DISSERTATION

RECENT AND FUTURE COLORADO WATER: SNOW DROUGHT, STREAMFLOW, AND WINTER RECREATION

Submitted by

Anna K. D. Pfohl

Department of Ecosystem Science and Sustainability

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 2023

Doctoral Committee:

Advisor: Steven R. Fassnacht

David M. Barnard
Stephanie K. Kampf
Kristen L. Rasmussen

ABSTRACT

RECENT AND FUTURE COLORADO WATER: SNOW DROUGHT, STREAMFLOW, AND WINTER RECREATION

Water in the western United States is a crucial resource for ecosystems, the abiotic environment, and people (for industrial, agricultural, and residential purposes). A majority of this water originates in the seasonal snowpack in the mountains. The snowpack is responsible for maintaining the water supply, and changes to this system have broad and severe implications. Various metrics have been used to quantify these patterns when snow is less than normal, often referred to as a snow drought or a low snow year. In recent decades, the number of years with low snow have increased, and this will continue and intensify into the future. With observed decreases in long-term snow and modeled decreases for the future, high snow years become more critical to support the water supply. Beyond supplying water for downstream use, the seasonal snowpack also sustains the winter recreation industry, which is a large component of many local and state economies.

The Weather Research and Forecasting Model (WRF) is a 4-km mesoscale model that can capture orography and convective processes over complex terrain. WRF includes two time periods: the control (CTL) based on historic conditions and the future under pseudo-global warming (PGW) conditions. This dataset was used to drive SnowModel (WRF-SM) to produce 100-m, daily snow water equivalent (SWE), total precipitation, solid precipitation, snowmelt, runoff, and air temperature. Using these datasets, this research examines past and future snow and streamflow in Colorado. We evaluated 1) common metrics and trends for snow drought; 2) used WRF data to drive the Ages hydrologic model to examine changes (snow, streamflow, and flow partitioning) in two high snow years; and 3) ski opportunities at nine different resorts.

To evaluate methods of defining snow drought, we used SWE and winter precipitation data from Snow Telemetry stations and the WRF-SM dataset described above. Classifying drought with the ratio of SWE to winter precipitation resulted in drought occurrence for more than 50% of station-years from 1981 to 2020. Using percentiles of long-term peak SWE indicated that occurrence of low or very low years increased from 2001 to 2020 compared with the previous 20 years. Under PGW conditions, elevations between 1800 and 2400 m shifted drought classification towards low or very low, with higher elevations (3200 m and above) remaining relatively unchanged.

To examine changes in snow, streamflow, and flow partitioning under a PGW scenario for two high snow years (2008 and 2011), we used Ages, a spatially distributed watershed model, in the Upper Blue River watershed in central Colorado. Changes in snow (snowmelt and solid precipitation) were greatest in magnitude at high elevations. Timing of peak streamflow shifted to nearly two months earlier under a PGW scenario.

To examine ski opportunities, we developed metrics to quantify ski conditions. The number of opportunities for snowmaking in the future will decrease throughout the season, but especially in October and November. Ski days (snow depth greater than 50 cm) will decrease in early and late season and increase at lower elevations from January through March. Powder days (fresh depth greater than 15 cm and fresh density greater than 125 kg/m^3) follow a similar pattern. Ski resorts at low elevations will generally be more susceptible to changes under a PGW scenario. Additionally, using a fine-resolution dataset allowed investigation of smaller study areas to understand the changes that are not captured with coarser resolutions.

ACKNOWLEDGEMENTS

Completing this document and degree would not have been possible without the support of many important people in my life. To Dr. Steven Fassnacht, I don’t think I can ever truly find the words to express my gratitude for your willingness to be my advisor (and now colleague!) the last few years. Thank you for your patience, understanding, and encouragement. To Dr. Dave Barnard, thank you for helping to secure funding for the last year of my PhD, giving me the opportunity to focus on research for the first time in pursuing this degree. Thank you for your critical eye and incisive advice. To Drs. Stephanie Kampf and Kristen Rasmussen, thank you for your willingness to serve on my committee and offer your time and expertise to help better my research and foster my growth as a scientist.

To the Kahn and Vienhage household, thank you for providing a home for me in Fort Collins and welcoming me into your family. To my friends and extended family who are too many to name, thank you for cheering me on and for bringing levity when I needed it the most.

To Shelby, you have been the best possible addition to the Pfohl family imaginable. I am so grateful to call you my sister and have your grace and kindness of spirit in my life. To Josh, thank you for being an amazing big brother, for always answering the phone and telling me that everything will indeed be okay when life and circumstances seemed to tell me otherwise. To my dad, Ted, I don’t know where to start as your support and love for me are both unending. You have served the role of coach and cheerleader so many times in my life and continue to be my greatest champion. To my mom, Mary, thank you for overcoming burdens that have made my life easier and for paving the way in so many different forms, especially in becoming the first Dr. Pfohl. I can’t imagine a greater honor than sharing that title with you.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

1.1 Research Motivations

Water, in a variety of forms, is plentiful, but water that can be used to sustain life or as a resource is far more limited. Civilizations are built around access to and availability of water. Climate change threatens the systems upon which people have designed societies. The effects of short- and long-term climate change are not uniform, resulting in greater consequences for systems and processes that are more susceptible to variations, such as mountains. Mountains are resource abundant and are often cited as the world's water towers (Hock et al., 2022; Huss et al., 2017; Immerzeel et al., 2020; Siirila-Woodburn et al., 2021; Viviroli et al., 2007), with nearly a quarter of the global population dependent on mountains as their water source (Immerzeel et al., 2020). In the western United States, the water that originates in the mountains is stored in the seasonal snowpack from the start of accumulation to the end of the melt season (Cayan, 1996; Clow, 2010; Hale et al., 2023; Serreze et al., 1999) and is the primary driver of streamflow, contributing as much as 70% to total runoff (Li et al., 2017). In addition to being a water source, the seasonal snowpack provides economic opportunities in the form of winter recreation (Burakowski & Magnusson, 2012; Sturm et al., 2017).

The historic effects of climate change on snow, streamflow, and related processes in the have been extensively studied (Bales et al., 2006; Barnett et al., 2005; Barnett et al., 2008; Kunkel et al., 2016; Siirila-Woodburn et al., 2021). In many high-elevation, snow-dominated watersheds in the western United States, the amount of water is decreasing (for both snow and streamflow) and the timing of key components (e.g., onset of accumulation, peak SWE, streamflow response to snowmelt) of this seasonal cycle is shifting (Ficklin et al., 2013; Hamlet et al., 2007; Pfohl, 2016; Schrock et al., 2021; Siirila-Woodburn et al., 2021; Stewart, 2009). To understand the degree to which different emissions scenarios and subsequent warming have on these processes, a variety of datasets and models have been used (Clow, 2010; Hamlet et al., 2007; Li et al., 2017; Siirila-Woodburn et al., 2021; Stewart et al., 2005). This chapter explores past datasets, methodologies, and results of the state-of-the-science of water, snow, and associated human impacts in the western United States.

1.2 Background

1.2.1 Historic and Future Changes

Within the Upper Colorado River Basin (UCRB), precipitation during the entire 20th century had little variability (Udall & Overpeck, 2017; Woodhouse et al., 2016), though there were periods below the long-term mean (e.g.,1953 to 1967), which resulted in decreased streamflow (Udall & Overpeck, 2017). Precipitation in the western U.S. at high elevations, primarily falls as snow (Klos et al., 2014). At the end of the 20th century, 75% of precipitation (long-term mean) was in the form of snow in the headwaters of the Colorado River (Klos et al., 2014). Long-term trends (1951 to 2014) in precipitation phase show that snow is decreasing (McCabe et al., 2018). Modeled conditions for the mid-21st century indicate a shift toward increased precipitation as rain (Klos et al., 2014; Vano, 2020), with the snowline increasing in elevation (Vano, 2020).

The shift in precipitation phase is linked with elevation (Knowles et al., 2006). As the snowline increases in elevation (Vano, 2020), the snow-covered area (SCA) decreases (Dyer & Mote, 2006; Stewart, 2009). Change in SCA has been a metric to quantify years with low snow since the 1980s (Wiesnet, 1981); however, this variable does not include information about the volume of water, snow water equivalent (SWE), in the snowpack. Since then, additional metrics (e.g., percentiles of peak SWE, percentiles of winter precipitation, ratio of peak SWE to winter precipitation) have been used to help examine the frequency and intensity of “snow drought” or low snow years (Dierauer et al., 2019; Harpold et al., 2017; Hatchett & McEvoy, 2018; Hatchett et al., 2022; Heldmyer et al., 2023; Rhoades et al., 2022; Siirila-Woodburn et al., 2021). Low snow years decreased from 2001 to 2020 compared with the two decades prior (Schrock et al., 2021; Siirila-Woodburn et al., 2021). These patterns continue into the middle and end of the 21st century (Dierauer et al., 2019; Rhoades et al., 2022; Siirila-Woodburn et al., 2021).

Current infrastructure was built based on historic streamflow patterns and timings (Siirila-Woodburn et al., 2021), but climate change has impacted the magnitude and timing of peak streamflow and runoff volume (Stewart, 2009). Streamflow timing metrics have been used as indicators of changes (e.g., land use or total annual runoff) happening within a watershed and have been applied considerably across the Western United States (Clow, 2010; Dudley et al., 2017; Stewart et al., 2005). The Center of Volume (COV) is a popular timing metric and is the day at which 50% of streamflow has passed and has been used as an indicator of changes in snowmelt timing (Clow, 2010; Dudley et al., 2017; Stewart et al., 2005). In the Western United States, trends show that the COV is occurring earlier in the year, typically by 5 to 10 days (Clow, 2010; Dudley et al., 2017; Stewart et al., 2005). In some areas in the second half of the 20th century, the COV occurred earlier by as many as 20 days (Clow, 2010; Dudley et al., 2017; Stewart et al., 2005). Peak spring streamflow is also occurring earlier, with a change in mean date ranging from 8 to 14 days (Ryberg et al., 2016). Changes in the total annual volume of flow have also been observed, with streamflow 22% less during the years 1976 to 2012 compared to 1939 to 1975, though precipitation was relatively constant (Griffin & Friedman, 2017). These metrics are static (Whitfield, 2013), and dynamic approaches (Pfohl & Fassnacht, 2023) illustrate that the onset and end of snowmelt-based streamflow are not occurring earlier in all locations (Pfohl, 2016).

1.2.2 Role of the Seasonal Snowpack

Snow in the western United States is essential for maintaining the water supply for residential, industrial, and agricultural purposes. (Siirila-Woodburn et al., 2021; Tidwell et al., 2014; Viviroli et al., 2007). Snow can affect the overall viability of recreational activities (Jones et al., 2012; Miller et al., 2022; Scott & Lemieux, 2010). Snowmelt-driven streamflow in the late spring and summer sustains flows necessary for white-water rafting (Buckley, 2017). The seasonal snowpack also creates recreational opportunities during winter months (Fassnacht et al., 2018; Scott et al., 2006; Steiger et al., 2017), which are crucial economic sources for many states and communities (Burakowski & Magnusson, 2012).

Since snow is the predominant water supply for mountain rivers, it also plays a critical role in maintaining ecosystem health. The timing of snow disappearance and snowmelt are linked to peak soil moisture (Bales et al., 2011; Molotch et al., 2009; Williams et al., 2009) and has continuous effects on summer soil moisture late into the season (Blankinship et al., 2014; Webb et al., 2015). Increased temperatures shift the onset of snowmelt to earlier in the year (Musselman, Clark, et al., 2017; Musselman, Molotch, et al., 2017); the timing of peak soil moisture subsequently occurs earlier (Harpold & Molotch, 2015). Persistent low snow and precipitation affect subsurface flows and reduce soil moisture (Griffin & Friedman, 2017; Siirila-Woodburn et al., 2021), which in turn reduces streamflow and increases wildfire susceptibility, resulting in earlier peak SWE (Griffin & Friedman, 2017; Kampf et al., 2022; Westerling et al., 2006).

1.3 *In situ* and Modeled Datasets

The purpose of Snow Telemetry (SNOTEL) stations, monitored by the Natural Resources Conservation Service (NRCS) (https://www.nrcs.usda.gov/wps/portal/wcc/home/), is to collect and disseminate climate data (e.g., SWE, precipitation, temperature) for water supply forecasts (NRCS, 2023). SNOTEL station data have been used in scientific research since they record SWE, not just depth or snow-covered area, and provide climate conditions at high elevations.

As computing capabilities and technology have progressed, modeled datasets have become common for use in research (Boyle et al., 2000; Y. Liu & Gupta, 2007). Such datasets are useful for examining past processes and conditions where station data were not available. Global Circulation Models (GCMs) and Regional Climate Models (RCMs) have coarse resolutions (50- to 300-km) that are often suitable for studies conducted over large areas (e.g., North America) (Hay et al., 2002) but do not account for processes that exist at smaller scales (Salathé et al., 2010). The Weather Research and Forecasting (WRF) Model is often run at much finer resolutions (Ikeda et al., 2010; C. Liu et al., 2017; C. Liu et al., 2011). WRF is a 4-km, mesoscale meteorological model that is convective-permitting and suitable for application over complex terrain (C. Liu et al., 2017; Salathé et al., 2010). A portion of the WRF data include variables for two time periods, recent past and future. The recent past (retrospective) is an atmospheric reanalysis, modeled from 2001 to 2013 for the North American Water Year. The future is modeled under pseudo-global warming (PGW) conditions by adding the difference between conditions in the late 21st and 20th century to the retrospective atmospheric reanalysis (C. Liu et al., 2017; Rasmussen et al., 2014; Rasmussen et al., 2011).

Physically-based snow models seek to address difficult-to-measure processes, such as redistribution (e.g., blowing snow) and sublimation, by solving for the energy balance (Liston & Elder, 2006; Voordendag et al., 2021). Not all snow models are suitable for application in mountainous regions. Recently, Hammond et al. (2023) used SnowModel (Liston & Elder, 2006), driven by WRF meteorological data, to model snow conditions for the two time periods described above. This is a fine-resolution (100-m) dataset and can be used to help study processes in areas where spatial variability in snow is difficult to measure.

1.4 Research Objectives

We seek to further understand the *changes* between a PGW scenario and the recent past with three studies. First, we explore snow drought, using different methods and different datasets to examine historic and future low and high snow years in Colorado. Second, we apply a distributed hydrologic model to a high-elevation watershed to quantify how a PGW scenario would affect snow, streamflow, and flow partitioning for a high snow year. Third, we examine recent and future snow conditions as they relate to the ski industry. The Discussion chapter integrates and addresses the broad implications of the findings. The final chapter is a reflection on what the author has learned and future opportunities.

1.5 References

Bales, R. C., Hopmans, J. W., O'Geen, A. T., Meadows, M., Hartsough, P. C., Kirchner, P., et al. (2011). Soil Moisture Response to Snowmelt and Rainfall in a Sierra Nevada Mixed-Conifer Forest. *Vadose Zone Journal, 10*(3).

Bales, R. C., Molotch, N. P., Painter, T. H., Dettinger, M. D., Rice, R., & Dozier, J. (2006). Mountain hydrology of the western United States. *Water Resources Research, 42*(8).

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature, 438*(7066), 303-309.

Barnett, T. P., Pierce, D. W., Hidalgo, H. G., Bonfils, C., Santer, B. D., Das, T., et al. (2008). Human-Induced Changes in the Hydrology of the Western United States. *Science, 319*, 4.

Blankinship, J. C., Meadows, M. W., Lucas, R. G., & Hart, S. C. (2014). Snowmelt timing alters shallow but not deep soil moisture in the Sierra Nevada. *Water Resources Research, 50*(2), 1448-1456.

Boyle, D. P., Gupta, H. V., & Sorooshian, S. (2000). Toward improved calibration of hydrologic models: Combining the strengths of manual and automatic methods. *Water Resources Research, 36*(12), 3663-3674.

Buckley, R. (2017). Perceived Resource Quality as a Framework to Analyze Impacts of Climate Change on Adventure Tourism: Snow, Surf, Wind, and Whitewater. *Tourism Review International, 21*(3), 241-254.

Burakowski, E., & Magnusson, M. (2012). *Climate Impacts on the Winter Tourism Economy in the United States*. Retrieved from Washington, DC:

Cayan, D. R. (1996). Interannual Climate Variability and Snowpack in the Western United States. *Journal of Climate, 9*, 928-948.

Clow, D. W. (2010). Changes in the Timing of Snowmelt and Streamflow in Colorado: A Response to Recent Warming. *Journal of Climate, 23*(9), 2293-2306.

Dierauer, J. R., Allen, D. M., & Whitfield, P. H. (2019). Snow Drought Risk and Susceptibility in the Western United States and Southwestern Canada. *Water Resources Research, 55*(4), 3076-3091.

Dudley, R. W., Hodgkins, G. A., McHale, M. R., Kolian, M. J., & Renard, B. (2017). Trends in snowmelt-related streamflow timing in the conterminous United States. *Journal of Hydrology, 547*, 208-221.

Dyer, J. L., & Mote, T. L. (2006). Spatial variability and trends in observed snow depth over North America. *Geophysical Research Letters, 33*(16).

Fassnacht, S. R., Heath, J. T., Venable, N. B. H., & Elder, K. J. (2018). Snowmobile impacts on snowpack physical and mechanical properties. *The Cryosphere, 12*(3), 1121-1135.

Ficklin, D. L., Stewart, I. T., & Maurer, E. P. (2013). Climate change impacts on streamflow and subbasin-scale hydrology in the Upper Colorado River Basin. *PLoS One, 8*(8), e71297.

Griffin, E. R., & Friedman, J. M. (2017). Decreased Runoff Response to Precipitation, Little Missouri River Basin, Northern Great Plains, USA. *JAWRA Journal of the American Water Resources Association, 53*(3), 576-592.

Hale, K. E., Jennings, K. S., Musselman, K. N., Livneh, B., & Molotch, N. P. (2023). Recent decreases in snow water storage in western North America. *Communications Earth & Environment, 4*(1).

Hamlet, A. F., Mote, P. W., Clark, M. P., & Lettenmaier, D. P. (2007). Twentieth-Century Trends in Runoff, Evapotranspiration, and Soil Moisture in the Western United States*. *Journal of Climate, 20*(8), 1468-1486.

Hammond, J. C., Sexstone, G. A., Putman, A. L., Barnhart, T. B., Rey, D. M., Driscoll, J. M., et al. (2023). High Resolution SnowModel Simulations Reveal Future Elevation-Dependent Snow Loss and Earlier, Flashier Surface Water Input for the Upper Colorado River Basin. *Earth's Future, 11*(2).

Harpold, A. A., Dettinger, M. D., & Rajagopal, S. (2017). Defining Snow Drought and Why It Matters. *EOS, 98*.

Harpold, A. A., & Molotch, N. P. (2015). Sensitivity of soil water availability to changing snowmelt timing in the western U.S. *Geophysical Research Letters, 42*(19), 8011-8020.

Hatchett, B. J., & McEvoy, D. J. (2018). Exploring the Origins of Snow Drought in the Northern Sierra Nevada, California. *Earth Interactions, 22*(2), 1-13.

Hatchett, B. J., Rhoades, A. M., & McEvoy, D. J. (2022). Monitoring the daily evolution and extent of snow drought. *Natural Hazards and Earth System Sciences, 22*(3), 869-890.

Hay, L. E., Wilby, R. L., Gutowski, W. J., Leavesley, G. H., Pan, Z., Arritt, R. W., & Takle, E. S. (2002). Use of Regional Climate Model Output for Hydrologic Simulations. *Journal of Hydrometeorology, 3*, 571-590.

Heldmyer, A. J., Bjarke, N. R., & Livneh, B. (2023). A 21st-Century perspective on snow drought in the Upper Colorado River Basin. *JAWRA Journal of the American Water Resources Association*.

Hock, R., Rasul, G., Adler, C., Cáceres, B. v., Gruber, S., Hirabayashi, Y., et al. (2022). High Mountain Areas. In *The Ocean and Cryosphere in a Changing Climate* (pp. 131-202).

Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J., et al. (2017). Toward mountains without permanent snow and ice. *Earth's Future, 5*(5), 418-435.

Ikeda, K., Rasmussen, R., Liu, C., Gochis, D., Yates, D., Chen, F., et al. (2010). Simulation of seasonal snowfall over Colorado. *Atmospheric Research, 97*(4), 462-477.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., et al. (2020). Importance and vulnerability of the world's water towers. *Nature, 577*(7790), 364-369. https://www.ncbi.nlm.nih.gov/pubmed/31816624

Jones, R., Travers, C., Rodgers, C., Lazar, B., English, E., Lipton, J., et al. (2012). Climate change impacts on freshwater recreational fishing in the United States. *Mitigation and Adaptation Strategies for Global Change, 18*(6), 731-758.

Kampf, S. K., McGrath, D., Sears, M. G., Fassnacht, S. R., Kiewiet, L., & Hammond, J. C. (2022). Increasing wildfire impacts on snowpack in the western U.S. *Proc Natl Acad Sci U S A, 119*(39), e2200333119. https://www.ncbi.nlm.nih.gov/pubmed/36122238

Klos, P. Z., Link, T. E., & Abatzoglou, J. T. (2014). Extent of the rain-snow transition zone in the western U.S. under historic and projected climate. *Geophysical Research Letters, 41*(13), 4560-4568.

Knowles, N., Dettinger, M. D., & Cayan, D. R. (2006). Trends in Snowfall versus Rainfall in the Western United States. *Journal of Geophysical Research, 19*.

Kunkel, K. E., Robinson, D. A., Champion, S., Yin, X., Estilow, T., & Frankson, R. M. (2016). Trends and Extremes in Northern Hemisphere Snow Characteristics. *Current Climate Change Reports, 2*(2), 65-73.

Li, D., Wrzesien, M. L., Durand, M., Adam, J., & Lettenmaier, D. P. (2017). How much runoff originates as snow in the western United States, and how will that change in the future? *Geophysical Research Letters, 44*, 6163-6172.

Liston, G. E., & Elder, K. (2006). A Distributed Snow-Evolution Modeling System (SnowModel). *Journal of Hydrometeorology, 7*(6), 1259-1276.

Liu, C., Ikeda, K., Rasmussen, R., Barlage, M., Newman, A. J., Prein, A. F., et al. (2017). Continental-scale convection-permitting modeling of the current and future climate of North America. *Climate Dynamics, 49*(1-2), 71-95.

Liu, C., Ikeda, K., Thompson, G., Rasmussen, R., & Dudhia, J. (2011). High-Resolution Simulations of Wintertime Precipitation in the Colorado Headwaters Region: Sensitivity to Physics Parameterizations. *Monthly Weather Review, 139*(11), 3533-3553.

Liu, Y., & Gupta, H. V. (2007). Uncertainty in hydrologic modeling: Toward an integrated data assimilation framework. *Water Resources Research, 43*(7).

McCabe, G. J., Wolock, D. M., & Valentin, M. (2018). Warming is Driving Decreases in Snow Fractions While Runoff Efficiency Remains Mostly Unchanged in Snow-Covered Areas of the Western United States. *Journal of Hydrometeorology, 19*(5), 803-814.

Miller, A. B., Winter, P. L., Sanchez, J. J., Peterson, D. L., & Smith, J. W. (2022). Climate Change and Recreation in the Western United States: Effects and Opportunities for Adaptation. *Journal of Forestry, 120*(4), 453-472.

Molotch, N. P., Brooks, P. D., Burns, S. P., Litvak, M., Monson, R. K., McConnell, J. R., & Musselman, K. (2009). Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests. *Ecohydrology, 2*(2), 129-142.

Musselman, K. N., Clark, M. P., Liu, C., Ikeda, K., & Rasmussen, R. (2017). Slower snowmelt in a warmer world. *Nature Climate Change, 7*(3), 214-219.

Musselman, K. N., Molotch, N. P., & Margulis, S. A. (2017). Snowmelt response to simulated warming across a large elevation gradient, southern Sierra Nevada, California. *The Cryosphere, 11*(6), 2847-2866.

NRCS. (2023). Automated Snow Monitoring. Retrieved from https://www.nrcs.usda.gov/wps/portal/wcc/home/aboutUs/monitoringPrograms/automatedSnowMonitoring/

Pfohl, A. K. D. (2016). *Examining trends in snowmelt contribution to streamflow in the Southern Rocky Mountains of Colorado.* (Master of Science), Colorado State University, Fort Collins, CO.

Pfohl, A. K. D., & Fassnacht, S. R. (2023). Evaluating Methods of Streamflow Timing to Approximate Snowmelt Contribution in High-Elevation

Mountain Watersheds. *Hydrology, 10*(75), 9.

Rasmussen, R., Ikeda, K., Liu, C., Gochis, D., Clark, M., Dai, A., et al. (2014). Climate Change Impacts on the Water Balance of the Colorado Headwaters: High-Resolution Regional Climate Model Simulations. *Journal of Hydrometeorology, 15*(3), 1091-1116.

Rasmussen, R., Liu, C., Ikeda, K., Gochis, D., Yates, D., Chen, F., et al. (2011). High-Resolution Coupled Climate Runoff Simulations of Seasonal Snowfall over Colorado: A Process Study of Current and Warmer Climate. *Journal of Climate, 24*(12), 3015-3048.

Rhoades, A. M., Hatchett, B. J., Risser, M. D., Collins, W. D., Bambach, N. E., Huning, L. S., et al. (2022). Asymmetric emergence of low-to-no snow in the midlatitudes of the American Cordillera. *Nature Climate Change, 12*(12), 1151-1159.

Ryberg, K. R., Akyüz, F. A., Wiche, G. J., & Lin, W. (2016). Changes in seasonality and timing of peak streamflow in snow and semi-arid climates of the north-central United States, 1910-2012. *Hydrological Processes, 30*(8), 1208-1218.

Salathé, E. P., Leung, L. R., Qian, Y., & Zhang, Y. (2010). Regional climate model projections for the State of Washington. *Climatic Change, 102*(1-2), 51-75.

Schrock, I. J. Y., Fassnacht, S. R., Collados-Lara, A.-J., Sanford, W. E., Pfohl, A. K. D., & Morán-Tejeda, E. (2021). Snow Water Equivalent Accumulation Patterns from a Trajectory Approach over the U.S. Southern Rocky Mountains. *Hydrology, 8*(3).

Scott, D., & Lemieux, C. (2010). Weather and Climate Information for Tourism. *Procedia Environmental Sciences, 1*, 146-183.

Scott, D., McBoyle, G., Minogue, A., & Mills, B. (2006). Climate Change and the Sustainability of Ski-based Tourism in Eastern North America: A Reassessment. *Journal of Sustainable Tourism, 14*(4), 376-398.

Serreze, M. C., Clark, M. P., Armstrong, R. L., McGinnis, D. A., & Pulwarty, R. S. (1999). Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data. *Water Resources Research, 35*(7), 2145-2160.

Siirila-Woodburn, E. R., Rhoades, A. M., Hatchett, B. J., Huning, L. S., Szinai, J., Tague, C., et al. (2021). A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment, 2*(11), 800-819.

Steiger, R., Scott, D., Abegg, B., Pons, M., & Aall, C. (2017). A critical review of climate change risk for ski tourism. *Current Issues in Tourism, 22*(11), 1343-1379.

Stewart, I. T. (2009). Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes, 23*(1), 78-94.

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes toward Earlier Streamflow Timing across Western North America. *Journal of Climate, 18*, 1136-1155.

