Dear Dr. Viviroli,
Below please find a summary list of changes made to the revised manuscript “*Technical note: Precipitation phase partitioning at landscape-to-regional scales”* by Lynn et al. and submitted to HESS. We addressed all major, minor, and specific reviewer comments (detailed replies are attached) and are pleased to submit a revised manuscript. A few comments requested additional analyses or details that exceed the scope of a technical note intending to highlight a new method, but we included some discussion about these details in the revised manuscript in an effort to motivate continued, and more detailed, research on this topic.

1. Performed an additional analysis where we compared the original method with the older NCEP/NCAR reanalysis to a modern reanalysis product (ERA5). This comparison was a major comment request by both reviewers. Two supplementary figures were added to support our findings of this analysis.
2. We added a panel to Fig. 1 to show another example water year (an average year).
3. We added a panel to Fig. 5 (and Supplementary Fig. 2) to show the Fall trends in the western United States.
4. The panels on Fig. 4 were reversed to match the text.
5. Substantial revisions to the text were made throughout to clarify a number of points raised by reviewers, particularly with respect to the details of the methodology.
6. Where requested, detail was added to improve the description of terminology (e.g., definition of the flood pool).
7. A conceptual diagram was produced and added to the main text with the goal to improve the description of the methodology.
8. Figure captions were corrected and made more descriptive where applicable.
9. Additional references were added where applicable, and we corrected several original references that were initially omitted or incorrect.
10. Addressed all specific comments pertaining to grammar and style.

If you have any additional comments or concerns regarding the manuscript, please do not hesitate to contact me.

Sincerely,
Benjamin Hatchett

Author Responses to Reviewer 1 (Alan Rhoades) for "Technical note: Precipitation phase partitioning at landscape-to-regional scales" by Lynn et al.

Reviewer comments are provided in normal text.
Responses are given in blue
*Revised text given in italics (**bold for emphasis**)*

Summary Lynn et al. in "Technical note: Precipitation phase partitioning at landscape-to-regional scales" unveil a new rain-snow partitioning algorithm, the North American Freezing Level Tracker (NAFLT), and assess trends in California (and western US-wide) snowfall percentages in Winter (Dec-Feb), Spring (Mar-Apr), and Cool Season (Oct-Apr) over the last~70 years. To build the NAFLT, the authors utilize the NCEP/NCAR reanalysis (2.5-degree resolution) along with the PRISM (4km) reanalysis products. The authors find a more notable decline in rain-snow partitioning in spring (-2/decade to -4%/decade) than winter (-1%/decade to -2%/decade). Overall, I think the paper by Lynn et al. is well within the scope of the Journal of Hydrology and Earth System Sciences and a valuable contribution to the scientific community. The figures and results are well-posed and, importantly, the findings have both scientific and societal impact as rain-snow partitioning in mountains (particularly a regular, "healthy" seasonal snowfall total) is a critical assumption in water supply management of western US states.

Most of my comments and revision suggestions are regarding the need to fine-tune the narrative of the manuscript and further discuss/evaluate methodological uncertainties. I would suggest that the editor assign minor revisions to this manuscript.

We appreciate the positive comments and constructive comments to improve upon the manuscript provided by Dr. Rhoades. Each comment is addressed below.

Review Comments and Suggested Revisions:

Page 1 Line 11 – Change to, "...into rain and snow, particularly snow as it maximizes available water in spring-to-summer."

Thank you for the suggestion. We edited the text following the suggestion, but went for a broader 'warm season' as reservoir deliveries occur from spring through fall:
", particularly snow as it maximizes available water for warm season use"

Line 21 – You might want to cite Huss et al., 2017 here...Huss, M., Bookhagen, B.,Huggel, C., Jacobsen, D., Bradley, R., Clague, J., Vuille, M., Buytaert, W., Cayan,D., Greenwood, G., Mark, B., Milner, A., Weingartner, R. and Winder, M. (2017), Toward mountains without permanent snow and ice. Earth's Future, 5: 418-435.doi:10.1002/2016EF000514

Excellent suggestion, reference has been added.

Line 23-24 – Change to, "...and, in particular, frozen (snow) components was a foundational assumption of climate stationarity in the development of water management infrastructure and practices..."

Thank you for the suggestion to improve this sentence. We made a slight change to the suggested revision to account for the phase partitioning being an assumption as well as the concept of climate stationarity in water management. In other words, precipitation comes as rain and (mostly) snow, and we assume this will not change, so this guides our management strategies.

New text:
"The partitioning of precipitation into liquid (rain) and, ***in particular***, frozen (snow) components ***along with climatic stationarity were foundational assumptions in the development of*** water management infrastructure ***and practices*** in…"

Line 35 – Change to, "...Some examples include an upslope shift in winter snow levels..."

Change made, thank you for the suggested change in phrasing:
"…an ***upslope shift*** in…"

Line 37 – What do you mean by "decreased snowpack water storage efficiency"? Does this have to do with cold content decreases and snow ripening occurring more frequently throughout the snow accumulation season? Please clarify.

Thanks for pointing out our initially confusing text. Your interpretation is valid but not our original intent. We added a brief bit of text better describing the metric used by Das et al. (2009). The ratio of SWE to P declining implies less precipitation is being stored in the snowpack by early spring (e.g., April 1 SWE) and thus the snowpack as a reservoir is less efficient.

New text:
"decreased snowpack water storage efficiency ***as measured by ratios of cool season snow water equivalent to precipitation***"

Page 2 Line 13 – Might want to point to a study (or several) that discuss the dataset/metric inadequacies that water managers/decision makers face when using climate information. For example...Jagannathan, K., A.D. Jones, and I. Ray, 0: The making of a metric: Co-producing decision-relevant climate science. Bull. Amer. Meteor. Soc., 0, https://doi.org/10.1175/BAMS-D-19-0296.1

Great suggestion to include this concept. We added a sentence highlighting this issue:
"These are among many inadequacies regarding datasets or climate metrics faced by water managers (e.g., Jagannathan et al., 2020)."

Line 19 – Change to, "...scales and, therefore, could be an informative diagnostic for both model development and water resource management in snow dependent regions..."

Good suggestion to add impact to model development and change 'important' to 'informative'. We made the changes (though we changed the order on model development since the paper is focused on management):
"We suggest that this approach is scalable to regional-to-continental scales and therefore could be ***an informative diagnostic for water resources management and model development in other snowmelt dependent regions.***"

Line 31 – Change to, "...higher with decreasing latitude where median annual precipitation greatest in the Northern Sierra Nevada..."

Thanks for requesting clarity regarding where the wettest regions are in a latitudinal sense. We re-wrote this sentence as two:
"The elevation distribution of the analysis zones shifts higher with decreasing latitude**.** ***Median*** annual precipitation is the greatest in the ***higher latitude*** Northern Sierra Nevada and Southern Cascade regions."

Figure 1 caption – Change to, "Estimated historical (1950-1969) percentages of..." In my opinion, the dataset resolution part is TMI in the figure and should just be stated in the methods.

We removed the horizontal resolution part from the caption.
New text:
"*Estimated historical (1950-1969) percentages…*"

Page 3 Line 3 – Just to clarify, DWR uses the proprietary 800m PRISM product, but did not give you access for this analysis?
Yes, DWR uses the 800 m PRISM, and we did initially consider doing the analysis at 800 m. However after discussions, we felt that doing the analysis at the 4 km scale was reasonable from both a physical perspective (see below) but more so since many agencies or groups may not have the resources to pay for the 800 m PRISM products and wanted to show that the method works for the 4 km product.

It would be interesting to know how much of a different answer one would get for rain-snow partitioning if you were to use the 800m vs 4km (i.e., 5x coarsening) PRISM product (particularly in the Southern Cascades)? Similarly, performing a sensitivity analysis of another 5x coarsening (~20km) of the 4km PRISM product could be informative for climate modelers too.
In our preliminary analyses, the results did not appear sensitive to the 800 m vs. 4 km resolution. This is likely because potential differences at finer spatial scales were smoothed out by the elevation-bin size. Spatial differences between the two PRISM products resulting from the

interpolation scheme may also not be physical, since no additional data at finer scales is being included in PRISM (remembering that mountain observations are very sparse to begin with). Further, these spatial differences likely also are canceled out when aggregating to the watershed scales that matter most for water management. We would expect fine scale differences to appear when doing site-specific comparisons (and not aggregating to watershed scales), especially in areas of very complex terrain or large elevation gradients. However, challenges would emerge to test the robustness of these differences in areas where no observations are nearby to ensure that they are physical and not a product of PRISM. This is a limitation with all gridded data products.

We added a note in the limitations section that differences between the PRISM products likely cancel out at the scales of interest here but that site-specific comparisons should show differences:

"Differences between PRISM products at the 4 km and 800 m scales likely cancel out both from the elevation binning procedure and from the aggregation of data to the watershed scales used by water management. However, we would expect site-specific comparisons to yield differences."

The coarsening experiment is a good suggestion, and worth investigating further in subsequent work. We added a sentence to the concluding remarks to highlight this:

"The main advantage of the described approach is that the NAFLT can be periodically updated as higher resolution gridded data products become available (e.g., TerraClimate; Abatzoglou et al., 2018). ***It could also be expanded in scope to evaluate global rain-snow partitioning in global or regional climate models by aggregating to the spatial resolutions used in these models."***

Given that these are diagnostic estimates of rain-snow partitioning, could the authors use the Sierra Nevada Snow Reanalysis (SNSR) from Margulis' group at UCLA - https://margulis-group.github.io/data/ - to explore how different of answer one might get using the author's method vs other methods? This could also include (at least qualitatively) a comparison between more physics-based rain-snow partitioning estimates/trends in the literature versus NAFLT.

This is a great suggestion, and something we are actively working on. One limitation is the robustness of the SNSR at elevations below 1500 m: "The reanalysis dataset presented herein covers 20 watersheds and is applied to elevations above 1500 m, which represents the nominal snow line (Bales et al. 2006; Guan et al. 2013)" (quoted from Margulis et al. 2016). While beyond the scope of this study, as this is intended as a technical note to describe a general methodology with the hope/intent to inspire work exactly as the reviewer noted, we are also exploring other SWE reanalyses and remote sensing products. Our approach does not technically resolve SWE, but rather snowfall liquid water equivalent. Hence comparisons with SWE products would be flawed by not considering ablation processes. That all said, we added a line to the concluding remarks section describing how snow reanalyses offer a complementary approach to other methods of analyzing changes in mountain snowpack:

Added sentence:

"These products provide complementary information to high resolution snow reanalyses that incorporate satellite and/or in situ data (e.g., Margulis et al., 2016; Zeng et al. 2018)."

Added citations:

Margulis, S. A., Cortés, G., Girotto, M., and Durand, M.: A Landsat-era Sierra Nevada snow reanalysis (1985–2015), J. Hydrometeor, 17(4), 1203-1221, 2016.

Zeng, X., Broxton, P., and Dawson, N.: Snowpack change from 1982 to 2016 over conterminous United States. Geophys. Res. Lett., 45, 12,940– 12,947. https://doi.org/10.1029/2018GL079621, 2018.

Line 20-25 – Might be helpful to cite Jennings et al., 2018 when discussing the "hydrometeor energy balance theory" of snowflakes persisting in above freezing temperatures. Jennings, K.S., Winchell, T.S., Livneh, B. et al. Spatial variation of the rain–snow temperature threshold across the Northern Hemisphere. Nat Commun 9, 1148 (2018) https://doi.org/10.1038/s41467-018-03629-7 As you expand NAFLT for use beyond the Sierra Nevada (i.e., a more maritime mountain), it might be important to build in (or at least assess the sensitivity of adding in) specific humidity/relative humidity into the rain-snow partitioning algorithm.

This is a great suggestion, we added the citation and also added a line to the limitations section about including RH or wet bulb temperature (among other variables) as potential ways to further improve the method:

"Further, comparisons with approaches that include relative humidity or wet bulb temperatures are recommended to further improve the methodology, as these have been shown to improve the quality of rain-snow partitioning (Harpold et al., 2017, Wang et al., 2019)."

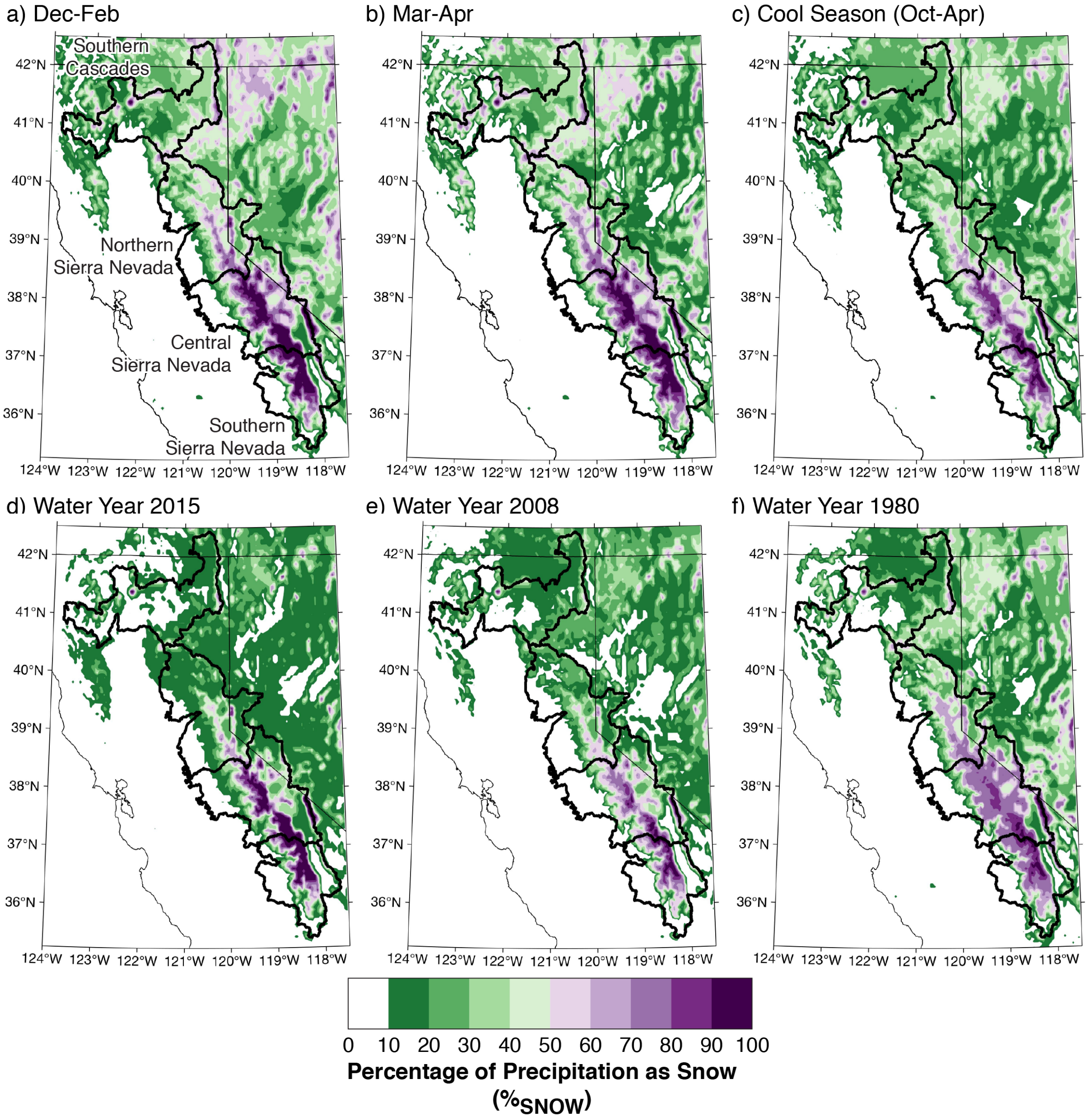
Added citations:

Harpold, A. A., Rajagopal, S., Crews, J. B., Winchell, T., and Schumer, R.: Relative humidity has uneven effects on shifts from snow to rain over the western US, Geophys. Res. Lett., 44(19), 9742-9750, doi:10.1002/2017GL075046, 2017.

