

Patterns of trends in niveograph characteristics across the western United States from snow telemetry data

S.R. FASSNACHT (✉)^{1,2,3}, J.I. LÓPEZ-MORENO⁴

¹ ESS-Watershed Science, Colorado State University, Fort Collins, CO 80523-1472, USA

² Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO 80523-1375, USA

³ Natural Resources Ecology Laboratory, Colorado State University, Fort Collins, CO 80523-1499, USA

⁴ Instituto Pirenaico de Ecología, CSIC, Campus de Aula Dei 50080, Spain

© Higher Education Press 2020

Abstract The snowpack is changing across the globe, as the climate warms and changes. We used daily snow water equivalent (SWE) niveograph (time series of SWE) data from 458 snow telemetry (SNOTEL) stations for the period 1982 through 2012. Nineteen indices based on amount, timing, time length, and rates were used to describe the annual temporal evolution in SWE accumulation and ablation. The trends in these annual indices were computed over the time period for each station using the Theil-Sen slope. These trends were then clustered into four groups to determine the spatial pattern of SWE trends. Temperature and precipitation data were extracted from the PRISM data set, due to the shorter time period of temperature measurement at the SNOTEL stations.

Results show that SNOTEL stations can be clustered in four clusters according to the observed trends in snow indices. Cluster 1 stations are mostly located in the Eastern- and South-eastern most parts of the study area and they exhibit a generalized decrease in the indices related with peak SWE and snow accumulation. Those stations recorded a negative trend in precipitation and an increase in temperature. Cluster 4 that is mostly restricted to the North and North-west of the study area shows an almost opposite pattern to cluster 1, due to months with positive trends and a more moderate increase of temperature. Stations grouped in clusters 2 and 3 appear mixed with clusters 1 and 4, in general they show very little trends in the snow indices.

Keywords snow water equivalent, cluster analysis, SNOTEL

1 Introduction

A changing climate has been observed across the western United States (US) as a decrease in the amount of snow accumulation at the peak and an earlier peak (Cayan et al., 2001; Keithley, 2002; Stewart et al., 2005; Clow, 2010; Fritze et al., 2011; Harpold et al., 2012; Fassnacht et al., 2018). Many previous studies have used the snow water equivalent (SWE) measured at snow course stations on or about April 1st (Cayan, 1996; Cayan et al., 2001; Lo and Clark, 2002; Stewart et al., 2004; Mote et al., 2005; Regonda et al., 2005; Stewart, 2009; Mote et al., 2018), due to their long period of record, often back to the mid-1930s. While numerous of the Natural Resources Conservation Service (NRCS) snow courses have shown a significant decrease in April 1st SWE (Cayan et al., 2001; Stewart, 2009), it has been shown that the snow courses underestimate peak SWE by up to 12% (Bohr and Aguado, 2001). Daily SWE has been measured at automated NRCS snow telemetry (SNOTEL) stations since the late 1970s with over 800 stations currently in operation (NRCS, 2018), and these data are useful to estimate snowpack (Fassnacht and Patterson, 2013) and runoff (Fassnacht et al., 2014) patterns. Across the state of Colorado and the Upper Colorado River basin, peak SWE at SNOTEL stations has decreased significantly at many locations (Clow, 2010 and Harpold et al., 2012, respectively).

When April 1st or peak SWE are solely used to cluster stations, the groups are mostly contiguous; however, patterns are not spatially grouped when clustered using daily SWE data (Fassnacht and Derry, 2010). These daily SWE data allow us to capitalize on the 31-year (1982–2012) time series at 458 SNOTEL stations to estimate the spatial pattern of snow accumulation and melt trends. The specific objectives of this paper are as follows: 1) to analyze the temporal evolution of snow accumulation and

melt using a set of indices that accurately describe the annual niveograph (time series of SWE), and 2) to examine their spatial distribution by identifying clusters of stations that show similar trends.

2 Data set and methodology

The SNOTEL stations provide a network of snow observations in the mountains across the Western US. The daily time series of SNOTEL SWE data for the 11 western states were obtained from the NRCS and used to identify snowpack characteristics. SWE is measured with a snow pillow and the reported precision is 2.54 mm (0.1 inches). Thus, in this analysis a threshold of ± 5.08 mm was used to identify changes, specifically, when a change in SWE greater than 5 mm was observed, an actual snowpack change and not a fluctuation in the system occurred. The SWE data were quality-controlled using the procedure outlined by Serreze et al. (1999). The following tests were performed to mask outliers and eliminate negative SWE values: stations with missing values for the first 15 days of the water year (October) were assumed to be indicative of delays in servicing and the entire year was deemed to have no data recording, daily SWE increments greater than 25.4 cm or consecutive days with increases and subsequent decreases each greater than 6.35 cm were deemed to have no data, monthly SWE decreases more than five standard deviations from the

mean were deemed to be erroneous, and monthly SWE increases more than five standard deviations from the mean without a comparable extreme value for precipitation or a corresponding precipitation increase of more than three standard deviations were deemed to be erroneous. Where erroneous data were identified, all subsequent SWE measurements were also considered no data, to eliminate the contaminating effect of an individual erroneous value. We only considered stations with less than three years of missing data. The starting of the study period in 1982 provides a good balance between number of observatories and having a sufficiently long study period. Due to a statistically significant drought in parts of the domain, including California (Mann and Gleick, 2015; Williams et al., 2015; Allen and Anderson, 2018) and the American South-west (Cook et al., 2015), the end of the study period was set at 2012. This year 2012 ensures that we had a 30-year period that is the standard, and it avoids finishing the time series with a climate extreme, i.e., a drought, which could mask detecting the most habitual spatial-temporal patterns in western US. After applying the abovementioned criteria, a total of 458 SNOTEL stations were used.