Sturm, M., Goldstein, M. A., & Parr, C. (2017). Water and life from snow: A trillion dollar science question. *Water Resources Research, 53*(5), 3534-3544.

Tidwell, V. C., Moreland, B. D., Zemlick, K. M., Roberts, B. L., Passell, H. D., Jensen, D., et al. (2014). Mapping water availability, projected use and cost in the western United States. *Environmental Research Letters, 9*, 16.

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research, 53*(3), 2404-2418.

Vano, J. A. (2020). Implications of losing snowpack. *Nature Climate Change, 10*(5), 388-390.

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., & Weingartner, R. (2007). Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resources Research, 43*(7).

Voordendag, A., Réveillet, M., MacDonell, S., & Lhermitte, S. (2021). Snow model comparison to simulate snow depth evolution and sublimation at point scale in the semi-arid Andes of Chile. *The Cryosphere, 15*(9), 4241-4259.

Webb, R. W., Fassnacht, S. R., & Gooseff, M. N. (2015). Wetting and Drying Variability of the Shallow Subsurface Beneath a Snowpack in California’s Southern Sierra Nevada. *Vadose Zone Journal, 14*(8).

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science, 313*, 940-943.

Whitfield, P. H. (2013). Is ‘Centre of Volume’ a robust indicator of changes in snowmelt timing? *Hydrological Processes, 27*(18), 2691-2698.

Wiesnet, D. (1981). Winter Snow Drought. *EOS, 62*, 137.

Williams, C. J., McNamara, J. P., & Chandler, D. G. (2009). Controls on the temporal and spatial variability of soil moisture in a mountainous landscape: the signature of snow and complex terrain. *Hydrology and Earth System Sciences, 13*, 1325-1336.

Woodhouse, C. A., Pederson, G. T., Morino, K., McAfee, S. A., & McCabe, G. J. (2016). Increasing influence of air temperature on upper Colorado River streamflow. *Geophysical Research Letters, 43*, 2174-2181.

CHAPTER 2: PAST AND FUTURE SNOW YEAR CLASSIFICATIONS IN THE HEADWATERS OF THE COLORADO RIVER

2.1 Introduction

Water is a scarce resource in the western United States. Most water has a designated use and allocation prior to ever reaching the ground (Tidwell et al., 2014), and ever-increasing water demand regularly outpaces supply (Tidwell et al., 2018). Understanding the processes and patterns that are responsible for availability is essential. For much of the western U.S., the water supply originates in the mountains as snow, which acts as temporary storage during the winter and early spring, before melting, entering rivers, and making its way downstream (Barnett et al., 2005; Li et al., 2017; Serreze et al., 1999). Adaptations have been made (e.g., reservoirs) based on these seasonal patterns to overcome issues with inconsistent supply, not only during the dryer summer months, but also during years with decreased snow (Udall & Overpeck, 2017). This water is also finite, and consecutive years with low snowpack strain an already stressed system (Udall & Overpeck, 2017).

Using a combination of modeled and observed data, historic snow patterns and properties have been extensively studied and indicate an overall decrease in the seasonal snowpack across the western United States, with the degree of change varying by location. Snow-covered area (SCA) has decreased (Dyer & Mote, 2006; Stewart, 2009). Snow depth, especially in the spring, has decreased across North America (Dyer & Mote, 2006). Peak snow water equivalent (SWE) and April 1st SWE (often used as a proxy for peak) have decreased (Clow, 2010; Fassnacht & López-Moreno, 2020; Ficklin et al., 2013; Mote et al., 2018; Siirila-Woodburn et al., 2021; Stewart, 2009). Increased temperatures have resulted in changing the precipitation phase, with early and late season snow shifting to rain (Fassnacht et al., 2018; Hale et al., 2023; Jennings et al., 2018).

For the Colorado River basin, these changes have corresponded with decreased runoff volume (McCabe et al., 2017; Udall & Overpeck, 2017; Woodhouse et al., 2016). Streamflow timing has also changed, as summarized by various metrics (e.g., onset of melt, center of volume, etc.) illustrating an earlier occurrence (Clow, 2010; Pfohl & Fassnacht, 2023; Rauscher et al., 2008; Stewart et al., 2005). Earlier melt results in decreased late-summer soil moisture (Harpold & Molotch, 2015; Harpold et al., 2015; Molotch et al., 2009), which increases susceptibility to wildfires (Westerling et al., 2006) and decreases carbon uptake (Winchell et al., 2016).

Drought conditions are primarily classified as meteorological, soil moisture, and hydrological (Van Loon & Van Lanen, 2012), where hydrological droughts focus on deficits in water storages, primarily surface water (streamflow) and groundwater. Very few present drought indices include snow. Staudinger et al. (2014) proposed using a Snow Melt and Rain Index, which focuses deficits of rain and snow melt, not the seasonal snowpack itself. “Snow drought” has been used to define years or winters with decreased snow, but the metric for quantifying snow conditions is not consistent. For example, “snow drought” was broadly applied to conditions in North America and Eurasia during Water Year (WY; October 1, 1980, to September 30, 1981) 1981 based on satellite SCA data (Wiesnet, 1981). The ratio of SWE to total precipitation was used to examine long-term changes in snow patterns in New England (Huntington et al., 2004). Low winter precipitation and SWE values were described as drought for Colorado in WY 2002 (Pielke et al., 2005).

Extreme low snow conditions in the Pacific Northwest and California in 2015 and 2016 highlighted the necessity of having a clear definition of the term and on the conditions which create warm and dry snow drought, ultimately using the ratio of SWE to winter precipitation (SWE/P) (Harpold et al., 2017). A *warm* snow drought occurs with low snow and near-normal winter precipitation, and conditions are driven by increased temperatures. A *dry* snow drought occurs with low snow and low winter precipitation, and conditions are driven by decreased precipitation (Harpold et al., 2017) (Table 2-1). Different versions of the SWE/P percentiles have been applied in areas of the western U.S. (Dierauer et al., 2019; Heldmyer et al., 2023) (Table 2-1). Different snow years have also been classified as no or low snow, based on the 10th and 30th percentiles of peak SWE, respectively, with an additional classification of high snow for the 70th percentile (Siirila-Woodburn et al., 2021). A hybrid version of these two methods incorporated using daily SWE and winter precipitation percentiles but following the US Drought Monitor's (https://droughtmonitor.unl.edu) more stringent percentile breaks (Hatchett et al., 2022). Regardless of the method, the definition has evolved and is now used to describe a decrease in the amount of water stored in snow (Olsen et al., 2023).

Existing methods for examining and classifying snow conditions are either based on a measure of SWE and winter precipitation (Harpold et al., 2017; Hatchett et al., 2022) or a combination of snow-covered area (SCA) with meteorological conditions (Hidalgo-Hidalgo et al., 2022). The snow conditions are computed from varying data sources, such as observations and measurements (Harpold et al., 2017), and with increasing frequency, modeled datasets, such as state variables computed in the Variable Infiltration Capacity (VIC) model (Dierauer et al., 2019; Hale et al., 2023; Heldmyer et al., 2023; Marshall et al., 2019; Siirila-Woodburn et al., 2021). Finer spatial resolution datasets exist, such as the Airborne Snow Observatory (Painter et al., 2016), but to date, they lack the temporal resolution to ensure that critical times within a snow season (e.g., peak SWE) are appropriately captured.

We seek to address snow conditions in terms of snow drought and high versus low snow years in Colorado, using a combination of measured and modeled SWE and precipitation data with robust temporal and spatial resolution. This study compares 1) different methods of classifying snow drought and how results affect interpretations of long-term snow drought occurrence; and 2) 13 recent years (CTL) and 13 years under pseudo-global warming (PGW) conditions to examine future drought occurrence.

2.2 Data and Methodology

2.2.1 Study domain

For our station-based analysis, we based our study area on the west-central Colorado domain defined in Hammond et al. (2023) (Figure 2-1). For the high-resolution dataset, we used the domain within the watershed boundaries of the Eagle and Blue Rivers, two headwaters of the Colorado River (Figure 2-1). Elevation ranged from 2600 m to 3540 m for the SNOTEL stations and from 1870 m to 4330 m for the gridded dataset.

2.2.2 Datasets

We used SWE data from WRF-driven SnowModel runs (WRF-SM), a high-resolution (100-m) daily dataset developed for the Upper Colorado River by Hammond et al. (2023) which uses the Weather Research and Forecasting (WRF) Model meteorological variables (Ikeda et al., 2021; Liu et al., 2017; Rasmussen et al., 2014; Rasmussen et al., 2011) as input to run SnowModel (Liston & Elder, 2006). The 4-km WRF runs can capture complex atmospheric and land-surface processes better than other global/climate models, including orography and convection (Liu et al., 2011). This WRF dataset allows for comparison of historic and future conditions by examining how increased temperatures would affect historic conditions, i.e., investigating differences between high and low snow year and how PGW conditions may or may not exacerbate years that are already considered extremes. SnowModel simulates snow conditions (SWE, solid precipitation, snowmelt) and can be applied in mountainous terrain (Liston & Elder, 2006). We also used SWE and precipitation data from 45 SNOTEL stations (Figure 2-1), monitored and maintained by Natural Resources Conservation Service (https://www.nrcs.usda.gov/wps/portal/wcc/home/), with at least a 30-year period of record between WY 1981 and 2020. We used 1717 station-years; 4 were excluded from analysis due to missing more than 30 days of data.

2.2.3 Temporal analysis

For each SNOTEL station, we calculated the annual SWE:P using four different methods that characterize peak SWE and the snow accumulation period differently (Table 2-1). The first method (Figure 2-2a) used SWE on April 1st and winter precipitation from November 1 to April 1 (Harpold et al., 2017). The second method (Figure 2-2b) used peak SWE and winter precipitation from November 1 to April 1 (Dierauer et al., 2019). The third method (Figure 2-2c) used peak SWE and calculated winter precipitation from onset of accumulation to peak SWE, where onset occurred on the day at which SWE was greater than 5% of the long-term mean (Heldmyer et al., 2023). The fourth method (Figure 2-2d), developed for this study, uses peak SWE and defines winter precipitation as the cumulative amount from the first day of continuous snow accumulation to the date of peak SWE. Based on Dierauer et al. (2019) and Heldmyer et al. (2023), a given year is in snow drought if SWE is less than the long-term mean. Snow drought can then be classified as warm or dry: warm snow drought occurs when winter precipitation is greater than long-term mean, and dry snow drought occurs when winter precipitation is less (Harpold et al., 2017). Rather than define a third classification of warm and dry snow drought, we instead focused on comparing methodologies through their subsequent results. To examine the difference between the various drought types, we used the non-parametric Kruskal-Wallis test (Hollander & Wolfe, 1973).

2.2.4 Spatial analysis

Siirila-Woodburn et al. (2021) used percentiles of peak SWE to classify snow years. We used very low, low, medium, high, or very high, corresponding with 10th, 30th, 70th, and 90th percentiles, respectively. The 90th percentile was an addition from Siirila-Woodburn et al. (2021) to examine how years with near-record high snow changed throughout the study. Percentiles were calculated for SNOTEL stations individually for the 40-year period of record. For the WRF-SM dataset, percentiles were calculated by pixel and by 100-m elevation band, for 26 years, combining the CTL and PGW periods. We also applied these percentiles to winter precipitation from onset of accumulation (described above) to peak SWE (Hatchett et al., 2022).

2.3 Results

2.3.1 SNOTEL stations

Drought occurrences identified with the different methods of SWE/P are similar (Table 2-2), with no drought happening 48% of the years using the Harpold et al. (2017) method and 45% for the others. Dry snow drought was more common than warm, with a dry snow drought occurrence of 45% using the Harpold et al. (2017) and Dierauer et al. (2019) methods, 48% with Heldmyer et al. (2023) method, and 49% with the methods developed for this analysis (Table 2-2). Warm drought occurred most frequently (10%) with the Dierauer et al. (2019) method and

7% for the remaining methods. The timing of the drought years and specific drought types are relatively similar across the different methods, especially in WY 1981, 2002, and 2012, which were some of the driest years on record (Figure A-1). WY 1983 was classified as “no drought” for all methods. SWE/P ranged between 0 to 1.22, 0.2 to 1.78, 0.21 to 1.04, and 0.23 to 0.97 for the Harpold et al. (2017), Dierauer et al. (2019), Heldmyer et al. (2023), and this analysis, respectively (Table 2-2). Results from the Kruskal-Wallis test indicate that the different drought types are statistically different ($p < 0.05$) from each other for all of the methods (Table 2-2).

For the percentile-based drought classifications, drought (low and very low snow) conditions occurred at 50% or more of the SNOTEL stations in WY 1981, 1987, 1990, 1992, 2001, 2002, 2004, 2012, 2013, 2015, and 2018 (Table 2-3; Figure 2-3). High and very high conditions occurred at 50% or more of the SNOTEL stations in WY 1982, 1983, 1984, 1986, 1993, 1995, 1996, 1997, 2008, 2011, 2014, and 2019 (Table 2-3; Figure 2-3). Comparing the percentile of precipitation versus the percentile of SWE shows there are 122 station-years (7.1% of the record) when precipitation is in the 30th percentile or above, but SWE is classified as low or very low (Table A-1; Figure 2-4F). Similarly, there are 111 station-years (6.5%) when precipitation is less than 30th percentile and SWE is categorized as a medium or high year (Table A-1; Figure 2-4).

2.3.2 WRF-SnowModel runs

Snowpack SWE was classified as low or very low from WY 2001 to 2013 more frequently at SNOTEL stations than the CTL of the SnowModel runs (Figure A-2a and 2-6b). The years 2001, 2002, and 2012 were classified as low or very low snow for both CTL and PGW scenarios at more than 50% of the total area for the Blue River and Eagle River Watersheds and during 2007 and 2013 for the PGW scenario alone (Figure A-2a and 2-6c). The years 2005, 2008, and 2011 were classified as high or very high snow for the CTL and PGW runs; 2009 was also a high/very high year for CTL (Figure A-2a and 2-6c). Comparing PGW and CTL (Figure 2-5), there was an increase in the low and very low classifications in 2001, 2003 through 2007, and 2013. In 2012 and 2013, there was an increase in the number of low snow classifications and decrease in very low. In 2008, 2010, and 2011, there was an increase in the very high or high designations, and all remaining years except for 2001, 2002, and 2012 decreased (Figure 2-5).

Within a given CTL year, across varying elevations (1800 to 4300m elevation bands), the snow year classification was consistent (Figure A-3a). There was more variation among elevation bands within a given year for the PGW scenario, particularly in 2003, 2005, and 2011 (Figure A-3b). The most changes between PGW and CTL happened at elevations below 2800m (Figure 2-6). The relationship between winter precipitation and peak SWE percentiles changed between CTL and PGW in 2008 and 2011 (Figure A-4). In 2008, the range in SWE percentiles decreased, and the minimum percentiles increased. In 2011, the overall range increased, with the occurrence in lower percentiles increasing, especially for peak SWE.

Total water storage at peak SWE for the Eagle and Blue River watersheds was just under 11 MAF for CTL and about 10.1 MAF for PGW (Figure 2-7). Storage increased under PGW conditions in 2008, 2010, and 2012 by 0.16 MAF but decreased in all other years. The largest decrease was about 0.2 MAF in 2011 (Figure 2-7).

2.4 Discussion

2.4.1 Method comparison of drought occurrence

Combining the warm and dry snow drought types results in drought conditions occurring more than 50% of the time across the varying methods of SWE/P (Table 2-2). Of years with drought, dry snow drought is more common, making up between 78% and 85% of droughts across all station-years, illustrating that when SWE is low, winter precipitation is as well, indicating a low occurrence of winter rain (Moran-Tejeda et al., 2022). In dividing the forty-year study period in half, drought defined by SWE/P increased in frequency from 2001 to 2020, happening in 60% of all station-years (Udall & Overpeck, 2017). Decreased streamflow and snow have been observed in other studies, just not to the same degree as what these results suggest (McCabe et al., 2017; McCabe et al., 2018; Vano et al., 2014; Woodhouse et al., 2016).

The drought types within each methodology lead to different values and groups that were statistically different (Table 2-2; Figure A-1). However, the ranges are such that snow drought type can't be determined based on the ratio alone (Table 2-2). April 1 SWE does not always correspond with the timing of peak SWE (Bohr & Aguado, 2001). In this analysis, SWE/P was equal to 0 at low elevation SNOTEL stations when melt started and ended early in the spring before April 1. Using November 1 to April 1 to represent winter precipitation (Figure 2-2b) is similarly arbitrary, and, depending on the year, could start and end early or late depending on the winter conditions.

Results were most similar between this current analysis (Table 2-2; Figure A-1d) and Heldmyer et al. (2023) (Table 2-2; Figure A-1c). Using the Heldmyer et al. (2023) definition of onset is generally reliable, except for years with early snowfall that quickly melts (Figure 2-8a) or years when SWE increases more slowly (Figure 2-8b). Both these examples lead to a difference of a month for determining onset of accumulation. Using different SNOTEL stations that cover a larger area or a different time frame would make this variability more pronounced.

The SWE/P ratio was greater than one for all methods except for those developed in this analysis, indicating that SWE exceeded cumulative winter precipitation (Table 2-2). This occurred when precipitation was underestimated. Using November 1 to April 1 for winter precipitation excludes any snow accumulation that may occur in October (Figure 2-8b). As described above, the 5% threshold is insufficient for years with slow initial accumulation.

The addition of precipitation percentiles to SWE percentiles provides more context on overall winter conditions compared to the long-term, especially for years that may be considered very low snow but have winter precipitation close to the mean. This indicates that there was more precipitation as rain (Moran-Tejeda et al., 2022) or melt that occurred mid-season (Fassnacht et al., 2022) (Figures 2-5 and 2-8). The inclusion of precipitation percentiles is the same principle as the SWE/P ratios but is an improvement since there is more information about how and to what extent a given year compares to others.

Drought occurrence and low/very low snow years were more frequent from 2001 to 2020 than from 1981 to 2000 (Tables 2-2 and 2-3). Conversely, the frequency of high/very high snow years decreased from 2001 to 2020 (Table 2-3). The primary criterion of drought classification with the SWE/P method is peak SWE being less than the long-term, resulting in the frequent occurrence of droughts outlined here and in Heldmyer et al. (2023). Years just slightly below the long-term mean are classified as snow drought, even if water supply was able to meet demand for that particular year. This is likely an overestimation of drought occurrence (Dierauer et al., 2019) and classifies all snow droughts, regardless of intensity, as the same. Unlike with using the percentiles, the SWE/P provides no information about high snow years, which provide a buffer to the water supply during low snow years (Figure 2-3).

2.4.2 Recent and future snow years

Increased frequency in low and very low snow years is consistent with other studies that have examined changes to the long-term snowpack (Ayers et al., 2016; Ficklin et al., 2013;

Gergel et al., 2017; Hammond et al., 2023; Siirila-Woodburn et al., 2021), though the warming scenarios and datasets from these studies are not the same. Except for Hammond et al. (2023), past studies have used relatively coarse (>4-km) resolution datasets to examine the seasonal snowpack when reporting findings for entire basins (e.g., Upper Colorado River). These studies have been critical in understanding broad changes but may obscure subtle, yet still important, differences in past and future snow conditions. For example, Hammond et al. (2023) found that peak SWE will decrease for much of their study domain under a PGW scenario, except for a few areas where SWE increases, including our study domain. Past research has largely focused on the decreases in snow, but areas and years with increased winter water storage will be critical in the future (Figure 2-7).

Changes between low snow (e.g., 2002 and 2012) years from PGW to CTL were not the same (Figure 2-7a and Figure 2-7b). At high elevations, drought classification shifted from low to very low in 2002 but from very low to low or medium in 2012. The most extreme changes occurred in high snow years (e.g., 2005 and 2011) at low elevations (Figure 2-6), with shifts from high or very high to low or very low. These findings are similar to Hammond et al. (2023), in particular with 2011 (a high snow year) where the differences are more pronounced at low elevations (Figure 2-6 and Figure 8). Additionally, Ficklin et al. (2013) found that lower elevations within the Upper Colorado River Basin will experience greater aridity in the future.

2.5 Conclusions

We compared different methods of classifying snow drought using two different datasets in Colorado. Results for the different methods of peak SWE to winter precipitation ratios were similar and classified more than half of all station-years as either a dry or warm snow drought, overstating the number of years with drought. Using percentiles of peak SWE, we found that drought (peak SWE in 10th and 30th percentiles) frequency increased for the period from 2001 to 2020 compared to 1981 to 2000, and frequency of high snow (peak SWE in 70th and 90th percentiles) years decreased. When examining snow drought conditions for future studies, we suggest looking at peak SWE and winter precipitation percentiles (10th and 30th for drought conditions) since these metrics provide information about how a given year compares to the period of record and has more stringent criteria than what has been proposed with the SWE/P ratios. Under PGW conditions, lower elevations will be more susceptible to snow drought and will have more low snow years. A high snow year, like 2011, in the future will have the greatest reduction in water storage at peak SWE. Understanding these changes, especially the differences across elevations and over different years, is critical for present and future water management. Additional research should be conducted to see how these changes are reflected across larger study areas.

2.6 Tables

Table 2-1. Description of the different methods used to calculate SWE/P for temporal analysis with SNOTEL stations. The percent occurrence of each drought type (warm, dry, no drought) based on specified criteria.

Method	SWE	Winter precipitation	Drought criteria
Harpold et al. (2017)	April 1	November 1 to April 1	Snow drought occurs when $(SWE_i < \overline{SWE})$ Dry when $(P_i < \bar{P})$ Warm when $(P_i > \bar{P})$
Dierauer et al. (2019)	peak	November 1 to April 1	
Heldmyer et al. (2023)	peak	Onset (SWE greater than 5% of long-term mean) to peak	
this analysis	peak	Onset (continuous SWE accumulation) to peak	

Table 2-2. Summary of results using different methods and time frames of SWE/P

Method	Drought type	Drought occurrence (%)	Drought occurrence 1981 to 2000 (%)	Drought occurrence 2001 to 2020 (%)	Min SWE/P	Max SWE/P	Median SWE/P	χ^2
Harpold et al. (2017)	No drought	48	52	43	0.21	1.22	0.83	200.41**
	Dry	45	39	51	0	1.15	0.76	
	Warm	7	9	6	0	0.88	0.67	
Dierauer et al. (2019)	No drought	45	50	40	0.38	1.68	0.95	202.07**
	Dry	45	38	52	0.24	1.78	0.85	
	Warm	10	12	8	0.20	1.04	0.77	
Heldmyer et al. (2023)	No drought	45	50	40	0.44	1.01	0.79	180.9**
	Dry	48	42	52	0.28	1.04	0.78	
	Warm	7	8	8	0.21	0.77	0.64	
this analysis	No drought	45	50	40	0.45	0.97	0.77	216.93**
	Dry	49	42	52	0.26	0.96	0.75	
	Warm	7	8	8	0.23	0.76	0.62	

**indicates statistically significant at $p < 0.05$.

Table 2-3. Occurrence of low and high snow years using percentile of peak SWE for SNOTEL stations and WRF-SM.

Time frame	Low/very low snow (%)	High/very high snow (%)
1981 to 2000	25	36
2001 to 2020	36	24
2001 to 2013 (SNOTEL)	39	23
WRF-SM CTL	21	37
WRF-SM PGW	41	24

2.7 Figures

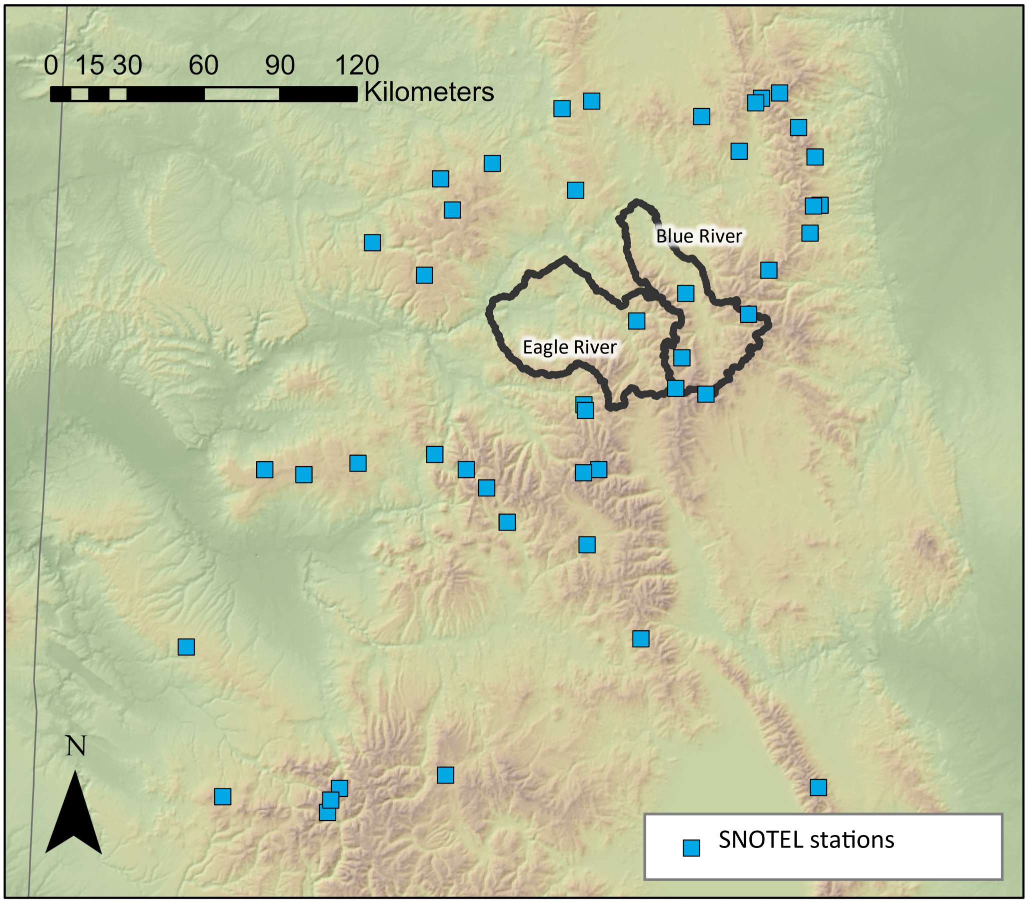


Figure 2-1. Map of study locations and SNOTEL stations.

