

Author responses to: “Brief Communication: Early season snowpack loss and implications for over-snow vehicle recreation travel planning”

Responses to reviewers are in **bold**, *new text is in italics (bold italics for emphasis)*

Responses to Reviewer 1

Review comments by Glenn Patterson on Hatchett and Eisen, 2018, Brief Communication: Early season snowpack loss and implications for over-snow vehicle recreation travel planning. Thank you for the opportunity to review this brief communication. In general I found the paper to be well-written, representing a significant contribution to our understanding of climate change, snowpack trends, and winter recreation.

Dear Dr. Patterson,

We appreciate your constructive comments and positive feedback. Please find below responses and our revisions to address all of your comments.

My only substantive suggestions are: (1) Based on figure 1(b) and on intuition, median timing of achieving SWE_{min} appears to be negatively, not positively, correlated with elevation.

Thank you for pointing out this oversight. You are correct, the timing of SWE_{min} is negatively correlated with elevation. We have changed the text to “*negatively correlated*”.

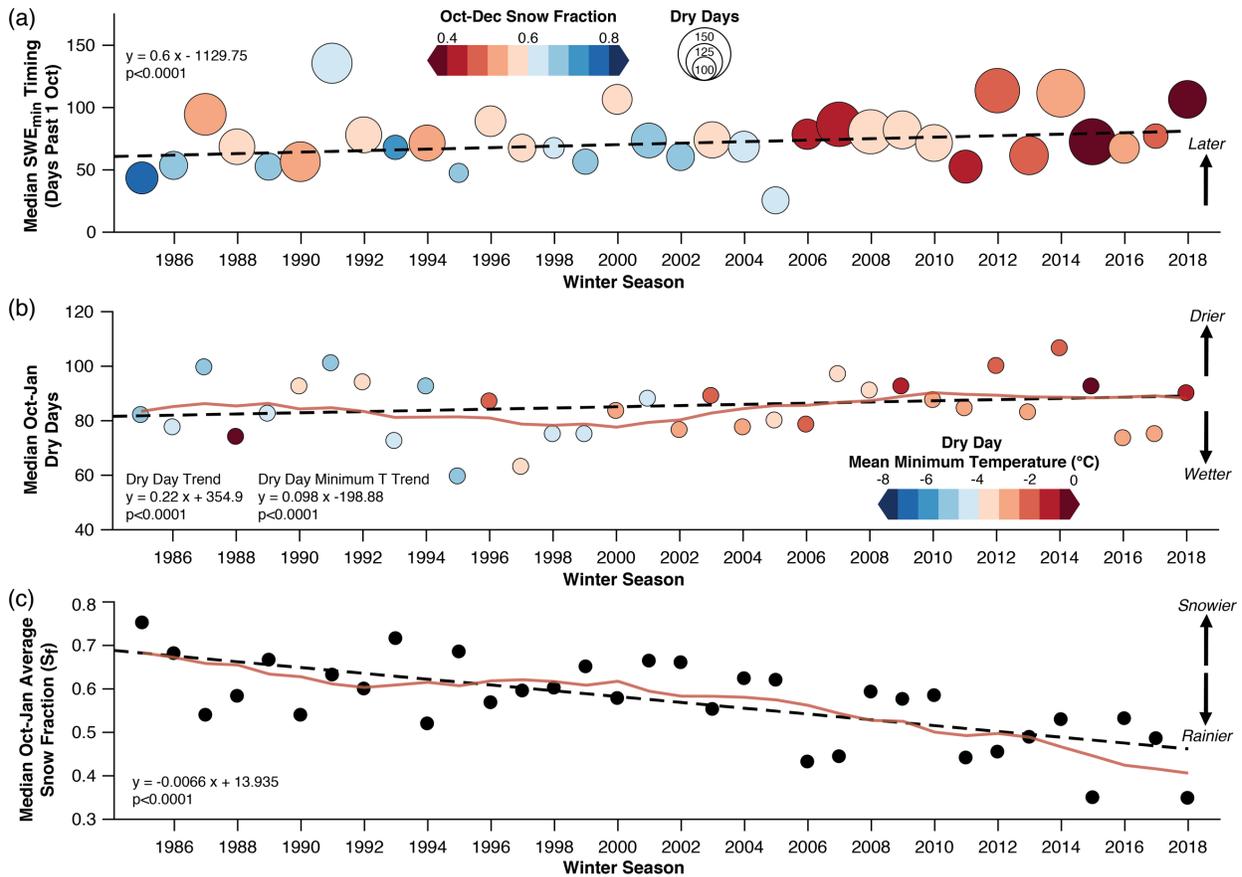
(2) I realize that it might not be feasible to add another parameter to the analysis at this late date, and I also realize that SNOTEL temperature records can be suspect, but I still feel it’s worth bringing up this point. As you state well on page 4, line 23, warming temperatures are likely to be an important driver for the trends toward later SWE_{min}, and are also likely to be the primary factor involved in the shift toward more rain and less snow. Would it be possible to add a figure showing the trend in a relevant measure of temperature? It could be something like average daily (or max daily) early cold-season (Oct-Dec) temperature, or something like that. From what you are describing, one would expect to see a shift from predominantly freezing to melting temperatures.

We appreciate this useful suggestion. The snow fraction calculation is based upon average temperature and thus captures the shift from snow to rain you mention, but for non-precipitating (dry) days, we have added the average early season dry day minimum temperature value to Panel b on Figure 2. Minimum temperature is an excellent metric to observe how regional warming (via changes in longwave radiation balance driven by changes in atmospheric composition) is impacting the study area. The Mann-Kendall trend test was applied to the minimum temperature timeseries. It yielded a statistically significant trend of $0.098^{\circ}\text{C yr}^{-1}$ ($p < 0.0001$). This suggests regional warming is reducing precipitation falling as snow on wet days and is driving a warming of an ever-increasing number of dry days, both of which will act to negatively force the snowpack. For consistency, we have calculated dry days,

average dry day minimum temperature, and snow fraction over the early season (mid fall through early winter) period spanning October-January. The main text and figure 2 have been updated with the adjusted results.

The new text is as follows:

The new figure 2 and caption:



We also agree that the SNOTEL temperature records can be suspect (based on the Oyler et al. 2015 work and have noted this in the text at the end of section 3.2 (possible drivers of SWE loss):

“The analysis of SNOTEL temperature is limited by inhomogeneities introduced by temperature-dependent sensor biases leading to over-estimation of trends (Oyler et al., 2015). While over-estimation is greatest at elevations above 3000 m, additional assessments are needed to validate the robustness of the role of regional warming in reducing early season snowpack”

Added reference:

Oyler, J.W., Dobrowski, S.Z., Ballantyne, A.P., Klene, A.E. and Running, S. W.: Artificial amplification of warming trends across the mountains of the western United States, *Geophys. Res. Lett.*, 42(1), 153-161, <https://doi.org/10.1002/2014GL062803>, 2015.