Nineteen indices were derived for each SNOTEL station-year when the SWE time series, or the niveograph was complete, i.e., there were no missing data from prior to onset of accumulation to after the end of melt. Four sets of indices (Table 1) were derived: timing and duration, peak,

Table 1 Niveograph indices used to characterize snow accumulation and melt. The short name for each index is underlined and italicized. Indices are grouped as duration (A–D), peak (E–I), accumulation (J–P), and melt (Q–S)

#	name and description
A	<u>duration</u> of snowcover = days with SWE > 5 mm
B	start of continuous snowcover = <u>start date</u> with 14 or more days of snow and peak during that period > 50 mm
C	end of continuous snowcover (<u>end date</u>) = last day of snow after start date
D	duration of <u>continuous</u> snowcover = end date – start date
E	amount of <u>peak</u> SWE = maximum SWE
F	date of peak SWE (<u>peak date</u>) = date of peak SWE
G	peak SWE at onset of melt (<u>peak at melt</u>) = start date of 10 day period when decrease in SWE is greatest compared to SWE over the previous 10 days
H	date of melting onset (<u>onset date</u>) = date of peak at onset of melt
I	<u>peakedness</u> = persistence of high SWE; days when SWE is greater than 50% of peak
J	length of accumulation season (<u>accum length</u>) = peak date – start date
K	number of days with snowfall (<u>snow days</u>) = days when SWE increase > 5 mm
L	number of accumulation days with snowfall (<u>accum snow days</u>) = as above but only during the accumulation season
M	average daily accumulation (<u>avg accum</u>) = peak SWE / days with snowfall
N	days with melt during accumulation season (<u>melt days accum</u>) = days when SWE decrease > 5 mm prior to peak
O	amount of snow melted during accumulation season (<u>melt during accum</u>) = sum of SWE decrease > 5 mm prior to peak
P	<u>cumulative SWE</u> = peak SWE + amount of melt prior to peak
Q	days of melt during melt season (<u>melt days melt</u>) = days when SWE decrease > 5 mm after peak
R	days of accumulation during melt season (<u>accum days melt</u>) = days when SWE increase > 5 mm after peak
S	average <u>melt rate</u> during melt season = peak SWE / (last day with snow- date of peak)

accumulation period or season (prior to peak), and melt period or season (after peak). For each station, the trend of each index for the period 1982–2012 was assessed by means of the Theil-Sen slope non-parametric test (Theil, 1950; Sen, 1968; Gilbert, 1987). Significance levels were computed using the Mann-Kendall test (Mann, 1945; Kendall, 1975; Gilbert, 1987).

Subsequently, the 19 trend coefficients for each SNOTEL station were considered as variables in a cluster analysis, to classify the 458 SNOTEL stations in different groups where the 19 indices have evolved in a similar temporal manner. The k-means method was used for clustering (Lloyd, 1982). The Silhouette statistic test (Rousseeuw, 1987) was used as a measure of how tightly grouped all the data in the cluster were, to define the final number of distinct clusters. While four different cluster were chosen for the final analysis, six and eight clusters were also investigated (e.g., Fassnacht and Derry, 2010).

Monthly trends in precipitation, maximum and minimum temperatures were computed for the study period to

relate the temporal evolution of niveograph characteristics with the evolution of the climate in each discriminated cluster. Gridded monthly data (Daly et al., 1997) were obtained from the PRISM data set and used to represent the climatic evolution at each SNOTEL station. These data were used due to the uncertainty in the discrepancies of the temperature measurements at the SNOTEL stations (Oyler et al., 2015; Fassnacht et al., 2017; Ma et al., 2019), and the shorter length of record (Julander et al., 2007).

3 Results

The SNOTEL stations were grouped into 4 clusters with some spatial coherence (Fig. 1). The average and the frequency distribution of the elevation, latitude, longitude, average temperature and precipitation (November–May) and accumulated SWE of the stations varies between clusters (Fig. 2). There are obvious differences in cluster 1, that is mostly decreasing, and cluster 4, that is mostly

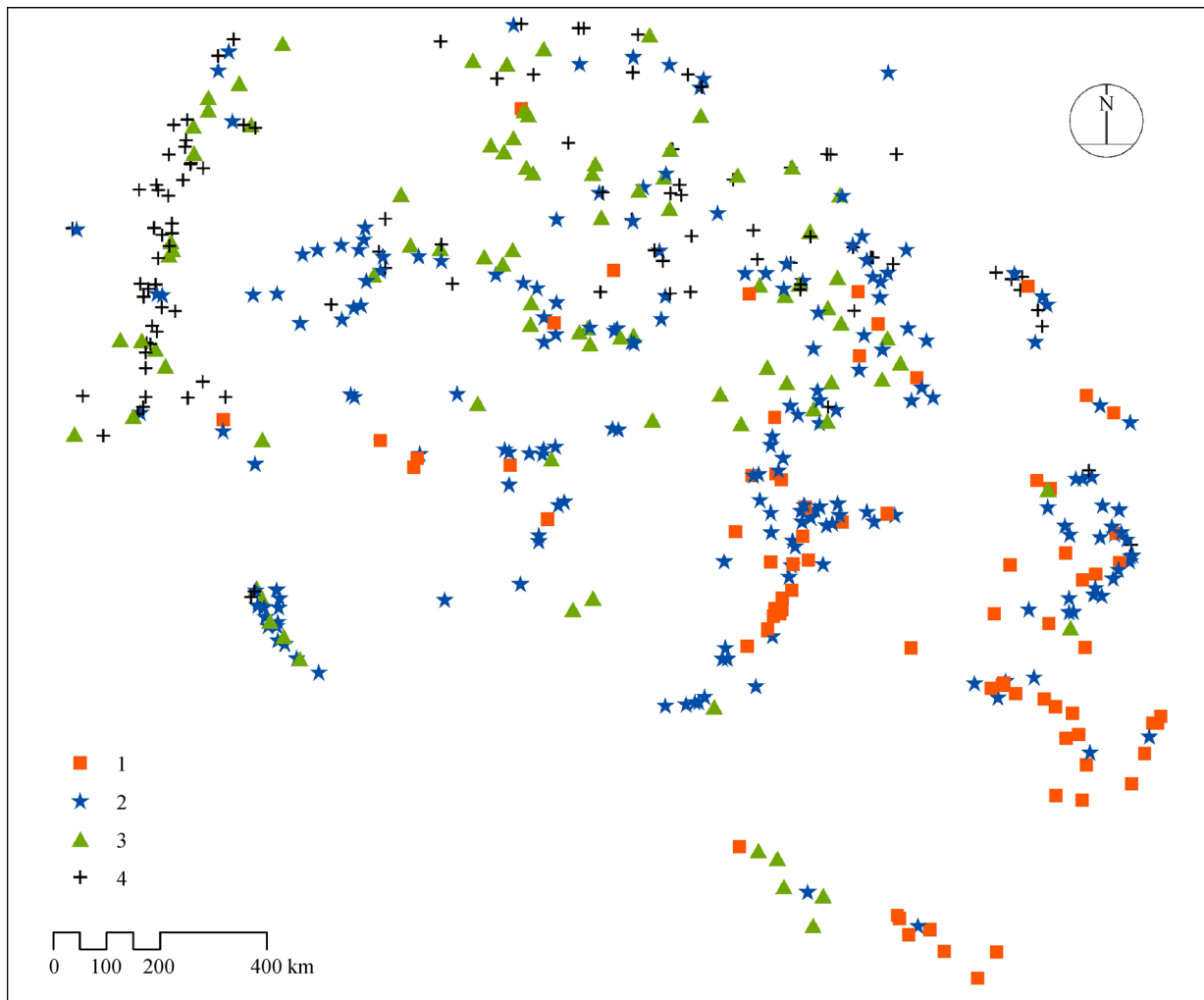


Fig. 1 Map of the western United States showing the four clusters of the 458 long-term SNOTEL stations, grouped based on trends in niveograph characteristics.