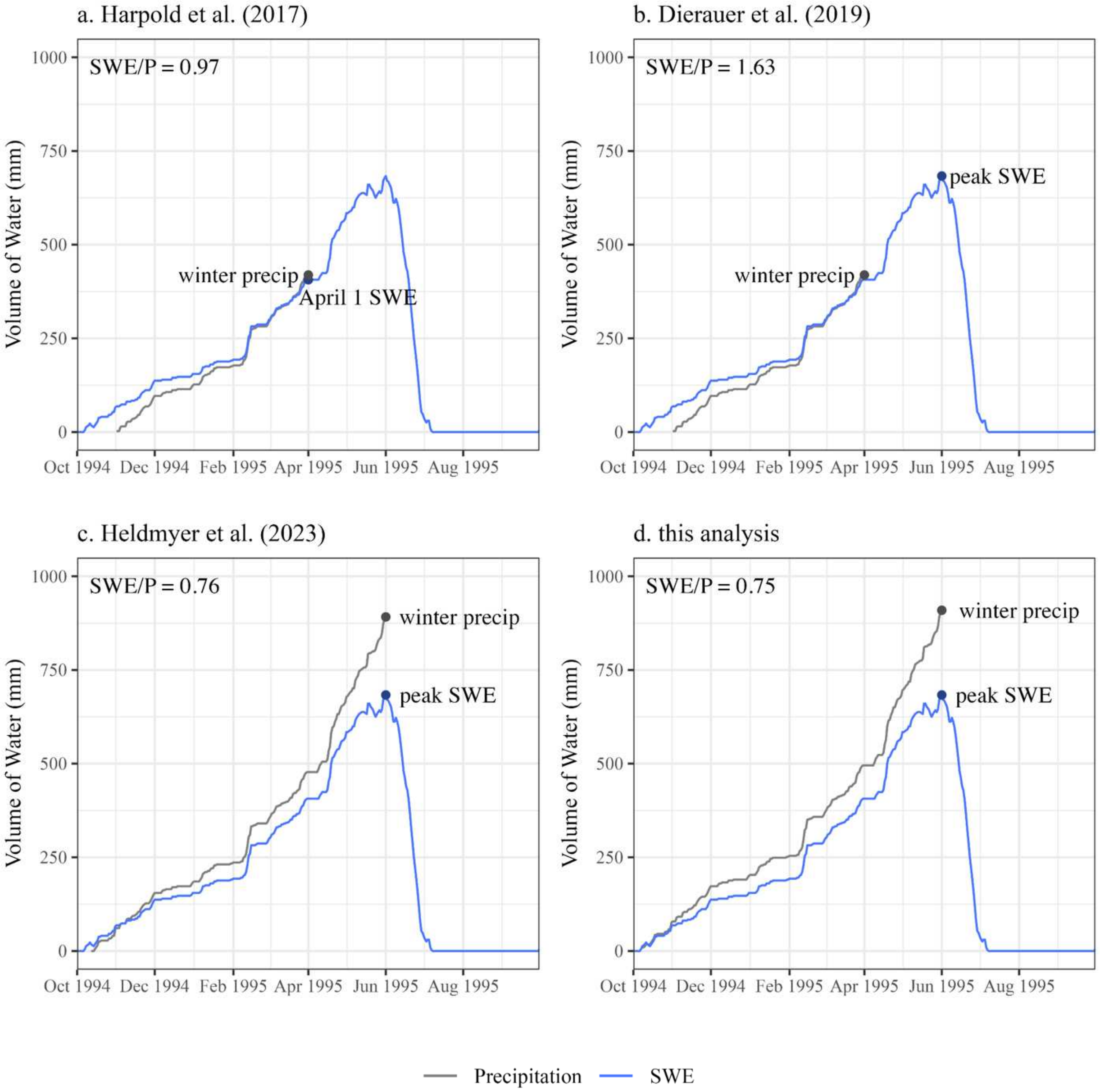


Figure 2-2. Hoosier Pass SNOTEL Station SWE and winter precipitation for WY 1995 for each of the four methods of calculating SWE/P.

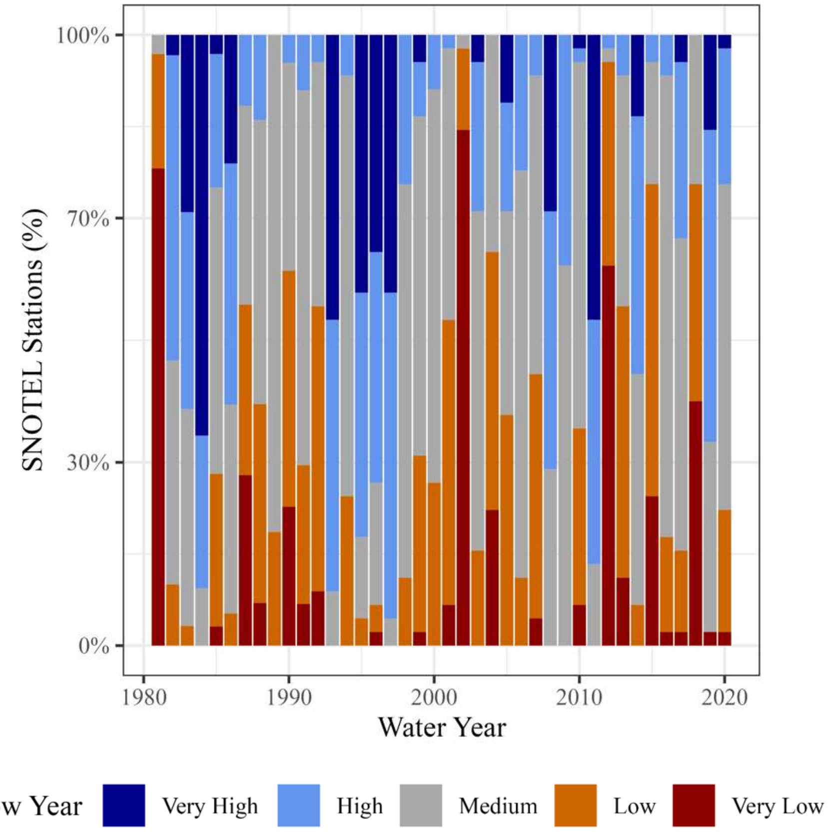


Figure 2-3. Snow year classifications based on percentiles of peak SWE for SNOTEL stations.

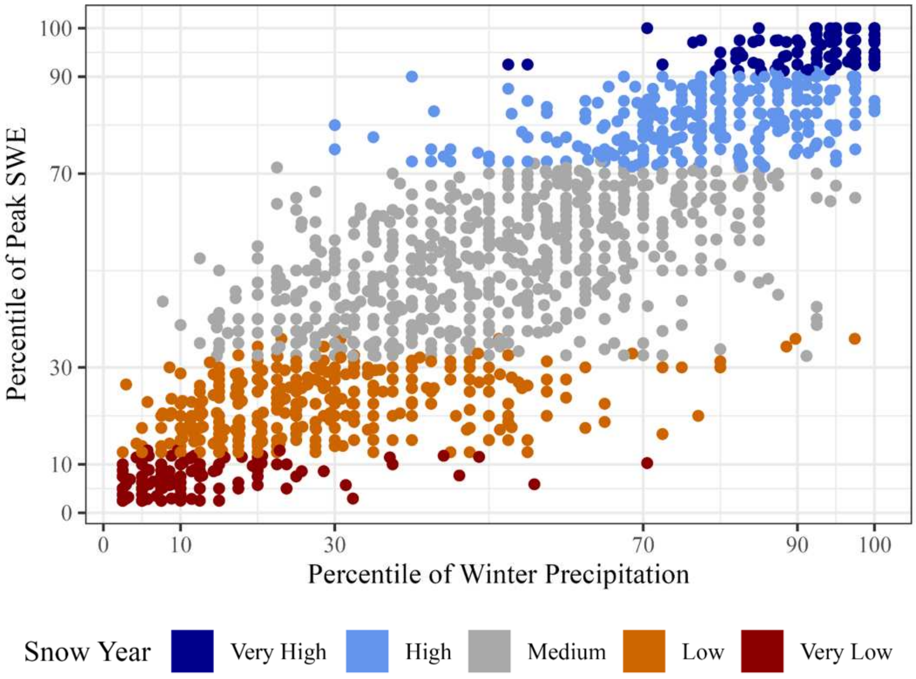


Figure 2-4. Winter precipitation percentile and peak SWE percentile for SNOTEL stations.

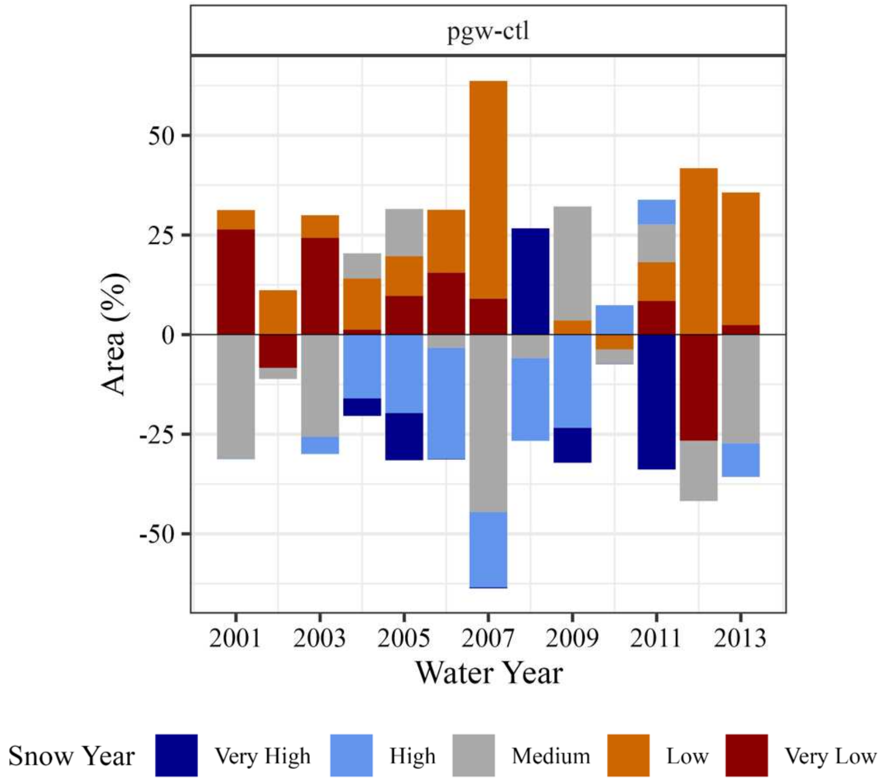


Figure 2-5 Snow year classifications for peak SWE using WRF-SM dataset.

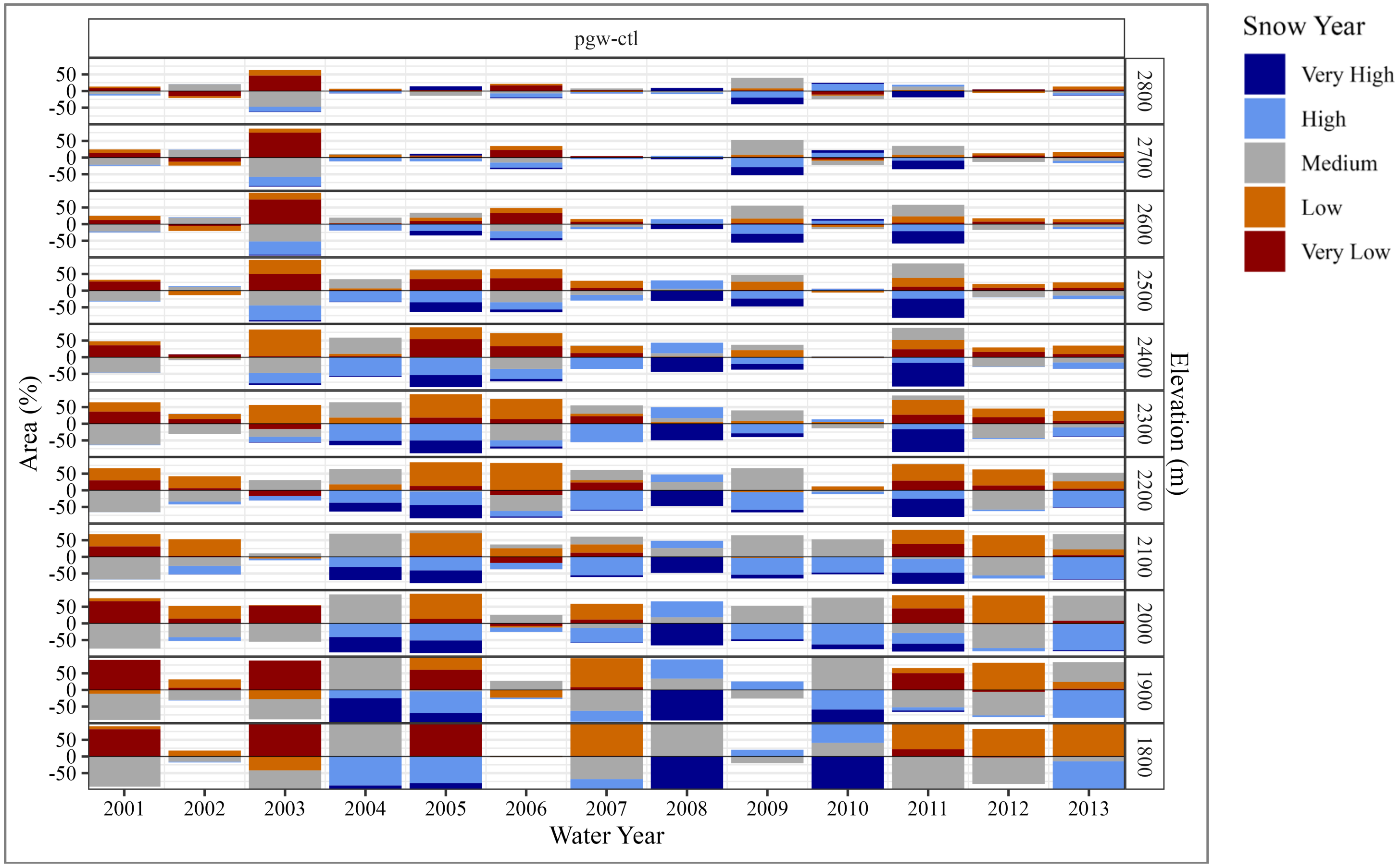


Figure 2-6. Snow year classifications for peak SWE by elevation band using WRF-SM dataset.

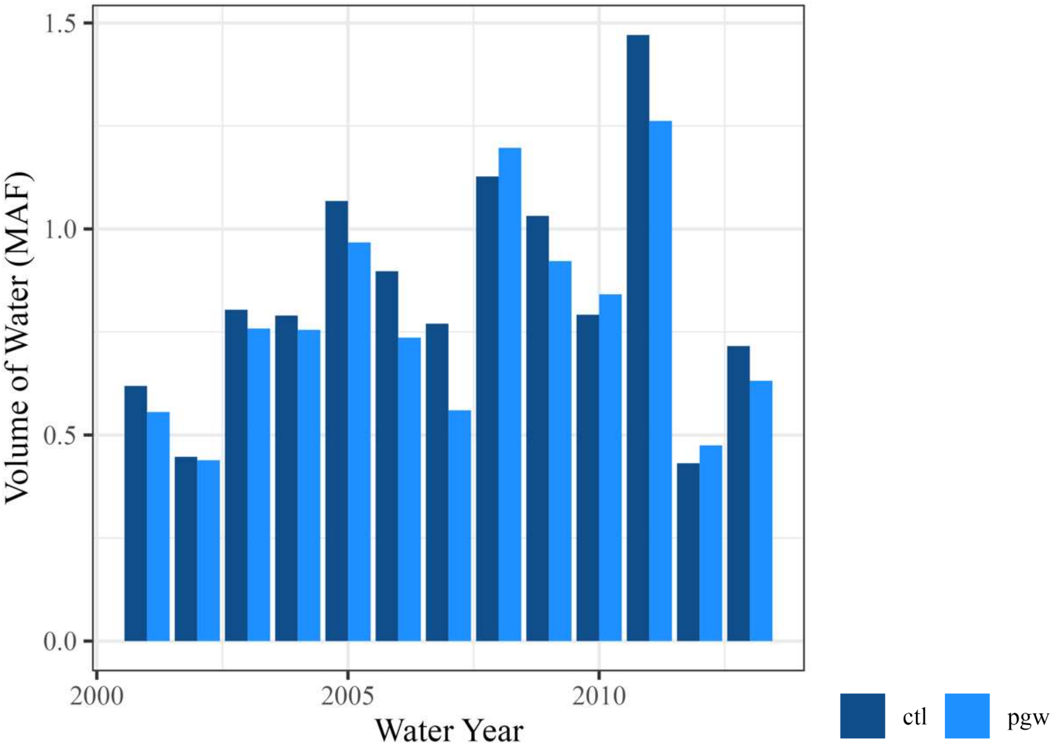


Figure 2-7. Total storage in the Eagle River and Blue River watersheds at time of peak SWE.

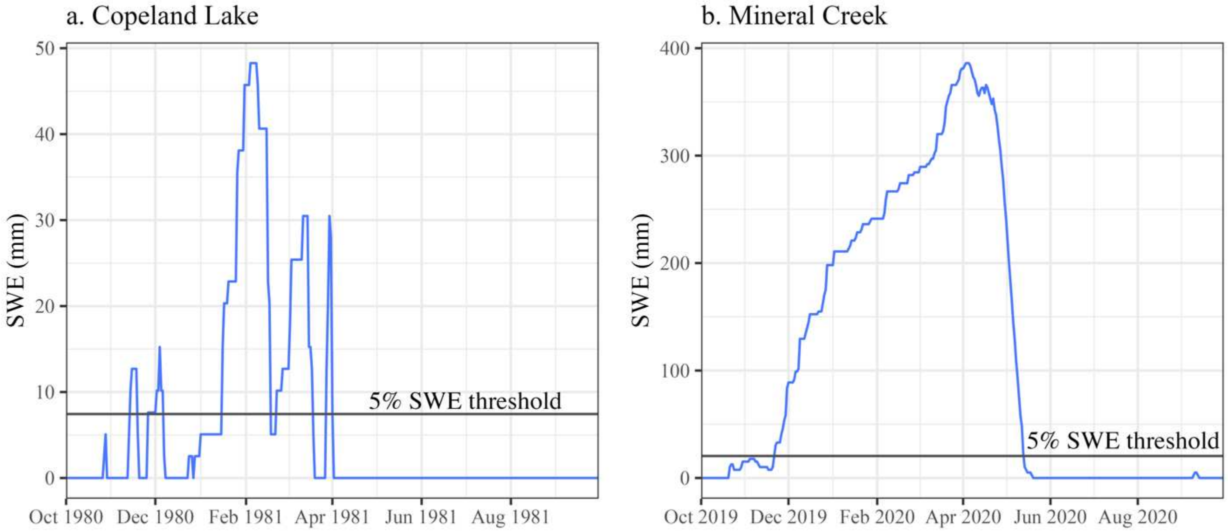


Figure 2-8. Daily SWE for a. Copeland Lake SNOTEL in 1981 where onset is November 14, 1980 (Heldmyer et al., 2023) or December 20, 1980 (this analysis); and b. Mineral Creek SNOTEL in 2020 where onset is October 21, 2019 (this analysis) or November 22, 2019 (Heldmyer et al., 2023).

2.8 References

Ayers, J., Ficklin, D. L., Stewart, I. T., & Strunk, M. (2016). Comparison of CMIP3 and CMIP5 projected hydrologic conditions over the Upper Colorado River Basin. *International Journal of Climatology, 36*(11), 3807-3818.

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature, 438*(7066), 303-309.

Bohr, G. S., & Aguado, E. (2001). Use of April 1 SWE measurements as estimates of peak seasonal snowpack and total cold-season precipitation. *Water Resources Research, 37*(1), 51-60.

Clow, D. W. (2010). Changes in the Timing of Snowmelt and Streamflow in Colorado: A Response to Recent Warming. *Journal of Climate, 23*(9), 2293-2306.

Dierauer, J. R., Allen, D. M., & Whitfield, P. H. (2019). Snow Drought Risk and Susceptibility in the Western United States and Southwestern Canada. *Water Resources Research, 55*(4), 3076-3091.

Dyer, J. L., & Mote, T. L. (2006). Spatial variability and trends in observed snow depth over North America. *Geophysical Research Letters, 33*(16).

Fassnacht, S. R., Collados-Lara, A.-J., Xu, K., Sears, M. G., Pulido-Velazquez, D., & Morán-Tejeda, E. (2022). *Defining Actual Daily Snowmelt Rates from In Situ Snow Water Equivalent Measurements.* Paper presented at the 39th IAHR World Congress, Granada Spain.

Fassnacht, S. R., Heath, J. T., Venable, N. B. H., & Elder, K. J. (2018). Snowmobile impacts on snowpack physical and mechanical properties. *The Cryosphere, 12*(3), 1121-1135.

Fassnacht, S. R., & López-Moreno, J. I. (2020). Patterns of trends in niveograph characteristics across the western United States from snow telemetry data. *Frontiers of Earth Science, 14*(2), 315-325.

Ficklin, D. L., Stewart, I. T., & Maurer, E. P. (2013). Climate change impacts on streamflow and subbasin-scale hydrology in the Upper Colorado River Basin. *PLoS One, 8*(8), e71297.

Gergel, D. R., Nijssen, B., Abatzoglou, J. T., Lettenmaier, D. P., & Stumbaugh, M. R. (2017). Effects of climate change on snowpack and fire potential in the western USA. *Climatic Change, 141*(2), 287-299.

Hale, K. E., Jennings, K. S., Musselman, K. N., Livneh, B., & Molotch, N. P. (2023). Recent decreases in snow water storage in western North America. *Communications Earth & Environment, 4*(1).

Hammond, J. C., Sexstone, G. A., Putman, A. L., Barnhart, T. B., Rey, D. M., Driscoll, J. M., et al. (2023). High Resolution SnowModel Simulations Reveal Future Elevation-Dependent Snow Loss and Earlier, Flashier Surface Water Input for the Upper Colorado River Basin. *Earth's Future, 11*(2).

Harpold, A. A., Dettinger, M. D., & Rajagopal, S. (2017). Defining Snow Drought and Why It Matters. *EOS, 98*.

Harpold, A. A., & Molotch, N. P. (2015). Sensitivity of soil water availability to changing snowmelt timing in the western U.S. *Geophysical Research Letters, 42*(19), 8011-8020.

Harpold, A. A., Molotch, N. P., Musselman, K. N., Bales, R. C., Kirchner, P. B., Litvak, M., & Brooks, P. D. (2015). Soil moisture response to snowmelt timing in mixed-conifer subalpine forests. *Hydrological Processes, 29*(12), 2782-2798.

Hatchett, B. J., Rhoades, A. M., & McEvoy, D. J. (2022). Monitoring the daily evolution and extent of snow drought. *Natural Hazards and Earth System Sciences, 22*(3), 869-890.

Heldmyer, A. J., Bjarke, N. R., & Livneh, B. (2023). A 21st-Century perspective on snow drought in the Upper Colorado River Basin. *JAWRA Journal of the American Water Resources Association*.

Hidalgo-Hidalgo, J.-D., Collados-Lara, A.-J., Pulido-Velazquez, D., Rueda, F. J., & Pardo-Igúzquiza, E. (2022). Analysis of the Potential Impact of Climate Change on Climatic Droughts, Snow Dynamics, and the Correlation between Them. *Water, 14*(7).

Hollander, M., & Wolfe, D. A. (1973). *Nonparametric Statistical Methods*. New York: John Wiley & Sons.

Huntington, T. G., Hodgkins, G. A., Keim, B. D., & Dudley, R. W. (2004). Changes in the Proportion of Precipitation Occurring as Snow in New England (1949-2000). *Journal of Climate, 17*.

Ikeda, K., Rasmussen, R., Liu, C., Newman, A., Chen, F., Barlage, M., et al. (2021). Snowfall and snowpack in the Western U.S. as captured by convection permitting climate simulations: current climate and pseudo global warming future climate. *Climate Dynamics, 57*(7-8), 2191-2215.

Jennings, K. S., Winchell, T. S., Livneh, B., & Molotch, N. P. (2018). Spatial variation of the rain-snow temperature threshold across the Northern Hemisphere. *Nat Commun, 9*(1), 1148.

Li, D., Wrzesien, M. L., Durand, M., Adam, J., & Lettenmaier, D. P. (2017). How much runoff originates as snow in the western United States, and how will that change in the future? *Geophysical Research Letters, 44*, 6163-6172.

Liston, G. E., & Elder, K. (2006). A Distributed Snow-Evolution Modeling System (SnowModel). *Journal of Hydrometeorology, 7*(6), 1259-1276.

Liu, C., Ikeda, K., Rasmussen, R., Barlage, M., Newman, A. J., Prein, A. F., et al. (2017). Continental-scale convection-permitting modeling of the current and future climate of North America. *Climate Dynamics, 49*(1-2), 71-95.

Liu, C., Ikeda, K., Thompson, G., Rasmussen, R., & Dudhia, J. (2011). High-Resolution Simulations of Wintertime Precipitation in the Colorado Headwaters Region: Sensitivity to Physics Parameterizations. *Monthly Weather Review, 139*(11), 3533-3553.

Marshall, A. M., Abatzoglou, J. T., Link, T. E., & Tennant, C. J. (2019). Projected Changes in Interannual Variability of Peak Snowpack Amount and Timing in the Western United States. *Geophysical Research Letters, 46*(15), 8882-8892.

McCabe, G. J., Wolock, D. M., Pederson, G. T., Woodhouse, C. A., & McAfee, S. (2017). Evidence that Recent Warming is Reducing Upper Colorado River Flows. *Earth Interactions, 21*(10), 1-14.

McCabe, G. J., Wolock, D. M., & Valentin, M. (2018). Warming is Driving Decreases in Snow Fractions While Runoff Efficiency Remains Mostly Unchanged in Snow-Covered Areas of the Western United States. *Journal of Hydrometeorology, 19*(5), 803-814.

Molotch, N. P., Brooks, P. D., Burns, S. P., Litvak, M., Monson, R. K., McConnell, J. R., & Musselman, K. (2009). Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests. *Ecohydrology, 2*(2), 129-142.

Moran-Tejeda, E., Fassnacht, S. R., Pfohl, A. K. D., Collados-Lara, A. J., Tedesche, M. E., & Pulido-Velazquez, D. (2022, 19-24 June 2022). *A proposal for studying rain-on-snow* *events: a case study from SNOTEL data in the Southern Rocky Mountains, U.S.A.* Paper presented at the Proceedings of the 39th IAHR World Congress, Granada, Spain.

Mote, P. W., Li, S., Lettenmaier, D. P., Xiao, M., & Engel, R. (2018). Dramatic declines in snowpack in the western US. *npj Climate and Atmospheric Science, 1*(1).

Olsen, J. R., Dettinger, M. D., & Giovannettone, J. P. (2023). Drought Attribution Studies and Water Resources Management. *Bulletin of the American Meteorological Society, 104*(2), E435-E441.

Pfohl, A. K. D., & Fassnacht, S. R. (2023). Evaluating Methods of Streamflow Timing to Approximate Snowmelt Contribution in High-Elevation

Mountain Watersheds. *Hydrology, 10*(75), 9.

Pielke, R. A., Doesken, N., Bliss, O., Green, T., Chaffin, C., Salas, J. D., et al. (2005). Drought 2002 in Colorado: An Unprecedented Drought or a Routine Drought? *Pure and Applied Geophysics, 162*(8-9), 1455-1479.

Rasmussen, R., Ikeda, K., Liu, C., Gochis, D., Clark, M., Dai, A., et al. (2014). Climate Change Impacts on the Water Balance of the Colorado Headwaters: High-Resolution Regional Climate Model Simulations. *Journal of Hydrometeorology, 15*(3), 1091-1116.

Rasmussen, R., Liu, C., Ikeda, K., Gochis, D., Yates, D., Chen, F., et al. (2011). High-Resolution Coupled Climate Runoff Simulations of Seasonal Snowfall over Colorado: A Process Study of Current and Warmer Climate. *Journal of Climate, 24*(12), 3015-3048.

Rauscher, S. A., Pal, J. S., Diffenbaugh, N. S., & Benedetti, M. M. (2008). Future changes in snowmelt-driven runoff timing over the western US. *Geophysical Research Letters, 35*(16).

Serreze, M. C., Clark, M. P., Armstrong, R. L., McGinnis, D. A., & Pulwarty, R. S. (1999). Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data. *Water Resources Research, 35*(7), 2145-2160.