(3) I like the discussion pertaining to table 1, and the suggestions contained in the table. I would like to suggest one additional management strategy. As both human-powered and OSV winter recreational use are likely to be confined in the future to smaller geographic areas and shorter-duration seasons, conflicts among user groups are likely to increase. In the Rabbit Ears Pass area of Colorado, managers from Routt National Forest minimize those conflicts by clearly designating separate areas for motorized and non-motorized use (non-motorized can actually occur in both areas). In this case it is the east side and the west side of the pass. My suggestion is to develop such conflict-reduction strategies for the Lake Tahoe area, as well.

Thank you for the suggestion, we have added this strategy to the table. From personal experience, although some areas are well-signed (designated), problems can still arise due to lack of resources to enforce closures, but such an issue should be addressed during the travel management planning process and through subsequent budget requests.

Below are some specific suggestions for minor editorial issues.

Abstract: In the first sentence (line 8), it would be good to clarify whether “negative impacts” refer to impacts on the over-snow vehicle recreational experience, or on the environment.

Based on the paper, it appears to be the latter.

You are correct, it is the latter. We have added “*on the environment*” to clarify.

I agree with the previous suggestion, that it would be good to speak (line 11) in terms of later onset of SWE sufficient for recreation, rather than increasing date.

We have changed the text to reflect ‘*later onset*’ rather than increasing date.

Introduction:

Page 1

Line 15: I would be a little more comfortable with “warming” of the cryosphere, rather than “decline”. “Warming” is clear; “decline” carries complex connotations.

We have changed the text to “*warming*”.

Line 27: “Economic revenue” strikes me as redundant. I would suggest either “revenue” or “economic impact”. Also, it would be helpful to specify that the revenue is on an annual basis: “...annual revenue...”

Thank you for the suggestions. We have changed the text to “*estimates of annual economic impact*”.

Page 2

Lines 4-9: This would be a good place to address one of the important aspects of the SWE-depth relationship that is central to this discussion. I would suggest stating that the 30-cm minimum depth refers to 30 cm of uncompacted or fresh snow, something like this: "Minimum snow depth restrictions have been proposed by several forests undergoing winter travel management planning across the Sierra Nevada. This restriction is usually proposed as a minimum depth of 30 cm of uncompacted snow (United States Forest Service (USFS), 2013)"

Good point, we have changed the text to follow your suggested phrasing:

"...across the Sierra Nevada. This restriction is usually proposed as a minimum depth of 30 cm of un-compacted snow (United States Forest Service (USFS), 2013)."

Data and Methods:

Page 3

Line 9: This is a little nit-picky, but this sentence seems to indicate that SWE is a measure of depth. I would suggest rewording to: "...we specified 90 mm SWE (hereinafter SWE_{min}) as the required minimum SWE corresponding to a minimum uncompressed depth of 30 cm for approval of OSV use."

Change has been made, thank you for helping to clarify this and hopefully reduce confusion.

The new text is as follows:

"...we specified 90 mm SWE (hereafter SWE_{min}) as the required minimum SWE corresponding to a minimum un-compacted depth of 30 cm for approval of OSV use."

Line 14: I agree with the earlier suggestion to maintain consistency of depth units by sticking with cm instead of mm.

We are now using cm as the primary unit with respect to depth and mm for snow water equivalent. The text has been changed to "30 cm".

Line 24: I would suggest using "when" instead of "that": "Dry days were days when zero precipitation was measured..."

Change has been made to "when", thank you.

Results and Discussion:

Page 3

Lines 31-31: Based on figure 1(b) and on intuition, median timing of achieving SWE_{min} appears to be negatively, not positively, correlated with elevation.

Change to “*negatively correlated*” has been made, again we apologize for the oversight.

Page 4

Line 1: Delete unneeded “in” after “trends”.

We have removed “in”.

Line 8: Thanks for looking at the elevation dependency of the SWE_{min} trends. I, too, found indications of elevation-dependent warming, meaning steeper trends at higher elevations. Some of the references in my 2016 dissertation go into this in a little more detail.

While our station-based SWE analysis did not find a relationship between trend in onset date, the gridded SWE analysis did indicate more significant trends at higher elevations, however this is still likely due to the early season weather variability (as previously noted in the original submission) and the bias of reanalysis validation data (snow pillows and snow courses) being located at intermediate elevations.

We added some additional text to the concluding remarks suggesting further assessment of the controls of elevation-dependent warming (notably, changes in humidity):

“However, further research is needed to estimate specific contributions from each cause and constrain the role of surface-albedo and/or humidity feedbacks at various elevations throughout the region (Patterson, 2016; Walton et al., 2017).”

Line 23: I realize that it might not be feasible to add another parameter to the analysis at this late date, and I also realize that SNOTEL temperature records can be suspect, but I still feel it’s worth bringing up this point. As you state well here, warming temperatures are likely to be an important driver for the trends toward later SWE_{min}, and are also likely to be the primary factor involved in the shift toward more rain and less snow. Would it be possible to add a figure showing the trend in a relevant measure of temperature? It could be something like average daily (or max daily) early cold-season (Oct-Dec) temperature, or something like that. From what you are describing, one would expect to see a shift from predominantly freezing to melting temperatures.

This is a great suggestion and we have added this analysis to the manuscript, despite the limitations of the SNOTEL temperature data. Please see the response to main suggestion 2) above.

Table 1--Page 11:

I like the discussion pertaining to table 1, and the suggestions contained in the table. I would like to suggest one additional management strategy. As both human-powered and OSV winter recreational use are likely to be confined in the future to smaller geographic areas and shorter-duration seasons, conflicts among user groups are likely to increase. In the Rabbit Ears Pass area of Colorado, managers from Routt National Forest minimize those conflicts by clearly designating separate areas for motorized and non-motorized use (non-motorized can actually occur in both areas). In this case it is the east side and the west side of the pass. My suggestion is to develop such conflict-reduction strategies for the Lake Tahoe area, as well.

Thank you for the suggestion, we have added this strategy to Table 1.

Responses to Reviewer 2

I appreciate the opportunity to review this brief communication, as there is very limited work on the implications of changing cryosphere for the multi-billion dollar over-snow vehicle (OSV) ('snowmobile') industry. This industry is far more at risk to cryosphere changes than the ski industry, which has much higher adaptive capacity through cost-effective snowmaking. I concur with G. Patterson that the paper is very well written and the comments on methods and interpretation, and will build on those remarks.