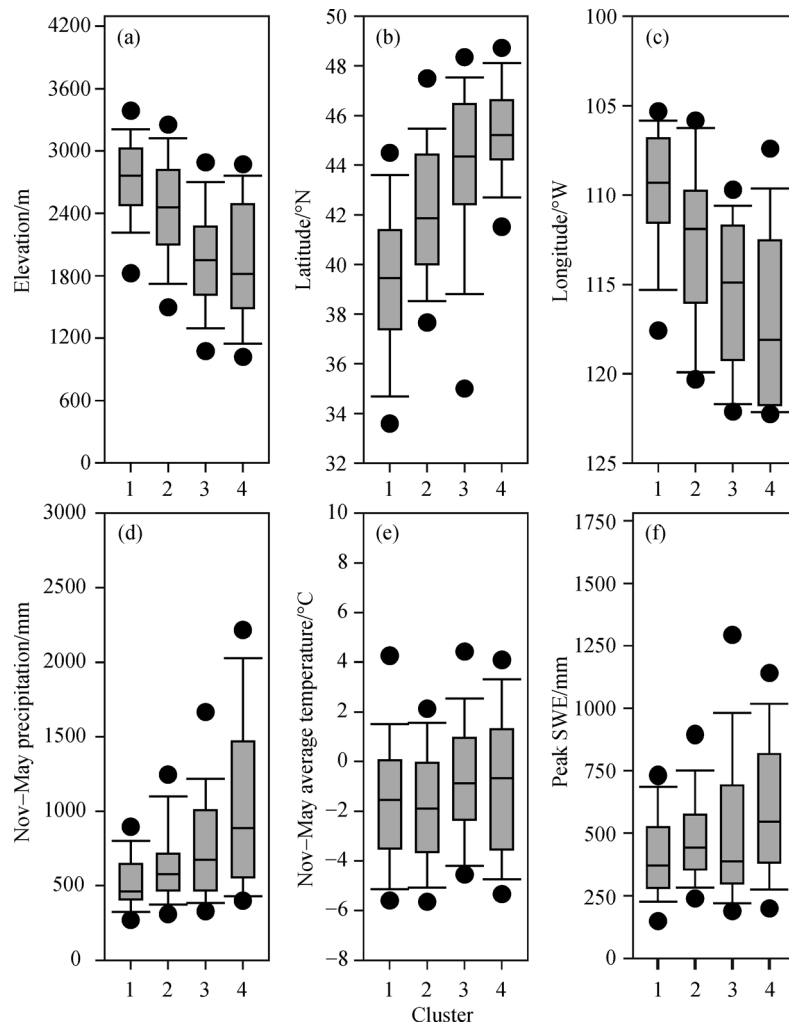


Fig. 2 Distribution of location (a. elevation, b. latitude, c. longitude) and average hydroclimatology (d. November to May total precipitation, e. November through May average temperature, f. peak snow water equivalent) shown per cluster as box and whisker plots of the maximum and minimum (dots), 90th and 10th percentiles (bars), ± 1 standard deviation (box) and mean (line in box).

increasing, as shown by two sample stations (Fig. 3). These decreases of cluster 1 (Figs. 3(a)–3(c), and 4(a)) correspond to the significant decrease ($p < 0.05$) of the Pacific Decadal Oscillation (Fig. 3(h)), while the cluster 4 increases (Figs. 3(d)–3(f), and 4(d)) correspond to the increase of the Oceanic Niño Index (at a significance level of $p < 0.1$) (Fig. 3(g)). The trends are more variable for Clusters 2 and 3 so those relate less to ONI or PDO. The evolution from cluster 1 through 4 is seen by the average trends, and the number of stations significantly increasing and decreasing for the 19 selected indices (Fig. 4 and Table 2). In general, most of the indices do not have statistically significant trends ($p < 0.05$) in the whole region (Table 2 and Fig. 4).

Cluster 1 (C1) groups the majority of the SNOTEL sites located in the easternmost and southernmost portions of the Western US (mostly New Mexico and South-western Colorado), presenting some of the highest elevations and

lowest precipitation and snow accumulation (Fig. 2). This group is characterized by a clear dominance of negative coefficients in the majority of the indices referred to snowpack duration, snow accumulation and magnitude of SWE peak. Approximately 50% of the stations of this group have shown a statistically significant decrease in the magnitude of the SWE peak, number of days of accumulation and cumulative SWE (Table 2). There are also abundant stations where snow duration has decreased (32%) as a consequence of a later (earlier) starting (ending) of the continuous snow cover. An almost opposite pattern to C1 is shown by cluster 4 (C4) that gathers most of the observatories located at the North-west (Washington, Oregon) and North (Montana and Idaho) of the study area. SNOTEL stations associated with these areas lie at the lowest elevations, and record the highest precipitation and snow accumulation of the network. These stations exhibited a generalized increase in the indices related to