Wang, Y. -H., Broxton, P., Fang, Y., Behrangi, A., Barlage, M., Zeng, X., and Niu, G. -Y.: A wet-bulb temperature-based rain-snow partitioning scheme improves snowpack prediction over the drier Western United States, Geophys. Res. Lett., 46, 13825– 13835, https://doi.org/10.1029/2019GL085722, 2019.

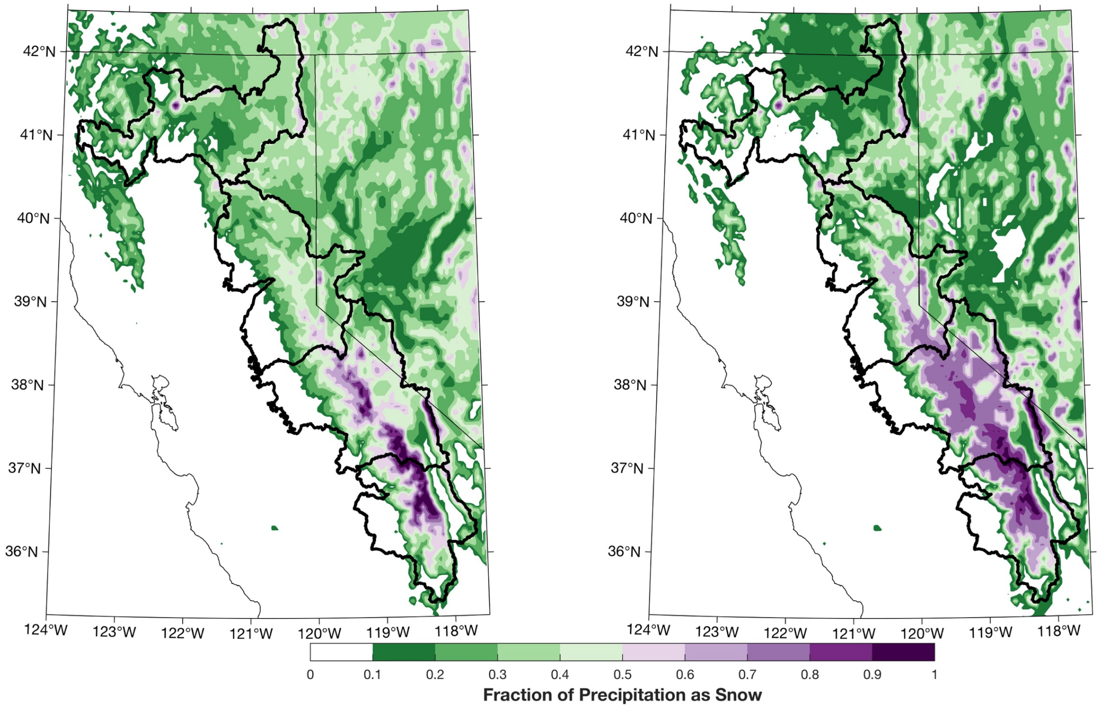
Page 4 Line 1-2, Figure 1 – It might be useful to also plot a median snow water year(e.g., 2007-2008)? Also, why not use 1982-1983 for the max snowpack year (DWR's max SWE year - http://cdec.water.ca.gov/snowapp/swcchart.action)?

We see the reviewers point, and have changed the lower panels of Figure 1 to better show examples of interannual variability. We used the suggestion for 2008 as the median year (b) and have a low $\%_{\mathrm{SNOW}}$ year (2015; panel (a)) and a high $\%_{\mathrm{SNOW}}$ year (1980; panel (c)). Our new Figure 1 is as follows:


a) Dec-Feb
b) Mar-Apr
c) Cool Season (Oct-Apr)
d) Water Year 2015
e) Water Year 2008
f) Water Year 1980

"Figure 1: Estimated historical (1950-1969) percentages of precipitation as snow for (a) winter (Dec-Feb), (b) spring (Mar-Apr), and (c) for the full cool season (Oct-Apr). Examples of $\%_{\mathrm{SNOW}}$ averaged over the cool season (October-April) of water years (d) 2015, ***(e) 2008***, and (f) 1980. Thick black contours denote California Department of Water Resources analysis zones."

To address the reviewer’s point, we did generate a plot of WY1983. However, it appears less snowy than 1980. This is likely a result of the signal of several warmer-than-normal storms during 1983 (recall there were some substantial flood events) and provides an example showing how $\%_{\mathrm{SNOW}}$ and SWE are not always directly linked. If one is measuring in terms of SWE, additional water added to the snowpack through rain (and under the assumption that this water was stored in the snowpack) could result in a bigger SWE year than a year that had all snow but less overall precipitation.



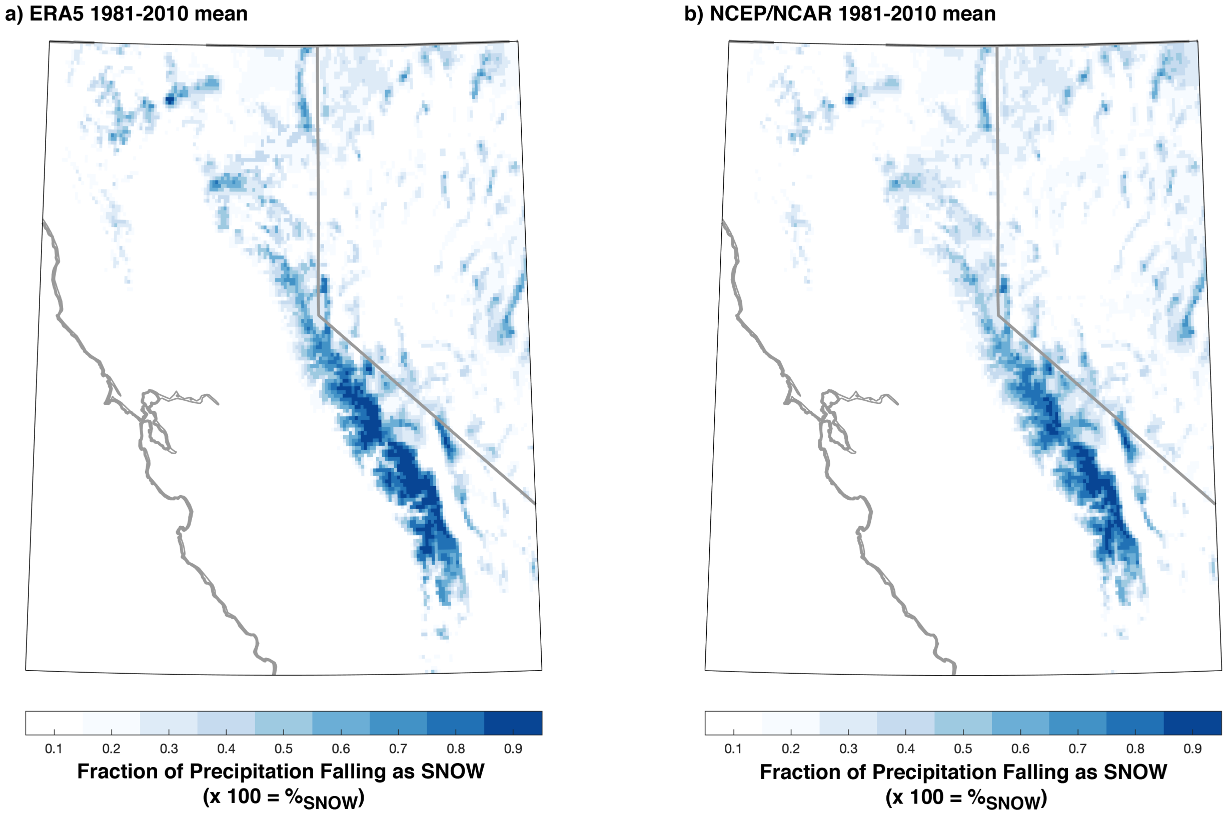
Fraction of precipitation as snow during water year 1983 (left) versus water year 1980 (right).

Line 4-8 - This is beyond the scope of this current study (and seems to be discussed more in Hatchet et al., 2017 and in the “Primary Limitations” section of this article), but given that NCEP/NCAR reanalysis is fairly coarse (2.5-degree resolution) do the authors have a sense of the magnitude of uncertainty baked into rain-snow partitioning estimates in the NAFLT (i.e., confidence intervals)? For example, the freezing isotherm may be influenced by aggregation of sharp gradients in topography in NCEP/NCAR (i.e., resolution dependence) and the precipitation estimates may lack extreme precipitation events (i.e., statistical relationship assumptions in PRISM and/or coarse grid averaging in NCEP/NCAR) and/or may be lower bound estimates of orographic enhancement of storms. The use of the new ECMWF generated ERA5 reanalysis product (i.e., global, 1950-present, hourly/monthly,~30km, up to~137 vertical levels) might be a path forward to explore/address any uncertainties in NAFLT too (https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation). At the very least, I think a brief discussion in the manuscript on the potential sources (or even magnitudes and confidence intervals) of uncertainty within the NAFLT rain-snow estimates might be useful and informative to users.

These are excellent points and similar concerns with NCEP/NCAR were also brought up by the other reviewer. Following both reviewer's suggestions, we repeated the analysis with ERA-5 for the four aggregated DWR watersheds to provide some estimates of how well NCEP/NCAR performs. We found encouraging results (figure below, added as a supplementary figure), with ERA-5 and NCEP/NCAR being very well-correlated over the overlapping time period (correlations exceeding 0.9). ERA-5 was a bit colder (more $\%_{SNOW}$), which is likely related to a number of improvements in the ERA-5 model compared to NCEP/NCAR (data assimilation, spatial/vertical resolution, terrain, physical process representation). We added a paragraph to the limitations section highlighting our use of an older model (which was state-of-the-art at the time the NAFLT was developed in ~2008) and showing that it still performs relatively well. All in all, this comparison suggests that the method we are showing is valid and can be a way to evaluate precipitation partitioning in models.

"The NCEP/NCAR reanalysis, which the NAFLT uses to identify freezing levels and partition precipitation, is an older generation reanalyses product. Recent advances in atmospheric reanalyses such as ERA-5 (Hersbach et al., 2020) provide advances in data assimilation procedures, have finer spatiotemporal resolution, and provide 0°C heights as standard products. A comparison of the NCEP/NCAR approach to ERA-5 during 1979-2018 showed strong similarity in the spatial distribution of $\%_{SNOW}$ *(Supplementary Figure 3) and high interannual correlations* ($0.9<R<0.99$)*, with slightly higher* $\%_{SNOW}$ *in ERA-5 (Supplementary Figure 4). The method for partitioning precipitation described herein shows promise using the older NCEP/NCAR reanalysis, but it flexible enough to incorporate advances in reanalyses products as well as climate model projections."*

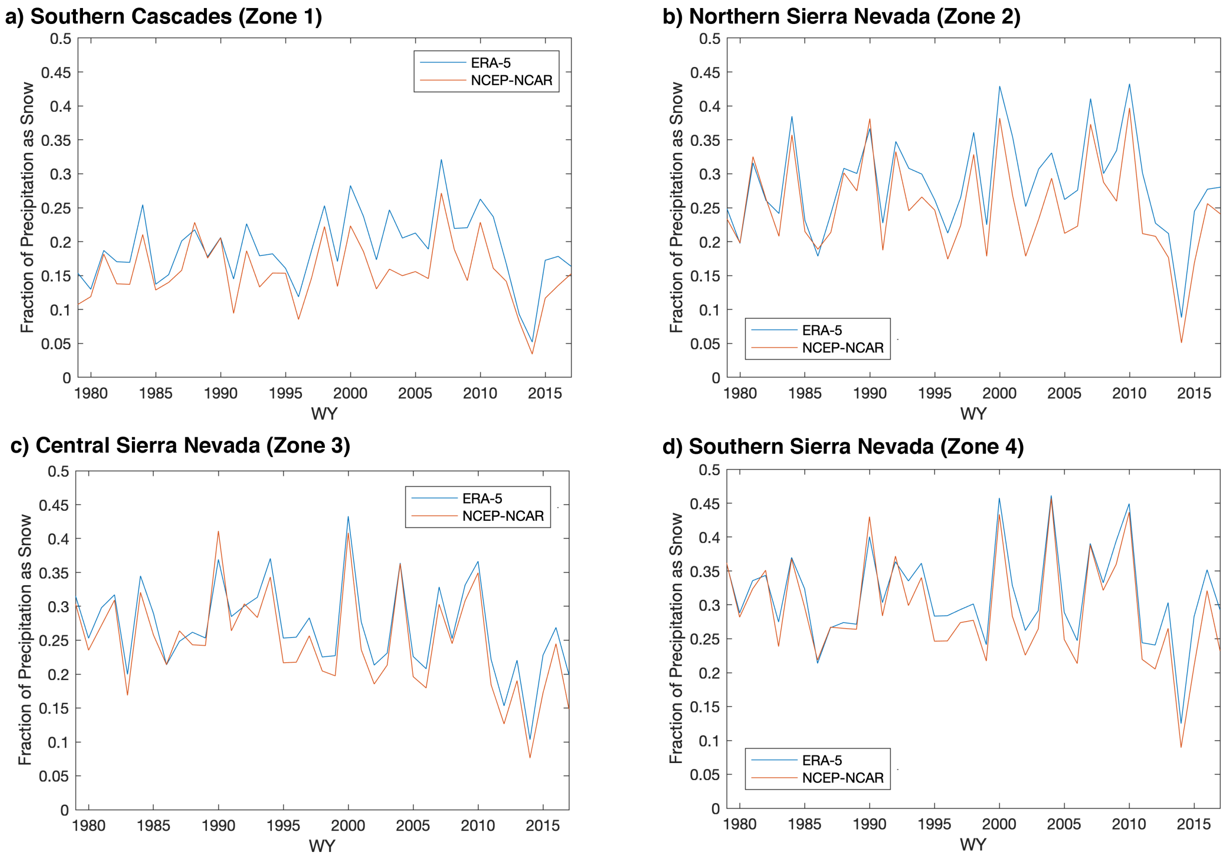
New Supplementary Figures have been added to the revised manuscript:



a) ERA5 1981-2010 mean

b) NCEP/NCAR 1981-2010 mean

Supplementary Figure 3: Comparison of 1981-2010 mean water year fraction of precipitation falling as snow (multiply by 100 to yield $\%_{SNOW}$) for northern California and western Nevada produced using ERA-5 (left) with NCEP-NCAR (right).