Siirila-Woodburn, E. R., Rhoades, A. M., Hatchett, B. J., Huning, L. S., Szinai, J., Tague, C., et al. (2021). A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment, 2*(11), 800-819.

Staudinger, M., Stahl, K., & Seibert, J. (2014). A drought index accounting for snow. *Water Resources Research, 50*(10), 7861-7872.

Stewart, I. T. (2009). Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes, 23*(1), 78-94.

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes toward Earlier Streamflow Timing across Western North America. *Journal of Climate, 18*, 1136-1155.

Tidwell, V. C., Moreland, B. D., Zemlick, K. M., Roberts, B. L., Passell, H. D., Jensen, D., et al. (2014). Mapping water availability, projected use and cost in the western United States. *Environmental Research Letters, 9*, 16.

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research, 53*(3), 2404-2418.

Van Loon, A. F., & Van Lanen, H. A. J. (2012). A process-based typology of hydrological drought. *Hydrology and Earth System Sciences, 16*(7), 1915-1946.

Vano, J. A., Udall, B., Cayan, D. R., Overpeck, J. T., Brekke, L. D., Das, T., et al. (2014). Understanding Uncertainties in Future Colorado River Streamflow. *Bulletin of the American Meteorological Society, 95*(1), 59-78.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science, 313*, 940-943.

Wiesnet, D. (1981). Winter Snow Drought. *EOS, 62*, 137.

Winchell, T. S., Barnard, D. M., Monson, R. K., Burns, S. P., & Molotch, N. P. (2016). Earlier snowmelt reduces atmospheric carbon uptake in midlatitude subalpine forests. *Geophysical Research Letters, 43*(15), 8160-8168.

Woodhouse, C. A., Pederson, G. T., Morino, K., McAfee, S. A., & McCabe, G. J. (2016). Increasing influence of air temperature on upper Colorado River streamflow. *Geophysical Research Letters, 43*, 2174-2181.

CHAPTER 3: HYDROLOGICAL MODELING OF RECENT AND FUTURE STREAMFLOW, SNOW, AND FLOW PARTITIONING

3.1 Introduction

The frequency of low snow years is increasing (Rhoades et al., 2022; Schrock et al., 2021; Siirila-Woodburn et al., 2021) and is expected to increase in the future (Dierauer et al., 2019; Heldmyer et al., 2023; Siirila-Woodburn et al., 2021), while the frequency of high snow years is expected to decrease (Lute et al., 2015). The western United States has largely been dependent on high snow years in the past to refill reservoirs and maintain water supply during times with increased scarcity (Rumsey et al., 2020; Udall & Overpeck, 2017). Past research has largely focused on examining the low snow years (Dierauer et al., 2019; Diffenbaugh et al., 2015; Hale et al., 2023; Heldmyer et al., 2023) with less attention to investigating how high snow years will change in the future.

Under simulated pseudo-global warming (PGW) conditions, total water stored in the seasonal snowpack at the time of peak SWE will decrease in watersheds that are tributaries of the Colorado River (Hammond et al., 2023) (Figure 3-1a), but the differences across years are not uniform. A near-record low snow year like 2012 will actually have a slight increase in total water stored in the snowpack at peak SWE in the PGW scenario, whereas the most substantial decrease in storage occurs in 2011, a near-record high snow year. Conversely, 2008 was another high snow year, but total volume of water stored in the snowpack at peak SWE increased in the PGW scenario (Figures 3-1a and 3-1b). Understanding the correlations and processes between snowpack and streamflow is especially important under these circumstances. Using a combination of modeled snow and streamflow data, the objectives of this study are to examine the historic and simulated future conditions of a high-elevation, snow-dominated watershed to quantify the overall changes in hydrology for high snow years in terms of 1) snow accumulation and melt, 2) streamflow, and 3) flow partitioning.

3.2 Data and Methodology

3.2.1 Study domain

We examined the 320 km^2 Blue River watershed in central Colorado, which ranges in elevation from 2251 m to 4329 m (Figure 3-2). We selected this watershed due to its location above Lake Dillon, a reservoir with a capacity of 257,304 acre-feet (AF) and the largest reservoir for the city of Denver (Denver Water, 2023). The watershed was divided into 488 Hydrologic Response Units (HRUs), delineated by elevation, slope, aspect, land cover, and soil type (Figure 3-2).

3.2.2 Datasets

Streamflow data were taken from three gauging stations, monitored by the United States Geological Survey (USGS) and Colorado Division of Water Resources (DWR) (Table 3-1; Figure 3-2). These gauging stations monitor daily streamflow throughout the year and have a continuous record during our study period from Water Year 2001 to 2013 (October 1, 2000*,* to September 30, 2013). The DWR controls operations for a high-elevation reservoir in the southwestern portion of the watershed. The area upstream of this reservoir was excluded from analysis. Daily release records from the outlet were used to establish streamflow at the start of the stream reach (Figure 3-3).

Soil data were obtained from the Soil Survey Geographic Database (SSURGO) (<https://www.nrcs.usda.gov/resources/data-and-reports/soil-survey-geographic-database-ssurgo

>). Soil data were missing from the eastern portion of the watershed. We used Random Forests (Breiman, 2001) to fill in missing data based on HRU characteristics (slope, aspect, elevation, and land cover).

Climate data were taken from the Weather Research and Forecasting (WRF) model, a mesoscale, convective-permitting dataset at 4-km resolution (Liu et al., 2017). WRF data were simulated for an historic period (CTL) and under pseudo-global warming (PGW) conditions. The CTL scenario was created using re-analysis data with the goal of reproducing the recent climate. The PGW scenario was created under a business-as-usual scenario using the difference in monthly mean climate variables between late 21st and 20th century, adding that difference to the reanalysis generated from the CTL scenario, and then rerunning the data to generate the future conditions. These two time periods allow for a comparison of conditions to understand how increased temperatures may exacerbate extreme events (e.g., high versus low snow years). We used daily precipitation, minimum/maximum temperature, wind speed, solar radiation, and relative humidity. Relative humidity was calculated using water vapor mixing ratio, pressure, and temperature.

Modeled snow data were taken from WRF-driven SnowModel runs (WRF-SM) (Hammond et al., 2023). They used WRF meteorological variables (Ikeda et al., 2021; Liu et al., 2017; R. Rasmussen et al., 2014; R. Rasmussen et al., 2011) as input to run SnowModel (Liston & Elder, 2006). The output includes 100-m resolution daily snow (SWE, total precipitation, solid precipitation, snowmelt, runoff, and air temperature) data for the Upper Colorado River.

3.2.3 Ages Watershed Model

The Ages Watershed Model is a spatially distributed model, originally developed for use in agricultural lands (Ascough II et al., 2012) but has since been used to successfully model higher elevation watersheds (Mankin et al., 2022). This is the first application in a snow-dominated system. Daily climate variables (station or gridded) are used to drive various hydrological processes and water movement within a watershed (precipitation, interflow, throughflow, groundwater storage, evapotranspiration, and streamflow). LUCA (**L**et **U**s **Ca**librate) was used for model calibration and is an iterative process comparing observed and simulated streamflow to maximize desired model performance statistics (Hay & Umemoto, 2006). We used equally weighted Nash-Sutcliffe and log of Nash-Sutcliffe efficiencies in an effort to capture peaks from snowmelt and winter low flows, respectively (Moriasi et al., 2007; Nash & Sutcliffe, 1970).

The WRF-SM SWE data were used to calibrate the snow processes within Ages (Hammond et al., 2023; Liston & Elder, 2006) (Figure 3-3). Spatial resolution of snow water equivalent (SWE) data were upscaled to each HRU by taking the mean of pixels within the HRU boundaries. We selected a random subset of 50 HRUs to optimize the parameters of the Ages snow processes. To examine the changes in snow conditions, we used daily snowmelt, precipitation, solid precipitation, and runoff data also from the WRF-SM dataset and then upscaled each variable to individual HRUs.

3.2.4 Additional analysis

We divided the water years into three separate periods: accumulation, ablation, and snow all gone (SAG). Accumulation was defined as onset, which started on the first day of the longest sequence with continuous snow, to peak SWE. Ablation was defined as peak SWE until SWE was equal to 0. SAG was defined as the first day when SWE was equal to 0. For each period, we compared snow variables (defined above), streamflow, and flow partitioning (runoff, interflow, and groundwater) between the CTL and PGW scenarios.

3.3 Results

3.3.1 Model calibration

3.3.1.1 Snow

For the subset of 50 HRUs, results from the snow calibration indicate that the Ages snow module was able to simulate SWE quite well, with overall NSE, KGE, and PBIAS values of 0.73, 0.73, and -18.9, respectively (Table 3-2). Across the different HRUs, model performance varied (Figure 3-4). In the easter portion of the watershed at HRU 210 (Figure 3-2), NSE was -0.473, indicating this particular area was poorly modeled and using the long-term mean would have produced better results (Figure 3-4a). However, in the southwestern portion of the watershed at HRU 475 (Figure 3-2), snow was modeled well at high elevations, NSE = 0.717 (Figure 3-4b). The model performed best during high snow years (2008 and 2011) and worse in low snow years (2002 and 2012) (Table 3-2).

3.3.1.2 Streamflow

Overall NSE and KGE values at the outlet were 0.53 and 0.46, respectively (Table 3-2). The modeled streamflow was generally able to capture the timing of the peaks, but the magnitude was greater than the observed for all years. Despite this, overall bias was negative. NSE values for 2002, 2004, and 2012 (low snow year) were -2.30, -0.35, and -2.14, respectively. The model performed well in 2008 and 2011 (NSE = 0.63 for both), which were both high snow years. The falling limb of the modeled streamflow had a steeper slope than the observed (Figure 3-5a). Since baseflow was poorly captured (equal to 0) by the model in every year from October to March (Figure 3-5a), cumulative runoff was calculated from March 1 to August 31 (Figure 3-6).

In 2008, observed and modeled cumulative runoff were 207 mm and 195 mm, respectively. In 2011, observed and modeled cumulative runoff were 379 mm and 283 mm, respectively. Under a PGW scenario, cumulative runoff was 22 mm greater in 2008 and 57 mm less in 2011 (Figure 3-6). Peak streamflow in a PGW scenario occurred a month earlier in the year (Figure 3-5b).

3.3.2 Comparing PGW and CTL

3.3.2.1 Snow conditions

For the SnowModel output, peak SWE increased across all HRUs for 2008 on average by 49 mm and decreased for 2011 on average by 63 mm, with the largest changes occurring at high elevations (Figure 3-7). For both 2008 and 2011, total precipitation increased under the PGW scenario. For 2011, precipitation decreased by 94 mm during accumulation across the watershed and also decreased at high elevations during ablation by 72 mm. Low elevations increased by as much as 200 mm, with an average of 70 mm during ablation and after SAG. For 2008, precipitation increased by 31 mm and 25 mm during accumulation and ablation, respectively (Figure 3-8). Snowmelt during accumulation increased under PGW conditions for 2008 and 2011 at low and high elevations but decreased at mid-elevations (Figure 3-9). Snowmelt increased by 91 mm during ablation for 2008. Across the entire watershed, snowmelt decreased an average of 20 mm in 2011, but decreased by an average of 95 mm at high elevations and increased by 51 mm at mid- and low elevations.

Onset of snow accumulation occurred 3 to 35 days later in the year in 2011 and 0 to 50 days later in 2008 (Figure 3-10). At high elevations, peak SWE did not shift in timing for 2011 but occurred 51 days earlier at low elevations. For 2008, peak SWE occurred earlier in the year by 30 days, except for a few HRUs in the southwestern portion of the watershed where peak occurred 34 days later in the year (Figure 3-10). At all HRUs, SAG occurred earlier by 20 to 24 days in 2008 and 15 to 53 days in 2011.

3.3.2.2 Flow partitioning

During ablation, surface runoff decreased by 300 mm at high elevations in 2011 and the mean increase in 2008 was 78 mm (Figure 3-11). The changes during ablation for 2008 and 2011 were similar ranging from -42 mm to 90 mm. Changes in interflow were minor but decreased most in 2011 during ablation (Figure 3-12). Modeled differences in groundwater were minimal (B-1 and B-2).

3.4 Discussion

3.4.1 Model performance

The upscaled WRF-SM SWE data allowed for improved spatial resolution for calibrating the Ages snow module (Figure 3-4). Using SNOTEL stations alone would have been a very small subset of the watershed (only 5 HRUs) and elevation range (Figure 3-2). Modeled SWE was greater than observed during low snow years (Figure 3-4) and so additional improvements towards model performance could focus on the snow module and parameters therein (rain/snow temperature threshold and melt factors).

WRF data have successfully been used as driving parameters in many hydrologic studies (Hammond et al., 2023; Holtzman et al., 2020; Powers et al., 2017; Sthapit et al., 2022; Tomasi et al., 2017; Zhuo et al., 2019). WRF data have been used in case studies in the southern Rocky Mountains (Ikeda et al., 2010; Ikeda et al., 2021; Liu et al., 2011; R. Rasmussen et al., 2014; R. Rasmussen et al., 2011). Several of these studies have checked the validity of the WRF dataset against SNOTEL and Parameter-elevation Regressions on Independent Slopes Model (PRISM) data and found that WRF agrees with the other datasets (Ikeda et al., 2010; Liu et al., 2011; R. Rasmussen et al., 2011).

In the late fall and winter, modeled streamflow was unable to recreate baseflow (Figure 3-5a) and rapidly decreased after peak and summer storm events, suggesting water is moving too rapidly within the watershed. Low baseflow and too rapid of a recession is common among models similar to Ages in snow-dominated basins (e.g., using the USGS Precipitation Runoff Modeling System for the Yampa and Salt Rivers (Fassnacht et al., 2006)). SSURGO data have been used successfully in other applications of this model. However, given that a portion of the watershed had missing soil data and that SSURGO data do not perform as well in mountainous regions, the soil characteristics may be contributing to poor performance with modeling baseflow. Further investigation of the SSURGO data across the study domain and how these data inform the model parameterization would provide additional insight into data versus process representation. Poorly modeled evapotranspiration may also be affecting overall model performance (Mutzner et al., 2015).

Annually, there is more water entering an HRU than there is leaving (Table 3-4). Modeled interflow (Figure 3-12) and groundwater (Figures B-1 and B-2) contribute an incredibly small amount, with most of the water coming from precipitation. However, interflow and groundwater should not be negligible, especially during snowmelt. Decreasing the number of HRUs by an order of magnitude or more may help to increase model performance and would provide a more direct comparison to the WRF input data. The current setup may be too complex given the resolution of the WRF dataset and uncertainty with the SSURGO data. Coarsening the spatial resolution generalizes the processes and could also help to resolve some of the issues related to subsurface flow and storage. At minimum, changing the resolution would provide insight into how subsurface processes are being modeled within the study watershed.

3.4.2 Comparing PGW and CTL

Results have often indicated a decrease in SWE in the future (Hammond et al., 2023; Ikeda et al., 2021; Siirila-Woodburn et al., 2021), but there has been more uncertainty for higher elevations (Siirila-Woodburn et al., 2021). The increase in peak SWE at high elevations under a PGW scenario for 2008 is consistent with other findings (K. L. Rasmussen et al., 2020; R. Rasmussen et al., 2014). For 2011, snowfall decreased across the watershed for the entire year Figure B-3). Total precipitation increased across the watershed, but modeled streamflow was greater for CTL than for PGW. This is consistent with findings from Berghuijs et al. (2014), where for snow-dominated systems, the fraction of precipitation as snow had a greater influence on streamflow than total precipitation.

An increase in peak SWE under a PGW scenario resulted in cumulative runoff increasing 15 and 50 mm at the lower and higher elevation gauges (difference in elevation of 240 m), respectively (Figure 3-6a and Figure 3-6c). Conversely, a decrease in peak SWE resulted in the greatest change in magnitude (90 mm less under a PGW scenario) at the higher elevation gauging station (Figure B-4). During ablation, total precipitation (Figure 3-8), snowmelt (Figure 3-9), and runoff (Figure 3-11) decreased at high elevations, which all contribute to streamflow and help to sustain streamflow throughout the year, not just during the melt season (Sprenger et al., 2022). The earlier runoff from snowmelt is expected in a warmer climate (Figure 3-6) as is a slower snowmelt (Figures 3-9 and B-4) due to less shortwave radiation earlier in the melt season (Musselman et al., 2017). Ages uses a constant snowmelt factor, and incorporating a variable snowmelt factor (Fassnacht et al., 2017) would yield a slower melt earlier and a faster melt later, which would better model the rising limb of the hydrograph (Figure 3-6).

3.5 Conclusions

We used the spatially distributed Ages Watershed Model in a high-elevation watershed, its first application in such an environment. Independent calibration of the snow module modeled SWE well (NSE = 0.73). The final streamflow model had NSE values of 0.53, 0.63, and -2.3, for overall performance, a high snow year, and a low snow year, with the best performance for high snow years (NSE = 0.63). Among two modeled higher snow years (2008 and 2011), changes in snow accumulation and streamflow from the CTL to PGW scenarios were not uniform with substantial increases (2008) and decreases (2011) due to variations in the amount of snow accumulation and the timing of accumulation, peak, and melt-out. The differences in the overall hydrology (snow, streamflow, flow partitioning) were most extreme at high elevations during a high snow year. At present, the modeled groundwater contributions have changed minimally, but these specific results should be approached with caution as subsurface processes and baseflow are currently poorly modeled. Less water during high snow years will exacerbate the impact of low snow years, but due to the modeled difference in high years (2008 versus 2011), it is important to assess the inter-annual variability and the sequence of wet and dry years. Both modeled high snow years resulted in an earlier snowmelt which will require new strategies for water management.

3.6 Tables

Table 3-1. Gauging station information and Ages reach/outlet designation.

Agency	Station Name	Station Number	Elevation (m)	Reach/Outlet
USGS	Blue River at Blue River, CO	09046490	2998	Reach 107
DWR	Blue River at Hwy 9 Bridge below Breckenridge, CO	3602053	2800	Reach 109
USGS	Blue River near Dillon, CO	09046600	2759	Outlet

Table 3-2. Results from snow calibration (left) and streamflow at the outlet (right) for each Water Year and overall efficiencies and bias.

Water Year	Snow			Streamflow		
	NSE	KGE	PBIAS	NSE	KGE	PBIAS
2001	0.72	0.80	14.9	0.46	0.32	-57.8
2002	0.55	0.66	-20.7	-2.30	0.05	-49.5
2003	0.75	0.77	-13.8	0.28	0.15	-61
2004	0.62	0.57	-29.4	-0.35	0.17	0.3
2005	0.67	0.76	-14.5	0.59	0.77	-11.9
2006	0.74	0.65	-23.9	0.59	0.46	-44.6
2007	0.68	0.70	-18.0	0.48	0.32	-46.1
2008	0.83	0.81	-11.9	0.63	0.57	-37.3
2009	0.46	0.56	-24.0	0.46	0.61	-29.8
2010	0.73	0.68	-22.3	0.30	0.37	-44.5
2011	0.78	0.76	-15.6	0.63	0.39	-46.3
2012	0.40	0.65	-14.6	-2.14	0.29	-58.6
2013	0.66	0.61	-25.7	0.32	0.57	-30.9
overall	**0.73**	**0.73**	**-18.90**	**0.53**	**0.46**	**-41.8**

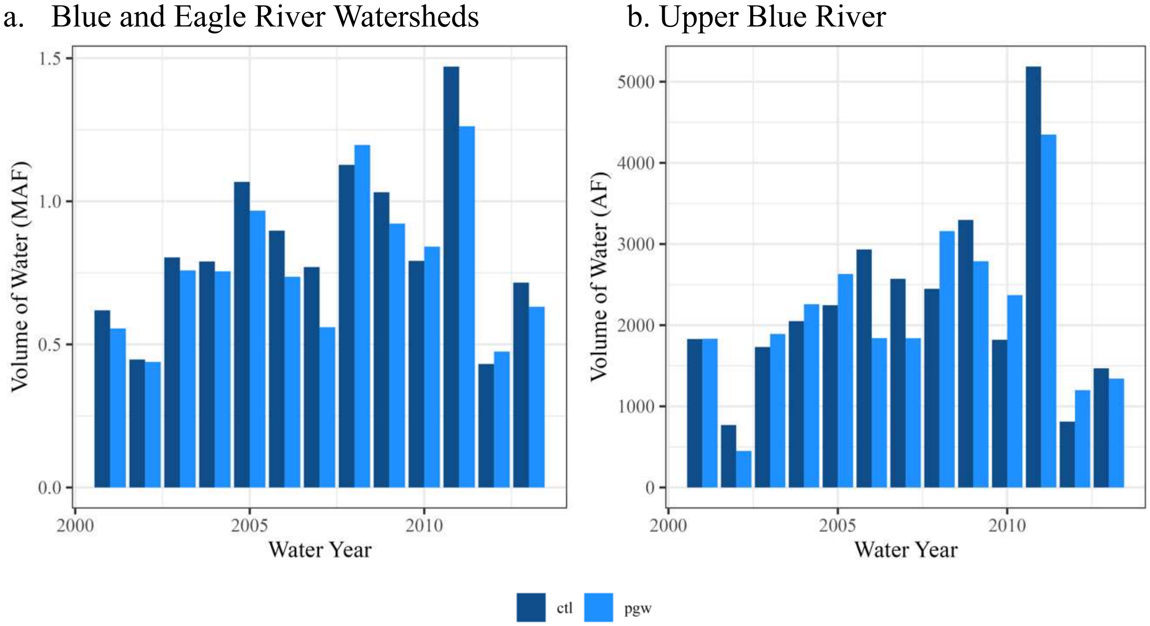
Table 3-3. Results from streamflow calibration during snowmelt (March 16 to June 30)

		Reach 107			Reach 109			Outlet		
	WY	NSE	KGE	Pbias	NSE	KGE	Pbias	NSE	KGE	Pbias
Snowmelt	2008	-7.22	-1.68	120.4	-0.78	-0.18	39.4	-0.19	0.05	31.9
	2011	0.30	0.19	35.4	0.47	0.40	20.5	0.91	0.78	-6.9

Table 3-4. Water balance for a select number of HRUs.

HRU	Water Year	In	Out	Net
6	2008	313	204	-109
6	2011	383	286	-97.1
79	2008	338	156	-182
79	2011	419	237	-182
210	2008	538	153	-385
210	2011	749	150	-599
231	2008	466	188	-278
231	2011	655	212	-442
385	2008	567	240	-327
385	2011	794	227	-567
475	2008	550	329	-221
475	2011	769	266	-503

3.7 Figures


a. Blue and Eagle River Watersheds

b. Upper Blue River

Figure 3-1. Total volume of water stored in the a) Blue and Eagle River Watersheds and b) Upper Blue River watershed at peak SWE.

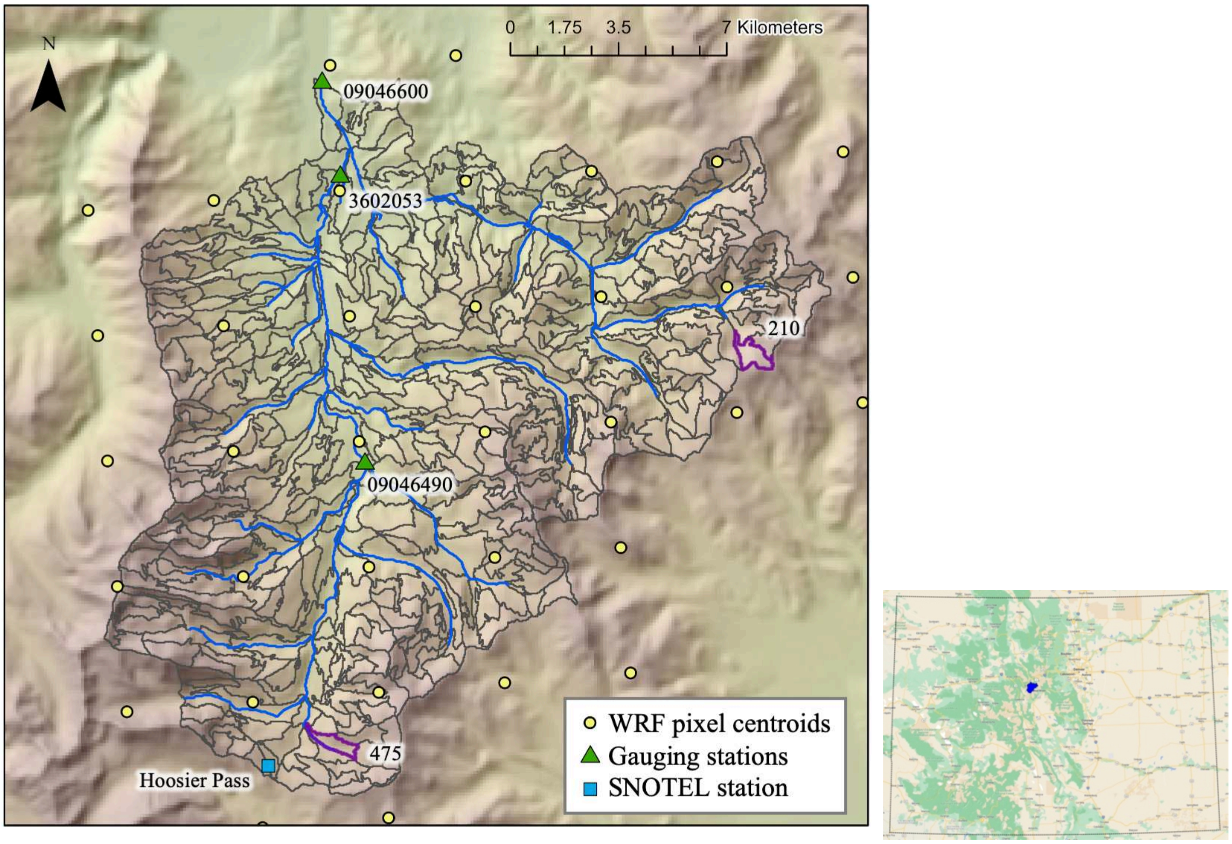


Figure 3-2. Map of Upper Blue River with HRUs and locations of WRF centroids.