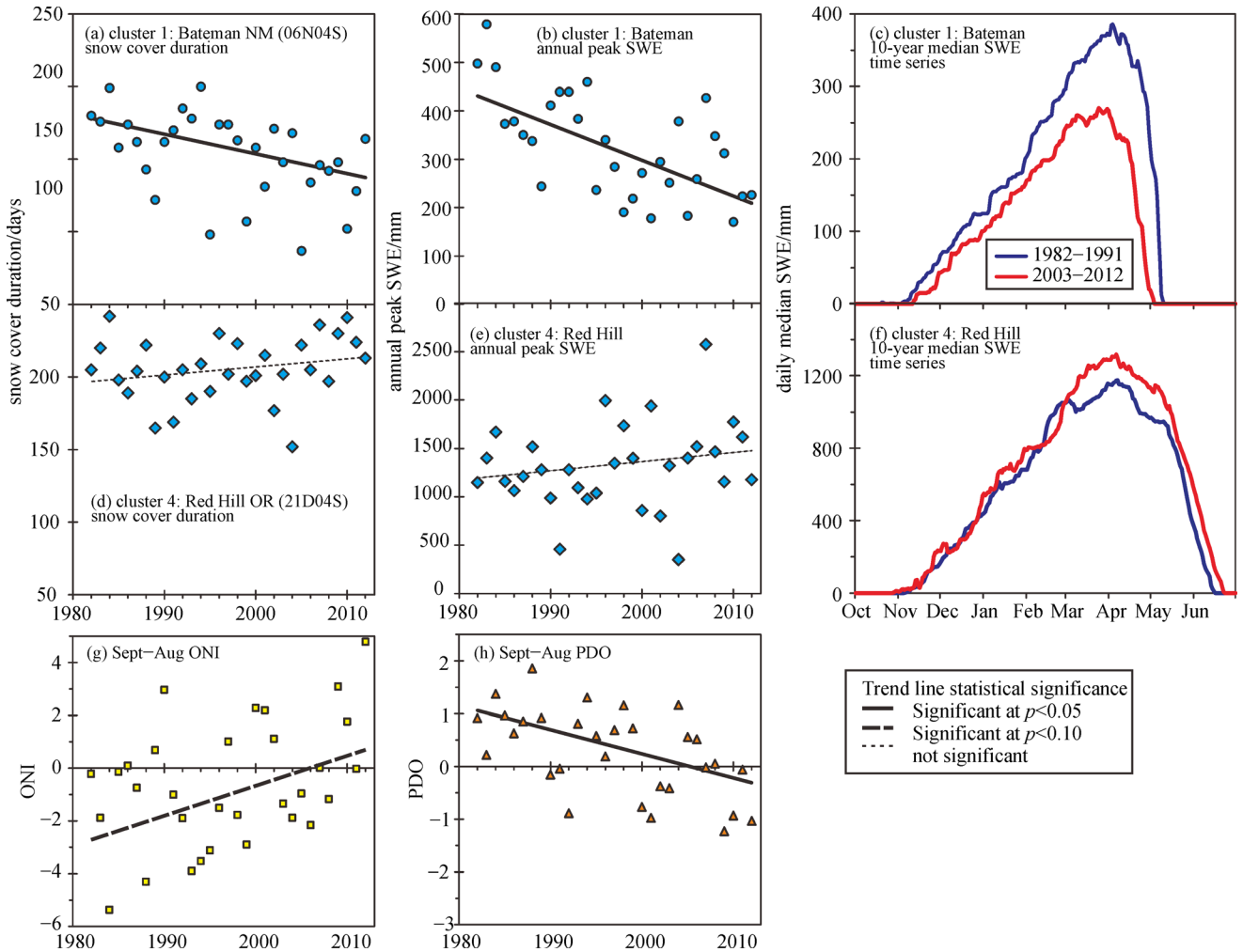


Fig. 3 Annual temporal evolution of selected indices at stations that showed the best correlation with the centroid of each cluster, for the cluster 1 Bateman New Mexico and cluster 4 Red Hill Oregon stations (a). and (d). annual snow cover duration, (b). and (e). annual peak SWE, (c). and (f). 10-year median daily SWE for 1982–1991 and 2003–2012, and the September through August (g). Oceanic Oscillation Niño Index (ONI) and (h). Pacific Decadal Oscillation (PDO).

duration of the snowpack (A–D), the peak SWE (E–I), and accumulation (J–P). The number of snow days, the end of continuous snowpack and accumulated SWE, are those that have exhibited a statistically significant increase ($p < 0.05$) in more stations grouped in C4 (20%–35%) (Table 2). Interestingly, there are also a number of stations where both accumulation (melting) events during the melting (accumulation) periods have increased. Subsequent investigation should evaluate these changes of conditions, i.e., melt during accumulation (N and O in Table 1) and accumulation during melt (R in Table 1), as these may further be indicators of change.

Clusters 2 and 3 (C2 and C3) are mostly in the central portions of the study area, but their distribution is less contiguous. They exhibit intermediate values in elevation, latitude, longitude and snow accumulation than C1 and C4. C2 stations are generally closer to C1, and they show very little observatories with statistically significant trends in

any of the 19 indices, but there is a generalized dominance of negative in many indices related with the duration of the snowpack, the accumulation and the magnitude of the SWE peak. C3 stations are geographically closer to C4, most of the indices show Theil-Sen slopes close to 0. Though the four clusters show noticeable differences in the frequency distribution of the elevation, latitude, longitude, precipitation and snow accumulation, they show a very similar distribution in average temperature.

The mean and standard deviation of the monthly trends in precipitation (P), maximum temperature (T_{mx}), and minimum temperature (T_{mn}) from October to June for each cluster of stations illustrates both difference among clusters and monthly variability (Fig. 5). C1 shows negative trends in P for the majority of the months, the decrease has been statistically significant in November and February. All months except February shows positive trends for T_{mx} , but only the average of November is close to the threshold of