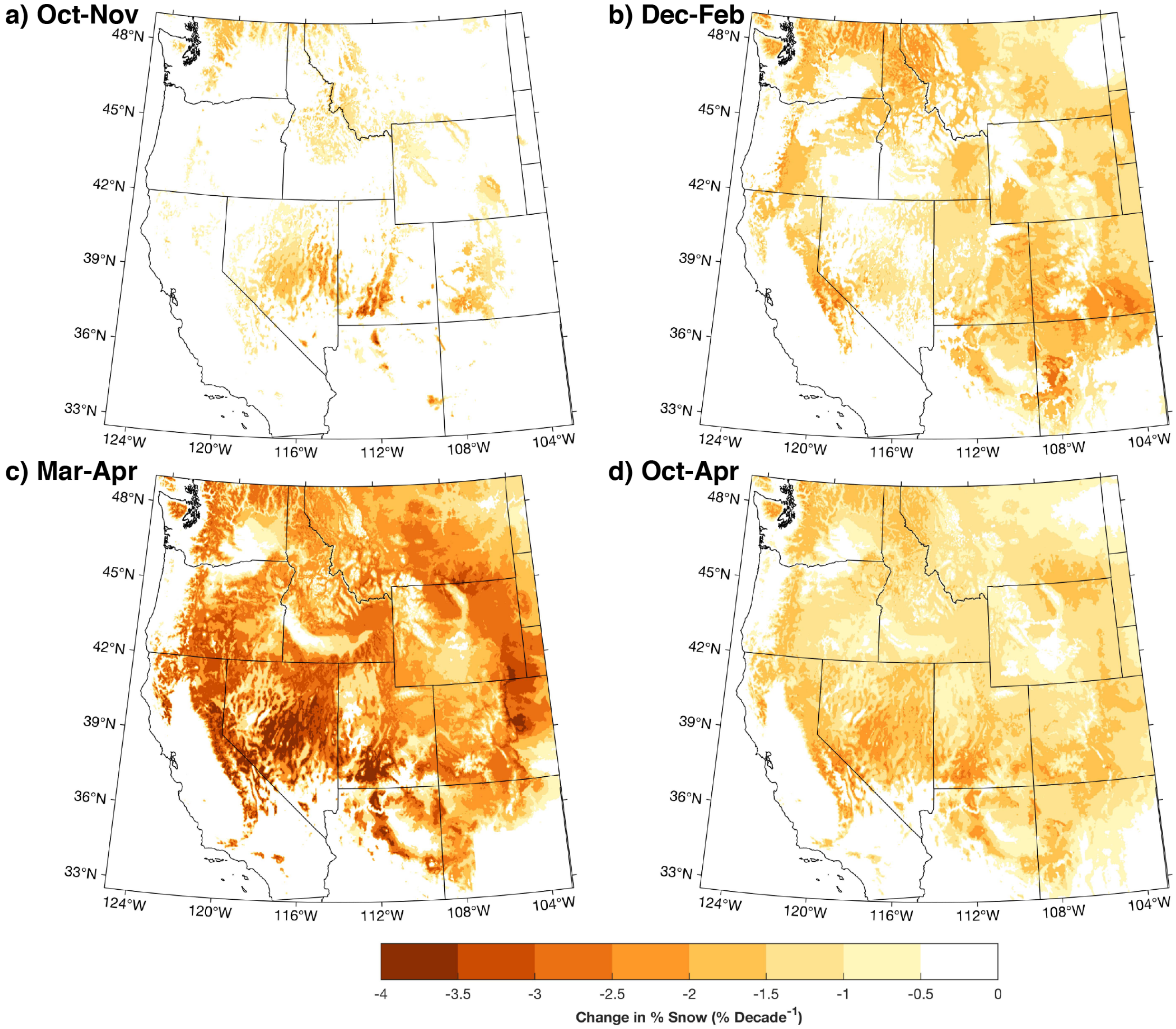
Supplementary Figure 4: Comparison of fraction of precipitation falling as snow for ERA-5 (blue line) and NCEP-NCAR (red line) for the period 1979-2018 for the four DWR analysis zones, ordered clockwise from upper left: Southern Cascades, Northern Sierra Nevada, Central Sierra Nevada, and Southern Sierra Nevada.

Figure 2 – Is there any value in looking at trends in Oct-Nov too? I am curious if there is an asymmetric or symmetric response in rain-snow partitioning between the “shoulder” months of the Cool Season.

Fall trends were not nearly as strong in California as other seasons, and west-wide there were only a few locations of stronger signals (leeside of the WA Cascades, central Great Basin, southern Utah, higher elevations in the Rockies) so initially we omitted these results.

Looking more closely, these trends are interesting since they do affect the highest elevations (CO Rockies, Wind Rivers, NW Montana ranges). There are also interesting signals in the eastern Great Basin, southern Utah, northern Arizona, and the northern Cascades of Washington. We will leave the main manuscript figures showing California as they are, but now include fall in the west-wide Figure 5:

New Figure 5:



Line 21-30 – Is there any added value in evaluating sliding (rather than fixed) decadal trend analysis? Or, more specifically (may be a follow-up study), isolate trends based on certain climate variability indices? For example, the ENSO Longitude Index (ELI)...Patricola, C.M., O'Brien, J.P., Risser, M.D. et al. Maximizing ENSO as a source of western US hydroclimate predictability. Clim Dyn 54, 351–372 (2020). https://doi.org/10.1007/s00382-019-05004-8
This is a great follow-up study suggestion, and the exact direct we'd like to go (in addition to improving the calculation of the metric). For example, Abatzoglou 2011 did find that trends in the PNA had contributed to a hastening of freezing level increases and declines in precipitation as snow; additional exploration of how modes of variability influence freezing levels would certainly add value.

While beyond the scope of this methods paper to evaluate modes of variability, we have added a note that this would be a fruitful area of further research:

"Further examination of how freezing levels are influenced by large scale modes of climate variability are also recommended. For example, Abatzoglou (2011) found trends in the Pacific-

North American pattern contributed to increases in freezing levels and declines in precipitation falling as snow. Evaluating freezing level and precipitation phase relationships to isolated modes of climate variability may provide useful guidance for hydroclimate predictability at lead times relevant for water management (e.g., Patricola et al. 2020).”

Line 21-30 – Figure 3 – Do the authors want to discuss potential physical mechanisms regarding the much larger Spring declines in rain-snow partitioning on the leeside (i.e.,-4%/decade) compared with windward (i.e., -1-2%\decade) of the Sierra Nevada, particularly in the northern-to-central HUC watersheds? Topography is mentioned but given that there is an asymmetric response between even abutting windward and leeward HUC watersheds (and this is more seen in the Spring rather than Winter), are there potential physical mechanisms that should be discussed? For example, are these changes due to less Spring storms overall or are there the same number of Spring storms, but they are warmer and thus more readily produce rain? Another difference could be that the leeward HUC regions mix trends in the Sierra Nevada with the White Mountains and mask storm-type changes in rain-snow partitioning (e.g., large-scale vs convective and/or inland AR penetration).

We appreciate the suggestion to add some discussion on the windward/leeward and spring trends. There are likely dynamic explanations for these trends, however without substantial effort that goes beyond the scope of a methods paper, we would be left speculating. We have included additional text that the method described can help identify curious spatial behaviors that warrant additional research to provide a physical explanation:
“The apparent asymmetric warming of the leeside of the Sierra Nevada compared to the windward side (Fig. 2) warrants additional investigation to elucidate physical mechanisms generating this asymmetry. The watershed-scale signal may also be a by-product of the greater land area at higher elevation in leeside watersheds. A benefit of the spatially distributed nature of the DWR approach is that it facilitates the identification of spatial behaviours that may not be readily apparent in station observations.”

Line 28 – Change to, “...remain upslope of the 0 degree C elevation...”
Change made, thank you for the suggestion.

Page 5 Line 5-6, Figure 4 – In addition to watershed area (i.e., proxy for volume of snowpack lost), it might be good to note or discuss other downstream impacts too (i.e., the acre-foot storage of reservoirs, importance of tributaries for surface water, endangered species habitat, etc.). For example, even smaller declines (at least from a water resource management perspective) above Lake Shasta might matter more than more marked declines in watersheds that do not have a reservoir downstream of them (or the reservoir storage capacity is much smaller).
Thank you for bringing up the need to include these discussion points. We added a sentence to briefly point out these impacts, as our metric could be much more (or less) useful for basins that are more (or less) susceptible to precipitation phase changes.

New text to get the idea in there:

“In watersheds with minimal or no reservoir storage, changes from snow to rain may have more impactful changes on flood hazard and habitat, especially during warm season low flows, thus requiring more creative or costly solutions.”

Line 30-31 – Might want to cite a healthy number of future climate modeling studies of the western US here.

Good suggestion, we added several studies to this sentence:
“…(Klos et al., 2014; Huang et al., 2018; Rhoades et al., 2018a; Sun et al., 2018).”

We also added a sentence further up to better connect with other Sierra Nevada-specific modeling and projection studies:

“Snowpack declines are robustly projected to continue into the 21st century (Rhoades et al., 2018a) and be further exacerbated during droughts (Berg and Hall, 2017) and extreme wet years (Huang et al., 2018).”

Added citations:

Berg, N., and Hall, A.: Anthropogenic warming impacts on California snowpack during drought, Geophys. Res. Lett., 44, 2511– 2518, doi:10.1002/2016GL072104, 2017.

Huang, X., Hall, A. D., and Berg, N.: Anthropogenic warming impacts on today's Sierra Nevada snowpack and flood risk. Geophys Res Lett, 45, 6215– 6222, https://doi.org/10.1029/2018GL077432, 2018.

Rhoades, A. M., Ullrich, P. A., & Zarzycki, C. M. Projecting 21st century snowpack trends in Western USA mountains using variable-resolution CESM. Clim. Dyn., 50(1), 261– 288. https://doi.org/10.1007/s00382-017-3606-0, 2018b.

Sun, F., Berg, N., Hall, A., Schwartz, M., and Walton, D.: Understanding end-of-century snowpack changes over California's Sierra Nevada. Geophys. Res. Lett., 46, 933– 943. https://doi.org/10.1029/2018GL080362, 2019.

Page 6 Line 1-2 – Although a bit tangential to the work in this study, it could be useful to cite some other water supply strategies that can help to offset decreases in mountain snowpack (e.g., recycled water, stormwater catchment, etc.). Some of these supply-side strategies have, historically, been undervalued, but now that co-benefits are being assessed the $/acre-foot start to make more sense and could help to offset the projected low-to-no snow future California might face...“Economic evaluation of stormwater capture and its multiple benefits in California” - https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0230549"...current economic analyses of storm water capture do not adequately examine differences in stormwater project types and do not evaluate co-benefits provided by the projects. As a result, urban stormwater capture is undervalued as a water supply option. To advance economic analyses of stormwater capture, we determined the levelized cost of water in U.S. dollar per acre-foot of water supply

(AF; 1 AF = 1233.5 m3) for 50 proposed stormwater capture projects in California, characterizing the projects by water source, process, and water supply yield." “The cost of alternative urban water supply and efficiency options in California.” - https://iopscience.iop.org/article/10.1088/2515-7620/ab22ca"...this analysis evaluates the costs of four groups of alternatives for urban supply and demand based on data and analysis in the California context: stormwater capture; water recycling and reuse; brackish and seawater desalination; and a range of water conservation and efficiency measures. We also describe some important co-benefits or avoided costs, such as reducing water withdrawals from surface water bodies or polluted runoff in coastal waterways...."

We appreciate the suggestions to dive a little deeper into this and have added to the discussion section (in ***bold italics***) that already gained additional insight from a previous reviewer comment (*italics*):
“*In watersheds with minimal or no reservoir storage, changes from snow to rain may have more impactful changes on flood hazard and habitat, especially during low warm season flows, thus requiring more creative or costly solutions.* ***Other non-traditional strategies to offset projected decreases in mountain snowpack and achieve water supply reliability exist, such as storm water recapture, water recycling, and water markets. However, these will require economic assessments to determine feasibility (Cooley et al., 2019).”***

Added reference:
Cooley, H., Phurisamban, R. and Gleick, P., 2019. The cost of alternative urban water supply and efficiency options in California. Environmental Research Communications, 1(4), p.042001.

Line 9-10 – I am still on the fence about the argument that “model-based estimates> gridded statistical estimates” for precipitation/snowfall in mountains. There is a lot of nuance that needs to be discussed with this “movement” (which seems primarily “all-in” on WRF). For example, I think some of the assumptions/limitations of micro-physics/macrophysics schemes and boundary layer schemes in climate models need to be discussed (particularly in the context of mountains). I know this is an on-going debate (and my $0.02 is one of many), but I would ease the definitive statement regarding “skill” made here.

Agreed, we revised this sentence to ease the definition about skill and be more qualitative (“more realistic”).

New text:
“Indeed, some high-resolution model simulations show more realistic precipitation amounts in mountains than some observational networks (Lundquist et al., 2020; Wrzesien et al., 2019).”

Line 29 – Change to, “...is that NAFLT can be periodically updated, as datasets become available, with higher resolution gridded data products (citations) and expanded in scope to evaluate global rain-snow partitioning.”

Thank you for the suggestion, we revised the text as follows:

“The main advantage of the described approach is that ***the NAFLT can be periodically updated as higher resolution gridded data products become available, including those at global scales*** (e.g., TerraClimate; Abatzoglou et al., 2018) ***and global and regional climate models***.”

Responses to Reviewer 2 for "Technical note: Precipitation phase partitioning at landscape-to-regional scales" by Lynn et al.

Reviewer comments are provided in normal text.
Responses are given in blue
*Revised text given in italics (**bold for emphasis**)*

Review of "Technical note: Precipitation phase partitioning at landscape-to-regional scales" by Lynn et al. Submitted to Hydrology and Earth system sciences. 2020. General Comments/Overview This paper describes a new approach developed by the California Department of Water Resources to produce a long term (30+years), monthly, high-resolution (4km), rain/snow partitioning dataset over the Western US. The authors use this dataset/method to estimate long-term changes in rain/snow partitioning. With warmer temperatures, more precipitation is falling as rain rather than snow –which will impact snow water storage and water management practices. The authors argue that due to the paucity of snow observational datasets and the complex topography of the western US multiple datasets are needed to monitor and model hydrologic conditions over the Western US. Therefore they combine high-resolution PRISM precipitation data with coarse resolution freezing level and fractional snowfall calculations from NCEP/NCAR reanalysis to generate high-resolution fractional snowfall over California (and the Western US). While I believe this is a novel approach and one that has scientific merits, I have deep concerns about the use of the NCEP/NCAR 1 reanalysis product used in this study. In particular, the fact that precipitation from NCEP/NCAR is used to estimate the fraction of precipitation falling as snow. I also do not think the methods used in this paper are adequately described. As this is a technical paper designed to describe a method I believe this paper could be accepted following major revisions.

We appreciate the constructive comments provided by the reviewer and have majorly revised the paper in order to address their major, minor, and specific concerns.

Major Concerns:
1. The NCEP/NCAR reanalysis dataset used in this study is one of the oldest reanalysis products. At the time of its production/publication the authors (Kalany et al, 1996) state that "C" variables (such as precipitation) are completely determined by the model and should be used with caution. As the fraction of precipitation falling as snow is determined from precipitation in NCEP/NCAR reanalysis, I believe this will add significant uncertainties into the study. At a bare minimum this uncertainty/limitation needs to be discussed in section 5.2 "Primary Limitations" and making sure the reader knows this is a limitation of the study. However I suggest the authors consider performing a similar analysis with a new reanalysis product that adjusts model derived precipitation (e.g. MERRA2 or ERA5) and compare the results with NCEP/NCAR reanalysis.