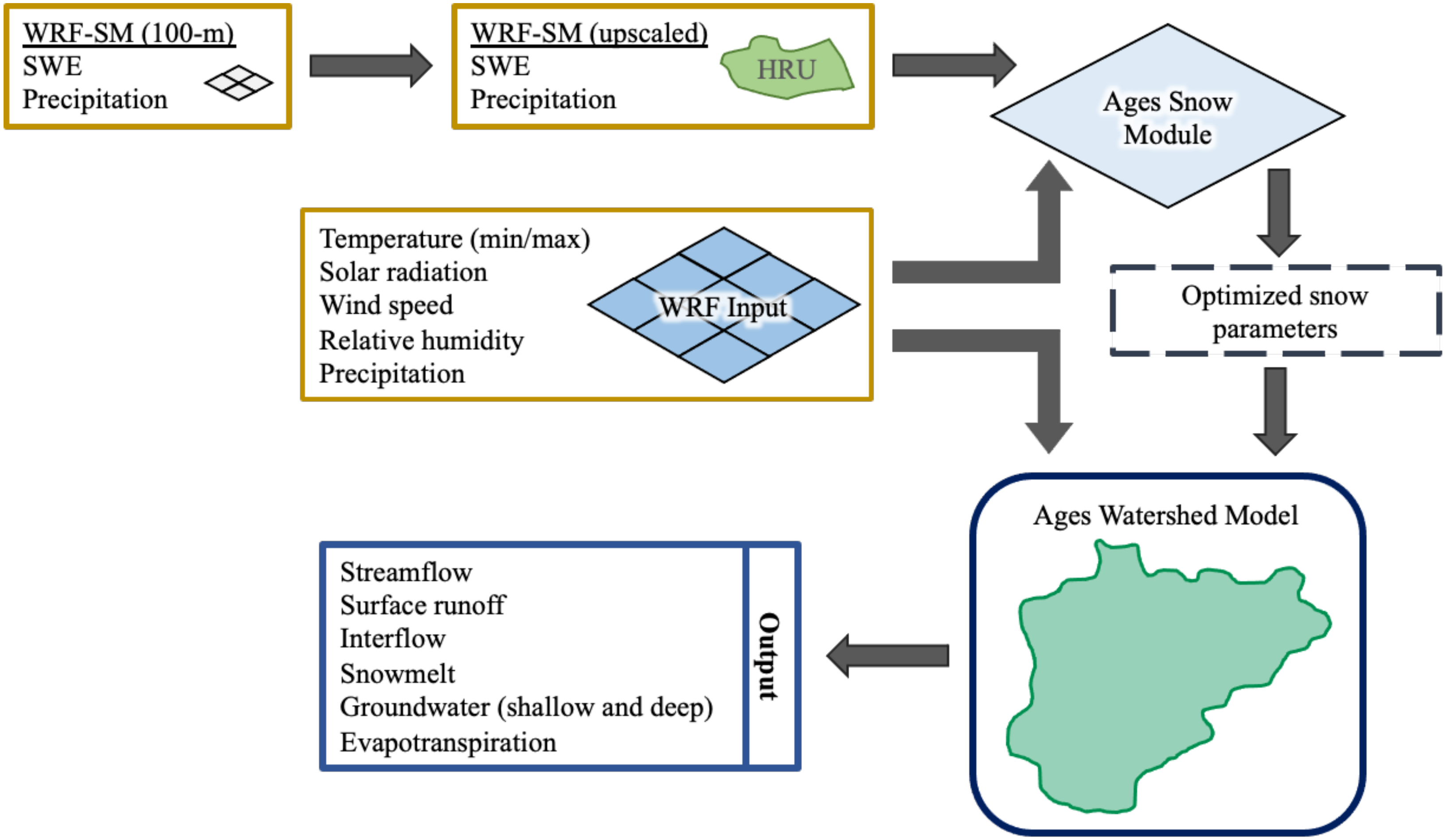


Figure 3-3. Methodology workflow with Ages Watershed Model and datasets.

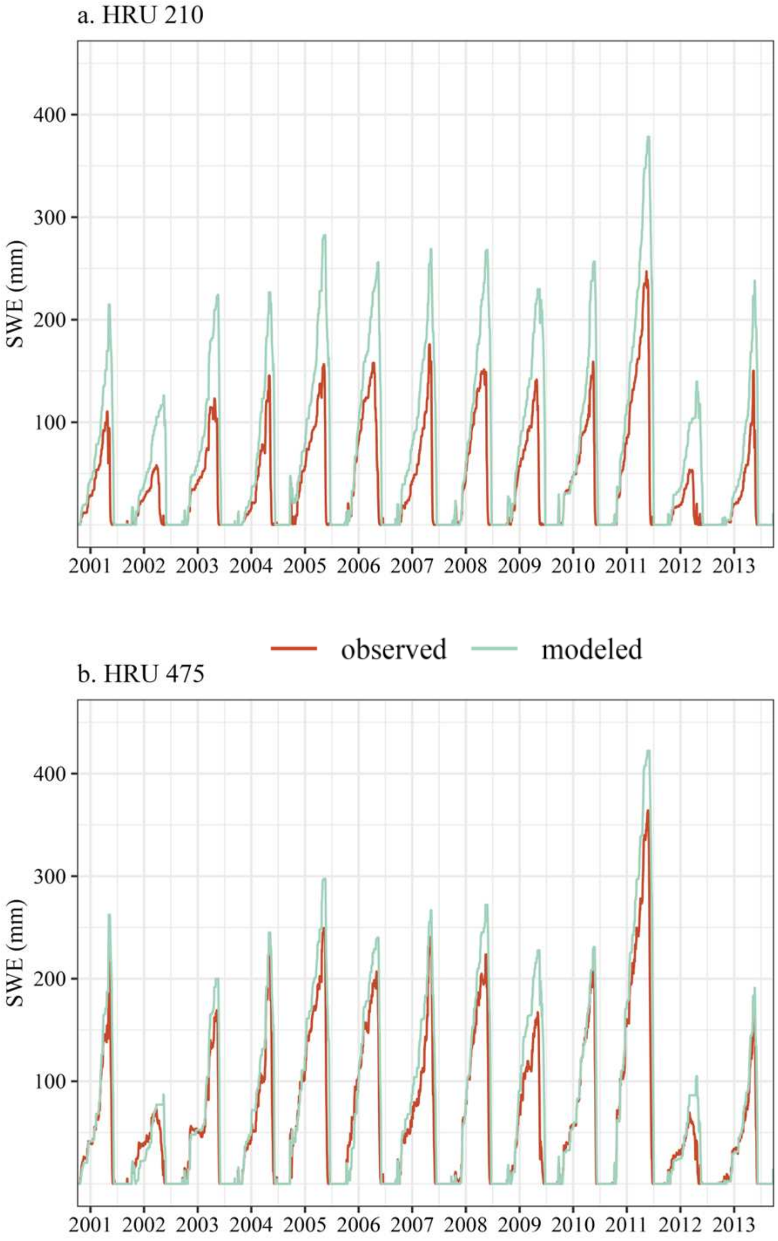
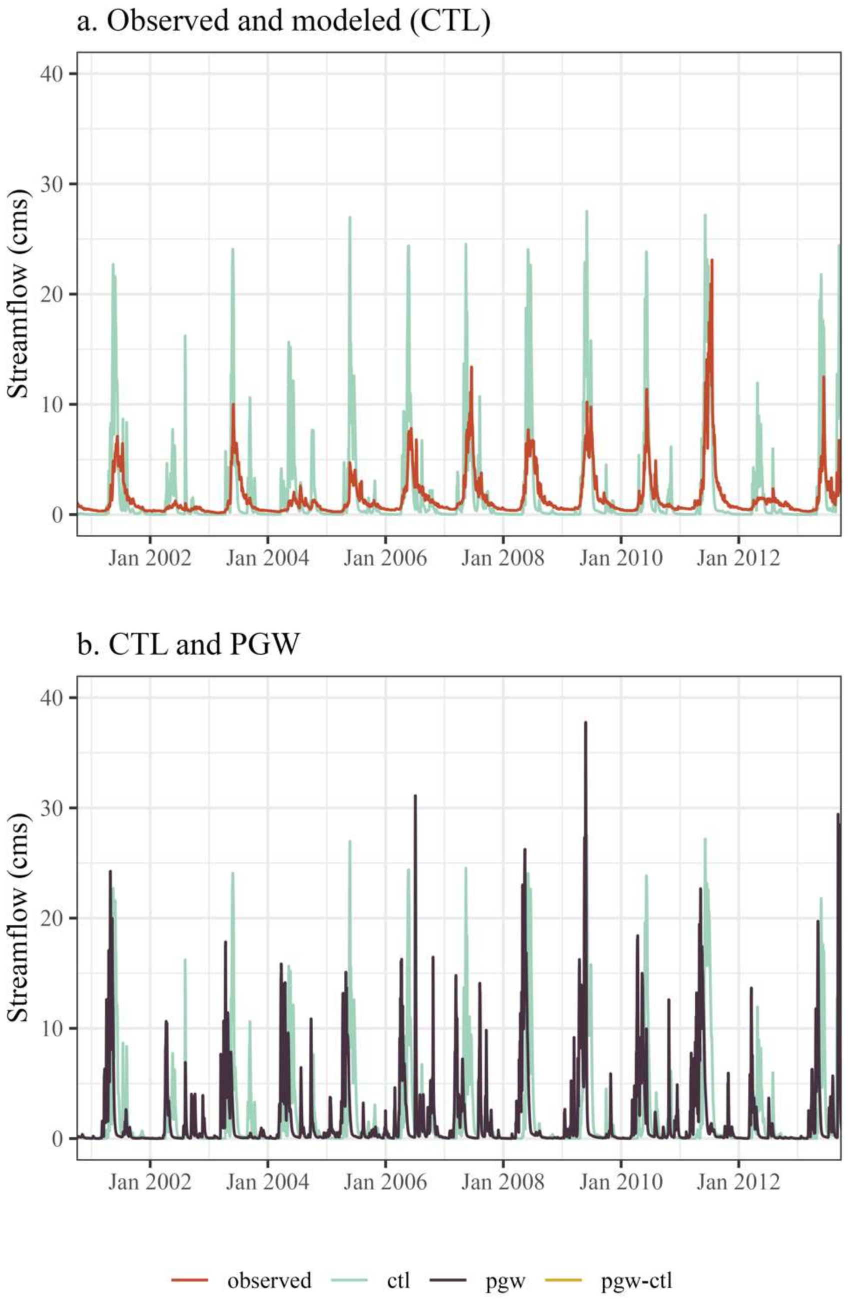


Figure 3-4. Observed (from WRF-SM) and modeled (from Ages) SWE at a) HRU 210 (NSE = -0.473), and b) HRU 475 (NSE = 0.717).



a. Observed and modeled (CTL)

b. CTL and PGW

Figure 3-5. Streamflow at the outlet for a) observed and modeled, driven by WRF CTL, and b) modeled WRF CTL and PGW.

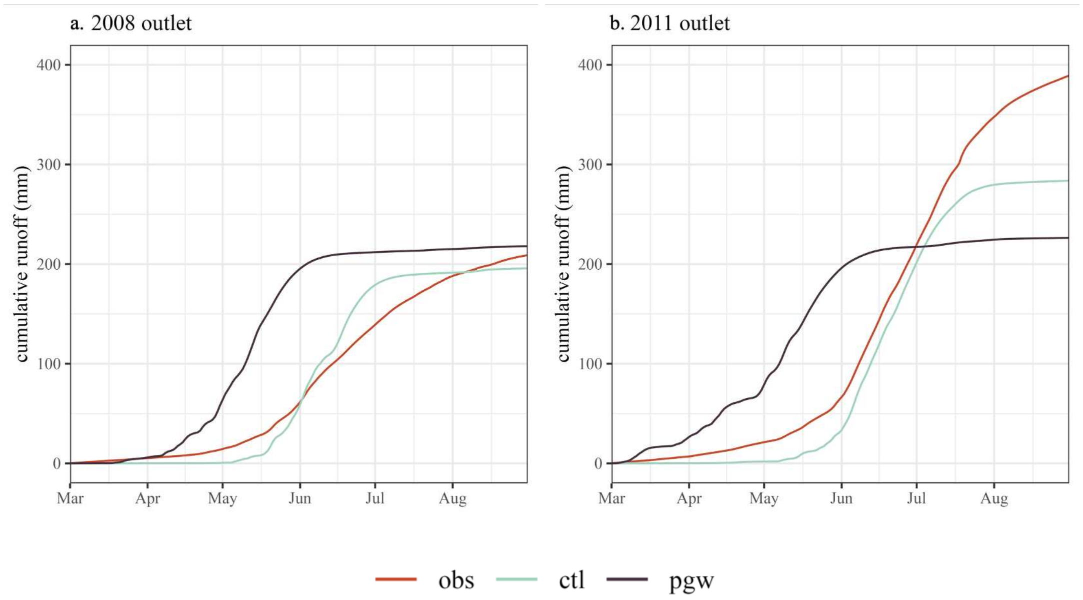


Figure 3-6. Observed, modeled, difference (PGW-CTL) cumulative hydrographs for a) 2008 at the outlet and b) 2011 at the outlet.

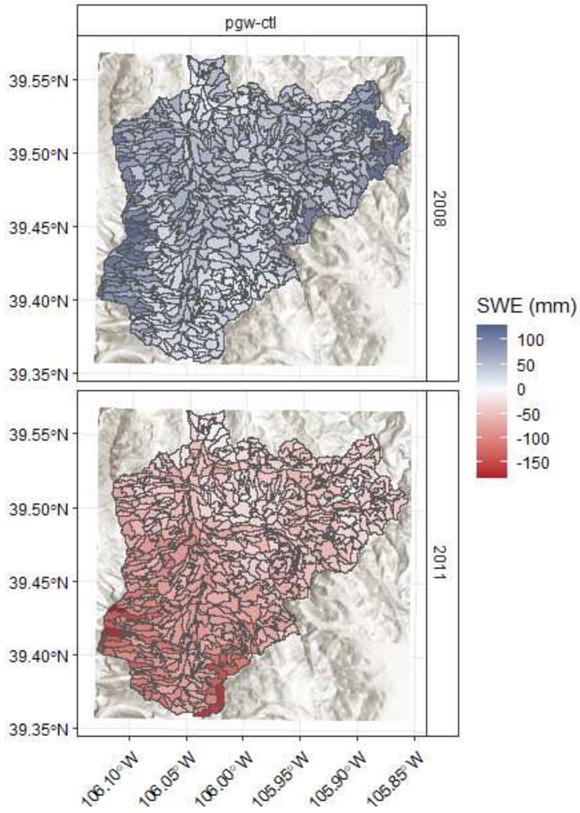


Figure 3-7. Difference in peak SWE from PGW to CTL from WRF-SM dataset.

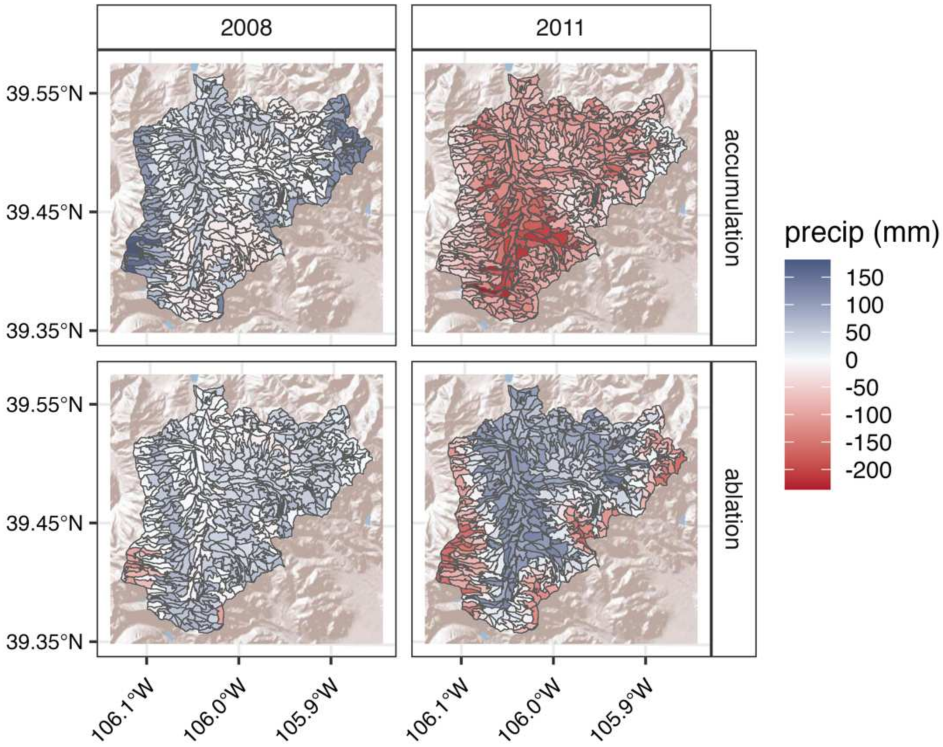


Figure 3-8. Difference in precipitation between PGW and CTL during accumulation and ablation from WRF-SM dataset.

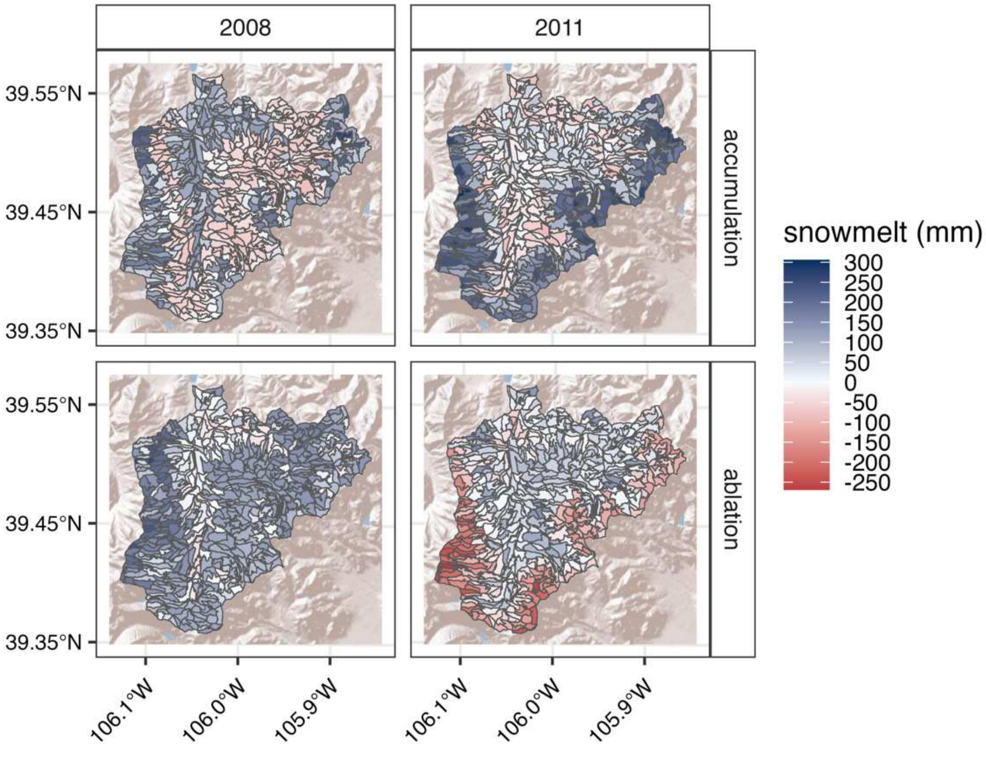


Figure 3-9. Same as above but for snowmelt.

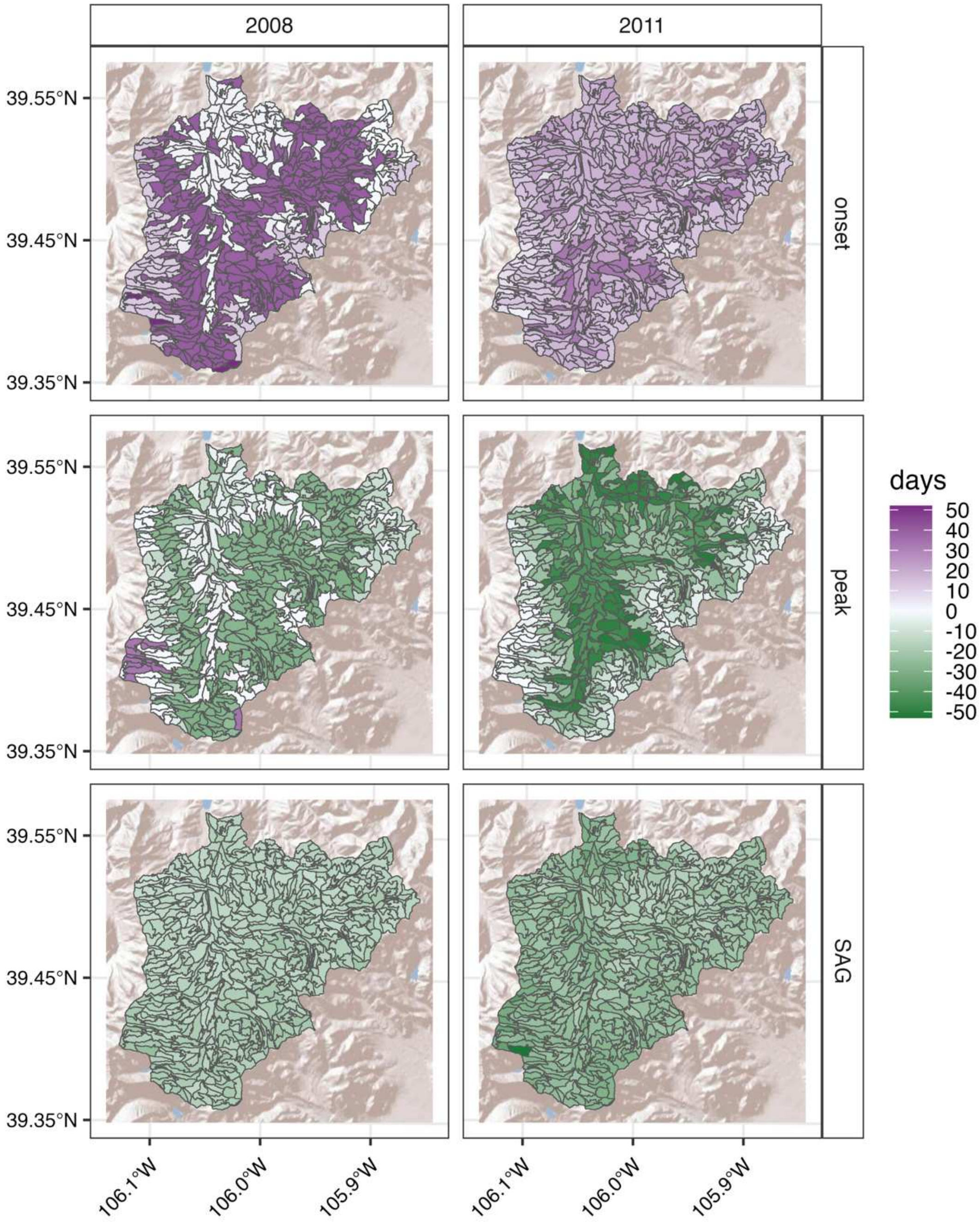


Figure 3-10. Difference in the timing of onset, peak SWE, and snow all gone between PGW and CTL from the WRF-SM dataset.

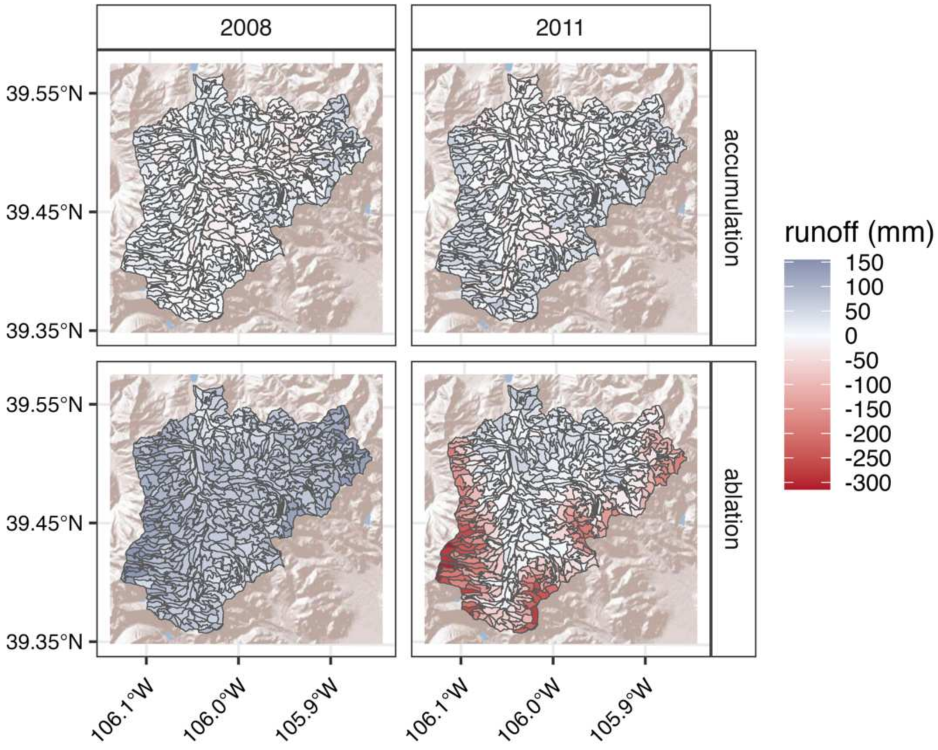


Figure 3-11. Same as 3-8 but for runoff.

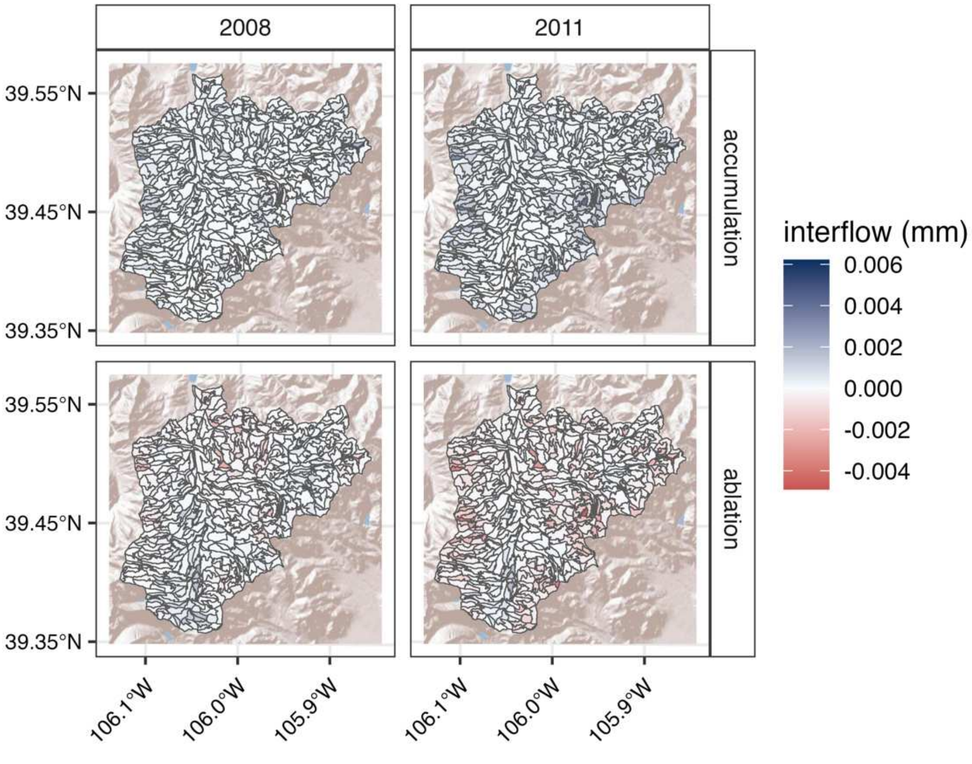


Figure 3-12. Same as 3-8 but for interflow and taken from the Ages Watershed Model.

3.8 References

Ascough II, J. C., David, O., Smith, D. R., Kipka, H., Fink, M., Green, T. R., et al. (2012). *AgroEcoSystem-Watershed (AgES-W) Model Evaluation for Streamflow and Nitrogen/Sediment Dynamics on a Midwest Agricultural Watershed*. Paper presented at the 2012 International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet, Leipzig, Germany.

Berghuijs, W. R., Woods, R. A., & Hrachowitz, M. (2014). A precipitation shift from snow towards rain leads to a decrease in streamflow. *Nature Climate Change, 4*(7), 583-586.