Dear Dr. Scott,

We appreciate your constructive comments and positive feedback. Please find below responses and our revisions to address all of your comments. We have included your insightful comment about the greater risk to climate change the snowmobile community faces due to the absence of snowmaking in the introduction (please see the response to your first comment below).

The dual data sources are very important to enable the exportability of the method to other regional markets across North America (mostly via reanalysis, as Snotel stations are limit in Eastern markets) that would allow inter-regional market comparisons. A limitation to the paper is that literature review is not comprehensive and given how limited this literature is, it should be complete in my opinion. While I acknowledge space is limited in a brief communication, this will provide future authors with a complete and current state of knowledge to build on. This will also strengthen some of the threshold assumptions made in this paper and comparisons with other regional markets. Specifically, the authors should consider the work on snowmobile tourism under climate change that was completed in New England (Scott et al. 2008. *Mitigation and Adaptation Strategies to Global Change*, 13, 5-6, 577-59) and parts of Canada (McBoyle et al. 2007. *Managing Leisure*, 12, 4, 237-250) about 10 years ago.

We agree and have included these citations (thank you for providing these) and relevant discussion in the introduction and discussion section. Specifically, we added two sentences summarizing the results of these two studies to the introduction:

“Due to the dependence on natural snowfall and reduced adaptive capacity compared to the ski community, which can use cost-effective snowmaking to augment the natural snowpack, over-snow vehicle (OSV) recreation is highly vulnerable to climate variability and change (McBoyle et al., 2007; Scott et al. 2007). Climate change projections for Canada and the northeastern United States under an aggressive greenhouse gas emissions scenario suggest that by the mid-21st century, OSV season lengths will be reduced by 50-100% in most areas (McBoyle et al., 2007; Scott et al., 2007).”

Discussion of impacts for visitor experience or economic impacts could be strengthened. Analyses of the impacts of recent record warm winters on the ski industry have revealed that shorter, more varied seasons result in increased congestion, which has adverse impacts on visitor experience (and thus economic surplus). The same impact is likely with OSV (particularly at trailheads) if demand remains stable.

Thank you for the suggestion to add the concept of increased congestion and the resultant impact on high quality experiences to the discussion. We utilized recent results from Perry et al. (2018) to highlight these adverse impacts:

“A survey of the OSV community in Vermont found that reductions in the length of the winter season with sufficient snow coverage for OSV use were observed by 45% of respondents, with 74% of respondents decreasing their OSV use in response to low snow conditions (Perry et al., 2018). This survey also found that encounters with other recreationalists, including OSV users, detracted from a high-quality recreation experience.”

Have recent record warm winters revealed any impacts on visitor use patterns or increased impacts on landscapes/ecology?

We are not aware of local (regionally-relevant) changes in visitor use (grouping this with economic impacts in an implicit sense) or ecological impacts, but we have added the latter to the concluding remarks sentence noting the need for additional studies on these topics (see bold italics below):

*“Additional studies on achieving regionally-relevant minimum snow depths and better quantification of economic **and ecological** impacts from reduced snow cover area and duration will guide more robust travel management plans in national forests.”*

The work of Hagenstad et al. (2018) does provide insight regarding visitor use pattern change as a function of recent climate variability, and we have added sentences on this to the introduction:

“Skier visits are positively correlated to snowfall (Hagenstad et al., 2018) and we assume that such a correlation is consistent across winter recreation activities.”

“The net effects of reduced season length, more congestion, and lower quality experiences result in lower economic benefits from consumer surplus, or the amount a person is willing to pay over the amount actually spent. For OSVs, consumer surplus is estimated to be approximately 61 USD day⁻¹ (Hagenstad et al., 2018).”

The adaptation table is very useful for resource managers to consider appropriate responses. I fully agree with the authors that there is no one-size-fits-all approach, and that climate adaptation has to be informed by local circumstances and stakeholders. Other options the might be included in this table could include: (1) improve smoothness/durability of trailhead and corridor trails, so to require less snow and reduce impacts; (2) restrict access to marked

trail areas in early/late season or during mid-season low snow periods; (3) if trail groomers are not used in this region, introduce them to improve the durability of corridor trails.

Great suggestions, thank you. We have added suggestions (1) and (3) to Table 1 and have adjusted an existing adaptation measure to include the marked trails noted in suggestion (2). Our new table is as follows (and includes the suggestion from Reviewer 1 as well):

Adaptation Measure	Benefit(s)	Challenge(s)
<i>Requirement of minimum snow depth off trail, but not on roads/marked trails, or a lower minimum snow depth on roads/marked trails</i>	Allow OSV use even under extremely low snow conditions, limits resource damage in wildlands; grooming could be utilized to maximize snow depth on road	Preventing users from going off trail under low snow conditions; enforcement, resources required to obtain snow condition information
<i>Ensure high elevation access via a right-of-way</i>	During warmer/drier years, snow conditions are likely to be better (deeper snowpack) at higher elevation	User group conflicts; presence of Wilderness at high elevation; impacts to snow-dependent wildlife species; demand; parking
<i>Removal of blanket opening dates</i>	Prevents opening before SWE _{min} achieved and will limit damage to landscape	Resources required to obtain snow condition information
<i>Identify corridors that collect/retain more snow</i>	During otherwise poor snow conditions, these areas may allow OSV recreation to occur, particularly at lower elevation areas	Need for data on these corridors
<i>Improve durability of trailhead and corridor trails</i>	Allows OSV recreation to occur when minimal snow exists thereby reducing negative impacts in high-use areas	Need for specific quantification of how to improve durability; potential permitting problems
<i>Trade-off: closure of low elevation/sensitive habitat for improved high elevation access</i>	Eliminate chance of damaging landscapes in low elevation regions, increase in the number of days/year that OSV recreation can occur by enhanced high elevation access	Need for collaboration between stakeholders/user groups to identify areas where compromise could occur; may be opposed by those who must travel much further for OSV use
<i>Fee increases to enhance access and offset impacts from higher demand (i.e., restoration projects)</i>	Would provide for additional resources to monitor trailhead conditions, improve parking/bathrooms at trailheads, fund restoration projects and creation of low-snow OSV trails	Fees are generally opposed by members of the public
<i>Additional grooming</i>	Allows additional area for OSV use when conditions are insufficient for off-trail use	Costs for grooming equipment and personnel, many OSV users are primarily interested in off-trail use
<i>Clear designation of non-motorized areas (i.e., signage)</i>	Reduces user conflicts by improving knowledge and awareness of areas open (or closed) to OSV use	Costs related to enforcement as well as installation and upkeep of signage

Table 1: Adaptation strategies to address loss of early winter snowpack for OSV recreation.

Based on reviewer 2's comments, we have added the following references:

Hagenstad, M., Burakowski, E.A., and Hill, R. Economic contributions of winter sports in a changing climate, available at:

<https://scholars.unh.edu/cgi/viewcontent.cgi?article=1190&context=ersc>, (last accessed 25 November 2018), 2018.