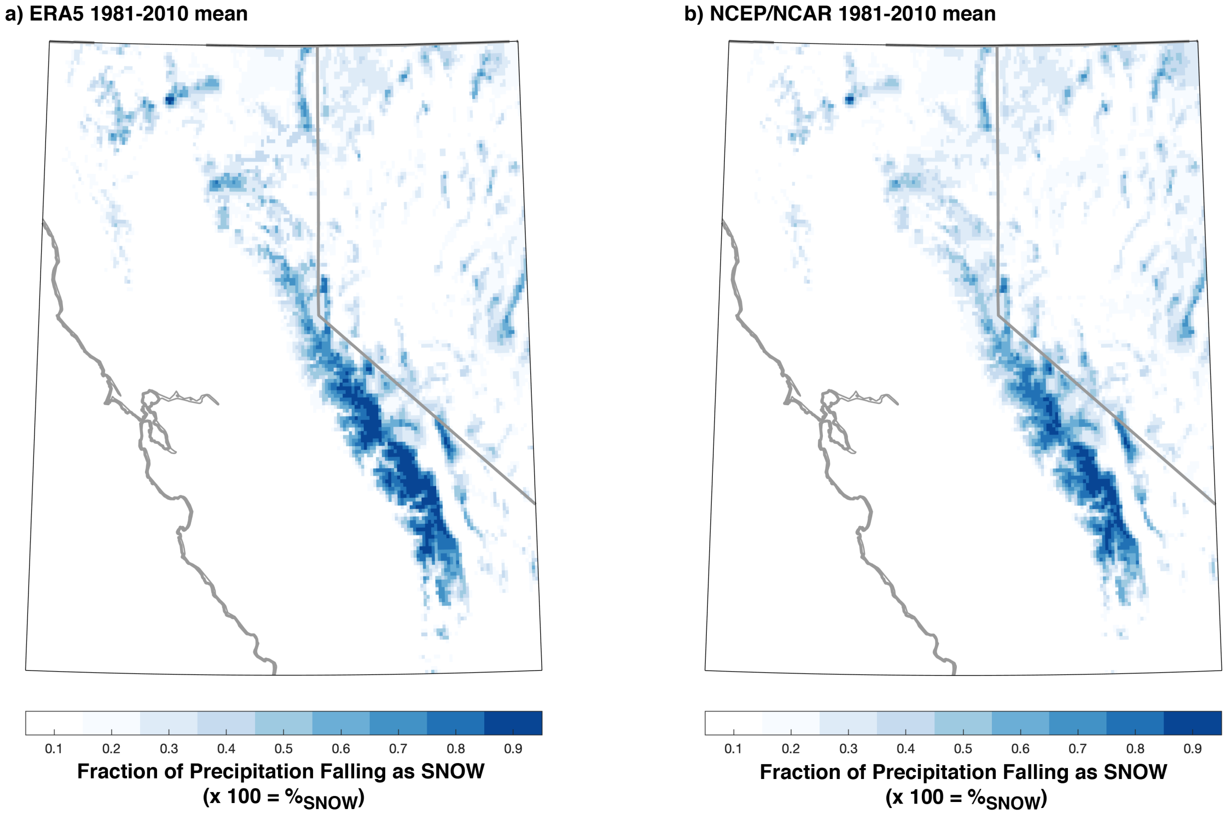
We appreciate the reviewer's concerns about the NCEP/NCAR reanalysis and thank them for requesting additional information regarding the uncertainties as well as the suggestion to perform a similar analysis with a modern reanalysis. Similar concerns with NCEP/NCAR were also brought up by Reviewer 1.

Following both reviewer's suggestions, we repeated the analysis with ERA-5 for the four aggregated DWR watersheds to provide some estimates of how well NCEP/NCAR performs. We found encouraging results (figures below, added as supplementary figures), with ERA-5 and NCEP/NCAR being very well-correlated over the overlapping time period (correlations exceeding 0.9). ERA-5 was a bit colder (more %SNOW), which is likely related to a number of improvements in the ERA-5 model compared to NCEP/NCAR (data assimilation, spatial/vertical resolution, terrain, physical process representation). We added a paragraph to the limitations section highlighting our use of an older model (which was state-of-the-art at the time the NAFLT was developed in ~2008) and showing that it still performs relatively well. All in all, this comparison suggests that the method we are showing is valid (despite limitations in NCEP/NCAR) and thus the method represents a useful way to evaluate precipitation partitioning in models and distribute this partitioning across landscapes when linked with a gridded precipitation product such as PRISM.

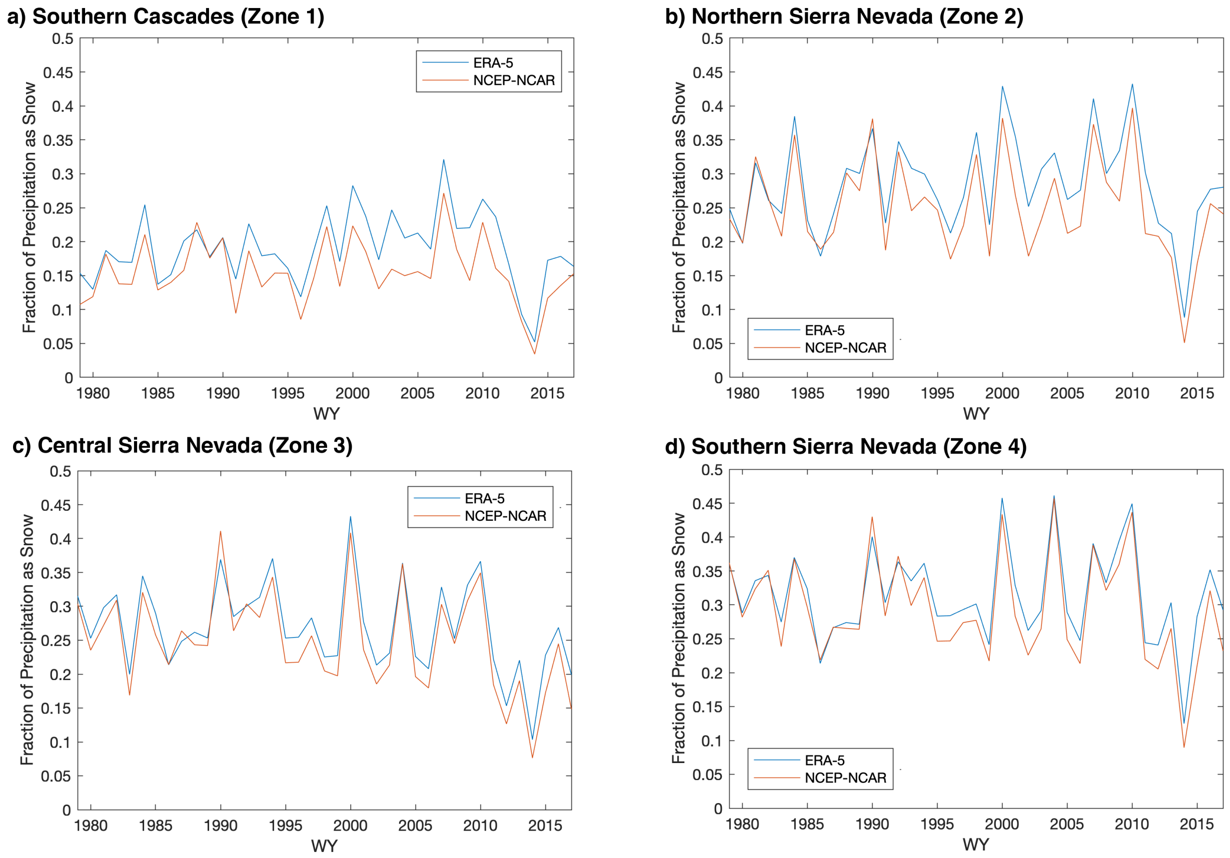
Added text:

"The NCEP/NCAR reanalysis, which the NAFLT uses to identify freezing levels and partition precipitation, is an older generation reanalyses product. Recent advances in atmospheric reanalyses such as ERA-5 (Hersbach et al., 2020) provide advances in data assimilation procedures, have finer spatiotemporal resolution, and provide 0°C heights as standard products. A comparison of the NCEP/NCAR approach to ERA-5 during 1979-2018 showed strong similarity in the spatial distribution of $\%_{SNOW}$ *(Supplementary Figure 3) and high interannual correlations* ($0.9<R<0.99$)*, with slightly higher* $\%_{SNOW}$ *in ERA-5 (Supplementary Figure 4). The method for partitioning precipitation described herein shows promise using the older NCEP/NCAR reanalysis, but it flexible enough to incorporate advances in reanalyses products as well as climate model projections."*

New Supplementary Figures were added to the revised manuscript:



Supplementary Figure 3: Comparison of 1981-2010 mean water year fraction of precipitation falling as snow (multiply by 100 to yield $\%_{SNOW}$*) for northern California and western Nevada produced using ERA-5 (left) with NCEP-NCAR (right).*



Supplementary Figure 4: Comparison of fraction of precipitation falling as snow for ERA-5 (blue line) and NCEP-NCAR (red line) for the period 1979-2018 for the four DWR analysis zones, ordered clockwise from upper left: Southern Cascades, Northern Sierra Nevada, Central Sierra Nevada, and Southern Sierra Nevada.

2.PRISM also provides daily precipitation and surface temperature at 4km resolution. One could estimate daily snowfall using a surface temperature threshold (as in the UA University of Arizona 4km SWE product estimations (https://nsidc.org/data/nsidc-0719; Broxton et al, 2019 and as is done in many land-surface models). The authors need to better explain the science behind why it is more useful or credible to use coarse freezing level data from NCEP/NCAR reanalysis (or another reanalysis product in 1.) to estimate snowfall percentages, than directly calculating these from PRSIM data. (I don't disagree that this surface temperature is not a great indicator of snow level, its just not explained/justified in the paper). An interesting comparison could be to look at snowfall estimated from daily T/P vs their method of approximating rain/snow partitioning.

We appreciate the reviewer's request for better justification about the use of freezing level data instead of surface-based temperatures. There are a number of issues with surface temperatures (data sparseness especially in complex terrain, inadequacies in resolving near-surface lapse rates (e.g., Lute and Abatzoglou, 2020)). These errors can be translated into significant errors in snow models. Another issue with daily-based gridded products are the daily time step that may miss the dynamics of change in snow level throughout the day (such as abrupt rises or falls with frontal passage). The 6-hourly approach with reanalysis may help address this issue somewhat. As a synoptic scale phenomenon, the freezing level is generally well-resolved by models (admittedly there can be substantial variation at finer scales due to microphysics/latent heating/hydrometeor dragging). We added additional text to the introduction to further motivate the study and the use of freezing elevations. We will continue thinking about this issue as we revise the paper, as this is a very important consideration to incorporate into the manuscript well.

New text:
"*Daily gridded products based on sparse observational networks in mountainous areas have their own suite of limitations, such as capturing sub-daily fluctuations in temperature or resolving lapse rates (Lute and Abatzoglou 2020).*"

"The purpose of this technical note is to describe the development of this diagnostic indicator aimed at quantifying how rain and snow are partitioned ***based upon the elevation of the atmospheric freezing (0°C) isotherm, which has been found to be well-resolved by global models in complex terrain (Abatzoglou 2011).***"

Added reference:
Lute, AC, Abatzoglou, JT. Best practices for estimating near-surface air temperature lapse rates. *Int J Climatol*. 2020; 1– 16. https://doi.org/10.1002/joc.6668

We agree it would be interesting to compare this approach to a surface-based approach and appreciate the suggestion. While beyond the scope of this methods paper to dive into comprehensive comparisons, we have added text to encourage this type of study using surface-based data (especially if the surface data includes RH or other necessary parameters to calculate wet bulb temperatures):

"***Further, comparisons with approaches that include relative humidity or wet bulb temperatures are recommended to further improve the methodology, as these have been shown to improve the quality of rain-snow partitioning (Harpold et al., 2017, Wang et al., 2019).***"

In the concluding remarks, we note our method is complementary to other approaches (such as snow reanalyses), and hope to encourage more detailed comparisons between the suite of available products:

"These products provide complementary information to high resolution snow reanalyses that incorporate satellite and/or in situ data (e.g., Margulis et al., 2016; Zeng et al. 2018)."

3.The sections describing the NAFLT methods and the DWR approach to rain/snow partitioning are not clear.

We appreciate the request for improving our description, and provide specific responses below.

It seems to me the lowest to the ground freezing level would matter most for snowfall and surface conditions. Why then does the NAFLT method use the uppermost level in areas where there may be a temperature inversion? Please justify this method.

Perhaps surprisingly, the surface temperature (what I am interpreting by 'ground freezing level'), does not have the 'final say' in precipitation phase. A multitude of physical processes, such as latent heating, hydrometeor fall speed, and others control the melting of a snowflake (see Minder et al., 2011 and Jennings et al., 2018 for further descriptions of processes; note the other reviewer suggested the additional Jennings reference). This means that the freezing level elevation is a maximum estimate of where snow may turn to rain, but it is often below (typically 100-300 meters) that elevation, hence why snow can be experienced at surface temperatures above freezing. Further, soundings may indicate freezing rain in overrunning types of situations (cold air pooling at the surface and being overrun by warmer air; this would produce an inversion in a sounding), which is not snow. We are avoiding this situation by following standard NWP definitions of freezing level. We approached this issue in the discussion, but we agree with the reviewer that some up-front justification would help readers when introducing the method.

With regards to the inversion issue, our original text used the standard NWP calculation (also used in ERA-5 but we slightly revised it for clarity: "The uppermost atmospheric level below which the 0°C isotherm occurs is considered for cases in which the vertical temperature profile includes inversion conditions *with* multiple incursions of the 0°C isotherm"

We have revised the text to improve the clarity of the description of the method and provide additional justification:
"*The* NAFLT calculates the freezing level as the ***highest elevation in the troposphere (200-1000 hPa)*** above mean sea level where ***free-air temperatures are 0°C.*** If the entire atmosphere is at or below freezing on a given 6-hr period, a value of zero meters above mean sea level is provided. The uppermost atmospheric level below which the 0°C isotherm occurs is considered for cases in which the vertical temperature profile includes inversion conditions ***with*** multiple incursions of the 0°C isotherm. In addition to providing estimates of the elevation of the 0°C isotherm, the NAFLT calculates the ***monthly*** percent of precipitation that falls ***as snow (%SNOW) at 200 m elevational increments from 0-4000 m. This is done by assigning all 6-hourly modelled precipitation from the NCEP/NCAR reanalysis as snow for elevations above the corresponding freezing level and all precipitation in a 6-hour increment as rain for elevations below the freezing level.*** The freezing level is a very conservative estimate of the snow level as precipitation can often persist as snow below the freezing elevation due to latent heat fluxes (e.g., snow falling in a sub-saturated atmosphere, deep isothermal temperature profiles, or during heavy precipitation episodes that entrains colder air to lower levels in the atmosphere; ***Minder et al., 2011; Jennings et al., 2018***). However, accumulations of snow below the elevation of the 0°C isotherm may be transient due to nominal cold content of snow."

We also revised the DWR approach text in section 3.1:
The DWR approach calculates $\%_{SNOW}$ *by first bilinearly interpolating of* $\%_{SNOW}$ *horizontally for each 200 m elevational increment from NAFLT and then assigning* $\%_{SNOW}$ *to each fine-scale grid point per the smallest elevational difference between fine-scale elevation (e.g., 4-km DEM) and*

the 200 m elevational bins. If the freezing level elevation is below the terrain elevation, all precipitation falls as snow (%$_{SNOW}$ = 100). Given the known inadequacies of coarse-scale reanalysis precipitation fields in complex terrain, we multiplied estimates of monthly PRISM precipitation by %$_{SNOW}$ to partition precipitation between total frozen (%$_{SNOW}$) and liquid (%$_{RAIN}$) components similar to Abatzoglou (2011).

It needs to be made clear that with this method –the freezing level can be below the surface topography.

Thank you for the suggestion, we added a sentence to make this clear:
"If the freezing level is below the terrain, all precipitation falls as snow (%$_{SNOW}$ = 100)."

Is the freezing level calculated independently for each 2.5º grid box?

Correct, we revised and added text to reflect this:
"*free-air temperatures are 0°C* ***for each 2.5° NCEP/NCAR grid point***"

"The DWR approach calculates %$_{SNOW}$ by first bilinearly interpolating the 2.5° grid point estimates of %$_{SNOW}$ horizontally for each 200 m elevational increment from the NAFLT. Then it assigns %$_{SNOW}$ to each fine-scale PRISM grid point per the smallest elevational difference between fine-scale elevation (e.g., 4 km DEM) and the 200 m elevational bins."

Most critical: This statement on Page 3 Line 20 "percent of precipitation that falls at elevations above the 0ºC isotherm at 200m increments from 0-4000m" does not make sense to me. Why wouldn't all elevations above the 0º isotherm also be below freezing, and therefore all precipitation would fall as snow? Is there an equation being applied to estimate the fraction of precip falling as snow?