Breiman, L. (2001). Random Forests. *Machine Learning, 45*, 5-32.

Dierauer, J. R., Allen, D. M., & Whitfield, P. H. (2019). Snow Drought Risk and Susceptibility in the Western United States and Southwestern Canada. *Water Resources Research, 55*(4), 3076-3091.

Diffenbaugh, N. S., Swain, D. L., & Touma, D. (2015). Anthropogenic warming has increased drought risk in California. *Proc Natl Acad Sci U S A, 112*(13), 3931-3936. https://www.ncbi.nlm.nih.gov/pubmed/25733875

Fassnacht, S. R., López-Moreno, J. I., Ma, C., Weber, A. N., Pfohl, A. K. D., Kampf, S. K., & Kappas, M. (2017). Spatio-temporal snowmelt variability across the headwaters of the Southern Rocky Mountains. *Frontiers of Earth Science, 11*(3), 505-514.

Fassnacht, S. R., Yang, Z.-L., Snelgrove, K. R., Soulis, E. D., & Kouwen, N. (2006). Effects of Averaging and Separating Soil Moisture and Temperature in the Presence of Snow Cover in a SVAT and Hydrological Model for a Southern Ontario, Canada, Watershed. *Journal of Hydrometeorology, 7*, 298-304.

Hale, K. E., Jennings, K. S., Musselman, K. N., Livneh, B., & Molotch, N. P. (2023). Recent decreases in snow water storage in western North America. *Communications Earth & Environment, 4*(1).

Hammond, J. C., Sexstone, G. A., Putman, A. L., Barnhart, T. B., Rey, D. M., Driscoll, J. M., et al. (2023). High Resolution SnowModel Simulations Reveal Future Elevation-Dependent Snow Loss and Earlier, Flashier Surface Water Input for the Upper Colorado River Basin. *Earth's Future, 11*(2).

Hay, L. E., & Umemoto, M. (2006). *Multiple-Objective Stepwise Calibration Using Luca Open-File Report 2006-1323*.

Heldmyer, A. J., Bjarke, N. R., & Livneh, B. (2023). A 21st-Century perspective on snow drought in the Upper Colorado River Basin. *JAWRA Journal of the American Water Resources Association*.

Holtzman, N. M., Pavelsky, T. M., Cohen, J. S., Wrzesien, M. L., & Herman, J. D. (2020). Tailoring WRF and Noah-MP to Improve Process Representation of Sierra Nevada Runoff: Diagnostic Evaluation and Applications. *Journal of Advances in Modeling Earth Systems, 12*(3).

Ikeda, K., Rasmussen, R., Liu, C., Gochis, D., Yates, D., Chen, F., et al. (2010). Simulation of seasonal snowfall over Colorado. *Atmospheric Research, 97*(4), 462-477.

Ikeda, K., Rasmussen, R., Liu, C., Newman, A., Chen, F., Barlage, M., et al. (2021). Snowfall and snowpack in the Western U.S. as captured by convection permitting climate simulations: current climate and pseudo global warming future climate. *Climate Dynamics, 57*(7-8), 2191-2215.

Liston, G. E., & Elder, K. (2006). A Distributed Snow-Evolution Modeling System (SnowModel). *Journal of Hydrometeorology, 7*(6), 1259-1276.

Liu, C., Ikeda, K., Rasmussen, R., Barlage, M., Newman, A. J., Prein, A. F., et al. (2017). Continental-scale convection-permitting modeling of the current and future climate of North America. *Climate Dynamics, 49*(1-2), 71-95.

Liu, C., Ikeda, K., Thompson, G., Rasmussen, R., & Dudhia, J. (2011). High-Resolution Simulations of Wintertime Precipitation in the Colorado Headwaters Region: Sensitivity to Physics Parameterizations. *Monthly Weather Review, 139*(11), 3533-3553.

Lute, A. C., Abatzoglou, J. T., & Hegewisch, K. C. (2015). Projected changes in snowfall extremes and interannual variability of snowfall in the western United States. *Water Resources Research, 51*(2), 960-972.

Mankin, K. R., Wells, R., Kipka, H., Green, T. R., & Barnard, D. (2022). Hydrologic Effects of Fire in a Sub-Alpine Watershed: AgES Outperforms Previous PRMS Simulations. *Journal of the ASABE, 65*(4), 751-762.

Moriasi, D. N., Arnold, J. G., Liew, M. W. V., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE, 50*(3), 885-900.

Musselman, K. N., Clark, M. P., Liu, C., Ikeda, K., & Rasmussen, R. (2017). Slower snowmelt in a warmer world. *Nature Climate Change, 7*(3), 214-219.

Mutzner, R., Weijs, S. V., Tarolli, P., Calaf, M., Oldroyd, H. J., & Parlange, M. B. (2015). Controls on the diurnal streamflow cycles in two subbasins of an alpine headwater catchment. *Water Resources Research, 51*(5), 3403-3418.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecassting through conceptual models Part I - A Discussion of Principles. *Journal of Hydrology, 10*, 282-290.

Powers, J. G., Klemp, J. B., Skamarock, W. C., Davis, C. A., Dudhia, J., Gill, D. O., et al. (2017). The Weather Research and Forecasting Model: Overview, System Efforts, and Future Directions. *Bulletin of the American Meteorological Society, 98*(8), 1717-1737.

Rasmussen, K. L., Sexstone, G. A., McGrath, D., Liston, G. E., Fassnacht, S. R., Dougherty, E., & Kingston, A. (2020). Peering into the future: The evolution of seasonal snow in the Colorado Rocky Mountains. *Colorado water, 37*(3), 9-12.

Rasmussen, R., Ikeda, K., Liu, C., Gochis, D., Clark, M., Dai, A., et al. (2014). Climate Change Impacts on the Water Balance of the Colorado Headwaters: High-Resolution Regional Climate Model Simulations. *Journal of Hydrometeorology, 15*(3), 1091-1116.

Rasmussen, R., Liu, C., Ikeda, K., Gochis, D., Yates, D., Chen, F., et al. (2011). High-Resolution Coupled Climate Runoff Simulations of Seasonal Snowfall over Colorado: A Process Study of Current and Warmer Climate. *Journal of Climate, 24*(12), 3015-3048.

Rhoades, A. M., Hatchett, B. J., Risser, M. D., Collins, W. D., Bambach, N. E., Huning, L. S., et al. (2022). Asymmetric emergence of low-to-no snow in the midlatitudes of the American Cordillera. *Nature Climate Change, 12*(12), 1151-1159.

Rumsey, C. A., Miller, M. P., & Sexstone, G. A. (2020). Relating hydroclimatic change to streamflow, baseflow, and hydrologic partitioning in the Upper Rio Grande Basin, 1980 to 2015. *Journal of Hydrology, 584*.

Schrock, I. J. Y., Fassnacht, S. R., Collados-Lara, A.-J., Sanford, W. E., Pfohl, A. K. D., & Morán-Tejeda, E. (2021). Snow Water Equivalent Accumulation Patterns from a Trajectory Approach over the U.S. Southern Rocky Mountains. *Hydrology, 8*(3).

Siirila-Woodburn, E. R., Rhoades, A. M., Hatchett, B. J., Huning, L. S., Szinai, J., Tague, C., et al. (2021). A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment, 2*(11), 800-819.

Sprenger, M., Carroll, R. W. H., Dennedy-Frank, J., Siirila-Woodburn, E. R., Newcomer, M. E., Brown, W., et al. (2022). Variability of Snow and Rainfall Partitioning Into Evapotranspiration and Summer Runoff Across Nine Mountainous Catchments. *Geophysical Research Letters, 49*(13).

Sthapit, E., Lakhankar, T., Hughes, M., Khanbilvardi, R., Cifelli, R., Mahoney, K., et al. (2022). Evaluation of Snow and Streamflows Using Noah-MP and WRF-Hydro Models in Aroostook River Basin, Maine. *Water, 14*(14).

Tomasi, E., Giovannini, L., Zardi, D., & de Franceschi, M. (2017). Optimization of Noah and Noah_MP WRF Land Surface Schemes in Snow-Melting Conditions over Complex Terrain. *Monthly Weather Review, 145*(12), 4727-4745.

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research, 53*(3), 2404-2418.

Zhuo, L., Dai, Q., Han, D., Chen, N., & Zhao, B. (2019). Assessment of simulated soil moisture from WRF Noah, Noah-MP, and CLM land surface schemes for landslide hazard application. *Hydrology and Earth System Sciences, 23*(10), 4199-4218.

CHAPTER 4: SKI CONDITIONS IN COLORADO, RECENT AND FUTURE

4.1 Introduction

The economic impact and societal importance of the water in the seasonal snowpack cannot be overstated (Scott & Lemieux, 2010; Sturm et al., 2017). Mountain systems, and the seasonal snowpack, are particularly vulnerable to a changing climate and increasing temperatures (Hock et al., 2022). There are numerous, compounding consequences of decreased snow resources (Sturm et al., 2017); water is an essential component of agriculture and industry in the west (Siirila-Woodburn et al., 2021; Sturm et al., 2017). Prior to melting, the seasonal snow in many mountainous regions offers recreational opportunities, which also have significant economic roles. Winter sports industries bring in more than $1 billion dollars to the state of Colorado (Burakowski & Magnusson, 2012). Numerous studies have shown that historic patterns related to snow are changing (Hatchett et al., 2022; Marshall et al., 2019), the amount of snow is decreasing (Rhoades et al., 2022; Siirila-Woodburn et al., 2021), and snow conditions will continue to decline in the future (Hammond et al., 2023).

The effects of the changing snowpack are broad and have already reached the ski industry (Berghammer & Schmude, 2014; Burakowski & Magnusson, 2012; Scott & Lemieux, 2010). A decrease in optimal ski days (defined by snow cover, snow depth, wind speed) results in a decrease in visitors and an increase economic strain on resorts (Berghammer & Schmude, 2014). By the 2030s, low elevations at resorts in Norway may have inadequate snow cover and depth to support recreation (Dannevig et al., 2020). Under high-emissions scenarios, ski seasons in the Midwest of the U.S. will decrease in length by more than 50% (Scott et al., 2021).

Past studies have had several shortcomings when examining the impact of climate change on the ski industry. First, the dataset resolution used for analysis is not appropriate (Steiger et al., 2017). Past studies that have examined the influence on climate change at ski resorts relied on coarse (100-km or greater), global climate models (GCMs) (Lazar & Williams, 2008; Scott et al., 2003). Finer spatial resolution datasets exist but have poor temporal coverage. With a spatial resolution of 50-m, the Airborne Snow Observatory primarily collects data during the spring (usually mid-April and mid-May) and thus misses much of the ski season snow conditions. Second, the metrics that have been used to identify effects of climate change do not align with industry needs (Steiger et al., 2017). Snow-covered area (SCA) has been used to determine ski season length, capturing snow presence but not addressing depth of the snowpack (Sauter et al., 2010; Steiger et al., 2017). Third, snowmaking has been excluded from studies that examine the effects of climate change on the ski industry (Steiger et al., 2017). Snowmaking has become an important part of operations, allowing resorts to open earlier in the fall or early winter and extending the length of the season into late spring (Scott & McBoyle, 2006).

This research overcomes these shortcomings with the use of a fine-resolution (100-m, daily) snow dataset for the recent past and the future under pseudo-global warming conditions (PGW) (Hammond et al., 2023). Next, we looked at ski conditions beyond snow depth, including fresh snow density and powder days. At present, there are no agreed upon thresholds for such metrics. Finally, we also examined past and future snowmaking viability. Ultimately, we quantified snow and ski conditions at nine ski resorts in central Colorado 1) to examine opportunities for skiing in the recent past and under a warming climate using these ski condition metrics, and 2) to assess the impact of elevation on the ski conditions, especially for low and high snow years.

4.2 Data and Methodology

4.2.1 Study domain

We examined conditions at nine ski resorts in Colorado (Figure 4-1). Ski area boundaries were taken from the U.S. Forest Service (<https://www.fs.usda.gov>). While only a portion of each resort is used for recreation, we used the entire resort area in our analysis.

4.2.2 Datasets

Data from the Weather Research and Forecasting (WRF) Model, a convective permitting, meso-scale hydrometeorological model, were used as input to drive SnowModel (WRF-SM runs) (Hammond et al., 2023). WRF data are generated for North American Water Year (WY) 2001 to 2013 and then rerun under pseudo-global warming conditions for late in the 21st century. A WY begins on October 1 of the previous year and ends on September 30 (e.g., WY 2001 is from October 1, 2000, to September 30, 2001). This allows for a comparison of specific storm events or prevailing conditions with a changing climate. SnowModel performs reasonably well across a variety of environments, including high-elevation mountainous terrain (Liston & Elder, 2006). The output from the SnowModel runs is a unique dataset with which to examine snow conditions (SWE, solid precipitation, total precipitation, snowmelt, runoff, and temperature) at 100-m resolution in the Upper Colorado River (Hammond et al., 2023).

We used both the CTL (historic) and PGW conditions and looked at various ski factors on a sub-monthly (1st through 15th and 16th through end of the month) time frame. We divided each resort into 100-m elevation bands when using the WRF-SM runs. In Colorado, snowmaking primarily occurs early in the snow season, so snowmaking conditions were assessed for October through January. All other variables were examined from mid-October to mid-May. To examine the interannual variability (e.g., influence of high and low snow years) across the entire 13-year

CTL and PGW time period, we focused on two resorts, Vail and Loveland, which represent the lowest and highest elevation resorts, respectively.

4.2.3 Quantifying ski conditions

4.2.3.1 Snowmaking

Snowmaking ability and the quality of made snow is dependent on the wet bulb temperature (T_{wet}) (Table 4-2). Wet bulb temperature is the temperature to which air can be cooled at constant pressure by water evaporating. Wet bulb temperature was calculated using the hourly WRF data and calculating mean daily temperature, pressure, and water vapor mixing ratio (Jensen & Allen, 2016).

4.2.3.2 Ski days

We categorized days as "skiable" if the minimum depth exceeded a given threshold. This varies between 20 and 50 cm (Looney, 2023). We used a depth of 50 cm (Scott & McBoyle, 2006; Scott et al., 2003). We calculated depth:

$$d_s = \frac{SWE}{\rho_s} \qquad (4.1),$$

where d_s is snow depth, SWE is the snow water equivalent from the WRF-SM dataset, and ρ_s is average snowpack density of 200 kg/m^3 (Lazar & Williams, 2008; Mizukami & Perica, 2008).

4.2.3.3 Powder days

We categorized a given day as a "powder day" if depth exceeded the minimum threshold defined above, fresh snow depth was greater than 15 cm, and fresh density was less than 125 kg/m^3. When solid precipitation was greater than 0, we calculated fresh snow density:

$$\rho_{s-fresh} = 0.326T^2 + 12.3T + 155 \qquad (4.2),$$

where $\rho_{s-fresh}$ is fresh snow density and T is air temperature in Celsius from the WRF-SM dataset (Judson & Doesken, 2000; Meinhardt & Fassnacht, 2020). The fresh density was then used with the amount of solid precipitation that fell to determine the depth of freshly fallen snow.

4.2.3.4 Rain and snowmelt

Rain and snowmelt can both negatively affect ski conditions. We used the WRF-SM snowmelt to determine how frequently melt occurred. We used the WRF-SM total precipitation and solid precipitation to determine how frequently rain occurred.

4.3 Results

4.3.1 General conditions

Across the study area, mean monthly solid precipitation increased by nearly 40 mm from December to March in the PGW scenario, but decreased by 50 mm in October, April, and May (Figure 4-2a). Air temperature increased by 4.7˚C in winter months (October through March) (Figure 4-2b). Wet bulb temperature changes were similar to air temperature and increased by 4.6˚C during the early ski season (October through January). In the following sections, we present results for the various ski conditions for high and low elevation resorts (Loveland and Vail, respectively) and a high and low snow year (2011 and 2012, respectively). Results for additional resorts and years are shown in Appendix C.

4.3.2 Snowmaking

For 2011 and 2012 combined, ideal or good snowmaking conditions occurred 70% and 60% of the time for Loveland and Vail resorts, respectively (Figure 4-3a). This decreased to 56% (Loveland) and 36% (Vail) under PGW conditions. Conditions were too warm in 2011 and 2012 14% (Loveland) and 27% (Vail). Under PGW conditions, this increased to 27% (Loveland) and

46% (Vail). At Loveland, for both CTL and PGW, there were more opportunities for snowmaking during the low snow year (CTL-81% and PGW-72%) than the high snow year (CTL-61% and PGW-65%). At Vail, the low snow year (CTL-75% and PGW-51%) also had more overall snowmaking opportunities than the high snow year (CTL-64% and PGW-48%). The decrease in snowmaking opportunities from CTL to PGW occurred because conditions become warmer (shift into the "too warm" category); there is no shift to "too cold" at any resorts or years.

Snowmaking (poor, good, or ideal snow) became possible for more than half days in mid-October and early November for Loveland and Vail, respectively (Figure 4-3b). Under the PGW scenario, this shifted to half a month later in early November and mid-November for Loveland and Vail, respectively. Ideal snow conditions are possible at Loveland a majority of the time starting in early November and mid-November for the CTL and PGW scenarios, respectively. At Vail, ideal conditions are possible a majority of the time in early December for the CTL scenario, but this never happens under the PGW scenario.

4.3.3 Ski days

For Loveland resort in the high snow year, the largest changes occurred at low elevations between mid-October and mid-December (Figure 4-4a). Ski days increased at Loveland resort in the low snow year from start of the season until mid-March. For Vail resort in the high snow year, there were fewer ski days throughout the season, but especially at low elevations from early April until the end of the season, when the ski days decreased by 100% (Figure 4-4a). The low snow year at Vail resulted in an increase of 25% of ski days at higher elevations, but the late season decrease (between 50% and 100%) occurred across all elevations.

Mid-season (late December to late March) ski days increased at both Loveland and Vail, particularly at elevations from 3000 m to 3500 m in December and early January (Figure 4-4b). The biggest decreases in ski days (more than 50% of the time) occurred in early and late season across all elevations for both ski resorts. For Vail, low elevations (2750 m and below) decreased the most, particularly in the late season (mid-March to end of season).

4.3.4 Powder days

Powder days happened more frequently across elevations and throughout the ski season in the high snow year for both Loveland and Vail resorts (Figure 4-5a). In the low snow year, late-season (mid-March on) powder days happened infrequently (10% of the time). Under the PGW scenario for the high snow year, early and late season powder days decreased at Loveland in early and late season. Vail was similarly affected, except for early February when powder days increased by as much as 20% at elevations above 2900 m. Under the PGW scenario for a low snow year at Loveland, powder days increased by 20% to 30% throughout the early and mid-season but then decreased by 30% at the end of the season from mid-April on. Under the PGW scenario for a low snow year at Vail, powder days increased by 24% from early January to early February at elevations above 3000 m but decreased by 27% from mid-January to early March at elevations below 3000 m.

For each scenario (resort, high/low snow year, CTL/PGW), powder days happened with the greatest frequency in late February (Figure 4-5b). While early and late season powder days decreased on average by 10% for both resorts under the PGW scenario, mid-season (early January to early March) powder days decreased at elevations above 3000 m by 26%. Overall powder days decreased more at elevations below 3000 m, having a larger impact on Vail than Loveland resort.

4.3.5 Fresh snow density and depth

Between the high and low snow year at the individual resorts, early and mid-season fresh snow density was similar at the two resorts but increased from 62 kg/m^3 to 101 kg/m^3 in early April for the low snow year (Figure 4-6b). Under the PGW scenario, fresh snow density increases for both years at all elevations at Loveland resort but decreases at Vail at low elevations mid-October and mid-April by an average of 18 kg/m^3. Mean fresh snow density for Loveland was 68 kg/m^3 and 93 kg/m^3 for the CTL and PGW scenarios, respectively (Figure 4-6b). Mean fresh snow density for Vail was 91 kg/m^3 and 117 kg/m^3 for the CTL and PGW scenarios, respectively (Figure 4-6b).

Fresh snow depth decreased in early and late season for the high and low snow years at both resorts (Figure 4-7a). Fresh snow depth varied more between 2011 and 2012 at Loveland (11 cm and 9 cm) than at Vail (8 cm and 8 cm) for the CTL scenario. Mean fresh depth for Loveland was 10 cm and 9 cm for the CTL and PGW scenarios respectively (Figure 4-7b). Mean fresh depth for Vail was 8 cm and 5 cm for the CTL and PGW scenarios, respectively (Figure 4-7b).

4.3.6 Rain and melt days

In the CTL scenario at Loveland, there were no days with rain in the high snow year, but rain occurred in a small portion of the resort (1% to 7%) in early April and early May at elevations below 3500 m (Figure 4-8a). At Vail resort in the CTL scenario, rain occurred in the early season in the high snow year and late in the season for both years. Frequency or rain days increased under the PGW scenario, especially in early October at elevations below 3900 m. Rain frequency increased in early April at elevations below 3500 m for Loveland in the high snow year and elevations below 4000 m in the high snow year. Rain occurred more frequently throughout the season at Vail resort, with instances of rain as much as 25% of the time at low elevations in late December and late March through the end of the season (Figure 4-8b).

There were no days with melt at Loveland from mid-November to mid-March in the CTL scenario (Figure 4-9a). Mid-season melt that occurred at Vail is limited to elevations below 2800 m during the high snow year. Under the PGW scenario, melt occurred at elevations below 3200 m at Loveland throughout the season (Figure 4-9b). For Vail, the only consistent snowmelt free areas were elevations above 3200 m from early January through the end of February.

4.4 Discussion

4.4.1 Spatio-temporal resolution

Earlier studies that examined changes in ski conditions used GCMs at 36-km and 500-km resolution (Lazar & Williams, 2008), and recent work with GCMs are still at a 50-km resolution (Steiger et al., 2017). The orography of a region like central Colorado is poorly resolved with these coarse GCMs, so the WRF data used herein (Liu et al., 2017) are at a more appropriate resolution (Ikeda et al., 2010). Further, the WRF-SM runs are at 100-m resolution, which enables the simulation of important processes, such as blowing snow, sublimation, snowpack metamorphism, and melt (Liston & Elder, 2006). The fine temporal resolution used in this study allows for a more thorough investigation of different metrics (e.g., powder days) that are not captured with monthly datasets and variables (Figure 4-2) that have been used in the past (Dannevig et al., 2020; Lazar & Williams, 2008).

4.4.2 Snowmaking

Wet bulb temperature is the industry standard for determining if conditions are conducive for snowmaking and, barring major technological changes, will continue to be used in the future.

Ski resorts in Colorado have incorporated snowmaking since the 1970s (Scott & McBoyle, 2006). Snowmaking has been a helpful adaptation for ski resorts, opening earlier and extending the ski season by months in certain areas (Scott & McBoyle, 2006). In Canada, global climate models were used to examine how snowmaking affected the length of the ski season and were deemed to be important in extending the ski season by several weeks (Scott et al., 2003). For this analysis, early season (October and November) snowmaking opportunities will decrease under the PGW scenario (Figure 4-3a), with an increase in conditions that are too warm and a decrease in snowmaking that results in ideal, good, or poor snow (Figures 4-3a and 4-3b). Low elevations are especially vulnerable to these changes (Figure 4-3b). With a decreased ability to make snow combined with a declining snowpack (Hammond et al., 2023; Rhoades et al., 2022; Siirila-Woodburn et al., 2021), opportunities for early season skiing will become less frequent (Figures 4-3 and 4-4).

As wet bulb temperature increased, ideal snowmaking conditions decreased in December and January as well (Figures 4-3a and 4-3b). In the eastern portion of the study domain, December through February snowfall has increased since 1981 (Fassnacht et al., 2018; Fassnacht & López-Moreno, 2020); February also saw cooler temperatures (Fassnacht et al., 2018) for most of the month (Fassnacht et al., 2020). Beaver Creek and Vail, the two resorts with lowest elevation, have the most drastic change (Figure C-1), demonstrating that some resorts will be more susceptible to a changing climate than others (e.g., Arapahoe Basin and Loveland; Figure C-1). These results are contrary to trends over the past few decades where the lower elevations have been getting more snow and the higher elevations have seen a decrease (Fassnacht et al., 2018; Fassnacht & López-Moreno, 2020; Fassnacht et al., 2020). This emphasizes the need to further our understanding of the changes that have occurred and may occur in the future. It should be noted that regardless of if future conditions allow for snowmaking, it cannot be used to replace natural snow in its entirety, as it is resource-intensive, requiring water, energy, and money (Scott et al., 2022a).

4.4.3 Ski conditions

There are no widely accepted metrics for ski quality, but past studies have used varying metrics to quantify ski conditions. Lazar and Williams (2008) examined fresh snow density and avalanche risk in Aspen, Colorado. Their calculated fresh density (50-120 kg/m^3) is similar to the calculated density under the CTL scenario (Figure 4-6). They also observed increased densities at lower elevations and at the tail ends of the ski season (Lazar & Williams, 2008). Fresh snow density is computed as a function of air temperature, but this poorly considers the other important atmospheric processes (Fassnacht & Soulis, 2002), such as formation conditions (Nakaya, 1954) and conditions through which the snow falls (Fassnacht et al., 2001). Under a PGW scenario, Colorado will have warmer temperatures but will still be a continental climate (Fassnacht & Soulis, 2002), but a different equation would need to be used to calculate density for different climate (e.g., Sierra Nevadas or Cascades).

Berghammer and Schmude (2014) used optimized ski days (OSD) across ski resorts in Germany and Austria. Their determination of an OSD was based on precipitation, how much of the ski area was operating, snow depth (artificial or natural), snow cover of adjacent areas, temperature, sunshine, wind, and type of day (weekday, weekend, holiday) (Berghammer & Schmude, 2014). Occurrence of OSDs in the future (2050s) decreased by 35 to 90% from the recent past (2010s). Their additional criteria beyond a minimum depth threshold likely account for difference in results to our study (Figure 4-4). Our inclusion of powder days captures a different component of an OSD (Figure 4-5). In a survey of elite winter snow sport coaches and athletes, fresh powder was ranked fourth out of twenty-two different conditions that influence if a competition is ideal or unacceptable (Scott et al., 2022b). Rain and wet snow (e.g., snowmelt) were also included in the survey results and ranked eighth and ninth, respectively (Scott et al., 2022b). Under a PGW scenario, with a decrease in the frequency of powder days (Figure 4-5), increase in days with rain (Figure 4-8), and increase in days with snowmelt (Figure 4-9), skiing experiences would be more likely to be classified as unacceptable over ideal (Scott et al., 2022b).

When snow conditions are inadequate, there are few replacements (Scott & McBoyle, 2006). Just over 25% of survey respondents indicated they would travel to a new location entirely to be able to ski if their preferred location had poor snow conditions (Scott & McBoyle, 2006). The economic impact of such decisions is costly: a low snow year in Colorado resulted in a loss of more than $150 million (Burakowski & Magnusson, 2012). In such years, the alternative for ski area operators is to increase snowmaking, but as outlined above, prevailing meteorological conditions and/or insufficient water supply (Scott et al., 2021) may make such an adaptation impossible.

Future research should have an interdisciplinary emphasis, connecting the results of the physical processes with the societal (social and economic) implications. Incorporating decision-making by the ski area operators or survey responses from skiers would strengthen these results. Quantifying the monetary effect of a PGW scenario on snow conditions would further contextualize future changes.