McBoyle, G., Scott, D., and Jones, B. Climate change and the future of snowmobiling in non-mountainous regions of Canada, *Manag. Leisur.*, 12 (4), 237–250, <https://doi.org/10.1080/13606710701546868>, 2007.

Perry, E., Manning, R., Xiao, X., Valliere, W., and Reigner, N.: Social climate change: The advancing extirpation of snowmobilers in Vermont, *J. Park Rec. Admin.*, 36, 31-51, <https://dx.doi.org/10.18666/JPra-2018-V36-I2-8307>, 2018.

Scott, D., Dawson, J., and Jones, B. Climate change vulnerability of the U.S. Northeast winter recreation–tourism sector, *Mitig. Adapt. Strat. Glob. Chang.*, 13 (5–6), 577–596, <https://doi.org/10.1007/s11027-007-9136-z>, 2008.

Responses to Editor Brown

Nice paper and a very useful contribution! A few comments for your consideration during the review process:

Dear Dr. Brown,

We appreciate your positive feedback and suggested revisions. Please find below responses and our revisions to address all of your comments.

1. Please make sure to use units of cm for depth throughout the paper to avoid confusion with SWE in mm e.g. p. 3 line 14 depth is given as 300 mm instead of 30 cm.

Thank you for the suggestion. We have edited the text to “30 cm”

2. I suggest you provide a brief description (method, resolution, caveats etc) for the Margulis et al. (2016) SWE reanalysis given this is one of your major data sources.

Good point, we have added the following discussion regarding the SWE reanalysis:

“The SWE reanalysis utilizes a Bayesian data assimilation framework to condition a priori snow model estimates on Landsat fractional snow-covered area images (Margulis et al., 2015). It verifies the posterior estimates against in situ daily snow pillow and monthly snow course data and is shown to compare favourably to previous studies (Margulis et al., 2016). The limitations of the remote sensing approach include lower temporal frequency of Landsat passes (approximately every 16 days) and potential obscuration of the land surface by clouds and vegetation. Challenges with the in situ verification data include representativeness, or the discrepancies resulting from point-based snow pillow versus transect-based snow course SWE measurements, undersampling of forested and sloped terrain, and the bias of sites in the intermediate elevations of the Sierra Nevada (50% of the stations are between 1500 and 2500 m; Margulis et al., 2016).”

The initial submission did include a sentence on the resolution in time and space of the reanalysis (see below in bold); this sentence precedes the newly added discussion on the method above. We did add the additional citation of the previous Margulis work for readers who might be interested in this approach.

“Daily, gridded estimates of SWE at 100 m horizontal resolution were provided by a satellite-era SWE reanalysis product (Margulis et al., 2015, 2016).”

Added reference:

Margulis, S., Giroto, M., Cortés, G., and Durand, M.: A particle batch smoother approach to snow water equivalent estimation, *J. Hydrometeor.*, 16, 1752–1772, doi:<https://doi.org/10.1175/JHM-D-14-0177.1>, 2015.

3. Your paper focusses only on SWE_{min} timing but the duration of SWE \geq SWE_{min} would also be very relevant, and may be more critical in terms of economic impacts. I'm curious as to why you didn't include this as part of the study.

Thank you for bringing this up. We did consider this, but wanted to focus on the early season onset as this is when (anecdotally) the desire to recreate on snow is the highest and when the snow depths are most likely to be at the threshold of insufficient coverage for safe OSV usage to avoid damage to the landscape. In other words, the greatest demand for OSV recreation coincides with the early season (holiday periods, excitement to recreate on snow) and in all but the worst snow years, the ability to recreate is not limited by lack of snow in the spring season. In most years (and especially poor snow years), interest wanes during the late season before lack of snow limits OSV recreation. The best economic impacts will likely be during the early-middle season as people are excited to purchase new equipment and utilize holiday periods for extended vacations. As the snow-covered area retreats uphill during the spring season, most users opt to enjoy higher elevation regions anyways given the favorable weather conditions and greater snow stability. The end of season SWE timing can be related to numerous and often interacting issues (radiative forcing due to dust on snow events, warm spells, lack of winter snowfall, cloudiness); addressing those would substantially extend beyond the scope of this paper. To clarify our focus on the early season, we added the following text to the introduction:

"We focus on the initial timing of sufficient snow depth since the greatest demands for OSV recreation and potential ecological impacts occur between early and middle winter."

4. In your abstract I suggest you talk about delayed onset date of SWE_{min} rather than the date increasing... the later is not intuitive to many people.

Thank you for the suggestion, we have revised the text accordingly to highlight the delayed onset date. Because this is a key message of the paper, we are happy to continue to revise the text to ensure the correct message is clearly conveyed to readers if need be.

*"Since 1985, median SWE_{min} **onset has shifted later** by approximately two weeks. Potential proximal causes of **delayed onset** are investigated;..."*

Best regards, Ross Brown (ed)

Brief Communication: Early season snowpack loss and implications for over-snow vehicle recreation travel planning

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Abstract. Over-snow vehicle recreation contributes to rural economies but requires a minimum snow depth to mitigate negative impacts on the environment. Daily snow water equivalent (SWE) observations from weather stations in the Lake Tahoe region (western USA) and a SWE reanalysis product are used to estimate the onset dates of SWE corresponding to ~30 cm snow depth (SWE_{min}). Since 1985, median SWE_{min} onset has shifted later by approximately two weeks. Potential proximal causes of delayed onset are investigated; rainfall is increasing during October-January with dry days becoming warmer and more frequent. Adaptation strategies to address over-snow vehicle management challenges in recreation travel planning are explored.

1 Introduction

Ongoing and projected climate change is accelerating the warming of the cryosphere throughout Earth's mountain regions (Huss et al., 2017). Reductions in winter season snow, ice, and permafrost cover and volume primarily result from rising air temperatures (Brown and Mote, 2009) and shifts in precipitation from snow to rain (McCabe et al., 2018). These changes have cascading effects from mountains to lowlands with wide-ranging socioeconomic and ecologic impacts (Huss et al., 2017). In mountain regions of the United States, Europe, and Canada, winter recreation and tourism are central to economic activity. The economic benefits from winter recreation are projected to decline as a result of continued climate change that reduces season length and makes access to reliable snow more difficult (McBoyle et al., 2007; Scott et al., 2007; Wobus et al., 2017; Steiger et al., 2017).