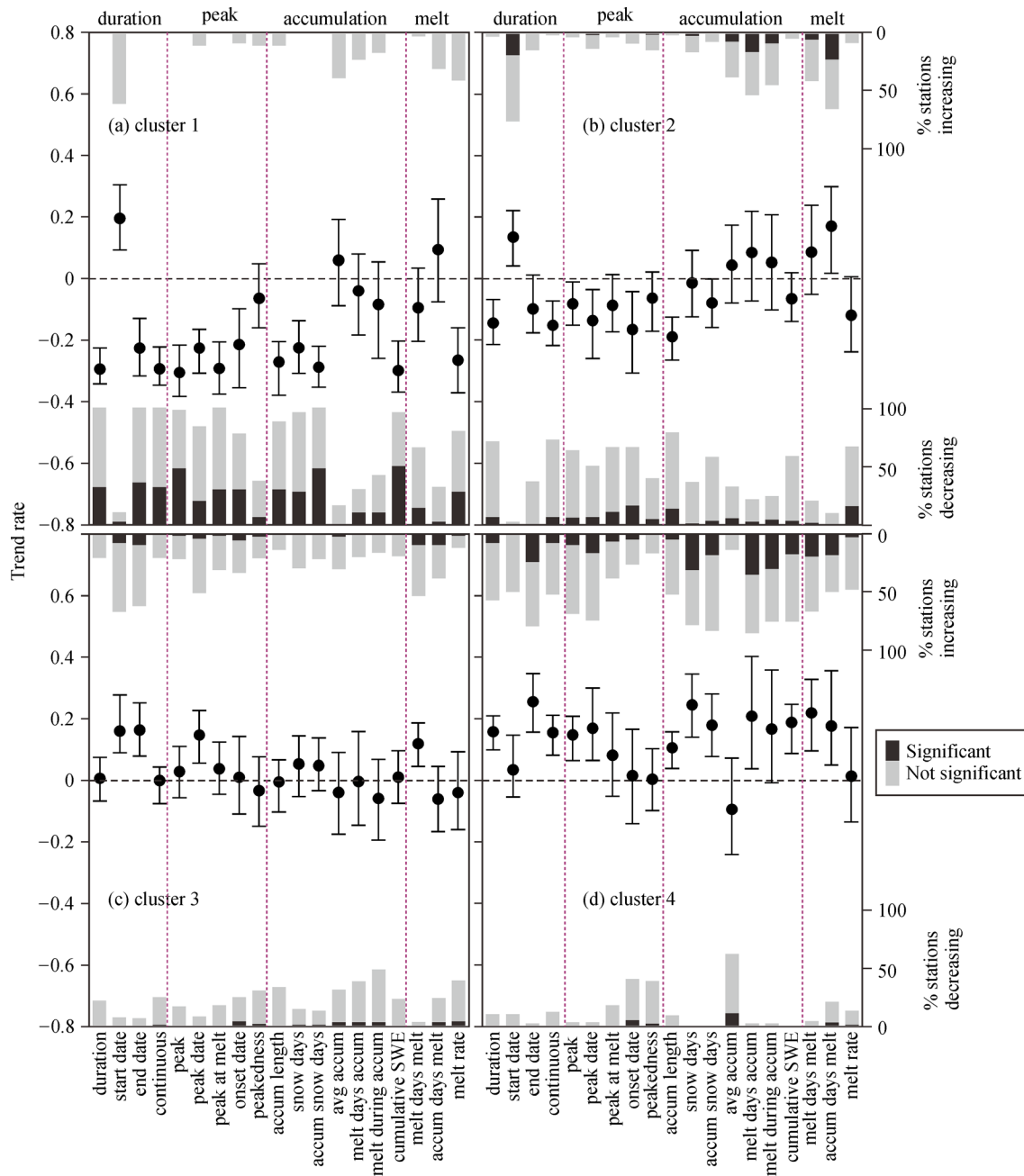


Fig. 4 Trends of the indices of the stations in each cluster for the 19 niveograph indices summarized in Table 1, shown as the mean (dot) and 25th and 75th percentiles (bars). The number of the stations as a % per that are increasing or decreasing at a significant ($p < 0.05$) (black) or not significant (gray) level are shown as bars for each index.

significance. In contrast all months except February have shown a statistically significant increase in minimum temperature or the average trends are very close to the significance level. Climatic variables in areas representing C4 shows noticeable differences with trends reported for C1. For all clusters, December, January and April exhibit positive precipitation trends, while November and February (C3 and C4) and March (C1 and C2) show a decrease that exceed the threshold of significance. Also, in contrast

with C1, the increase of T_{mn} in November and December are the only months that exceed the threshold of significance, while the coefficients from February to June are very far from this threshold. Climate evolution in areas representative of C2 and C3 shows a progressive transition between climatic evolution depicted for C1 and C4. Thus, C2 and C3 reflect respectively a progressive reduction of the positive trends reported for temperature and a moderation in the negative trends for precipitation (Fig. 5).

Table 2 Percent of stations in each cluster with significantly ($p < 0.05$) increasing or decreasing trends for each niveograph index. Bold station-indices are more than 10% of stations with a significant correlation

Index	Significant increase				Significant decrease			
	C1	C2	C3	C4	C1	C2	C3	C4
Duration	0	0	0	6.9	32	6.1	0	0
Start date	0	18.3	7.1	0	2	0	0	0
End date	0	0	8.7	23.5	36	0	0	0
Continuous	0	0	0	6.9	32	6.1	0.8	0
Peak	0	0	0.8	8.8	48	5.6	0	0
Peak date	0	1.1	3.2	15.7	20	6.1	0	0
Peak at melt	0	0	0.8	5.9	30	10.6	0	0
Onset date	0	0	4.8	3.9	30	16.1	4	4.9
Peakedness	0	0.6	1.6	0	6	4.4	1.6	2
Accum length	0	0	0	3.9	30	13.3	0	0
Snow days	0	1.7	0	30.4	28	0.6	0.8	0
Snow days accum	0	0	0	17.6	48	2.8	0.8	0
Avg accum	0	6.7	1.6	0	0	5	3.2	10.8
Melt days accum	0	15.6	0	34.3	10	2.2	3.2	0
Melt during accum	0	8.3	0	29.4	10	3.9	3.2	0
Cumulative SWE	0	0	0	16.7	50	2.8	0	0
Melt days melt	0	5	8.7	18.6	14	1.1	0	0
Accum days melt	0	22.2	8.7	17.6	2	0	3.2	2.9
Melt rate	0	0	0.8	2	28	15.6	4	1

4 Discussion

When the trends are clustered, general patterns are present (Fig. 1): most of cluster 1 was in the south-eastern portion of the study domain (New Mexico/Colorado/Utah), cluster 2 was dispersed more in middle (UT/WY/NV/ southern ID /east OR/WA), cluster 3 also in the middle, and cluster 4 in the coastal and northern states. Most studies use geographic or political boundaries to define regions of similar snowpack characteristics (e.g., Serreze et al., 1999; Pierce and Cayan, 2013). However, climatologies derived from daily, weekly or even monthly (8 values annually) SNOTEL data illustrate that clusters were less spatially contiguous (Fassnacht and Derry, 2010), as also shown here (Figs. 1 and 2).

On average, stations associated with cluster 1 are at the highest elevation but have the lowest annual and winter precipitation with the lowest April 1st SWE, while stations associated to cluster 4 are the opposite, being the lowest and the wettest (Fig. 2). These differences are in part due to the geography and climatology of the western US; C1 stations are more south (warmer at the same elevation) and more east (drier as they are further from moisture sources) (Figs. 1 and 2). Cluster 1 had the most stations with a significant decreasing April 1st SWE trend (37%) and decreasing winter precipitation (27%) (Fig. 4 and Table 2).

Cluster 2 had 11% of their stations illustrating a significant decrease in April 1st SWE with no other clusters having more than 5% of their stations seeing a decrease in SWE (Fig. 4). The distribution of peak SWE, date of peak SWE (e.g., Figs. 3(a) to 3(f)) and other trends (Fig. 4) are very different between clusters C1 and C4, with C2 and C3 being between C1 and C4.

Overall, the trends are similar to those seen by others (Cayan, 1996; Stewart et al., 2004; Regonda et al., 2005). However, when geography is solely used to group stations (e.g., Serreze et al., 1999), such as using the Regional Kendall test (Helsel and Frans, 2006), individual stations with different temporal snowpack characteristics may be estimated to have the same trend (Fassnacht et al., 2016). For example, the Lake Irene (05J10S) and Copeland Lake (05J18S) stations were grouped together in Clow's (2010) analysis (purple stations located in Rocky Mountain National Park, Colorado, 30 km apart, Lake Irene is 640 m higher). This analysis clustered Lake Irene with cluster 1 and Copeland Lake with cluster 4 (Fig. 2). There has been a significant decrease in peak SWE at the former station while it has increased significantly at Copeland Lake (Fig. 5; Fassnacht et al., 2018). This further illustrates why we did not use a geographic approach (e.g., Serreze et al., 1999) but a clustering approach, as per Fassnacht and Derry (2010).