4.5 Conclusions

Under a PGW scenario, compared to the recent past, monthly average temperatures warmed by 4 to 7 ˚C. Except for April, that saw no change, precipitation increased in all months by 5 to 18 mm, and most of those increases in the winter were solid precipitation. However, solid precipitation decreased in October, April, and May by 15 to 20 mm per month. The future will likely yield poorer conditions for skiers and snowboarders at the resorts investigated; temperatures will be too warm for snowmaking at the beginning of a ski season and the quality of the machine-made snow will be worse than in the past. The number of ski days, powder days, and fresh snow depth will all decrease, while the density of fresh snow, mid-season snowmelt, and rain events will increase. Resorts at lower elevations will be more susceptible to changes in snow conditions, but these changes are not consistent from year to year. There are no widely accepted metrics for determining snow and ski conditions, and the methods developed in this study are appropriate for a region like Colorado, but further adaptation may be necessary for different climates. Regardless of location, future methods should incorporate an interdisciplinary approach and link the physical processes discussed here with the human representation and experience of skiing.

4.6 Tables

Table 4-1. Ski resort metadata.

Resort name	Minimum elevation (m)	Mean elevation (m)	Maximum elevation (m)	Median elevation (m)	# cells (WRF-SM)
Arapahoe Basin	3145	3538	3977	3539	734
Beaver Creek	2527	3002	3501	2986	1542
Breckenridge	2949	3388	4004	3369	2880
Copper Mountain	2959	3439	4000	3457	3070
Keystone	2828	3376	3822	3371	3455
Loveland	3187	3585	4021	3603	2575
Ski Cooper	3195	3455	3855	3440	906
Vail	2480	3107	3582	3126	4949
Winter Park	2728	3139	3663	3117	2957

Table 4-2. Temperature ranges and resultant snowmaking conditions

Wet bulb temperature range (˚C)		Snowmaking conditions
Minimum	Maximum	
-2.5		Too warm
-4.5	-2.5	Poor
-6.5	-4.5	Good
-18	-6.5	Ideal
	-18	Too cold

4.7 Figures

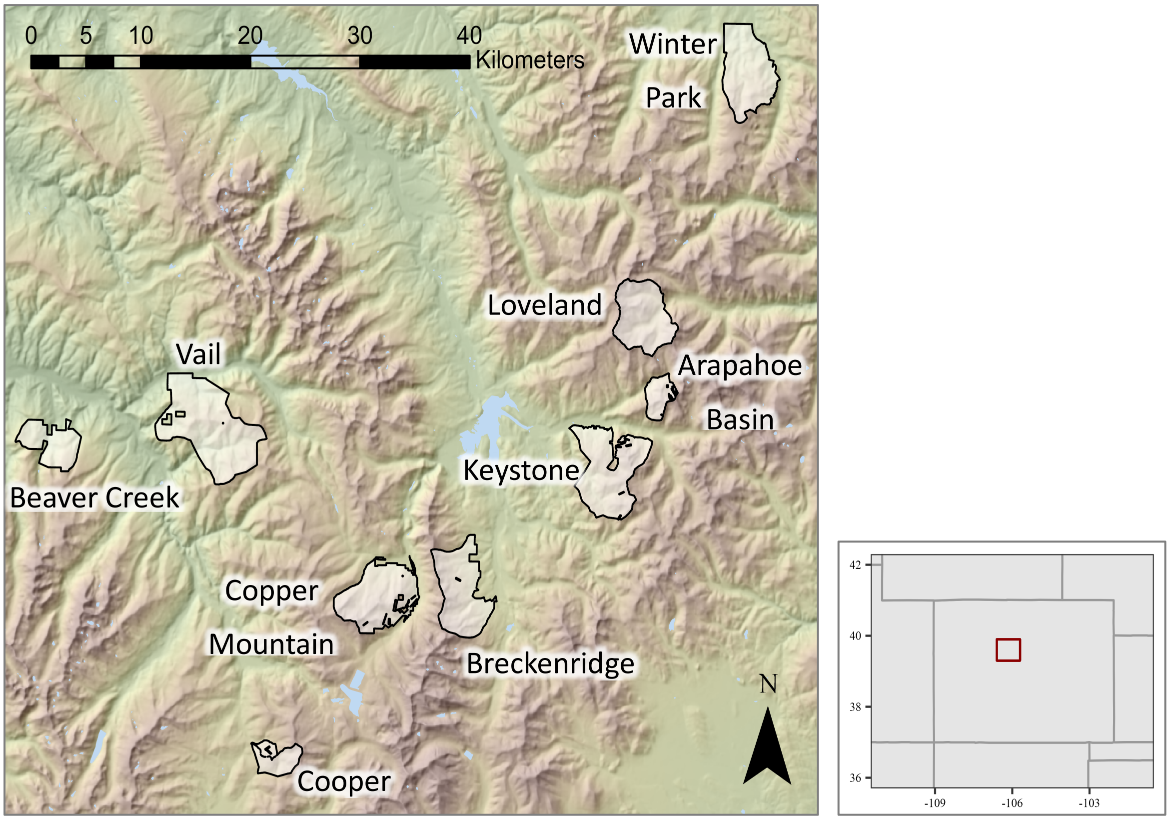


Figure 4-1. Map of ski resorts used in analysis.

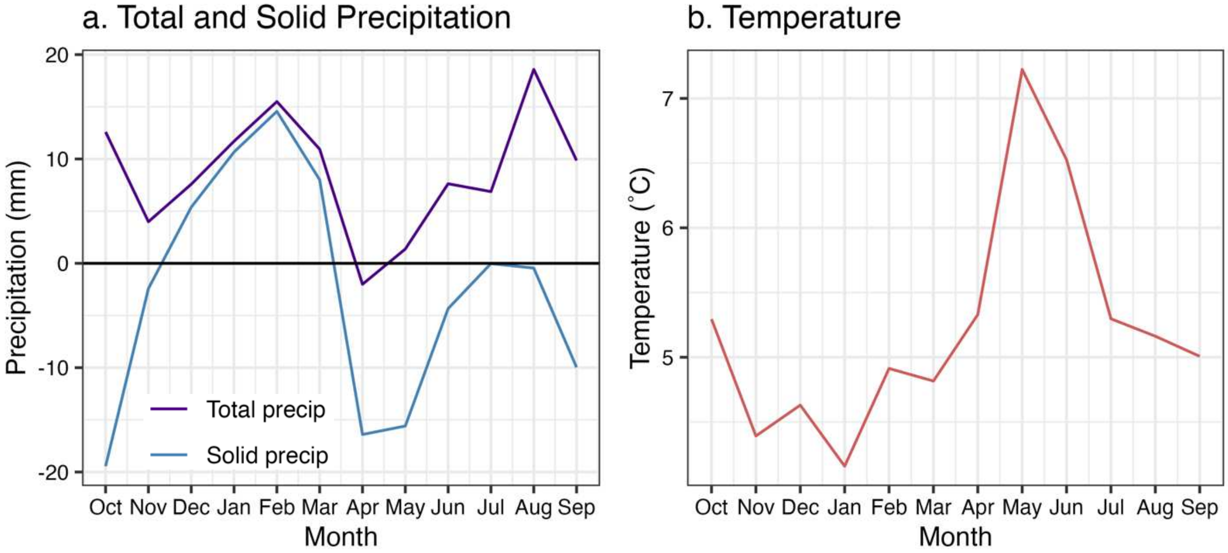
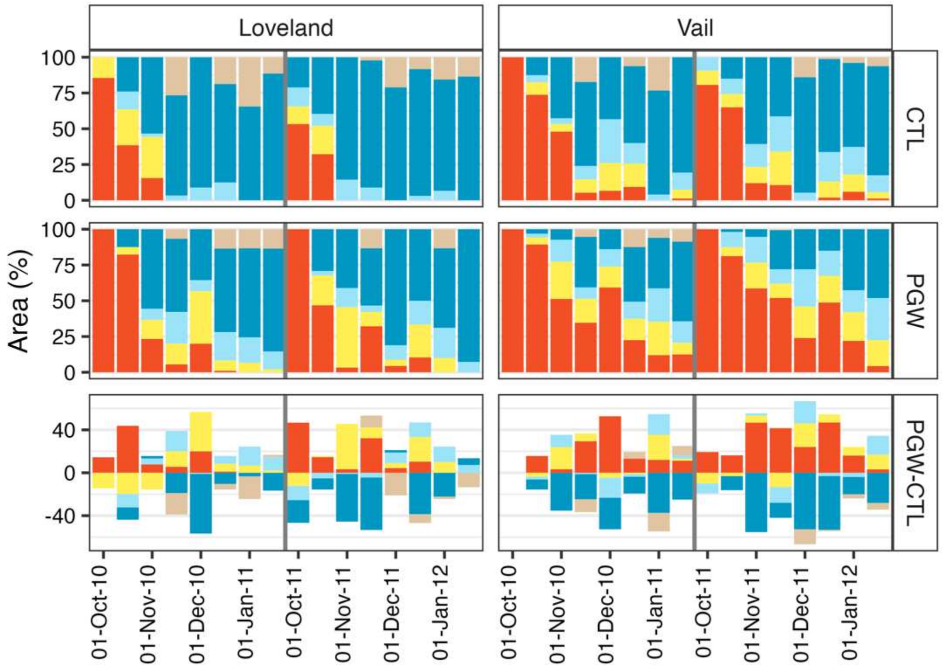


Figure 4-2. Mean monthly difference between PGW and CTL for ski resorts in Colorado for a) total and solid precipitation and b) air temperature.

a. Snowmaking, 2011 and 2012



b. Snowmaking, semi-monthly mean

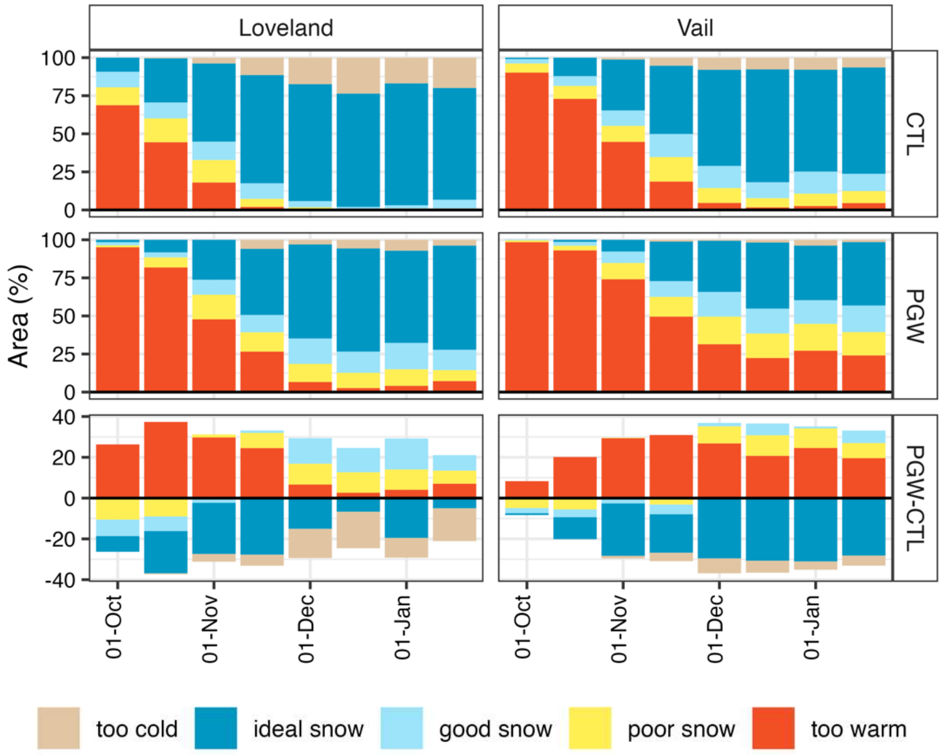
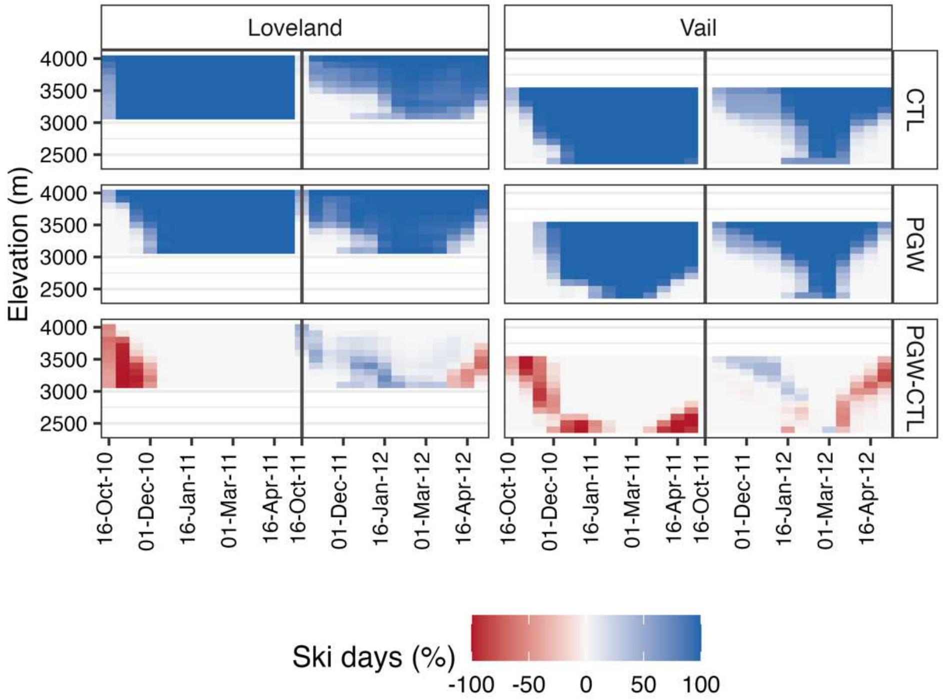


Figure 4-3. Snowmaking opportunities at Loveland and Vail resorts for a) WY 2011 and 2012 and b) semi-monthly mean for the 13-year period.

a. Ski days, 2011 and 2012



b. Ski days, semi-monthly mean

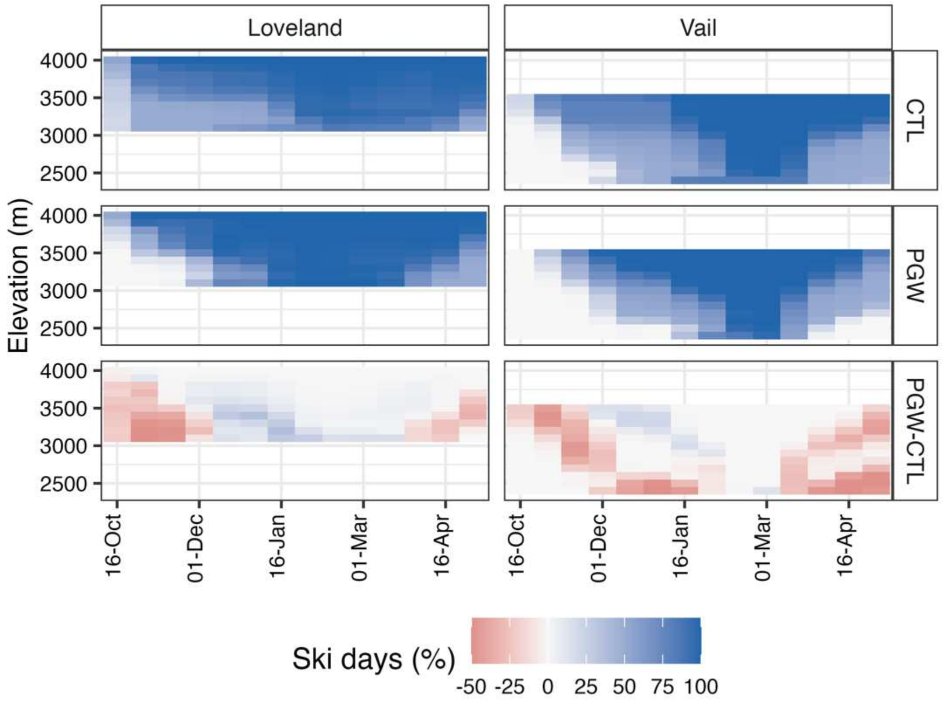
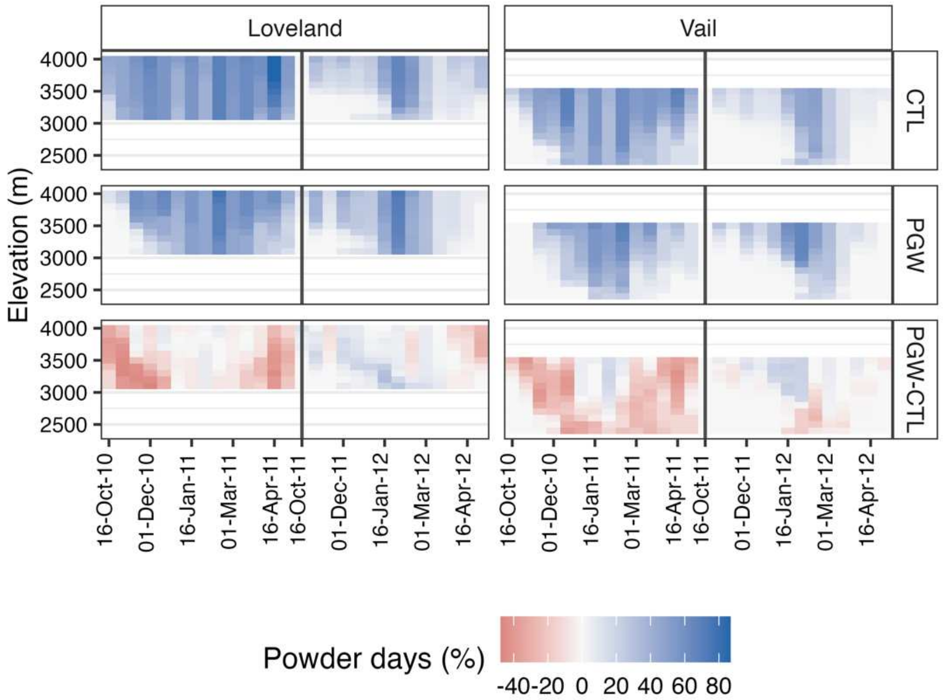


Figure 4-4. The same as above but for ski days (snow depth greater than 50 cm).

a. Powder days, 2011 and 2012



b. Powder days, semi-monthly mean

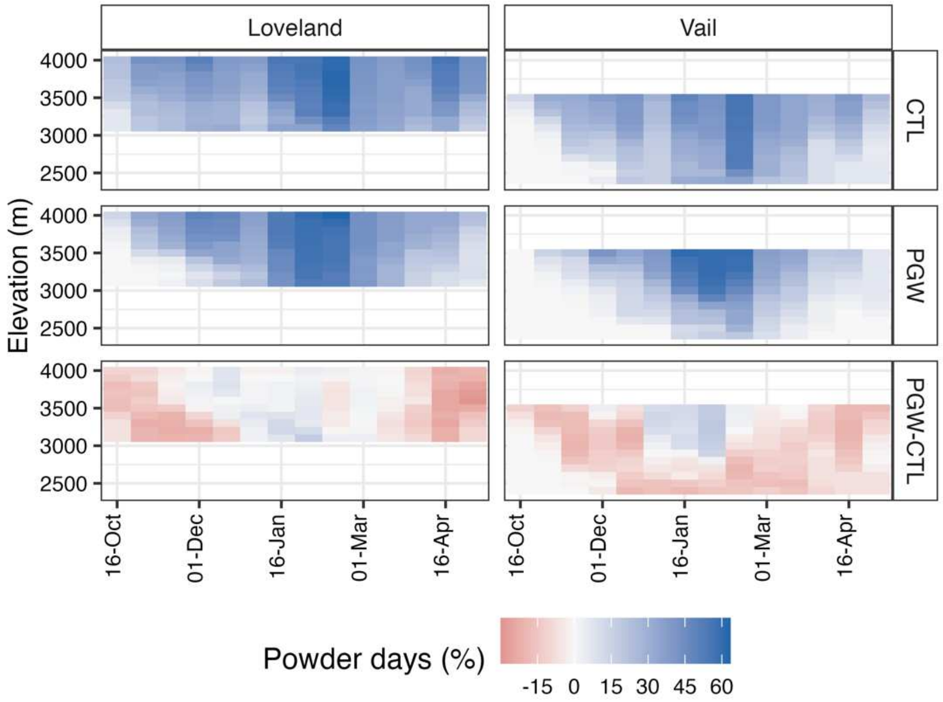
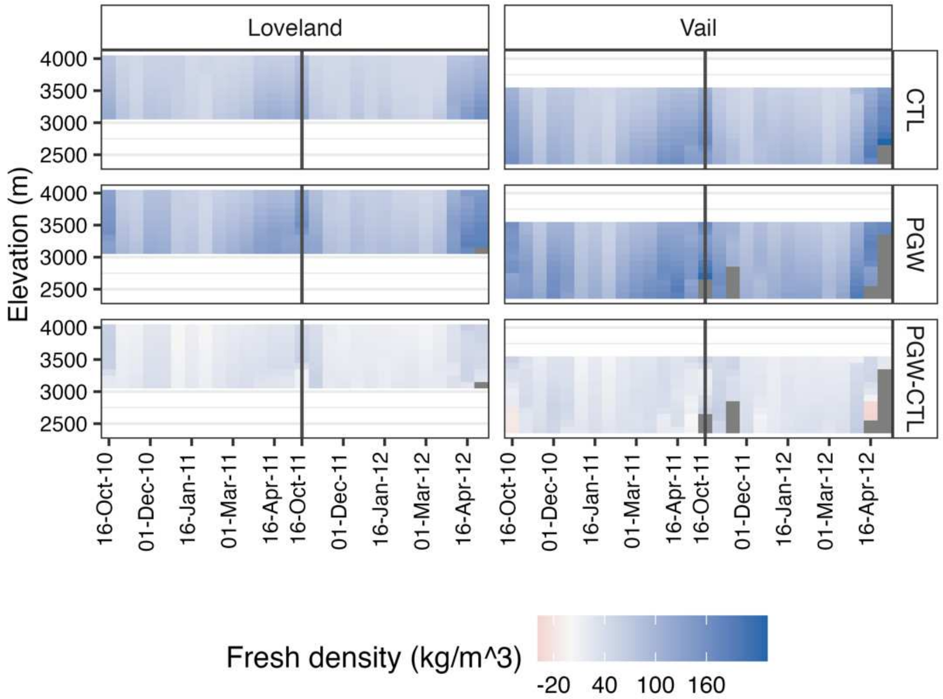


Figure 4-5. The same as above but for powder days.

a. Fresh density, 2011 and 2012



b. Fresh density, semi-monthly mean

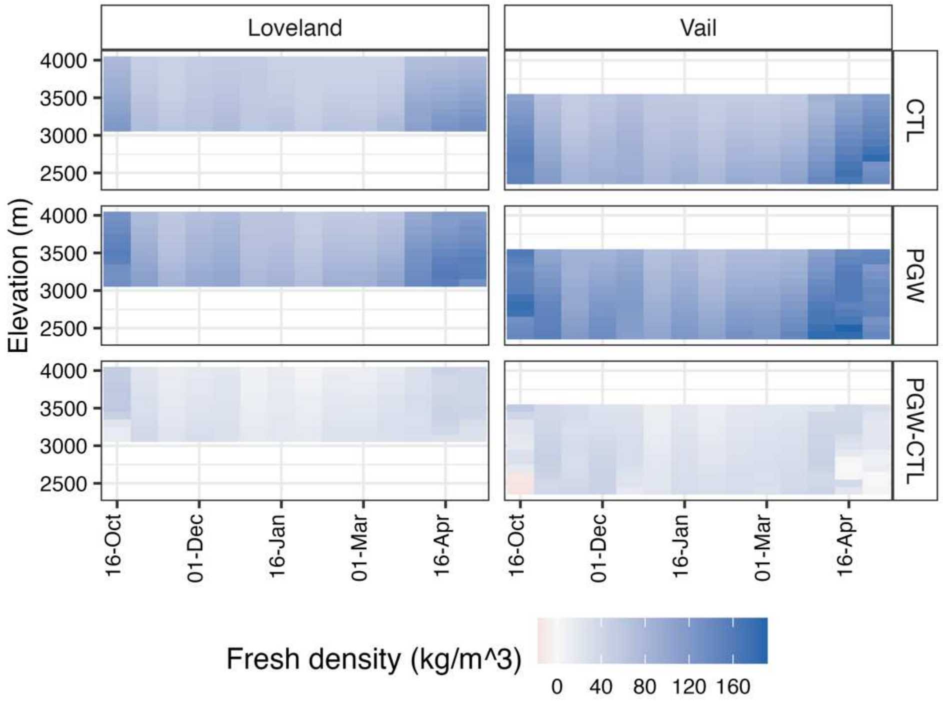
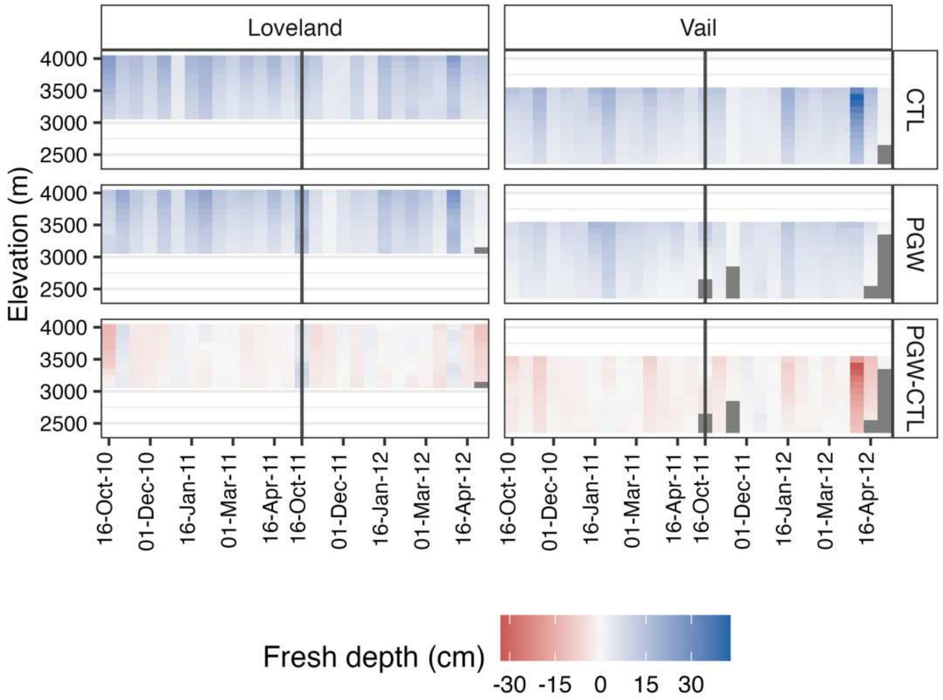


Figure 4-6. The same as above but for fresh snow density.