Most winter tourism-based climate change impact studies have focused on ski resort-related activity (Steiger et al., 2017), although research has begun to address how other recreation-based components of the winter economy may be affected (McBoyle et al., 2007; Scott et al., 2007; Tercek and Rodman, 2016; Wobus et al., 2017; Hagenstad et al., 2018). Skier visits are positively correlated to snowfall (Hagenstad et al., 2018) and we assume that such a correlation is consistent across winter recreation activities. Due to the dependence on natural snowfall and reduced adaptive capacity compared to the ski community, which can use cost-effective snowmaking to augment the natural snowpack, over-snow vehicle (OSV)

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recreation is highly vulnerable to climate variability and change (McBoyle et al., 2007; Scott et al. 2007). Climate change projections for Canada and the northeastern United States under an aggressive greenhouse gas emissions scenario suggest that by the mid-21st century, OSV season lengths will be reduced by 50-100% in most areas (McBoyle et al., 2007; Scott et al., 2007). A survey of the OSV community in Vermont found that reductions in the length of the winter season with sufficient snow coverage for OSV use were observed by 45% of respondents, with 74% of respondents decreasing their OSV use in response to low snow conditions (Perry et al., 2018). This survey also found that encounters with other recreationalists, including OSV users, detracted from a high-quality recreation experience. The net effects of reduced season length, more congestion, and lower quality experiences result in lower economic benefits from consumer surplus, or the amount a person is willing to pay over the amount actually spent. For OSVs, consumer surplus is estimated to be approximately 61 USD person⁻¹ day⁻¹ (Hagenstad et al., 2018).

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In the Lake Tahoe region of California (Figure 1a), and many other rural mountain areas of the western United States, OSV use is a regionally significant component of winter season recreation. Estimates of annual economic impact from OSV recreation in the United States range between 7 and 26 billion USD (Fassnacht et al., 2018). As a result, OSV recreation has an appreciable economic impact on rural counties within the northern Sierra Nevada, many of which have a greater dependence on tourism-related employment than elsewhere in California (United States Census, 2013).

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The proximity of the Lake Tahoe region to large population centres creates demand for OSV recreation over a limited and ecologically sensitive area. In order to limit potential negative impacts on natural resources (e.g., Keddy et al., 1979) during OSV operation, a minimum snow depth must be present. Minimum snow depth restrictions have been proposed by several forests undergoing winter travel management planning across the Sierra Nevada. This restriction is usually proposed as a minimum depth of 30 cm of un-compacted snow (United States Forest Service (USFS), 2013). Few forests have such a requirement at this time, but several are currently engaging in the process of winter travel management planning in response to a 2015 U.S. Federal Court ruling (Federal Register, 2015). The Eldorado National Forest in northern California (located in the southwestern quadrant of the study area) currently requires a minimum snow depth of approximately 30 cm for off-trail OSV use.

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To our knowledge, no precise value of this minimum depth has been established through comprehensive studies quantifying OSV use and impacts or disturbance. Nonetheless, evidence indicates that OSV use can alter the landscape when a shallow snowpack is present. Keddy et al. (1979) observed that OSV use on very shallow snow (10-20 cm deep) doubled snow density and compressed underlying vegetation. When OSV use began under a deeper snowpack, less difference in snow density and hardness was observed compared to a control (no-OSV use) snowpack (Fassnacht et al., 2018). Further complicating the minimum depth requirement is the dependence of snow depth on the density of the snow, which varies seasonally and as a function of weather conditions that drive snowpack metamorphism processes (Sturm et al., 2010).

Resource managers tasked with day-to-day operations such as opening and closing OSV trailheads over large, diverse areas may not have the resources to visit trailheads to obtain snow depth and density measurements. Instead, they often rely on subjectively-based qualitative assessments of what is deemed sufficient snow. Managers often do not set a specific OSV season, leaving it to user discretion to determine when OSV use is appropriate. This can potentially cause conflict with other uses during the start and end to the winter season and can allow opportunities for inadvertent damage to natural resources due to insufficient snow depth. Here, we estimate the median timing of achieving sufficient snow depths for OSV operation and their trends during the past 34 years using observations of snow water equivalent (SWE) and a reasonable assumption of snow density. We focus on the initial timing of sufficient snow depth since the greatest demands for OSV recreation and potential ecological impacts occur between early and middle winter. The proximal causes of the identified increasingly later onset of achieving a minimum SWE value are further investigated. Because the trend towards later onset is not expected to reverse under continued regional warming, we provide adaptation strategies to cope with diminishing early season snowpack resources that can be included in forest travel management plans. The techniques can be extended to other regions where OSV recreation is an important component of economic activity and where early winter snowpack losses may be impacting seasonal recreation.

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2 Data and Methods

The study area is the Lake Tahoe region of the western United States, a coastal, moderate elevation snow-dominated mountain range (Figure 1a). Daily maximum and minimum temperature, SWE, and precipitation were acquired for 16 SNOTEL stations from the Natural Resource Conservation Service (<http://www.nrcs.gov/snotel>). Daily, gridded estimates of SWE at 100 m horizontal resolution were provided by a satellite-era SWE reanalysis product (Margulis et al., 2015, 2016). The SWE reanalysis utilizes a Bayesian data assimilation framework to condition *a priori* snow model estimates with Landsat fractional snow-covered area images (Margulis et al., 2015). It verifies the posterior estimates against *in situ* daily snow pillow and monthly snow course data, which were found to compare favourably to previous studies (Margulis et al., 2016). The limitations of the remote sensing approach include lower temporal frequency of Landsat passes (approximately every 16 days) and potential obscuration of the land surface by clouds and vegetation, which can reduce usable imagery. Challenges with the *in situ* verification data include representativeness, or the discrepancies resulting from point-based snow pillow versus transect-based snow course SWE measurements, undersampling of forested and sloped terrain, and the bias of sites towards the intermediate elevations of the Sierra Nevada (50% of the stations are between 1500 and 2500 m; Margulis et al., 2016). The period studied encompasses October 1 1984 to March 31 2018 (2016 for the SWE reanalysis), which corresponds to the winter seasons of 1985-2018.

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No accepted value of a minimum snow depth exists for OSV operation. Anecdotal values used by managers vary between 15-45 cm depending on compaction (USFS, 2013), but these do not take into account variability in snow density. To provide

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a conservative and reasonable estimate of sufficient snow depth for what is assumed to be required for non-intrusive OSV operation, we specified 90 mm SWE (hereafter SWE_{min}) as the required [minimum SWE corresponding to a minimum un-compacted depth of 30 cm](#) for approval of OSV use. This value was obtained by equation (1):

$$SWE [mm] = d [mm] * \frac{\rho_s}{\rho_w}, \quad (1)$$

5 where d is depth, ρ_s is the density of the snow and ρ_w is the density of water. We assume that in a coastal snowpack with marginal compaction, ρ_s is typically 0.3 g/cm³ (Sturm et al., 2010). This value appears reasonable to approximate a depth of 30 cm for early season conditions and is consistent with values used by the USFS (2013). Our SWE_{min} value is close to Patterson (2016) and Tercek and Rodman (2017), who both chose 100 mm SWE as a threshold value for winter recreation in the Rocky Mountain National Park and Yellowstone National Park, respectively. We report the median timing of when each
10 SNOTEL station and reanalysis gridpoint achieves SWE_{min} and the annual timing as the median of the 16 SNOTEL stations.