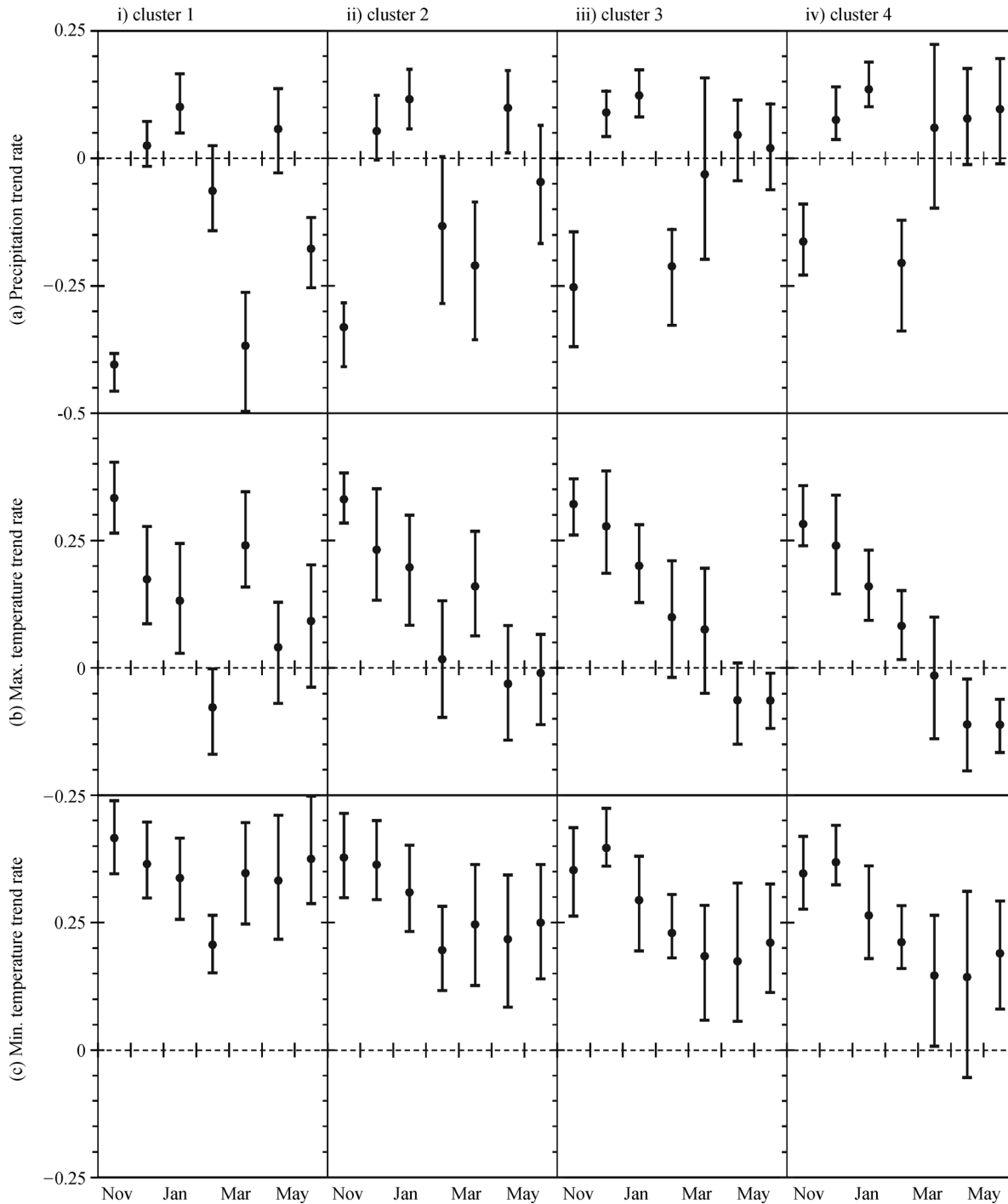


Fig. 5 Trends in the winter monthly (November through May) a) precipitation, b) maximum temperature, and c) minimum temperature for each cluster (i through iv for clusters 1 to 4), shown as the mean (dot) and 25th and 75th percentiles (bars).

The use of 19 indices attempted to fully characterize the nature of the nivograph. To compare to previous studies (e.g., Fassnacht and Derry, 2010), we also used a subset of seven indices. In particular, three duration indices (A duration, B start date, C end date), two peak indices (E amount or peak, F peak date) and two accumulation indices (N days with melt during accumulation or melt days

accum, P cumulative SWE) (Table 1) were used to compute trends and cluster the results. Reducing the number of indices yield only 48% of the clusters being the same, with cluster 1 being the most similar. We also examined the impact of a different number of total clusters and similar patterns were observed clustering the trends with 3, 4, 5, and 6 total clusters. When six total clusters

were used compared to four, 63% of the same clusters were found, with clusters 2 and 3 being the most different.

Snow course data have been used to investigate changes in April 1st snow water equivalent (SWE), which is used as a metric of maximum snow accumulation. For example, spatially from data over more than the past century (1900–2008), 76% of the annual deviation from average April 1st SWE could be attributed to the deviation in winter precipitation (+60%) and winter temperature (−40%) (McCabe and Wolock, 2009). The changes in the snowpack are complicated due to variable trends among the different metrics, even though there are some consistency (Fig. 4). There are also different trends based on elevation, latitude, and longitude (Fig. 1), specifically related to distance from moisture sources (Fassnacht et al., 2012). However, while many studies have used April 1st as an approximation of peak SWE (Serreze et al., 1999), the daily time series of SNOTEL data illustrate that the April 1st metric may underestimate peak SWE by 12% (Bohr and Aguado, 2001), and there can be monthly differences in snowpack trends (Fassnacht et al., 2018). Thus, this single metric does not tell the entire story (Fassnacht and Derry, 2010; Fassnacht et al., 2018). Even a sequence of first of the month SWE may not adequately represent SWE trends, due to changes over each month (Fassnacht et al., 2018). The daily SNOTEL data have also been useful to estimate an earlier onset of melt and date when half the snowpack has melted across most of Colorado (Clow, 2010).

