydrologic Network, RHN] and open [RHN-like] circles).

specific elevation while a hydrometric station integrates the area and elevations above the station location and may accentuate or mask point trends.

The effects of latitude and altitude observed here are complex. In the Sierra Nevada the mountains are high enough, and cold enough, that despite their latitude a snowpack can develop. At lower latitudes and lower elevations, snow courses demonstrate negative snowpack trends that are complicated (Mote et al. 2005), whereas at higher elevations and latitudes the trends are positive (Mote 2006). The present study shows that fewer trends in frequency and magnitude of snow were observed north of 44°N latitude in Canada and in the US Northern Rockies, presumably because the air temperatures were cold enough that increasing trends did not result in changes of precipitation phase.

Changes in autumn runoff event frequencies and durations, where significant, show both increasing and decreasing trends at high elevations and low latitudes, and at low elevations and high latitudes (Figures 5c and 9c). Rainfall frequency and duration trends, where significant, are increasing (Figures 5a and 9a), yet snow shows increases in frequency and duration at higher elevations, and decreases in frequency and duration at lower elevation (Figures 5b and 9b). These changes in autumn runoff events are consistent with the findings of Knowles and Cayan (2004) and Tennant et al. (2015) for flood peaks; lowelevation watersheds respond to rain, whereas higher elevation watersheds have larger snowmelt and rainon-snow floods.

The results presented here are for the time series of the autumn peak flows; future work should consider trends using partial duration series of all autumn events, particularly as each of the variables showed increases in its frequency and duration, suggesting that the flow totals might be changing, but without their being quantified. Studies that use a common time period would provide estimates of the rate of change. In a warming/warmed climate it is expected that in early winter rain events will replace some snow events, and generate streamflow, unlike the situation in a previously cooler climate where precipitation occurred as snow and contributed to the building of the winter snowpack. A wetter climate may see increased snow accumulation despite warmer temperatures.

Many prior studies have used restricted spatial domains or individual watersheds. In this study, changes in the autumn in terms of both space and time, particularly with respect to seasonal patterns, are addressed over a large spatial scale. In mountainous regions the annual cycle of snowpack development over the winter and depletion through melt in the spring is changing. Warmer temperatures at lower elevations result in an increasing frequency of rain events in the autumn at all elevations (Figure 6a), and



Figure 10. Trends in the duration of autumn events of (a) rain, (b) snowfall, and (c) runoff determined by logistic regression for >30 years of record plotted against latitude and elevation. Statistically significant decreasing trends are shown in orange, increasing in brown, and non-significant in grey. Symbols distinguish variables in the plots: rainfall (squares), snowfall (asterisks), and runoff (closed [Reference Hydrologic Network, RHN] and open [RHN-like] circles).

may include wetter conditions. High-elevation and high-latitude regions in the Rocky Mountains are relatively insensitive to temperature trends, and trends in snow accumulation are connected to trends in precipitation (Hamlet et al. 2005; Lute and Abatzoglou 2014; Harder et al. 2015). At high elevations there were increased frequencies and durations of snow events, while there were decreases at mid-elevations (Figures 6b and 10b). Autumn runoff events have increased in frequency and duration at low elevations in the north. Frequencies have increased in a few catchments in the south at high elevations, but decreased at mid-elevations (Figures 6c and 10c).

In historically colder conditions, snowfall contributed to the accumulation of the seasonal snowpack. In a warmed climate it has been expected that early winter snowfalls would transition into to rainfall or rain-on-snow runoff events. While autumn changes have not received the attention given to other seasons (Büntgen and Krusic 2018), increasing rainfall in autumn (Mekis and Vincent 2011; Shook and Pomeroy 2012) could lead to changes in hydrology (Leith and Whitfield 1998; Rood et al. 2008). However, such changes are often found to be statistically non-significant using nonparametric rank-based methods, because of the variability in timing and magnitude of events and the statistical methods used. The alternative approach presented here is better able to resolve changes in the frequencies, durations and magnitudes of autumn events.

Conclusion

Autumn trends of rainfall, snowfall and runoff events in the Rocky Mountains of North America are presented. The detected trends were more prevalent at low and middle elevations, rather than at high elevations. Trends were more prevalent in the southern and central parts of the spatial domain and were less common in the north, in Canada and the northern US. Rainfall events are predominantly increasing in frequency, magnitude and duration. Snowfall event trends are the most numerous, and are both increasing and decreasing in frequency, magnitude and duration. Increasing and decreasing trends in the frequency and duration of runoff events are more numerous than those of event magnitudes.

The increase in rainfall events and corresponding runoff events can be attributed to the widespread change in precipitation phase at low elevations. This effect, however, does not extend to high elevations where increased magnitudes, frequencies and durations of snowfall events were observed. These changes can simply be attributed to wetter conditions in the autumn resulting in more snowfall in colder regions of the domain.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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