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To explore possible processes controlling the onset date of SWE_{min}, snow fractions (S_f) between October 1 and [January 31](#) were calculated using the empirical hyperbolic tangent function formula developed by Dai (2008) with Sierra Nevada ecoregion parameter values estimated by Rajagopal and Harpold (2016). In contrast to Rajagopal and Harpold (2016), who
15 used maximum temperature to estimate snow fraction, we selected average temperature because it gave a closer approximation to the mean snow level (~1,750 m) based upon independent estimates from observations (Hatchett et al., 2017). Dry days were days [when less than the minimum measureable amount of precipitation \(2.54 mm\)](#), was measured at SNOTEL stations. [Mean minimum temperatures on dry days were calculated over the 16 stations for each year, as minimum temperature influences both snowpack dynamics and ecological processes \(Oyler et al., 2015\).](#)

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20 For all data, linear fits were estimated using a Theil-Sen slope and we report Spearman rank correlations. Statistical significance was tested using a modified Mann-Kendall test that accounts for serial correlation (see Hatchett et al., 2017 and references therein).

3 Results and Discussion

25 3.1 Timing of SWE_{min}

Median timing of achieving SWE_{min} ranged from early November to early January and was [negatively](#) correlated with elevation ($R^2=0.41$, $p<0.01$; Figures 1a and 1b). For the selected SWE_{min}, nine of the 16 stations have significant ($p<0.1$) trends [towards later onset of SWE_{min}](#) (Figure 1b). 13 of the 16 stations demonstrated a significant ($p<0.1$) trend when a value of SWE_{min} between 80 and 100 mm was chosen (Figure 1b). There was no relationship between trend in onset date and elevation, which suggests that regional weather variability is a first-order control on snowpack conditions. At the regional level, the median trend across all stations was [0.6 day year⁻¹](#) ($p<0.001$; Figure 2a). This equates to SWE_{min} being achieved approximately [20 days](#) later between the present day and the beginning of the record, although interannual variability still

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exists (Figure 2a). Results from the SWE reanalysis product are broadly consistent with the station-based analysis, indicating timing of SWE_{min} is largely a function of elevation (Figure 1a). The median trend of the domain (approximately 15 days over the study period or 0.48 day year⁻¹) is close to the SNOTEL-based trend with the largest trends occurring above 2000 m (Figure 1c). The median trend of the domain when only considering statistically significant gridpoints ($p < 0.05$) is approximately 21 days over the study period or 0.67 day year⁻¹ (Figure 1d). The consistency of the results between the independent SNOTEL data and the SWE reanalysis product support the hypothesis that a delayed onset of SWE_{min} is occurring in the Lake Tahoe region. During years with later onset of SWE_{min} (such as 1991, 2012, or 2014; Figure 2a) most OSV users would likely opt out of recreating during much of the season due to potential mechanical damage to their vehicles. However, if sufficient snow existed above a certain elevation, inadvertent damage to the landscape could result when OSVs travel over shallow snowpacks in order to reach destinations with deeper snow. To ensure access to higher elevation areas for OSV use during poor lower elevation snowpack conditions, management plans could identify and implement corridors or rights-of-way that minimize landscape impacts while allowing access (Table 1).

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3.2 Possible drivers of timing changes of SWE_{min}

The increasingly later onset of SWE_{min} (Figures 1c, 1d and 2a) is consistent with an observed increase (0.22 days yr⁻¹, $p < 0.0001$) in the number of dry days during early winter (October-January; Figure 2b). Minimum temperatures on dry days are also increasing (0.098 °C yr⁻¹, $p < 0.0001$). The observed decreasing trend towards reduced early season snow fraction (S_r ; 0.66% year⁻¹, $p < 0.0001$; Figure 2c), implies increasing numbers of warmer dry days and a shift towards increased rainfall are likely contributing to later onset of SWE_{min} . The reduction in precipitation falling as snow is primarily driven by warming temperatures (McCabe et al., 2018), which may be controlled by regional atmospheric and oceanic circulations that favour higher snow level storms (Hatchett et al., 2017). The higher snow levels (and hence lower S_r ; Figures 2a and 2c) reduce snowpack accumulation during precipitation events and can allow for snowpack loss due to turbulent heat fluxes and heat input by rain. The more frequent and warmer dry conditions create additional opportunities during which snowpack loss can occur via radiative and turbulent fluxes. The analysis of SNOTEL temperature is limited by inhomogeneities introduced by temperature-dependent sensor biases leading to over-estimation of trends (Oyler et al., 2015). While over-estimation is greatest at elevations above 3000 m, additional assessments are needed to validate the robustness of the role of regional warming in reducing early season snowpack.

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3.3 Implications for regional winter travel management planning

Due to its moderate elevation, the Lake Tahoe region is susceptible to climate change-induced warming (Walton et al., 2017). Our results provide another metric (later onset date of SWE_{min}) that is consistent with observations of ongoing changes in the Sierra Nevada cryosphere, including rising winter snow levels (Hatchett et al., 2017) and snowpack declines (Mote et al., 2018). Climate model projections for California support the continuation of these trends, with a drying and warming of the fall season (Swain et al., 2018) and an increased frequency of dry days (Polade et al., 2015). Projected snow-

covered area declines are estimated to be the greatest during the beginning and end of the snow season (Walton et al., 2017). As a result, forest travel management plans should include adaptation strategies (Table 1) that can help managers and recreators cope with the increasing chances of a later opening date for OSV use but also provide flexibility in the event of an early, snowier-than-normal start to the winter. Flexible strategies developed by diverse stakeholder groups through public
5 discourse are encouraged, as the continued reduction of area available for motorized and non-motorized users will lead to increasingly frequent use conflicts if not addressed. [More frequent use conflicts, particularly at trailheads or in congested areas, may lead to decreases in high quality experiences \(Perry et al., 2018\) and contribute to declines in OSV or other forms of recreational usage that reduce positive economic impacts \(Hagenstad et al., 2018\).](#)