There are several causes for a decreased snowpack (Harpold et al., 2017) which include less precipitation in the winter and/or warmer temperature that causes less snow accumulation and earlier melt. Some of the difference in precipitation and temperature trends relate merely to spatial variability, especially over small scales. For example, in the northern Front Range of Colorado that lower elevation locations are getting more snow, while higher elevations are getting less (Fassnacht et al., 2018). Yet, temperature and precipitation trends were relatively consistent and vary more temporally (month to month) than spatially (Fassnacht et al., 2018). Precipitation trends are more variable than temperature trends (Fig. 5; Fassnacht et al., 2018). Even in relatively homogeneous terrain, there can be larger and even opposite trends in temperature (Pielke et al., 2002) and precipitation (Fassnacht et al., 2016). Thus, a station in a particular region at a particular elevation will respond differently to precipitation and temperature anomalies and thus will be very different depending of the index that is evaluated (Fig. 4). In this paper we are examining snowpack indices and considering their trends together. We use these daily SNOTEL data to derive 19 measures of snowpack accumulation and melt to investigate changes in the snowpack patterns. These go beyond the summaries presented by Fassnacht and Derry (2010), Clow (2010) and Harpold et al. (2012) to highlight the patterns in the

annual niveograph (SWE time series). The trend for each annual index is determined for each station and the composite of trends are used to cluster the stations in groups illustrating similar snowpack patterns (trends). The results show strong linkages between decadal atmospheric circulation patterns that we examined, i.e., PDO and ONI, and the spatial distribution shown by the changes in niveograph characteristics reported in this study (Fig. 4). These differences are further due to topography, relative location (e.g., continental versus maritime), and the large latitudinal range covered by this study. The Oceanic Niño Index (ONI) was increasing over the study period at a significance level of $p < 0.1$ while the Pacific Decadal Oscillation (PDO) was significantly decreasing ($p < 0.05$) (Figs. 3(g) and 3(h), respectively). Interestingly, the ONI increase corresponded to increasing snowpack trends seen in cluster 4 (e.g., Figs. 3(d) and 3(e)), while the PDO decrease corresponded to decreasing snowpack trends seen in cluster 1 (e.g., Figs. 3(a) and 3(b)). Over the time period that we evaluated, clusters 2 and 3 saw a mix of decreasing and increasing trends (Fig. 4), and thus were not as well correlated with PDO or ONI as clusters 1 and 4, respectively. While the correlation between ONI, PDO and snowpack trends has not been studied extensively, the correlation between each of the climatic oscillations and snowpack patterns has been illustrated in the western US (Cayan, 1996; Lo and Clark, 2002; Abatzoglou, 2011), North America (Sobolowski and Frei, 2007) and the Andes (Veetil and Simões, 2019).

Due to the recent drought in California (Mann and Gleick, 2015; Williams et al., 2015; Allen and Anderson, 2018) and other parts of the study area, we used the SNOTEL SWE data only through 2012. An examination of a sample station (Virginia Lakes Ridge) showed that the annual decrease in SWE was almost the same for the period 1982 to 2012 as for the period 1982 through 2018, yet this change was only significant for the longer period. Both the length of record (Chen and Grasby, 2009; Venable et al., 2012; Fassnacht et al., 2016) and the specific period of SWE, i.e., the window of time, (Venable et al., 2012) can alter the rate of change and the significance. Future work will need to examine different time periods as the length of record for the SNOTEL stations increases to that of the snow course network (Fassnacht and Hultstrand, 2015).

5 Conclusions

The snowpack is changing across the world, including the western US, where the SNOTEL network has been monitoring the snowpack at hundreds of locations on a daily basis since the late 1970s. These data were used to define the temporal evolution of the snowpack. The characteristics of the annual niveograph were described by 19 indices. The non-parametric trends were computed

for each index for each station. These trends illustrated specific patterns across the study domain. The spatial distribution of these patterns was identified as clusters of stations that showed similar trends. There is some spatial coherence in the patterns of the clusters, such as one (cluster 4) in the northern and western part of the domain, and another one primarily in the south and eastern part of the domain (cluster 1). Overall, the snowpack was increasing for cluster 4 while it was decreasing for cluster 1. However, the spatial coherence of clusters of trends is not fully based on geographic proximity; with the exception of New Mexico, stations from at least three of the four clusters are found in 10 of the 11 western states. Stations in all four clusters were found in the states of Oregon, Idaho, and Wyoming. Using few indices or more clusters produced similar results than the four clusters with 19 indices used herein.

Acknowledgements Funding for this work was provided by the NASA Terrestrial Hydrology Program Project NNX11AQ66G “Improved Characterization of Snow Depth in Complex Terrain Using Satellite Lidar Altimetry” (Principal Investigator Dr. Michael Jasinski from NASA-Goddard Space Flight Center). Thanks are due to Fergus Reig Gracia from IPE for extracting all the data.

Data Access The SNOTEL daily data are available from the National Water and Climate Center of the Natural Resources Conservation Service at < www.wcc.nrcs.usda.gov/snow/ > (last access 25 January 2020). The spatial data used in Fig. 1 were obtained from the US Geological Survey National Viewer Data set < viewer.nationalmap.gov/advanced-viewer > (last access 21 February 2019). The PRISM data set was obtained from < www.prism.oregonstate.edu > (last access 25 January 2020).