Thank you for pointing out the confusing nature of this sentence in its original form. This sentence has been revised for clarity:
"*This is done by assigning all 6-hourly modeled precipitation from NCEP/NCAR* ***reanalysis as snow for elevations above the corresponding freezing level***"

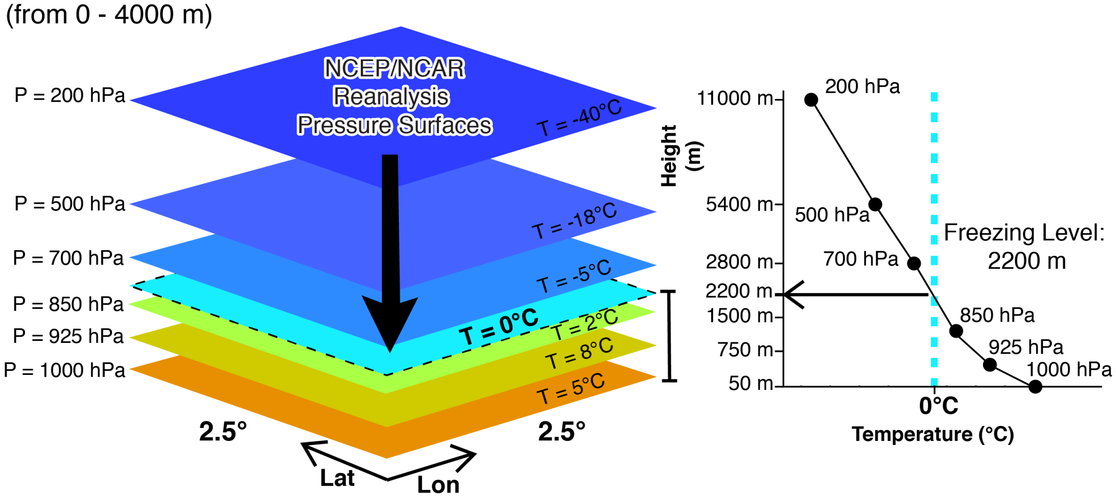
Also, does the method start at the freezing level elevation and work up from there (is the reference point for the 0-4000m) then from the freezing level. Or does it start from the surface? Does the method really estimate the % of snowfall below the 0º isotherm (where you could have mixed precipitation). Similar language is used in section 3.1 to describe how you apply this method to the high-resolution precip data from prism (Page 3 Lines 29-31).

Per standard approaches with Numerical Weather Prediction models and freezing-level outputs that are now part of modern reanalyses (e.g., ERA-5), the 0°C level is defined as the highest atmospheric level in the troposphere where the 0°C level is crossed. This is done to avoid inversions in the case of freezing rain/sleet that might otherwise assign the precipitation type as snow. We further clarified that the approach used is binary in the sense that for a given 6-hour period, elevations above the freezing level are assigned 100% snow, and those below 0% snow. Please see major revisions to the text provided above.

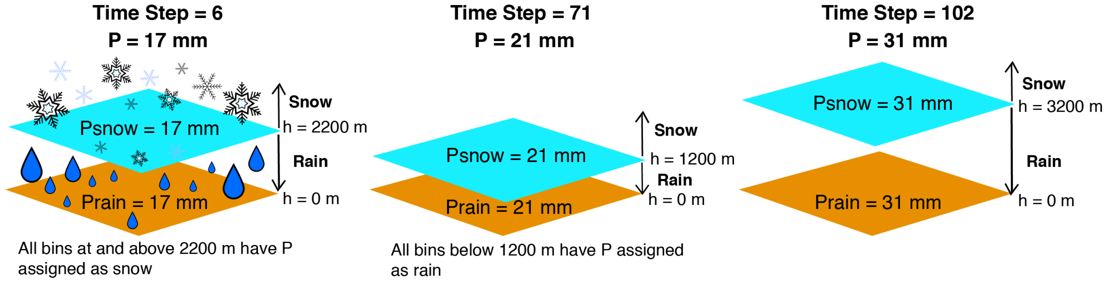
In the Primarily Limitations section you state the assumption was made that %snow linearly relates to the NAFTL –but that was not actually stated in the discussion of the methods, it needs to be. My suggestion is to think about how to describe this method to someone who does not know what the freezing level is, or how %snow is calculated and really step through the process–if this is too much detail you might put some of this in supplemental (a diagram could be helpful as well!).

We appreciate the suggestion to describe the method in a more step-by-step manner. Please see specific changes noted above and in the revised manuscript that includes a heavily-revised methods section. Including a diagram is an excellent idea to visually explain the method, and we thank the reviewer for this suggestion. We now include a schematic in the revised manuscript (see next page) and have referenced the diagram throughout the sections describing the NAFLT and the DWR approach.

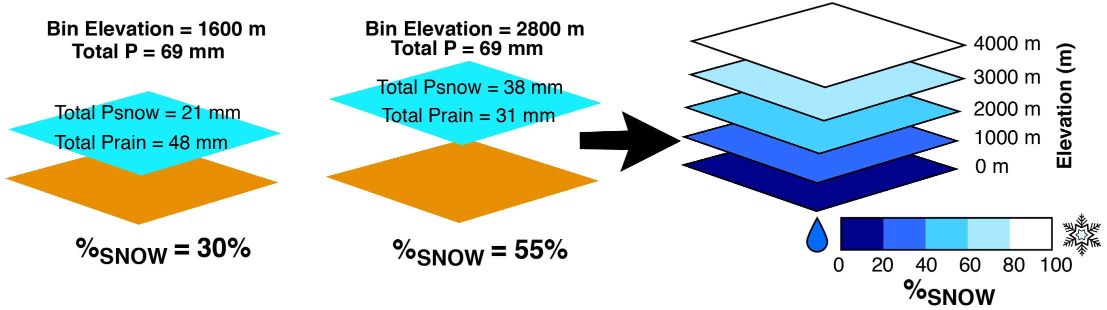
Step 1: Working downward from 200 hPa, identify height of freezing level for each NCEP/NCAR grid cell at each 6 hr time step via linear interpolation, assign to 200 m bin (from 0 - 4000 m)



Step 2: Assign phase to precipitation based on freezing level for bins above and below.



Step 3: For each 200 m elevation bin at each grid point, sum Psnow and Prain over all time steps in the month then divide by total P to calculate monthly $\%_{SNOW}$



Step 4: Distribute $\%_{SNOW}$ over the 4 km PRISM grid points (binned by 200 m intervals) using bilinear interpolation. For seasonal values, use PRISM P to scale $\%_{SNOW}$

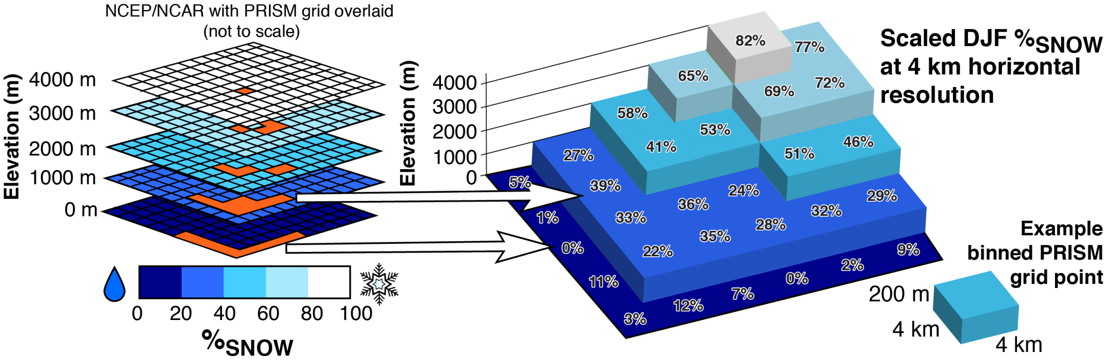


Figure 2: Conceptual diagram illustrating the four key steps in the calculation of %SNOW at 4 km horizontal resolution and using 200 m elevation bins starting with 2.5° x 2.5° horizontal resolution NCEP/NCAR reanalysis.

Minor Concerns
One thing that is missing from the introduction and could be a nice addition is an understanding of how this indicator could actually be used for water resource planning. This is touched upon in the Discussion (Page 5), but I think some of this type of information needs to be included in the introduction to further motivate the need for this method. You do say that changes in rain-snow partition are important for water storage –however it wasn't until the Discussion that I could really see why this indicator might actually be used for planning purposes.

This is a valuable suggestion, especially for a methods/technical note type paper intended to help other practitioners/managers as well as the science community. We have revised and added text to the introduction to better describe some of the specific ways that DWR is applying this information. For the most part, they use it as an indicator of change for situational awareness of where expected impacts of climate change are occurring (and how fast). We also added a final sentence noting the approach can be used to look forward as well (longer-term planning).

New text:
"***Since 2015, DWR has documented this indicator in its annual Hydroclimate Report (DWR, 2019). Though not used directly in operational forecasts, the indicator provides DWR with situational awareness regarding the location of changes in precipitation phase and the rates of these changes.*** Because the method uses publicly available gridded data sets, the indicator is scalable to regional-to-continental scales and therefore could be an informative diagnostic for water resources management and model development in snowmelt dependent regions. While we focus on California watersheds, an example application to the western United States is provided. ***Last, instead of historic data, it can also use model projections as input to help inform the development of adaptation strategies to achieve water resource management goals amidst a changing climate.***"

Page 1, Line 23: "components has been used as a foundation"

Thank you for suggesting a fix, in light of other reviewer comments we revised the sentence as follows:

"*The partitioning of precipitation into liquid (rain) and, in particular, frozen (snow) components along with climatic stationarity were foundational assumptions in the development of water management infrastructure and practices in California and other mountain environments in the western United States (US) since the mid-1800s (Milly et al., 2008).*"

Page 1, Line 27: The use of the word "fate" is a little awkward here, do you mean "phase"?

We agree 'fate' is awkward, though the original intent was a meaning of fate as "destiny", where the destiny of cool season precip is either rain that runs off or snow that accumulates. We changed to use the suggestion of "phase" as this is less awkward and is correct, as the phase does ultimately drive the management strategy.

New text:
"The ***phase*** of cool season precipitation ultimately drives"

Page 1, Line 36: Unclear what you mean by "winter snow levels" here. Do you mean the freezing level in the atmosphere or do you mean increase snow pack (which would be counter intuitive). The jargon of 'winter snow levels" is confusing.

We understand the reviewer's confusion and appreciate them pointing this out as they are not the first to be confused by the nomenclature. We changed the text to winter snow line elevation (which is close to the freezing level, but usually several hundred meters below due to melting times/other processes that influence melting rates).

New text: "winter snow ***line elevation***"

Page 2, Lines 9-11: The first sentence of this paragraph is not complete. It is unclear what are you incorporating multiple data sources and model outputs into.

We appreciate the suggestion to correct the structure of this sentence. We have revised it accordingly to be clearer that the problem is little data availability to apply hydrologic models or to evaluate change. Incorporation of multiple data sources or other model output can often provide the necessary pieces to perform the study of interest.

New text:
"The sparse observational networks and complex topography of the western US introduces challenges into basin-scale hydrologic monitoring and modelling**. *To address these challenges when applying hydrologic models or for monitoring long-term change,*** the incorporation of multiple sources of data (Bales et al., 2006) and/or model output (e.g., Wrzesian et al., 2019) ***is often required.***"

You mention on Page 2, Line 14 that DWR developed a methodology to study historical rain/snow trends at fine spatial resolutions and then on Page 2, Line 16 that the purpose of the note is to provide an updated approach and detail the methods of this indicator. It is unclear to me what in this paper is from the original DWR method and what is the "updated" approach. Is the only difference between the DWR method and the method described in the paper the resolution of the PRISM model data? If the goal of the paper is just to outline the DWR approach –then state that and remove the confusing "updated approach" language. However if the DWR approach is documented elsewhere, and you are documenting changes here in this paper, those differences need to be more explicitly stated.

We apologize for the confusing language. This document is intended to provide the first peer-reviewed documentation of the approach originally described in the 2014 DWR report. We have removed ‘updated’ to avoid confusion.

New text:
“The purpose of this technical note is to *describe the development of this diagnostic indicator aimed at quantifying how rain and snow are partitioned.*”

The reviewer is correct that the only difference described here is with regards to the PRISM spatial resolution. Because this is already described in the methods (section 2.2; the DWR approach uses 800 m but because of data accessibility (free vs. pay) we use the 4 km product), we chose not to further explain this difference in the introduction.

Page 2, Line 16: You say “detail the methods of this indicator” but at this point in the paper it is not clear what “indicator” you are talking about. A sentence about the “indicator” before this one is needed. (e.g. Page 6, Line 4 could also be stated here in the text).

Thank you for the request for additional clarity. We revised the text as follows:
“…indicator ***of how rain and snow are partitioned***.”

Page 2, Line 19: “and be an important” a modal verb is need before “be” as in “may be” or “can be” etc.
We appreciate the grammatical correction (and example!). The text now reads:
“and ***therefore could*** be an *informative*”

Page 3, Line 20: ...the percent of precipitation that falls (as snow??) at elevations above the 0°isotherm ...
Thank you for pointing out our omission. Text has been changed:
“…falls ***as snow*** at…”

2.1 the Study Area Did DWR create this method exclusively for studying trends in rain/snow partitioning, or is this data used in operational forecasts?

Correct, DWR did develop the method exclusively for studying trends. We revised to make it clear in the introduction that the indicator is not used operationally but to inform about trends:
“***Though not used directly in operational forecasts***, *the indicator provides DWR with situational awareness regarding the location of changes in precipitation phase and the rates of these changes.*”

Figure 4 has a number of problems:
What season is being plotted? Entire water year? Cold season etc?

Thank you for pointing out this omission. These are water year plots. The text has been changed to specify this (note this becomes Figure 5 since we added the suggested conceptual diagram):

“Figure 5: (a) Aggregated trends in $\%_{\text{SNOW}}$ (% decade^{-1}) by latitude and elevation ***for the water year.*** Dot size is scaled by area of watershed occupying each elevation and latitude bin. (b) Elevation-based trends (aggregated over all latitudes) of $\%_{\text{SNOW}}$ (% decade^{-1}) showing median (black line), the interquartile range (dark grey shading), and 90% confidence intervals (light grey shading) on the left y-axis. Right y-axis shows the total watershed area occupied by each elevation bin (red line; km^2). Aggregations were performed on gridpoints within the subset of California Department of Water Resources analysis zones (see Figure 1a).”

You discuss Figure 5b before 5a, they should be flipped in the panel.

Thank you for pointing this out, we flipped the panels (and adjusted the caption order as well). New figure and caption:

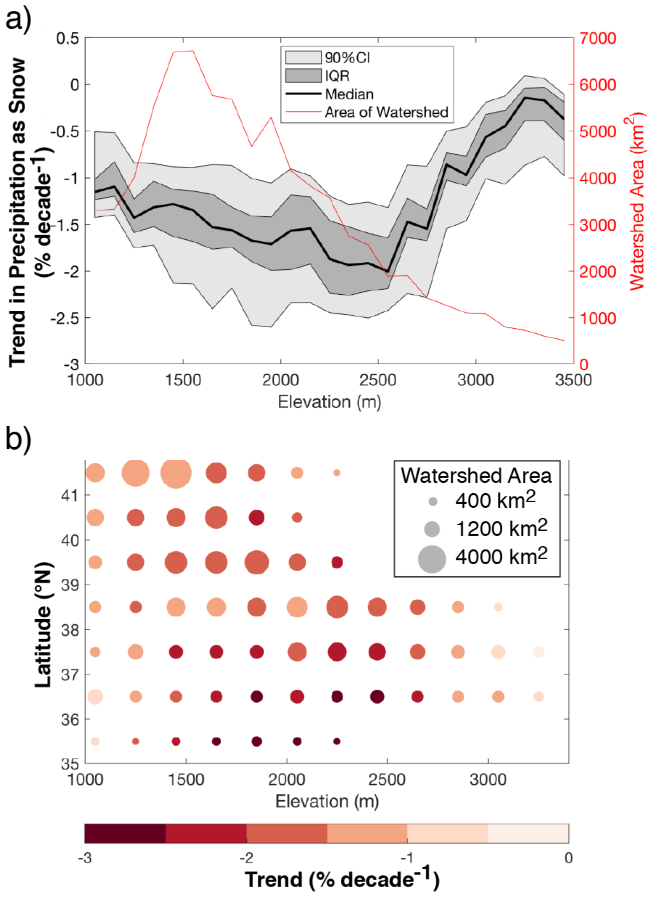


Figure 5: ***(a) Elevation-based trends (aggregated over all latitudes) of $\%_{\text{SNOW}}$ (% decade^{-1}) showing median (black line), the interquartile range (dark grey shading), and 90% confidence intervals (light grey shading) on the left y-axis. Right y-axis shows the total watershed area occupied by each elevation bin (red line; km^2). (b) Aggregated trends in $\%_{\text{SNOW}}$ (% decade^{-1}) by***

latitude and elevation for the water year. Dot size is scaled by area of watershed occupying each elevation and latitude bin. Aggregations were performed on gridpoints within the subset of California Department of Water Resources analysis zones (see Figure 1a) and sorted by elevation. The interquartile range (IQR) and 90% confidence interval (CI) were estimated using all grid points within each elevation band and analysis zone.