10 Developing a suite of adaptive management strategies is essential if land managers are to meet legal obligations to manage OSV recreation in a manner that minimizes impacts to natural resources, wildlife, and conflict between uses (Federal Register, 2015). As snow seasons become more variable and less dependable overall, it will be necessary to utilize several complementary management strategies if land managers want to continue to provide high quality opportunities for all forms of winter recreation. For example, setting season dates that encompass the general times of the year when OSV use is
15 appropriate, paired with a minimum SWE (or snow depth, depending on data availability), and allowing for OSV use on certain routes with a lower snowpack to provide access to higher-elevation areas may help to extend the OSV season. Likewise, it may be necessary to relocate winter trailheads to higher elevations as areas with consistent snowpack become shifted upwards in elevation. As the strategies in Table 1 show, however, there are tradeoffs with any strategy and OSV recreation is not the sole use of public lands in winter. Managing OSV recreation must occur in concert with managing other
20 forms of winter recreation and protecting wildlife and natural resources (Federal Register, 2015). There is no one-size-fits-all strategy that will work for every national forest. It is essential that land managers work with public and agency stakeholders to craft locally-appropriate and equitable adaptation measures, taking into account potential impacts to and conflicts with other recreation uses, wildlife, natural resources, and other land management goals. It may also be necessary to accept that in the future, OSV and other forms of winter recreation (e.g., backcountry skiing and snowshoeing) will not be supported
25 across all of the areas where it historically occurred. Winter travel planning is thus an excellent opportunity for land managers, particularly the United States Forest Service, to proactively address OSV management and consider how climate change is affecting OSV activities on national forests in order to maintain the opportunity for this form of winter recreation and its positive economic impact.

4 Concluding Remarks

30 Using snow water equivalent and a density assumption as a proxy for depth, we have presented a pilot study aimed at a better understanding of when the Lake Tahoe region attains sufficient snowpack depth to allow safe over-snow vehicle (OSV) usage. A station-based analysis of 16 remote weather stations in the region and a spatially distributed SWE reanalysis product indicated that the median timing of achieving sufficient depth varies with elevation from early November to late

December. The median timing of sufficient depth has increased by approximately two weeks during the past three decades with significant changes on the order of three weeks. The proximal causes for this shift towards later onset appear to be due to both a shift from snowfall to rainfall and increases in dry day frequency [and temperature](#) during the early winter season. However, further research is needed to estimate specific contributions from each cause and constrain the role of surface-albedo [and/or humidity](#), feedbacks [at various elevations throughout the region](#) (Patterson, 2016; Walton et al., 2017).

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A primary limitation of our study is the lack of an established snow depth to avoid negative impacts of OSV operation as a function of land cover type and snow density. The work of Fassnacht et al. (2018) represents an important advance towards achieving this value, which can be used to guide winter travel management planning, although the United States Forest Service has begun to recommend a depth (USFS, 2013). Additional studies on achieving regionally-relevant minimum snow depths and better quantification of economic [and ecological](#) impacts from reduced snow cover area and duration will guide more robust travel management plans in national forests. They also can help prioritize pragmatic adaptation strategies for specific regions. Given the economic impact of OSV recreation and [likely reduction in land available for OSV or other human-powered recreation uses](#) (McBoyle et al. 2007; Scott et al. 2007; Tercek and Rodman, 2016; Hagenstad et al., 2018), combined with increasing numbers of winter recreation participants (Fassnacht et al., 2018), achieving winter travel management plans that are adaptive to varying snowpack conditions while minimizing user conflicts will be a key step towards sustainable mountain recreation.

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Code Availability

The MATLAB code used for analysis is available upon request.

20 Data Availability

All data is publically available and has been properly cited in the text.

Competing Interests

HGE is employed by the Winter Wildlands Alliance (WWA). BJH has consulted for the WWA.

Author Contributions

25 BJH and HGE conceived and designed the study, interpreted the results, and wrote the paper. BJH acquired data and performed the analysis.

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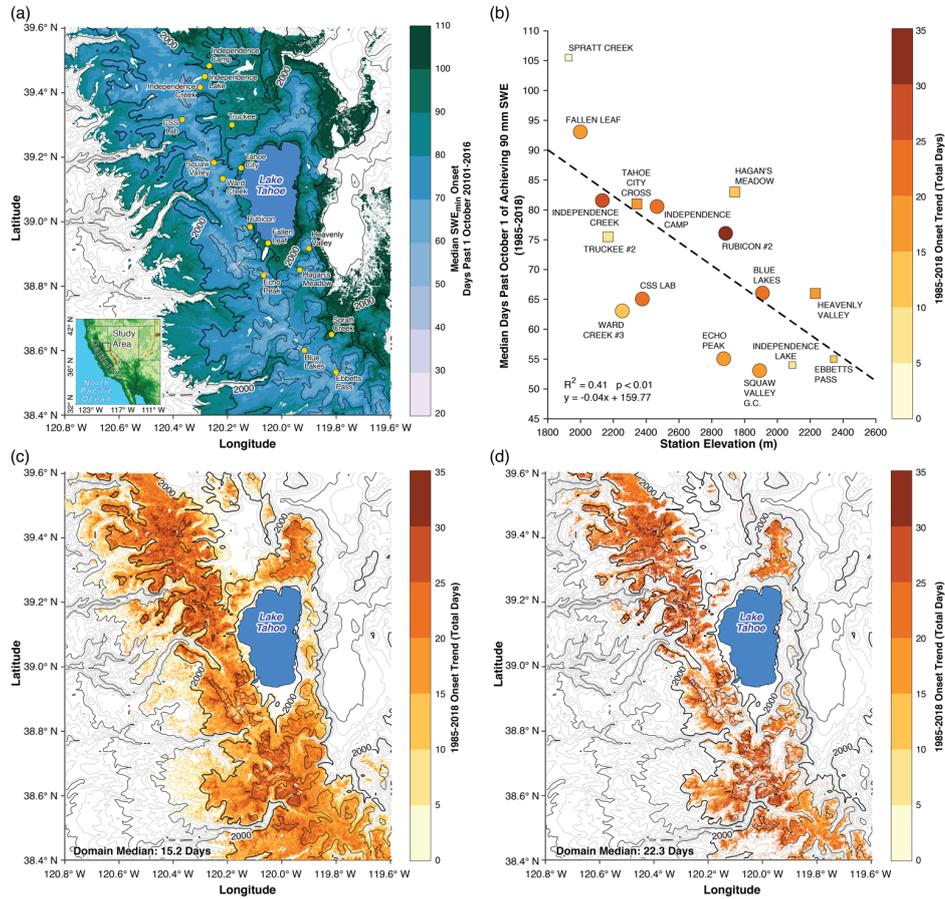
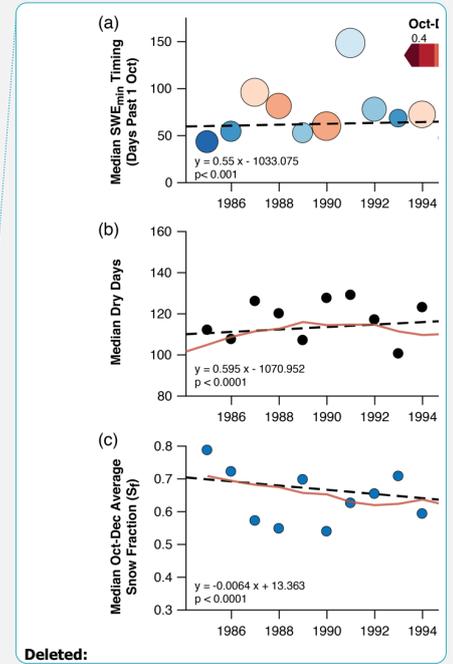
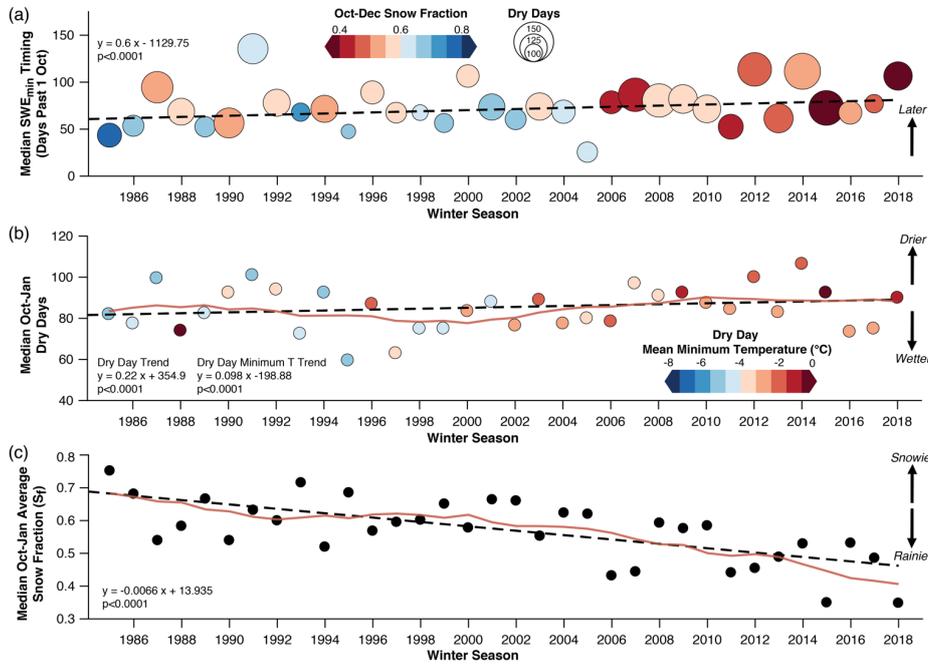