References

- Abatzoglou J T (2011). Influence of the PNA on declining mountain snowpack in the western United States. *Int J Climatol*, 31(8): 1135–1142
- Allen R J, Anderson R G (2018). 21st century California drought risk linked to model fidelity of the El Niño teleconnection. *NPJ Clim Atmos Sci*, 1(1):1–14
- Bohr G S, Aguado E (2001). Use of April 1 SWE measurements as estimates of peak seasonal snowpack and total cold-season precipitation. *Water Resour Res*, 37(1): 51–60
- Cayan D R (1996). Interannual climate variability and snowpack in the western United States. *J Clim*, 9(5): 928–948
- Cayan D R, Dettinger M D, Kammerdiener S A, Caprio J M, Peterson D H (2001). Changes in the onset of spring in the western United States. *Bull Am Meteorol Soc*, 82(3): 399–415
- Chen Z, Grasby S (2009). Impact of decadal and century-scale oscillations on hydroclimate trend analyses. *J Hydrol (Amst)*, 365 (1–2): 122–133
- Clow D W (2010). Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming. *J Clim*, 23(9): 2293–2306
- Cook B I, Ault T R, Smerdon J E (2015). Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Sci Adv*, 1(1): e1400082
- Daly C, Taylor G, Gibson W (1997). The PRISM approach to mapping precipitation and temperature. In: 10th Conference on Applied Climatology. Reno: Amer Meteor Soc, 10–12
- Fassnacht S R, Derry J E (2010). Defining similar regions of snow in the Colorado River Basin using self organizing maps (SOMs). *Water Resour Res*, 46(4): W04507
- Fassnacht S R, Patterson G G (2013). Niveograph interpolation to estimate peak accumulation at Two Mountain sites. In: Cold and Mountain Region Hydrological Systems Under Climate Change: Towards Improved Projections. Gothenburg: IAHS, 360: 59–64
- Fassnacht S R, Hultstrand M (2015). Snowpack variability and trends at long-term stations in Northern Colorado, USA. In: Proceedings of the International Association of Hydrological Sciences (Hydrologic Non-Stationarity and Extrapolating Models to Predict the Future), 371: 131–136
- Fassnacht S R, Deitemeyer D C, Venable N B H (2014). Capitalizing on the daily time step of snow telemetry data to model the snowmelt components of the hydrograph for small watersheds. *Hydrol Processes*, 28(16): 4654–4668
- Fassnacht S R, Dressler K A, Hultstrand D M, Bales R C, Patterson G G (2012). Temporal inconsistencies in coarse-scale snow water equivalent patterns: Colorado River Basin snow telemetry-topography regressions. *Pirineos*, 167(0): 165–186
- Fassnacht S R, Cherry M L, Venable N B H, Saavedra F (2016). Snow and albedo climate change impacts across the United States Northern Great Plains. *Cryosphere*, 10(1): 329–339
- Fassnacht S R, López-Moreno J I, Ma C, Weber A N, Pfohl A K D, Kampf S K, Kappas M (2017). Spatio-temporal snowmelt variability across the headwaters of the southern Rocky Mountains. *Front Earth Sci*, 11(3): 505–514
- Fassnacht S R, Venable N B H, McGrath D, Patterson G G (2018). Sub-seasonal snowpack trends in the Rocky Mountain National Park area, Colorado USA. *Water*, 10(5): 562
- Fritze H, Stewart I T, Pebesma E (2011). Shifts in western North American snowmelt runoff regimes for the recent warm decades. *J Hydrometeorol*, 12(5): 989–1006
- Gilbert R O (1987). *Statistical Methods for Environmental Pollution Monitoring*. New York: John Wiley & Sons
- Harpold A, Brooks P, Rajagopal S, Heidebuchel I, Jardine A, Stielstra C (2012). Changes in snowpack accumulation and ablation in the intermountain west. *Water Resour Res*, 48: W11501
- Harpold A A, Dettinger M, Rajagopal S (2017). Defining snow drought and why it matters. *Eos (Wash DC)*, 98
- Helsel D R, Frans L M (2006). Regional kendall test for trend. *Environ. Sci. Technol.* 40(13): 4066–4073
- Julander R P, Curtis J, Beard A (2007). The SNOTEL Temperature Dataset. *Mountain Views Newsletter*, 1(2): 4–7
- Keithley J (2002). All Across America. Track 5 on Win the Battle, Can. Friends, Sudden Death Records
- Kendall M G (1975). *Rank Correlation Methods*. 4th ed. London: Charles Griffin
- Lloyd S (1982). Least squares quantization in PCM. *IEEE Trans Inf Theory*, 28(2): 129–137
- Lo F, Clark M P (2002). Relationships between spring snow mass and summer precipitation in the Southwestern United States Associated with the North American monsoon system. *J Clim*, 15(11): 1378–

1385

- McCabe G J, Wolock D M (2009). Recent declines in western U.S. snowpack in the context of twentieth-century climate variability. *Earth Interact*, 13(12): 1–15
- Ma C, Fassnacht S R, Kampf S K (2019). How temperature sensor change affects warming trends and modeling—an evaluation across the State of Colorado. *Water Resources Research*, 55(11): 9748–9764
- Mann H B (1945). Non-parametric tests against trend. *Econometrica*, 13(3): 163–171
- Mann M E, Gleick P H (2015). Climate change and California drought in the 21st century. *Proc Natl Acad Sci USA*, 112(13): 3858–3859
- Mote P W, Hamlet A F, Clark M P, Lettenmaier D P (2005). Declining mountain snowpack in western North America. *Bull Am Meteorol Soc*, 86(1): 39–50
- Mote P W, Li S, Lettenmaier D P, Xiao M, Engel R (2018). Dramatic declines in snowpack in the western US. *NPJ Clim Atmos Sci*, 1(1): 2
- NRCS (2018). SNOTEL and the Snow Survey & Water Supply Forecasting Program. National Water and Climate Center, Natural Resources Conservation Service, US Department of Agriculture
- Oyler J W, Dobrowski S Z, Ballantyne A P, Klene A E, Running S W (2015). Artificial amplification of warming trends across the mountains of the western United States. *Geophys Res Lett*, 42(1): 153–161
- Pielke R A Sr, Stohlgren T, Schell L, Parton W, Doesken N, Redmond K, Moeny J, McKee T, Kittel T G F (2002). Problems in evaluating regional and local trends in temperature: an example from eastern Colorado, USA. *Int J Climatol*, 22(4): 421–434
- Pierce D W, Cayan D R (2013). The uneven response of different snow measures to human-induced climate warming. *J Clim*, 26(12): 4148–4167
- Regonda S K, Rajagopalan B, Clark M, Pitlick J (2005). Seasonal cycle shifts in hydroclimatology over the western United States. *J Clim*, 18(2): 372–384
- Rousseeuw P J (1987). Silhouettes: a graphical aid to the interpretation and validation of cluster analysis. *Comput Appl Math*, 20: 53–65
- Sen P K (1968). Estimates of the regression coefficient based on Kendall's tau. *J Am Stat Assoc*, 63(324): 1379–1389
- Serreze M C, Clark M P, Armstrong R L, McGinnis D A, Pulwarty R S (1999). Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data. *Water Resour Res*, 35(7): 2145–2160
- Sobolowski S, Frei A (2007). Lagged relationship between North American snow mass and atmospheric teleconnection indices. *Int J Climatol*, 27(2): 221–231
- Stewart I T, Cayan D R, Dettinger M D (2004). Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. *Climatic Change* 62: 217
- Stewart I T (2009). Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrol Processes*, 23(1): 78–94
- Stewart I T, Cayan D R, Dettinger M D (2005). Changes toward earlier streamflow timing across western North America. *J Clim*, 18(8): 1136–1155
- Theil H (1950). A rank-invariant method of linear and polynomial regression analysis, I, II, III. In: *Proceedings of the Royal Netherlands Academy of Sciences*, 53: 386–392, 521–525, 1397–1412
- Veetil B K, Simões J C (2019). The 2015/16 El Niño-related glacier changes in the tropical Andes. *Front Earth Sci*, 13(2): 422–429
- Venable N B H, Fassnacht S R, Adyabadam G, Tumenjargal S, Fernández-Giménez M, Batbuyan B (2012). Does the length of station record influence the warming trend that is perceived by Mongolian herders near the Khangai Mountains? *Pirineos*, 167(0): 69–88
- Williams A P, Seager R, Abatzoglou J T, Cook B I, Smerdon J E, Cook E R (2015). Contribution of anthropogenic warming to California drought during 2012–2014. *Geophys Res Lett*, 42(16): 6819–6828