It is unclear from the text how Figure 4b is calculated –what is the IQR and 90% CI based on (is this covering every grid point within that elevation band?).

Correct, and we apologize for the oversight to include this detail in our original submission. We added a sentence to the caption to describe how the IQR and CI were calculated (please also see complete revised caption above):

"The interquartile range (IQR) and 90% confidence interval (CI) were estimated using all grid points within each elevation band and analysis zone."

Does Figure A represent the values shown in Figure 3 but sorted by elevation?

Yes, the difference being values were aggregated by latitude and elevation and not by watershed. We added a note in the Figure 5 (previously Fig 3) caption that the aggregations were *"sorted by elevation"*.

Page 5, Line 37 –what is a flood pool? This should be stated in a way that non-flood forecasters/water managers can understand.

Good suggestion. We added the definition and some text clarifying why it matters. The flood pool exists to prevent downstream flooding when inflows are high (such as during storms). The states that a flood pool must be maintained during certain parts of the year, meaning that inflows into the flood pool must be released as soon as possible. Instead of water being stored upstream in the snowpack to flow into the reservoir in July (a resource), now this water can be lost for later consumptive use as it flows downstream in February (managed as a hazard).

New text:

"More precipitation falling as rain during storms, especially in regions with large watershed areas in lower elevations, increases *midwinter* inflow into reservoirs. Many current multipurpose reservoir management paradigms require the maintenance of a flood pool, ***which is reservoir storage space allocated to attenuate periods of heavy inflow and reduce flood hazard during cool season storms. Water captured during the flood is later released to maintain the flood pool storage capabilities during the next possible event. Flood pool releases*** mean this water cannot be stored for later beneficial use and must be managed as a hazard rather than a resource."

Page 6, Line 4 –this description of the goal of this paper needs to be moved up into the introduction.

Thank you for the suggestion. We moved the sentence to the introduction.

Technical note: Precipitation phase partitioning at landscape-to-regional scales

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Abstract. Water management throughout the western United States largely relies on the partitioning of cool season mountain precipitation into rain and snow, particularly snow as it maximizes available water for warm season use. Recent studies indicate a shift towards increased precipitation falling as rain, which is consistent with a warming climate. An approach is presented to estimate precipitation phase partitioning across landscapes from 1948-present by combining fine scale gridded precipitation data with coarse scale freezing-level and precipitation data from an atmospheric reanalysis. A marriage of these datasets allows for a new approach to estimate spatial patterns and trends in precipitation partitioning over elevational and latitudinal gradients in major water supply basins. This product is used in California as a diagnostic indicator of changing precipitation phase across mountain watersheds. Results show the largest increases in precipitation falling as rain during the past seven decades in lower elevation watersheds located within the climatological rain-snow transition regions of northern California during spring. Further development of the indicator can inform adaptive water management strategy development and implementation in the face of a changing climate.

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1 Introduction

Mountains are natural reservoirs of water for human and natural consumptive uses in many parts of the world (Huss et al., 2017). In snow-dominated mountain environments, substantial quantities of water stored as snow accumulates during the cool season and is released during the warm season as snow melts. The partitioning of precipitation into liquid (rain) and, in particular, frozen (snow) components along with climatic stationarity were foundational assumptions in the development of water management infrastructure and practices in California and other mountain environments in the western United States (US) since the mid-1800s (Milly et al., 2008). Precipitation phase partitioning during the cool season influences the timing and magnitude of surface runoff, evapotranspiration, and groundwater recharge (Berghuijs et al., 2014; Zhang et al., 2015; Musselman et al., 2017; Sturm et al., 2017; Abatzoglou and Ficklin, 2017). The phase of cool season precipitation ultimately drives water management strategies, especially in arid and semi-arid environments characterized by substantial interannual hydroclimate variability (e.g., Sterle et al., 2019).

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Many historically snow-dominated mountains in the western US, particularly those with mild winter temperatures, are undergoing declines in snow accumulation (Mote et al., 2018). Projections for the 21st century suggest continued warming and snowpack declines (Rhoades et al., 2018a). Because of downstream dependence on snow-derived water resources and susceptibility to flooding from snow melt events, California is an ideal location to examine changes in historical precipitation partitioning. Studies have found evidence for changes in California's cryosphere consistent with a warming climate including an upslope shift in winter snow line elevation (Hatchett et al., 2017), delayed early season snowpack accumulation (Hatchett and Eisen, 2019), earlier peak

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snow water equivalent (Kapnick and Hall, 2010), and decreased snowpack water storage efficiency as measured by ratios of spring snow water equivalent to cool-season precipitation accumulation (Das et al., 2009).

Decreases in snowpack and snow-covered area exacerbates snow loss through the snow-albedo feedback (Walton et al., 2017). This effect is pronounced in lower elevation, warmer regions of watersheds where snow cover tends to be shallower and more ephemeral. The effects of a warming climate on snowpack vary, with the greatest sensitivity found in warm snow climates located near the climatological rain-snow transition elevation (Howat and Tulaczyk, 2005; Mote et al., 2005), predisposing these regions to warming-induced hydrologic vulnerability (Huning and AghaKouchak, 2018; Klos et al., 2014; Rhoades et al., 2018a). Changes in rain-snow partitioning and its manifestation on water storage in spring snowpack are thus of paramount importance to guiding changes in water resource management operations intended to enhance water supply reliability.

The sparse observational networks and complex topography of the western US introduces challenges into basin-scale hydrologic monitoring and modelling. To address these challenges when applying hydrologic models or for monitoring long-term change, the incorporation of multiple sources of data (Bales et al., 2006) and/or model output (e.g., Wrzesian et al., 2019) is often required. Dataset inadequacies have limited the use of precipitation partitioning for operational purposes as readily-available metrics are provided at scales too coarse for decision making processes or involve observational records that are limited temporally (e.g., < 30-year records) for climatological context. Daily gridded products based on sparse observational networks in mountainous areas have their own suite of limitations, such as resolving lapse rates that lead to challenges in near-surface temperature estimates (Lute and Abatzoglou 2020). These are among many inadequacies regarding datasets or climate metrics faced by water managers (e.g., Jagannathan et al., 2020). To overcome such limitations, the California Department of Water Resources (DWR) developed a methodology to study historical precipitation partitioning trends at spatial scales relevant to broader management goals and capable of resolving finer scale details across elevational and climatic gradients (DWR, 2014). This technical note describes the development of this diagnostic indicator aimed at quantifying how rain and snow are partitioned at actionable scales for water management by integrating meteorological datasets.

Since 2015, DWR has documented this indicator in its annual Hydroclimate Report (DWR, 2019). Though not used directly in operational forecasts, the indicator provides DWR with situational awareness regarding the location of changes in precipitation phase and the rates of these changes. While we focus on California watersheds, an example application to the western United States is also provided. We suggest that this approach is scalable to regional-to-continental scales and therefore could be an informative diagnostic for water resources management and model development in other snowmelt dependent regions. Last, the methodology can also be applied to climate model projections to help inform the development of adaptation strategies to achieve water resource management goals amidst a changing climate.

2 Data

2.1 Study Areas

The study areas encompass the Sierra Nevada and Southern Cascades of California (Fig. 1a), with the middle and upper elevations historically receiving the majority of cool season precipitation as snow (Fig. 1c). Runoff originating from melting snow in these regions provides critical water resources for local, state, and federal water projects in California (Kahrl, 1979). Guided by hydroclimate conditions, such as accumulated winter precipitation and the spatial distribution of snow water equivalent (SWE; the amount of liquid water stored in the snowpack), DWR produces monthly forecasts of unimpaired April through July runoff

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forecasts beginning in early February and published as Bulletin 120 (DWR, 2019). The forecasts in Bulletin 120 are updated weekly until June as conditions evolve. Based upon DWR's management of state water resources, these snowpack-dominated mountain areas are subset into four analysis zones (from north to south: Southern Cascades, Northern, Central, and Southern Sierra Nevada; Figure 1a). The elevation distribution of the analysis zones shifts higher with decreasing latitude. Median annual precipitation is the greatest in the higher latitude Northern Sierra Nevada and Southern Cascade regions. In total, 33 United States Geological Survey eight-digit Hydrologic Unit Code (HUC-8) watersheds are included within the four analysis zones. The study period spans water years (WY) 1949-2018. A water year begins on 1 October of the prior calendar year and ends on 30 September.

2.2 Data used in DWR approach to rain/snow partitioning

The DWR approach uses monthly, 800 m horizontal resolution estimates of precipitation from the Parameter Regression Interpolated Slopes Model (PRISM; Daly et al., 2008), a digital elevation model (DEM) corresponding to the PRISM grid, and freezing level elevations from the North American Freezing Level Tracker (described in section 2.3). The method produces watershed-aggregated monthly time series of total precipitation and percentage total precipitation estimated as snow ($\%_{SNOW}$). These time series are analysed for the entire water year (October-September), fall (September-November), winter (December-February), and spring (March-May). Because the 800 m PRISM products are not freely available to the public, we use the 4 km monthly products spanning 1948-present from the PRISM group (http://www.prism.oregonstate.edu/).

2.3 The North American Freezing Level Tracker

The North American Freezing Level Tracker (NAFLT, https://wrcc.dri.edu/cwd/products/) was developed by the Western Regional Climate Center in 2008 to provide estimates of the height of the freezing level, or elevation of the 0°C isotherm across North America, based upon 6-hourly output from the National Center for Environmental Prediction/National Center for Atmospheric Research Global Reanalysis spanning 1948-present at a 2.5° horizontal resolution (hereafter "NCEP/NCAR reanalysis"; Kalnay et al., 1996). The height of the freezing level is an important parameter for evaluating climate variability and change in mountain environments (Diaz et al., 2003). Freezing level height influences the phase of precipitation at a given elevation, the state of the land surface (frozen or un-frozen), the thermodynamic processes occurring in an existing snowpack leading to snowpack ripening and melt, and the duration of the snow-free season.

The NAFLT calculates the freezing level as the highest elevation in the troposphere (200-1000 hPa) above mean sea level where free-air temperatures are 0°C for each 2.5° NCEP/NCAR grid point (Step 1 in the conceptual diagram shown in Figure 2). If the entire atmosphere is at or below freezing on a given 6-hr period, a value of zero meters above mean sea level is provided. The uppermost atmospheric level below which the 0°C isotherm occurs is considered for cases in which the vertical temperature profile includes inversion conditions with multiple incursions of the 0°C isotherm. In addition to providing estimates of the elevation of the 0°C isotherm, the NAFLT calculates the monthly percent of precipitation that falls as snow ($\%_{SNOW}$) at 200 m elevational increments from 0-4000 m. This is done by assigning all 6-hourly modelled precipitation from the NCEP/NCAR reanalysis as snow for elevations above the corresponding freezing level and all precipitation in a 6-hour increment as rain for elevations below the freezing level (Steps 2 and 3 in the conceptual diagram). The freezing level is a conservative estimate of the snow level as precipitation can often persist as snow below the freezing elevation due to latent heat fluxes (e.g., snow falling in a sub-saturated atmosphere, deep isothermal temperature profiles, or during heavy precipitation that entrains colder air and drags it downward to lower levels in the atmosphere; Minder et al., 2011; Jennings et al., 2018). However, accumulations of snow below the elevation of the 0°C isotherm may be transient due to nominal cold content of snow.

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3 Methods

3.1 Description of the DWR approach to rain/snow partitioning

The DWR approach calculates $\%_{SNOW}$ by first bilinearly interpolating the 2.5° grid point estimates of $\%_{SNOW}$ horizontally for each 200 m elevational increment from the NAFLT (Step 4 in the conceptual diagram). The approach next assigns $\%_{SNOW}$ to each fine-scale (4 km) PRISM grid point per the smallest elevational difference between fine-scale elevation (e.g., 4 km DEM) and the 200 m elevational bins. If the freezing level elevation is below the terrain elevation, all precipitation falls as snow ($\%_{SNOW}$ = 100%). Given the inadequacies of coarse-scale reanalysis precipitation fields, when calculating seasonal totals, we multiplied estimates of monthly PRISM precipitation by monthly $\%_{SNOW}$ to partition precipitation between total frozen ($\%_{SNOW}$) and liquid ($\%_{RAIN}$) components. We then sum over the months to calculate the seasonal or water year $\%_{SNOW}$ using the PRISM-weighted precipitation estimates. We report $\%_{SNOW}$ using the seasonal or water year ratio of frozen water to liquid water.

The statewide, analysis zone, and watershed average annual precipitation and total average annual $\%_{RAIN}$ (or $\%_{SNOW}$) can be calculated by aggregating data at the native resolution (e.g., 4 km) to the spatial unit of analysis, such as a watershed. These metrics are reported annually by DWR in annual hydroclimate reports. As examples, Figure 1 allows comparisons between three different water years, a record low snowpack year (2015; Fig. 1d), a near-average year (2008; Figure 1e), and a year with much higher partitioning of precipitation as snow (1980; Fig. 1f). State-wide 1 April SWE in 2015 was the lowest since DWR began record-keeping in 1929, while both 2008 and 1980 had SWE values near the long-term 1 April average.

The methodological approach of the NAFLT assumes that freezing levels at the chosen analysis points are representative of synoptic scale weather conditions. Despite known mesoscale variability in snow line elevation during individual events (e.g., Minder et al., 2011), reasonably little bias in snow levels (at the interannual timescale) exist between stations located within 200 km of one another along the windward side of the Sierra Nevada (Hatchett et al., 2017). Thus, the 2.5° (~280 km) horizontal resolution of NAFLT appears reasonable for the purpose of interannual tracking of rain/snow partitioning. By performing calculations of precipitation phase at 6-hourly intervals, our method is better able to capture changes in freezing level and its impact on precipitation (e.g., frontal passage) than daily approaches that can smooth out these influences.

3.2 Statistical Analysis

Temporal trends in historical rain/snow partitioning were evaluated spanning water years 1949-2018 using the non-parametric Mann-Kendall test modified to account for temporal autocorrelation (Hamed and Rao, 1998). Significance was determined using an alpha level of 0.05. When noted, only grid points with statistically significant trends are shown in the resulting figures, with all trends provided in the supplementary information. Trends were calculated by multiplying the Theil-Sen slope by 10 (yielding change in $\%_{SNOW}$ decade^{-1}) at each 4 km grid point for late fall (October-November), meteorological winter (December-February), early spring (March-April), and the cool season (October-April). These calculations were performed over the western United States, though we constrain most of our focus to the Sierra Nevada and Southern Cascades of California. To highlight the spatial information provided by the approach, we also calculated trends aggregated by latitude and elevation across the area within the four analysis zones over the cool season and also at HUC-8 watershed scales. For the watershed-level aggregations, a precipitation-weighted average $\%_{SNOW}$ was calculated over the area within a given watershed and the trend calculation was then performed. To account for precipitation heterogeneity within watersheds, we calculated watershed $\%_{SNOW}$ by separately summing the total frozen precipitation and total precipitation across all grids within a watershed and dividing the two.