Figure 1: (a) Median 2001-2016 SWE_{min} (days past October 1) based on the SWE reanalysis product (Margulis et al., 2016) with SNOTEL stations shown as gold dots. The inset map shows the study area. (b) Timing of median SWE_{min} (days past October 1) by SNOTEL station elevation. Dots are colored by the trend (annual rate of snow depth timing change times 34 years). Dashed black line denotes the Theil-Sen linear fit. Large circles indicate significant trends ($p < 0.1$) for SWE_{min}, while large squares indicate a significant ($p < 0.1$) trend in SWE_{min} was identified for a value of SWE_{min} between 80 and 100 mm. Small squares indicate no significant trend ($p < 0.1$) in SWE_{min} onset date. (c) Spatially distributed Theil-Sen linear trends in SWE_{min} over the period 1985-2016, calculated as the annual rate times the 32-year period. (d) As in (c) but showing only gridpoints with a statistically significant ($p < 0.05$) trend in onset date. In panels a, c, and d, the thin (thick) grey contour lines indicate elevations every 125 m (500 m) while the thick black line indicates the 2000 m elevation contour (labeled). Gridpoints with more than three missing years were excluded from the analysis.



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Figure 2: (a) Annual median timing of SWE_{min} (days past October 1) with dots colored by median October-January average snow fraction and sized according to the median number of October-January dry days. (b) Median early season (1 October-31 January) dry days with dots colored by average October-January minimum temperature. (c) As in (b) but for median snow fraction averaged over the 16 stations. In all figures, the dashed lines demonstrate Theil-Sen linear fits and red lines (b and c) show the five-year running mean.

5

Adaptation Measure	Benefit(s)	Challenge(s)
<i>Requirement of minimum snow depth off trail, but not on roads/marked trails, or a lower minimum snow depth on roads/marked trails</i>	Allow OSV use even under extremely low snow conditions, <u>limits resource damage in wildlands</u> ; grooming could be utilized to maximize snow depth on road	Preventing users from going off trail under low snow conditions; <u>enforcement resources required to obtain snow condition information</u>
<i>Ensure high elevation access via a right-of-way</i>	During warmer/drier years, snow conditions are likely to be better (deeper snowpack) at higher elevation	User group conflicts; presence of Wilderness at high elevation; impacts to snow-dependent wildlife species; demand; parking
<i>Removal of blanket opening dates</i>	Prevents opening before SWE _{min} achieved and will limit damage to landscape	Resources required to obtain snow condition information
<i>Identify corridors that collect/retain more snow</i>	During otherwise poor snow conditions, these areas may allow OSV recreation to occur, particularly at lower elevation areas	Need for data on these corridors
<i>Improve durability of trailhead and corridor trails</i>	Allows OSV recreation to occur when minimal snow exists thereby reducing negative impacts in high-use areas	Need for specific quantification of how to improve durability; potential permitting problems
<i>Trade-off: closure of low elevation/sensitive habitat for improved high elevation access</i>	Eliminate chance of damaging landscapes in low elevation regions, increase in the number of days/year that OSV recreation can occur by enhanced high elevation access	Need for collaboration between stakeholders/user groups to identify areas where compromise could occur; may be opposed by those who must travel much further for OSV use
<i>Fee increases to enhance access and offset impacts from higher demand (i.e., restoration projects)</i>	Would provide for additional resources to monitor trailhead conditions, improve parking/bathrooms at trailheads, fund restoration projects and creation of low-snow OSV trails	Fees are generally opposed by members of the public
<i>Additional grooming</i>	Allows additional area for OSV use when conditions are insufficient for off-trail use	Costs for grooming equipment and personnel; many OSV users are primarily interested in off-trail use
<i>Clear designation of non-motorized areas (i.e., signage)</i>	Reduces user conflicts by improving knowledge and awareness of areas open (or closed) to OSV use	Costs related to enforcement as well as installation and upkeep of signage

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Table 2: Adaptation strategies to address loss of early winter snowpack for OSV recreation.