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4 Results

Trends in estimated changes in %$_{\text{SNOW}}$ (shown as % decade^{-1}) for winter (Fig. 3a), spring (Fig. 3b), and the cool season of the water year (Fig. 3c) range from no change in the highest elevations of the central and southern Sierra Nevada (and Mt. Shasta in the southern Cascades) to decreases of 4% decade^{-1} in lower and middle elevation regions over the 70-year record. Winter season trends were largest in the southern portion of the northern Sierra Nevada region and throughout the central Sierra Nevada region and on the order of -1% to -2% decade^{-1}. Spring trends were of larger magnitude (-2% to -4% decade^{-1}) and concentrated in the middle elevations of all regions. The highest elevations of the southern Sierra Nevada showed no declines as these locations remain upslope of the 0°C elevation during these seasons. Fall trends (not shown) were negative, but magnitudes were smaller than winter trends. No statistically significant positive trends were observed for any season.

Trends at the HUC-8 watershed scale show similar results (Fig. 4). The largest negative changes are found in the central Sierra Nevada region on both westward and eastward draining watersheds (i.e., west and east of the Sierra Nevada crest, respectively). These areas show the greatest magnitudes of change at middle elevations during the spring (Fig. 4b). Fall and winter trends moderate the magnitudes of the cool season trends (Figure 4c).

Trends in %$_{\text{SNOW}}$ exhibit strong spatial patterns than can further be explored and understood by binning trends by elevation. The largest negative trends in water year partition of precipitation as snow across the four regions were seen at mid-elevations of 1800-2500 m (-1.5 to -2% decade^{-1}) and become notably weaker at higher elevations that are climatologically well above the 0°C elevation during winter months (Fig. 5a). Lower elevations (<1800m) occupy a larger portion of the collective watershed area and had significant declines in %$_{\text{SNOW}}$ (-1 to -1.5% decade^{-1}). Further decomposition of trends by elevation and latitude shows the largest declines in %$_{\text{SNOW}}$ at mid-elevations in the southern extent of the region (Fig. 5b), consistent with Figure 4. However, we note the strongest negative trends south of 38°N occupy a much smaller geographic extent of overall watersheds than those located further north in California.

Long-term trends throughout the western United States (Fig. 6) demonstrate similar magnitudes of change as found in California with decreases on the order of -0.5% to -4% decade^{-1}. Areas east of the Cascade Range (central and northern Washington and central Oregon), the Montana plains, western and northern New Mexico, and much of the non-mountainous terrain in Wyoming and in the Colorado River Basin show the greatest magnitudes of decreases in winter %$_{\text{SNOW}}$ (Fig. 5a). As we found in California, the spring season showed the largest magnitudes of decreases in %$_{\text{SNOW}}$ (Fig. 6b) with the greatest magnitudes in central Nevada, southwestern Utah, central Arizona, and along the Front Range of the Colorado Rockies. Averaged over the cool season, the western United States demonstrated decreases in %$_{\text{SNOW}}$ by approximately -1% to -2% decade^{-1} over the past ~70 years (Fig. 6c).

5 Discussion

5.1 Is there a transition to "more rain, less snow?"

Combining 4 km PRISM monthly precipitation and using freezing level estimates from reanalysis confirms widespread declines in the percent of precipitation falling as snow over California (Fig. 4) and the western United States (Fig. 6). The most notable, or largest magnitude, and widespread changes have occurred in spring at elevations near and below the climatological 0°C height. The apparent asymmetric warming of the leeside of the Sierra Nevada compared to the windward side (Fig. 3) warrants additional investigation to elucidate physical mechanisms generating this asymmetry. The watershed-scale signal (Fig. 4) may also be a by-

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The method presented agrees well with previous station-based observations showing declines in $\%_{SNOW}$ (e.g., Knowles et al. 2006). The gridded nature of the approach used allows detailed analyses at the regional or watershed level, both spatially (Fig. 4) and across binned elevations and latitudes (Fig. 5) that adds nuance to the analysis. In the case presented, the aggregation techniques highlight the magnitude of change as a function of elevation and latitude (Fig. 5a) to elucidate hydrologic basins that may be most susceptible to changes in precipitation partitioning (Fig. 4).

The spring season signal of increasing precipitation as rain, especially in middle elevation zones and southern upper elevation zones of California and throughout much of the western United States, is consistent with declines in peak snowpack, changes in plant phenology, and earlier timing of runoff (Cayan et al., 2001; Das et al., 2009; Kapnick and Hall, 2010; Mote et al., 2018). Snowpack declines are robustly projected to continue into the 21st century (Rhoades et al., 2018b) and be further exacerbated during droughts (Berg and Hall, 2017) and extreme wet years (Huang et al., 2018). The method presented also suggests that the highest elevation regions in the Sierra Nevada, the Wasatch Range, and the Rocky Mountains have not experienced significant declines in precipitation falling as snow to date during winter and spring. With continued warming and increased freezing levels, however, these areas are posited to undergo declines in $\%_{SNOW}$ (Klos et al., 2014; Huang et al., 2018; Rhoades et al., 2018b; Sun et al., 2019). A trend towards less precipitation as snow during fall in the higher elevations is noted in the Rocky Mountains in Colorado and northwestern Montana as well as the Wind River Range in Wyoming (Supplementary Figure 2).

The transition from snow to rain at lower and middle elevations of California's Sierra Nevada during the primary accumulation seasons (Fig. 5a-b) has reduced the amount of water stored as spring snowpack (Mote et al., 2018). This declining capability of mountains to act as natural reservoirs is a key response to climate warming (Rhoades et al, 2018a). It has also led to more frequent warm snow drought conditions (Hatchett and McEvoy, 2018). More precipitation falling as rain during storms, especially in regions with large watershed areas in lower elevations, increases midwinter inflow into reservoirs. Many current multipurpose reservoir management paradigms require the maintenance of a flood pool, which is reservoir storage space allocated to attenuate periods of heavy inflow and reduce flood hazard during cool season storms. Water captured during the flood is later released to maintain the flood pool storage capabilities during the next possible event. Flood pool releases mean this water cannot be stored for later beneficial use and must be managed as a hazard rather than a resource. Work is in progress to develop adaptation strategies such as forecast-informed or dynamic reservoir operations (Steinschneider and Brown, 2012; Talbot et al., 2019) and managed aquifer recharge (e.g., Dillon et al., 2010) to address this growing water management challenge as continued warming results in additional changes from snow to rain. In watersheds with minimal or no reservoir storage, changes from snow to rain may have more impactful changes on flood hazard and habitat, especially during low warm season flows, thus requiring more creative or costly solutions. Other non-traditional strategies to offset projected decreases in mountain snowpack and achieve water supply reliability exist, such as storm water recapture, water recycling, and water markets. However, these will require economic assessments to determine feasibility (Cooley et al., 2019).

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5.2 Primary Limitations

The approach described herein does have several primary limitations in its current form. A major limitation is the assumption that the NAFLT freezing level elevation linearly corresponds to the $\%_{SNOW}$ estimate, which is then multiplied by the PRISM precipitation amount at that grid point at the monthly time scale. One key limitation of PRISM in this application is that it remains an interpolation method based on observational data, which is sparse in mountainous regions (Henn et al., 2018). Indeed, some high-resolution model simulations show more realistic precipitation amounts in mountains than some observational networks (Lundquist et al., 2020; Wrzesien et al., 2019). At the watershed scale, differences between PRISM products (i.e., 4 km, 800 m) and their associated elevation for prescribing local $\%_{SNOW}$ is likely nominal. However, we would expect site-specific comparisons to yield differences that may be of importance for smaller watersheds and ecological processes.

Our assumption that coarse models (e.g., reanalysis products) accurately represent the freezing level ignores mesoscale effects of snowline variability in complex terrain (Minder et al., 2011) and the effects of near-surface humidity (Harpold et al., 2017). Both sources of uncertainty may result in substantial biases in rain/snow partitioning estimates as a function of individual storms, particularly during frontal passage and when the magnitude and spatial distribution of precipitation is also considered. Further, comparisons with approaches that include relative humidity or wet bulb temperatures are recommended to further improve the methodology, as these have been shown to improve the quality of rain-snow partitioning (Harpold et al., 2017, Wang et al., 2019).

The NCEP/NCAR reanalysis, which the NAFLT uses to identify freezing levels and partition precipitation, is an older generation reanalyses product. Recent advances in atmospheric reanalyses such as ERA-5 (Hersbach et al., 2020) provide advances in data assimilation procedures, have finer spatiotemporal resolution, and provide 0°C heights as standard products. A comparison of the NCEP/NCAR approach to ERA-5 during 1979-2018 showed strong similarity in the spatial distribution of $\%_{SNOW}$ (Supplementary Figure 3) and high interannual correlations ($0.9<R<0.99$), with slightly higher $\%_{SNOW}$ in ERA-5 (Supplementary Figure 4). The method for partitioning precipitation described herein shows promise using the older NCEP/NCAR reanalysis, but it flexible enough to incorporate advances in reanalyses products as well as climate model projections.

6 Concluding Remarks

Changes in the fraction of precipitation falling as snow during the cool season can have significant impacts on the ability of water managers to balance management objectives (e.g., water supply, ecosystem demands, and recreation) through reservoir operations. Expectations from climate change projections suggest that dynamic adaptation strategies will have to be employed to maintain the functionality of existing water management infrastructure. These strategies will rely on managers having estimates of spatially distributed historical precipitation phase partitioning at landscape scales readily available for use. We presented a method for estimating snowfall as a fraction of total precipitation at high spatial resolution (e.g., 4 km) and modest temporal resolution (monthly) with output from the North American Freezing Level Tracker (NAFLT) based on a global reanalysis product (NCEP/NCAR), PRISM precipitation, and a digital elevation model. A trend analysis indicates a greater fraction of precipitation across California's historically snow-dominated mountain regions with the spring showing the strongest trends (-2% to -4% decade^{-1}) followed by winter (-1% to -2% decade^{-1}). The largest decreases were found at mid-elevations near the climatological freezing level, which have previously been identified as the most vulnerable to warming (Huning and Aghakouchak, 2018). These products provide complementary information to high resolution snow reanalyses that incorporate satellite and/or *in situ* data (e.g., Margulis et al., 2016; Zeng et al. 2018).

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The developed method uses publicly-available gridded data sets that enable application to areas with similar natural resource or water management paradigms. Ongoing work seeks to address the limitations presented in order to produce more robust estimates of historical change in rain/snow partitioning and enable additional storm or place-based detail that can be utilized in adaptive strategy development and applications. The main advantage of the described approach is that the NAFLT can be periodically updated as higher resolution gridded data products become available, including those at global scales (e.g., TerraClimate; Abatzoglou et al., 2018) and global and regional climate models. Further examination of how freezing levels are influenced by large scale modes of climate variability are also recommended. For example, Abatzoglou (2011) found trends in the Pacific-North American pattern contributed to increases in freezing levels and declines in precipitation falling as snow. Evaluating freezing level and precipitation phase relationships to isolated modes of climate variability may provide useful guidance for hydroclimate predictability at lead times relevant for water management (e.g., Patricola et al. 2020).

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It is anticipated that an updated freezing level tracker tool will be developed and used to provide precipitation phase partitioning information to water managers to help inform decision making. California's investment in unique data sets like snow level radar (White et al., 2013) coupled with ongoing efforts to improve *in-situ* weather monitoring in headwater regions (Lundquist et al., 2016) creates an opportunity for further exploration of rain/snow partitioning including storm-based and place-based analyses. These analyses can play important roles in developing and implementing adaptive strategies for water management by providing analogues to future cool seasons or storm events in a warming climate (e.g., Berg and Hall, 2017; Hatchett, 2018; Huang et al., 2019; Sterle et al., 2019).

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7 Acknowledgements

This work was supported by the California Department of Water Resources. We dedicate this method to the late Dr. Kelly T. Redmond, who always encouraged the application of climate science to inform decision making in the western United States. We appreciate the constructive reviews provided by Alan Rhoades and an anonymous reviewer.

8 Code/Data availability

The processing code, and processed data (e.g., $\%_{\mathrm{SNOW}}$) is available upon request.

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9 Author contributions

Elissa Lynn, Aaron Cuthbertson, Minxue He, Jordi P. Vasquez, Michael L. Anderson, and Peter Coombe conceptualized the idea. Elissa Lynn supervised the project. Benjamin J. Hatchett wrote the manuscript with input from all authors and was responsible for analysis and visualization. John T. Abatzoglou developed the North American Freezing Level Tracker, generated the precipitation phase partitions, and performed the analysis and visualization shown in Figure 4. All authors contributed to the interpretation and presentation of data and results as well as the revision and editing of the original manuscript.

10 Competing interests

Authors Elissa Lynn, Aaron Cuthbertson, Minxue He, Jordi P. Vasquez, Michael L. Anderson, and Peter Coombe are employed by the California Department of Water Resources. Authors Benjamin J. Hatchett and John T. Abatzoglou declare that they have no competing interests.

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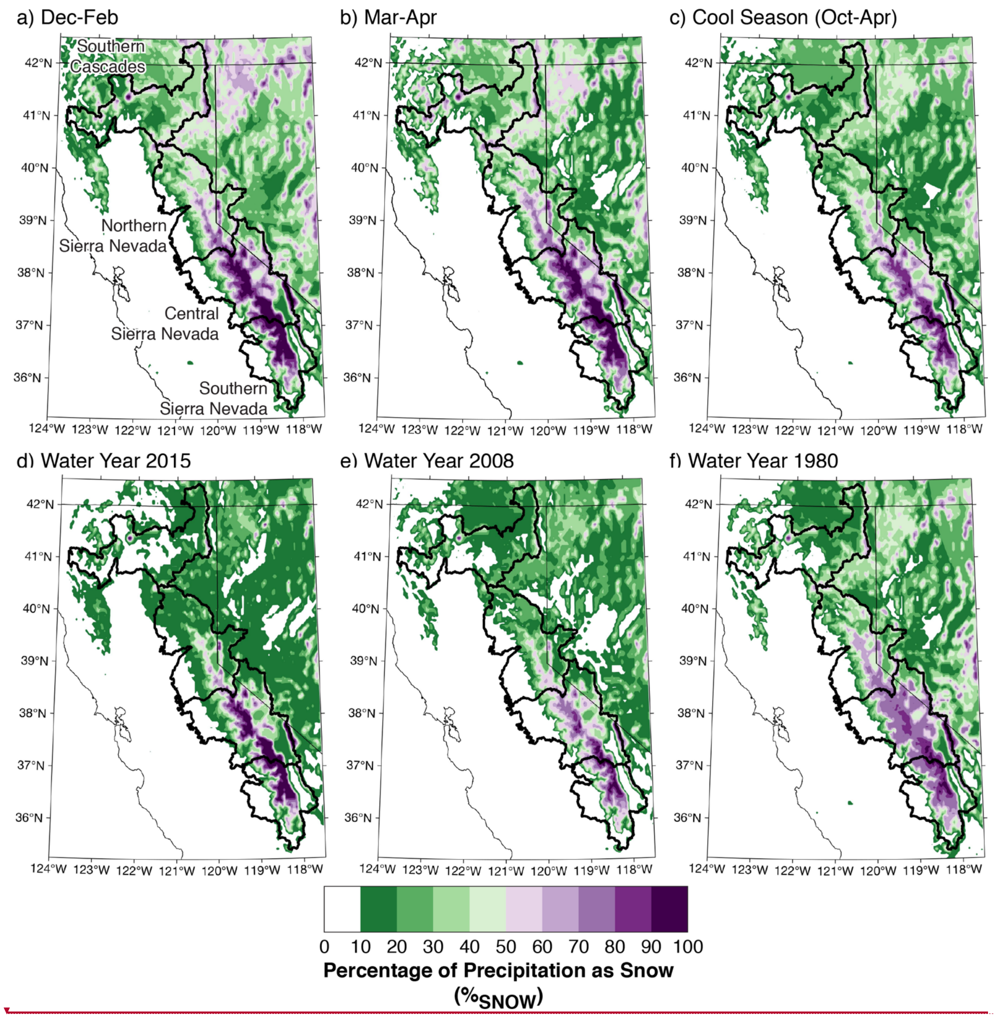

Figure 1: Estimated historical (1950-1969) percentages of precipitation as snow for (a) winter (Dec-Feb), (b) spring (Mar-Apr), and (c) for the full cool season (Oct-Apr). Examples of $\%_{SNOW}$ averaged over the cool season (October-April) of water years (d) 2015, (e) 2008, and (f) 1980. Thick black contours denote California Department of Water Resources analysis zones.

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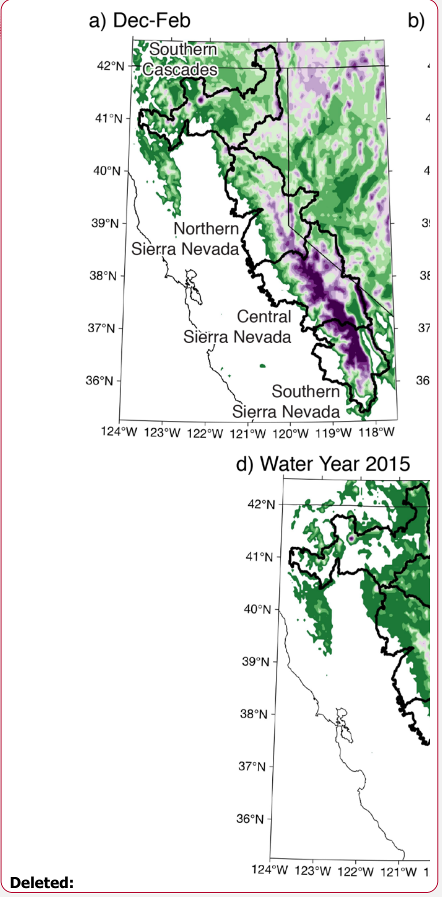

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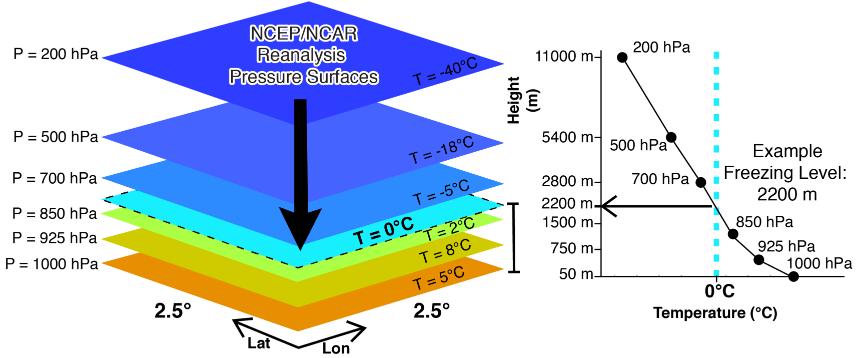
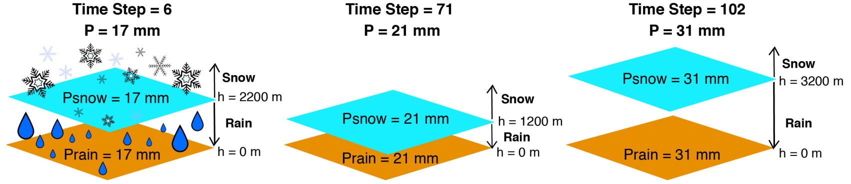
Step 1 (N. American Freezing Level Tracker): Working downward from 200 hPa, identify height of freezing level for each NCEP/NCAR grid cell at each 6 hr time step via linear interpolation, assign to 200 m bin (from 0 - 4000 m)



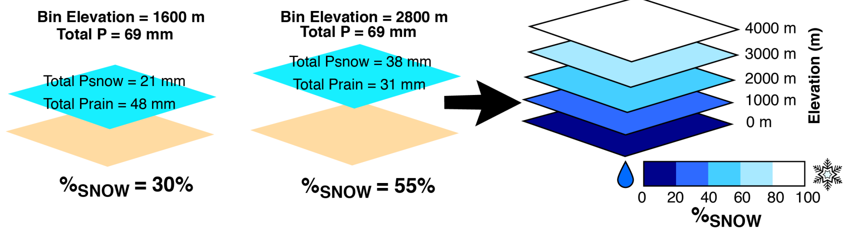
Step 2: Assign phase to precipitation (P) based on freezing level for bins above and below, where precipitation as snow = Psnow and precipitation as rain = Prain



All bins at and above 2200 m have P assigned as snow

All bins below 1200 m have P assigned as rain

Step 3: For each 200 m elevation bin at each grid point, sum Psnow Prain over all time steps in the month then divide by total P to calculate monthly $\%_{SNOW}$



Step 4: (DWR Method) Distribute $\%_{SNOW}$ over the 4 km PRISM grid points (binned by 200 m intervals) using bilinear interpolation. For seasonal values, use PRISM P to scale $\%_{SNOW}$

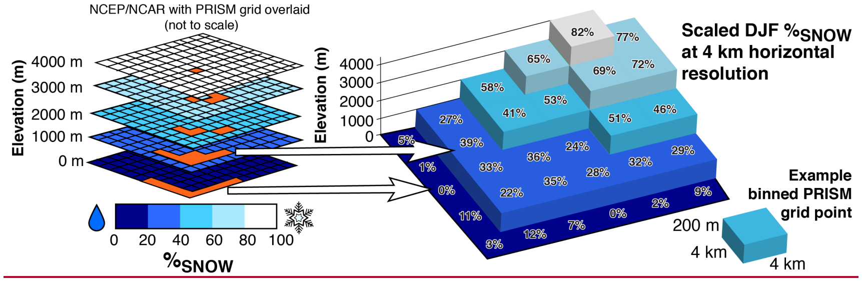


Figure 2: Conceptual diagram illustrating the four key steps in the calculation of $\%_{SNOW}$ at 4 km horizontal resolution and using 200 m elevation bins starting with 2.5° x 2.5° horizontal resolution NCEP/NCAR reanalysis.

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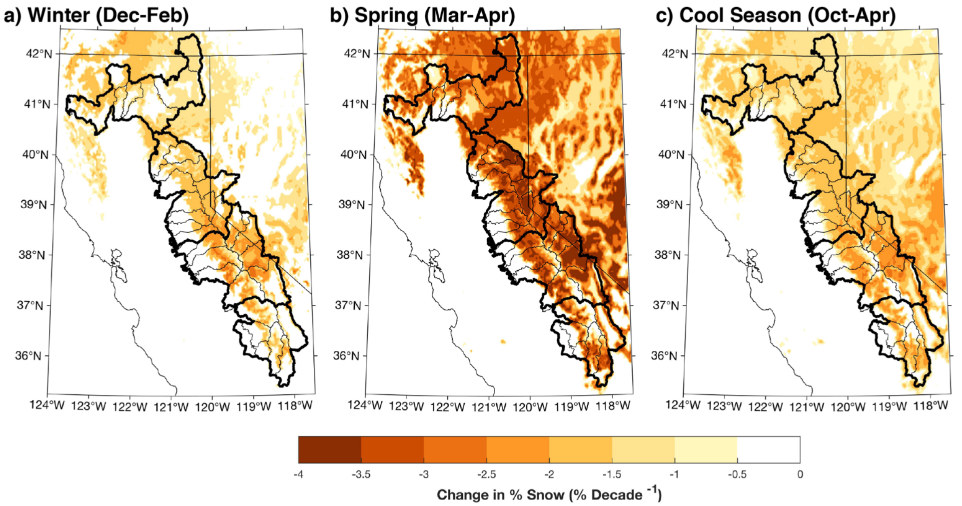

Figure 3: Estimated changes in %$_{\text{SNOW}}$ (in % decade^{-1}) for (a) winter (Dec-Feb), (b) spring (Mar-Apr), and (c) for the full cool season (Oct-Apr). Thick black contours denote California Department of Water Resources analysis zones. Thin black contours denote United States Geological Survey HUC-8 watersheds. Only gridpoints with statistically significant ($p<0.05$) trends are shown; Supplementary Figure 1 shows trends for all gridpoints.

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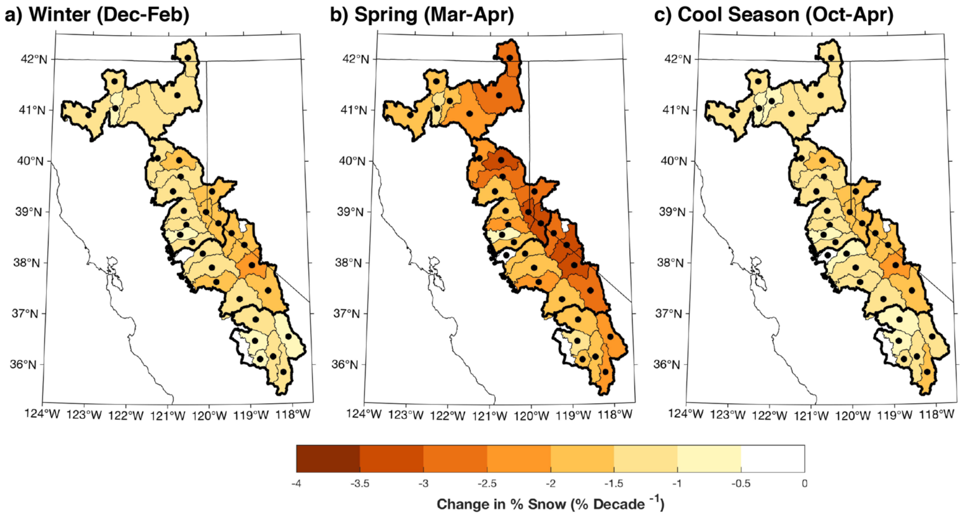

Figure 4: As in Figure 2 but with trends averaged over HUC-8 watersheds. Filled black circles indicate statistically significant ($p<0.05$) trends.

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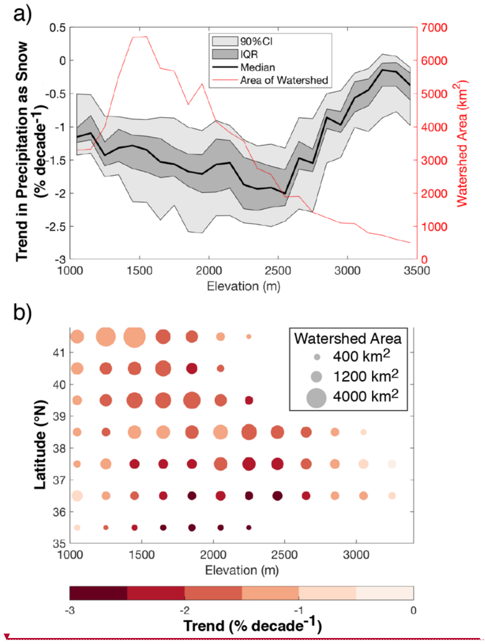
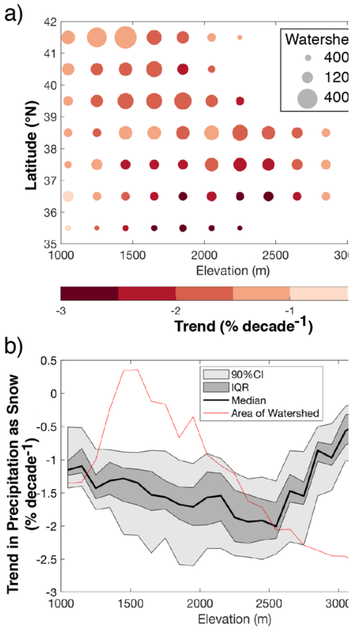


Figure 5: (a) Elevation-based trends (aggregated over all latitudes) of $\%_{SNOW}$ (% decade^{-1}) showing median (black line), the interquartile range (dark grey shading), and 90% confidence intervals (light grey shading) on the left y-axis. Right y-axis shows the total watershed area occupied by each elevation bin (red line; km^2). (b) Aggregated trends in $\%_{SNOW}$ (% decade^{-1}) by latitude and elevation for the water year. Dot size is scaled by area of watershed occupying each elevation and latitude bin. Aggregations were performed on gridpoints within the subset of California Department of Water Resources analysis zones (see Figure 1a) and sorted by elevation. The interquartile range (IQR) and 90% confidence interval (CI) were estimated using all grid points within each elevation band and analysis zone.



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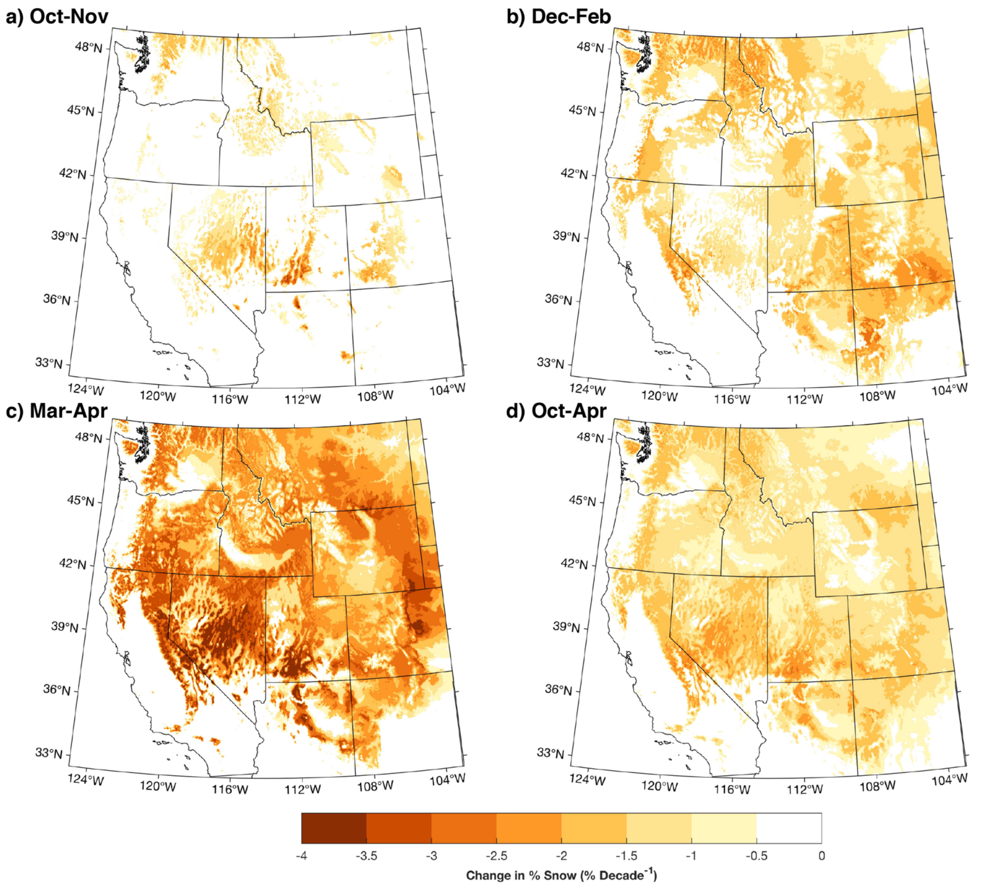
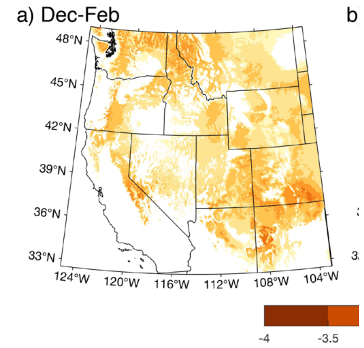


Figure 6: Decadal trends in $\%_{\mathrm{SNOW}}$ for the western United States during (a) fall (Oct-Nov) (b) winter (Dec-Feb), (c) spring (Mar-Apr), and (d) for the cool season of the water year (Oct-Apr). Only gridpoints with statistically significant (p<0.05) trends are shown; all gridpoint trends are shown in Supplementary Figure 2.



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