a. Fresh depth, 2011 and 2012



b. Fresh depth, semi-monthly mean

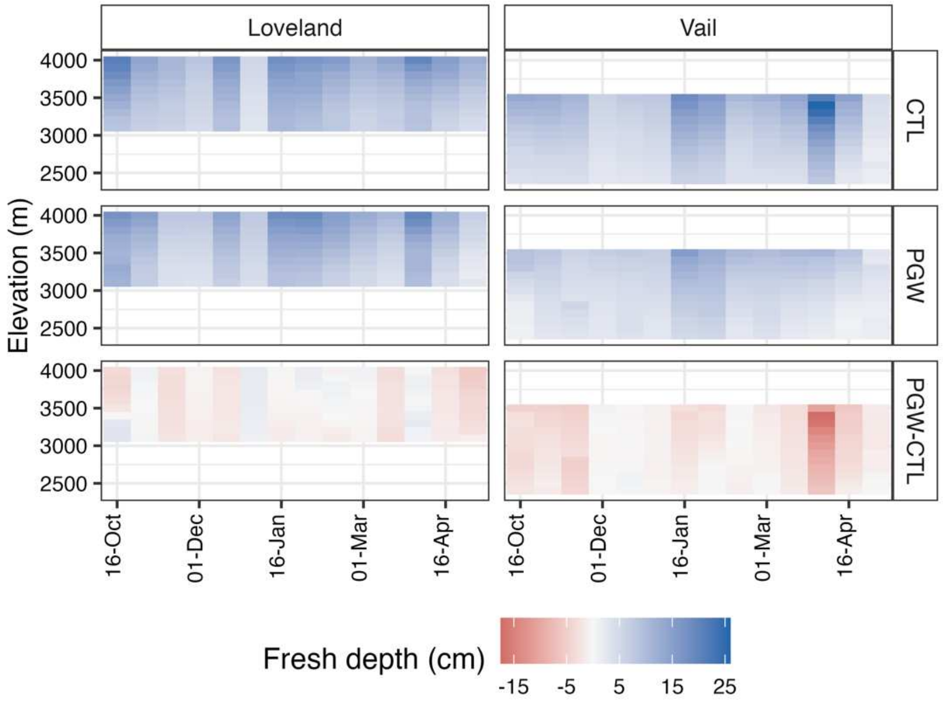
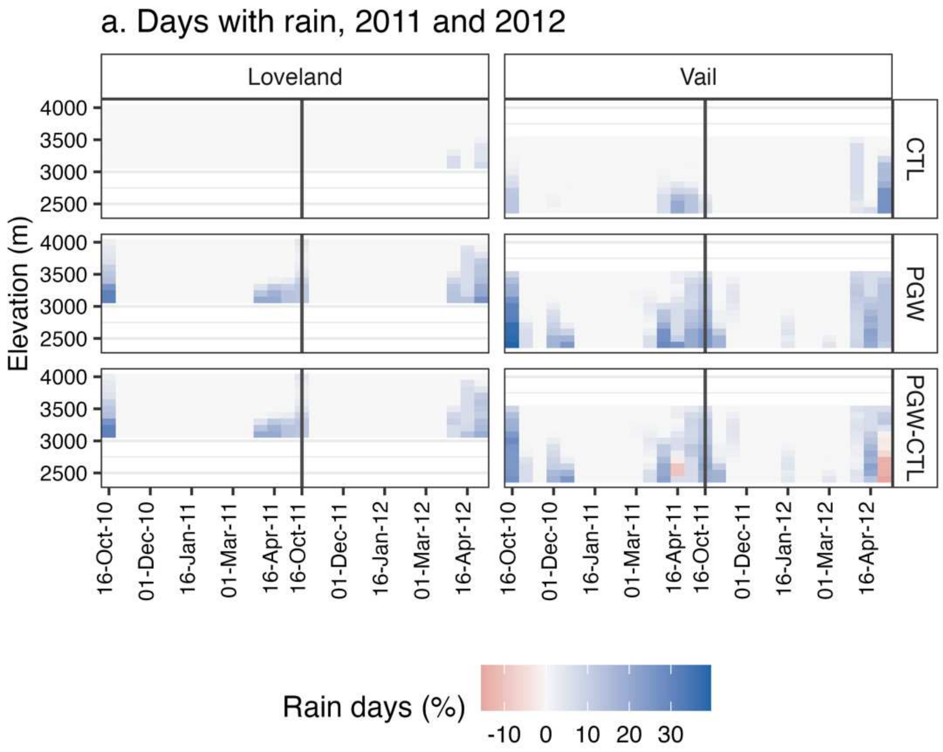
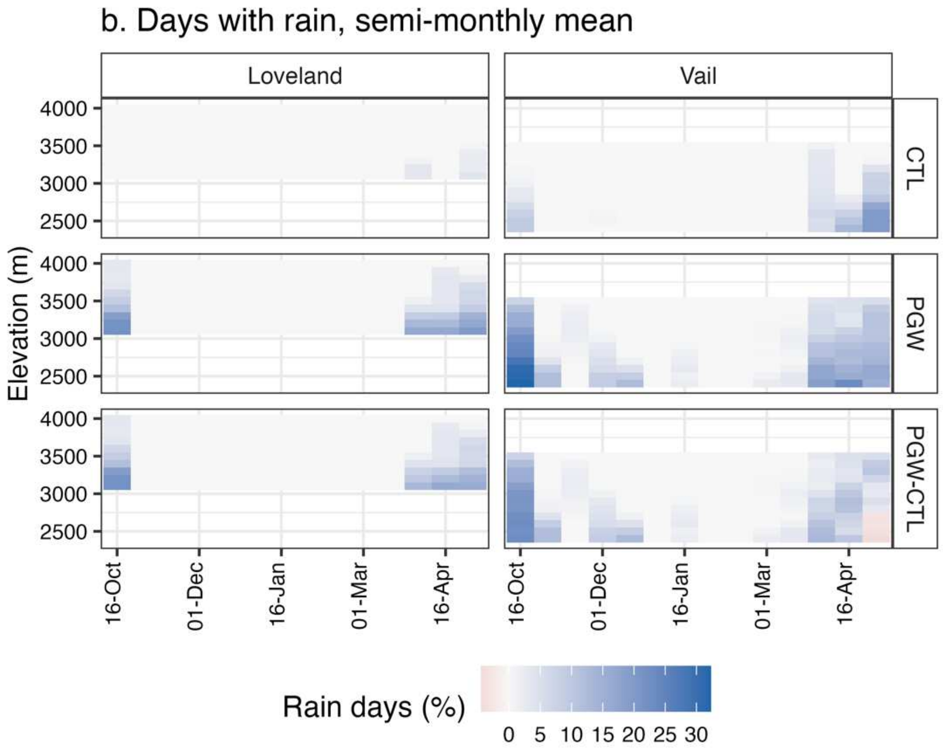


Figure 4-7. The same as above but for fresh snow depth.



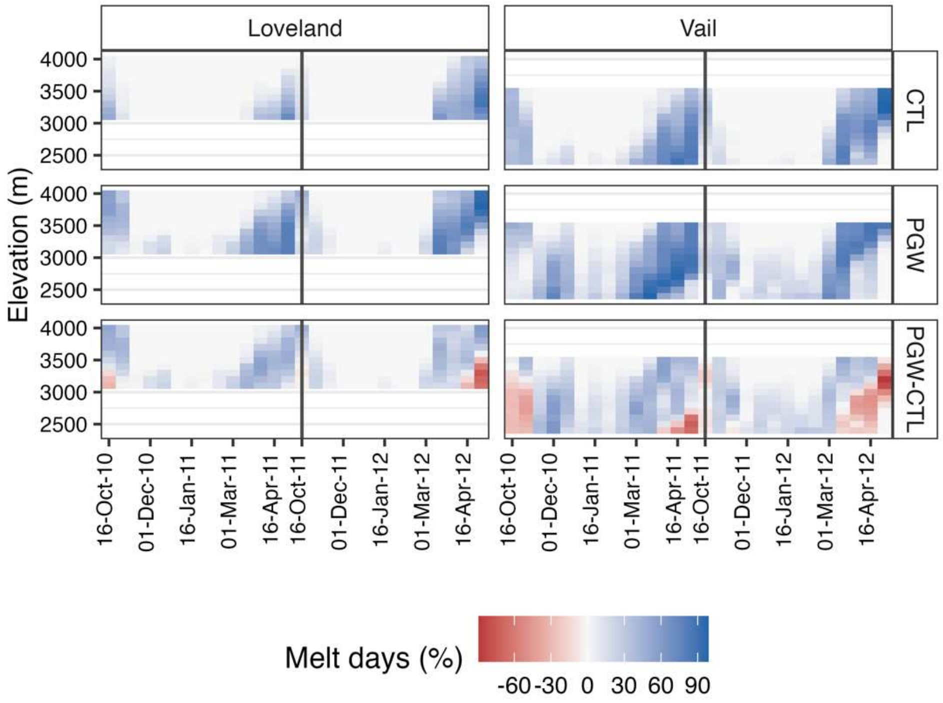
a. Days with rain, 2011 and 2012



b. Days with rain, semi-monthly mean

Figure 4-8. The same as above but for days with rain.

a. Days with melt, 2011 and 2012



b. Days with melt, semi-monthly mean

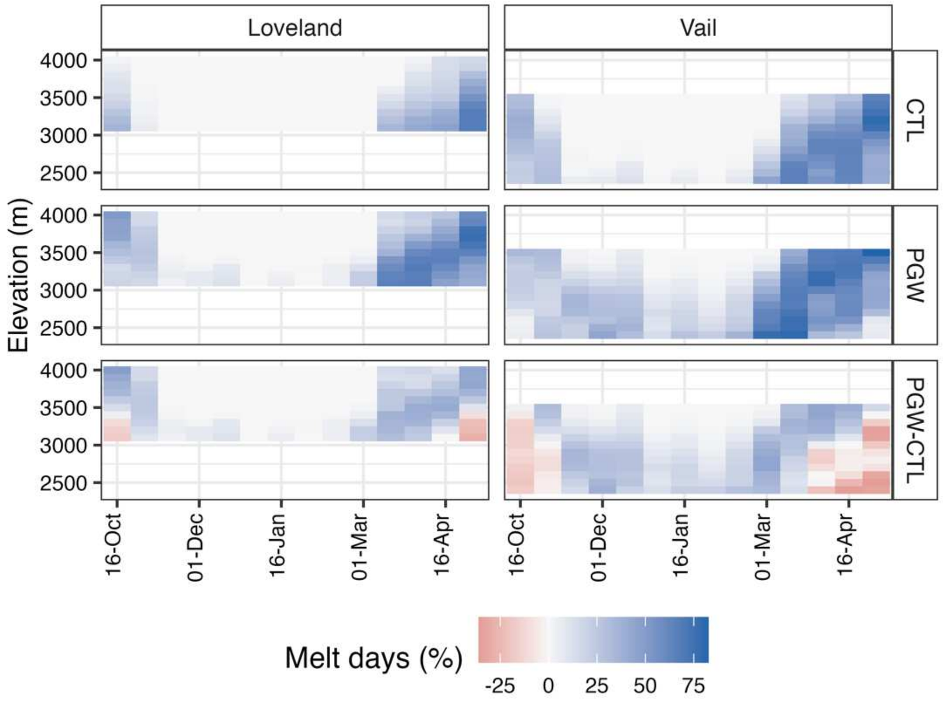


Figure 4-9. The same as above but for days with melt.

4.8 References

Berghammer, A., & Schmude, J. (2014). The Christmas—Easter Shift: Simulating Alpine Ski Resorts' Future Development under Climate Change Conditions Using the Parameter 'Optimal Ski Day'. *Tourism Economics, 20*(2), 323-336.

Burakowski, E., & Magnusson, M. (2012). *Climate Impacts on the Winter Tourism Economy in the United States*. Retrieved from Washington, DC:

Dannevig, H., Gildestad, I. M., Steiger, R., & Scott, D. (2020). Adaptive capacity of ski resorts in Western Norway to projected changes in snow conditions. *Current Issues in Tourism, 24*(22), 3206-3221.

Fassnacht, S. R., Venable, N., McGrath, D., & Patterson, G. (2018). Sub-Seasonal Snowpack Trends in the Rocky Mountain National Park Area, Colorado, USA. *Water, 10*(5).

Fassnacht, S. R., Kouwen, N., & Soulis, E. D. (2001). Surface temperature adjustments to improve weather radar representation of multi-temporal winter precipitation accumulations. *Journal of Hydrology, 253*, 148-168.

Fassnacht, S. R., & López-Moreno, J. I. (2020). Patterns of trends in niveograph characteristics across the western United States from snow telemetry data. *Frontiers of Earth Science, 14*(2), 315-325.

Fassnacht, S. R., Patterson, G. G., Venable, N. B. H., Cherry, M. L., Pfohl, A. K. D., Sanow, J. E., & Tedesche, M. E. (2020). How Do We Define Climate Change? Considering the Temporal Resolution of Niveo-Meteorological Data. *Hydrology, 7*(3).

Fassnacht, S. R., & Soulis, E. D. (2002). Implications during transitional periods of improvements to the snow processes in the land surface scheme - hydrological model WATCLASS. *Atmosphere-Ocean, 40*(4), 389-403.

Hammond, J. C., Sexstone, G. A., Putman, A. L., Barnhart, T. B., Rey, D. M., Driscoll, J. M., et al. (2023). High Resolution SnowModel Simulations Reveal Future Elevation-Dependent Snow Loss and Earlier, Flashier Surface Water Input for the Upper Colorado River Basin. *Earth's Future, 11*(2).

Hatchett, B. J., Rhoades, A. M., & McEvoy, D. J. (2022). Decline in Seasonal Snow during a Projected 20-Year Dry Spell. *Hydrology, 9*(9).

Hock, R., Rasul, G., Adler, C., Cáceres, B. v., Gruber, S., Hirabayashi, Y., et al. (2022). High Mountain Areas. In *The Ocean and Cryosphere in a Changing Climate* (pp. 131-202).

Ikeda, K., Rasmussen, R., Liu, C., Gochis, D., Yates, D., Chen, F., et al. (2010). Simulation of seasonal snowfall over Colorado. *Atmospheric Research, 97*(4), 462-477.

Jensen, M. E., & Allen, R. G. (2016). *Evaporation, evapotranspiration, and irrigation water requirements* (Second edition. ed.). Reston, Virginia: American Society of Civil Engineers.

Judson, A., & Doesken, N. (2000). Density of Freshly Fallen Snow in the Central Rocky Mountains. *Bulletin of the American Meteorological Society, 81*(7), 11.

Lazar, B., & Williams, M. (2008). Climate change in western ski areas: Potential changes in the timing of wet avalanches and snow quality for the Aspen ski area in the years 2030 and 2100. *Cold Regions Science and Technology, 51*(2-3), 219-228.

Liston, G. E., & Elder, K. (2006). A Distributed Snow-Evolution Modeling System (SnowModel). *Journal of Hydrometeorology, 7*(6), 1259-1276.

Liu, C., Ikeda, K., Rasmussen, R., Barlage, M., Newman, A. J., Prein, A. F., et al. (2017). Continental-scale convection-permitting modeling of the current and future climate of North America. *Climate Dynamics, 49*(1-2), 71-95.

Looney, M. (2023, August 2023). [St. Slope Maintenance and Snowmaking Manager].

Marshall, A. M., Abatzoglou, J. T., Link, T. E., & Tennant, C. J. (2019). Projected Changes in Interannual Variability of Peak Snowpack Amount and Timing in the Western United States. *Geophysical Research Letters, 46*(15), 8882-8892.

Meinhardt, M., & Fassnacht, S. R. (2020). Fresh Snow Density from the Fort Collins Colorado Meteorological Station and New Measurements. *Colorado water, 37*(2), 7-9.

Mizukami, N., & Perica, S. (2008). Spatiotemporal Characteristics of Snowpack Density in the Mountainous Regions of the Western United States. *Journal of Hydrometeorology, 9*(6), 1416-1426.

Nakaya, U. (1954). *Snow Crystals: Natural and Artificial*: Harvard University Press.

Rhoades, A. M., Hatchett, B. J., Risser, M. D., Collins, W. D., Bambach, N. E., Huning, L. S., et al. (2022). Asymmetric emergence of low-to-no snow in the midlatitudes of the American Cordillera. *Nature Climate Change, 12*(12), 1151-1159.

Sauter, T., Weitzenkamp, B., & Schneider, C. (2010). Spatio-temporal prediction of snow cover in the Black Forest mountain range using remote sensing and a recurrent neural network. *International Journal of Climatology, 30*(15), 2330-2341.

Scott, D., Knowles, N., & Steiger, R. (2022a). Is snowmaking climate change maladaptation? *Journal of Sustainable Tourism*, 1-22.

Scott, D., Knowles, N. L. B., Ma, S., Rutty, M., & Steiger, R. (2022b). Climate change and the future of the Olympic Winter Games: athlete and coach perspectives. *Current Issues in Tourism*, 1-16.

Scott, D., & Lemieux, C. (2010). Weather and Climate Information for Tourism. *Procedia Environmental Sciences, 1*, 146-183.

Scott, D., & McBoyle, G. (2006). Climate change adaptation in the ski industry. *Mitigation and Adaptation Strategies for Global Change, 12*(8), 1411-1431.

Scott, D., McBoyle, G., & Mills, B. (2003). Climate change and the skiing industry in southern Ontario (Canada): exploring the importance of snowmaking as a technical adaptation. *Climate Research, 23*, 171-181.

Scott, D., Steiger, R., Rutty, M., Knowles, N., & Rushton, B. (2021). Future climate change risk in the US Midwestern ski industry. *Tourism Management Perspectives, 40*.

Siirila-Woodburn, E. R., Rhoades, A. M., Hatchett, B. J., Huning, L. S., Szinai, J., Tague, C., et al. (2021). A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment, 2*(11), 800-819.

Steiger, R., Scott, D., Abegg, B., Pons, M., & Aall, C. (2017). A critical review of climate change risk for ski tourism. *Current Issues in Tourism, 22*(11), 1343-1379.

Sturm, M., Goldstein, M. A., & Parr, C. (2017). Water and life from snow: A trillion dollar science question. *Water Resources Research, 53*(5), 3534-3544.

CHAPTER 5: DISCUSSION

5.1 Objectives, revisited

The primary goal of this research was to investigate the changes in Colorado water (in terms of snow drought, streamflow, and winter recreation) from the recent past and under a PGW scenario.

5.1.1 What is a snow drought?

The metrics and terms used to define a snow drought (low snow) are not consistent (Dierauer et al., 2019; Harpold et al., 2017; Hatchett & McEvoy, 2018; Hatchett et al., 2022; Heldmyer et al., 2023; Rhoades et al., 2022; Wiesnet, 1981). The National Integrated Drought Information System (NIDIS), which has the "mandate to coordinate and integrate drought research" (NIDIS, 2023), has conflicting information on snow drought. They describe warm and dry snow drought (Dierauer et al., 2019; Harpold et al., 2017; Heldmyer et al., 2023) and include below- or near-normal precipitation in their definition but have additional metrics (percent of median SWE and percent of average SWE but not precipitation) linked to maps with current conditions. Shifting definitions makes comparisons more difficult, and misclassification more likely (e.g., Table 2-2 and Figure 2-3).

In their paper, Dierauer et al. (2019) used SWE/P to quantify a given year as snow drought across the western U.S. and into Canada when peak SWE was less than the long-term mean, regardless of how much less (Dierauer et al., 2019). They acknowledged that this could lead to an overestimation of drought classifications for dry snow drought, but their primary focus was wet snow drought, which is less affected by minor snow droughts (Dierauer et al., 2019). A minor snow drought occurs when SWE is less than the long-term mean, but not considered low

(Figures 2-4 and 2-6). Further, the SWE/P and snow drought classification was a component to calculate future drought susceptibility. When Heldmyer et al. (2023) used SWE/P and the mean SWE threshold in the Upper Colorado River Basin (UCRB), they did not include such caveats. Using their criteria, from 1916 to 2018, 59 years were classified as snow drought, a far greater occurrence of drought (or low snow) conditions than what has been reported in other studies (Dierauer et al., 2019; Siirila-Woodburn et al., 2021; Udall & Overpeck, 2017). Unsurprisingly, the results presented in Chapter 2 have similar, drastic findings (Figure 2-3). Snow in the UCRB has decreased in the past decades (Figure 2-4) (Schrock et al., 2021; Siirila-Woodburn et al., 2021; Udall & Overpeck, 2017) but not to the degree suggested by Heldmyer et al. (2023) or our analysis.

We do not have a better definition for snow drought and/or low snow than what is currently being used; however, we have clarity about metrics that may not add as much value as others. Snow drought classification based solely upon the criterion of long-term SWE is inadequate. We do suggest that future studies include metrics that address high snow years, which have been crucial in the past to help buffer water supply during times of actual snow drought.

5.1.2 Importance of capturing baseflow

Under a PGW scenario, the largest decrease in peak SWE happened during a high snow year (Figures 3-1 and 3-7). During this same year, streamflow (Figure 3-6) and winter precipitation as rain and snow decreased (Figures 3-8 and 3-9). The contribution to streamflow from snow decreases and winter rain increases at high elevations (Ban et al., 2023). Baseflow in the UCRB will decrease with a warming climate, especially at higher elevations and may change by as much 50% and result in a decrease in stream connectedness (Miller et al., 2021). Low snowmelt may have a larger impact on reduced streamflow and baseflow than peak SWE (Rumsey et al., 2020). For intermittent streams, total and spring precipitation are more important for sustaining flow than precipitation as snow (Kiewiet et al., 2022). Addressing past and future baseflow, its contribution to total streamflow, and its correlation with snowmelt and total runoff should be addressed after the Ages model performance is improved and better able to capture low flows (Figure 3-5a).

5.1.3 Applied snow science

Papers focusing on water in the western United States, especially the seasonal snowpack, start with the same few sentences about the importance of water in the west (see the introductions to all previous chapters for yet another example). The overarching goals are always presented, but often the additional implications are forgotten, omitted, or acknowledged with a single sentence. The papers (Immerzeel et al., 2020; Siirila-Woodburn et al., 2021; Sturm et al., 2017; Viviroli et al., 2007) that do include and underscore the impact on people often are most impactful (see the frequency of citations of the above papers). The work presented in Chapter 4 examines the implications of a changing snowpack. Comparing past and future snow cover, snowfall, occurrence of winter rain, and snowmelt are important in understanding the hydrology of the area; these calculations on their own are beneficial. By applying these findings to a relatable activity such as skiing, we have the opportunity to make the realities of climate change more tangible to those outside of the scientific community.

5.2 Towards smaller science

Coarse resolution data and the scientists who have utilized such datasets are responsible for our current level of understanding of water in the western United States. As a scientific community, the consequences of climate change on the seasonal snowpack are likely common knowledge: less snow is falling from the sky, less is on the ground (regardless of how we define that lack of snow), there is a later onset of accumulation, and earlier melt. These statements hold true for the western U.S. as a single entity, but the deviations that occur over smaller regions are lost. The research in this dissertation addressed these changes, but at a fine spatial resolution over a relatively small study area. The results presented in Chapter 4 are at much finer resolution (100-m) than what has been used (50-km) in other ski area studies (Dannevig et al., 2020; Lazar & Williams, 2008; Scott et al., 2003; Steiger et al., 2017).

In Chapter 2, we compared high and low snow years in the past and under PGW conditions at 100-m elevations. In Chapter 3, we modeled streamflow and examined associated hydrology for a high-elevation watershed. In Chapter 4, we examined past and future snow conditions and the implications on ski resorts. Everything herein could be replicated with a coarser resolution dataset but almost certainly the results would change. Large-scale studies are still relevant and important, and we are not suggesting their discontinued use. Rather, we are advocating that smaller case studies that create and utilize fine-resolution datasets become more common, such as the WRF-SM product developed by Hammond et al. (2023). All these analyses benefitted from the use of high-resolution data.

For our ski analysis, a single cell in a 30-km resolution dataset would have been used for each resort. For ski area managers, a single data point does not inform management decisions that need to be made at specific locations. Using information about how conditions vary within the resort allows results to be applied to those directly affected by changes. Hydrology is influenced by people, and people influence hydrology. Hydrologic research is often for the sake of society, and results need to be communicated as such.

5.3 References

Ban, Z., Li, D., & Lettenmaier, D. P. (2023). The Increasing Role of Seasonal Rainfall in Western U.S. Summer Streamflow. *Geophysical Research Letters, 50*(9).

Dannevig, H., Gildestad, I. M., Steiger, R., & Scott, D. (2020). Adaptive capacity of ski resorts in Western Norway to projected changes in snow conditions. *Current Issues in Tourism, 24*(22), 3206-3221.

Dierauer, J. R., Allen, D. M., & Whitfield, P. H. (2019). Snow Drought Risk and Susceptibility in the Western United States and Southwestern Canada. *Water Resources Research, 55*(4), 3076-3091.

Hammond, J. C., Sexstone, G. A., Putman, A. L., Barnhart, T. B., Rey, D. M., Driscoll, J. M., et al. (2023). High Resolution SnowModel Simulations Reveal Future Elevation-Dependent Snow Loss and Earlier, Flashier Surface Water Input for the Upper Colorado River Basin. *Earth's Future, 11*(2).

Harpold, A. A., Dettinger, M. D., & Rajagopal, S. (2017). Defining Snow Drought and Why It Matters. *EOS, 98*.

Hatchett, B. J., & McEvoy, D. J. (2018). Exploring the Origins of Snow Drought in the Northern Sierra Nevada, California. *Earth Interactions, 22*(2), 1-13.

Hatchett, B. J., Rhoades, A. M., & McEvoy, D. J. (2022). Monitoring the daily evolution and extent of snow drought. *Natural Hazards and Earth System Sciences, 22*(3), 869-890.

Heldmyer, A. J., Bjarke, N. R., & Livneh, B. (2023). A 21st-Century perspective on snow drought in the Upper Colorado River Basin. *JAWRA Journal of the American Water Resources Association*.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., et al. (2020). Importance and vulnerability of the world's water towers. *Nature, 577*(7790), 364-369. https://www.ncbi.nlm.nih.gov/pubmed/31816624

Kiewiet, L., Trujillo, E., Hedrick, A., Havens, S., Hale, K., Seyfried, M., et al. (2022). Effects of spatial and temporal variability in surface water inputs on streamflow generation and cessation in the rain–snow transition zone. *Hydrology and Earth System Sciences, 26*(10), 2779-2796.

Lazar, B., & Williams, M. (2008). Climate change in western ski areas: Potential changes in the timing of wet avalanches and snow quality for the Aspen ski area in the years 2030 and 2100. *Cold Regions Science and Technology, 51*(2-3), 219-228.

Miller, O. L., Miller, M. P., Longley, P. C., Alder, J. R., Bearup, L. A., Pruitt, T., et al. (2021). How Will Baseflow Respond to Climate Change in the Upper Colorado River Basin? *Geophysical Research Letters, 48*(22).

NIDIS. (2023). Snow Drought. Retrieved from https://www.drought.gov/topics/snow-drought

Rhoades, A. M., Hatchett, B. J., Risser, M. D., Collins, W. D., Bambach, N. E., Huning, L. S., et al. (2022). Asymmetric emergence of low-to-no snow in the midlatitudes of the American Cordillera. *Nature Climate Change, 12*(12), 1151-1159.

Rumsey, C. A., Miller, M. P., & Sexstone, G. A. (2020). Relating hydroclimatic change to streamflow, baseflow, and hydrologic partitioning in the Upper Rio Grande Basin, 1980 to 2015. *Journal of Hydrology, 584*.

Schrock, I. J. Y., Fassnacht, S. R., Collados-Lara, A.-J., Sanford, W. E., Pfohl, A. K. D., & Morán-Tejeda, E. (2021). Snow Water Equivalent Accumulation Patterns from a Trajectory Approach over the U.S. Southern Rocky Mountains. *Hydrology, 8*(3).

Scott, D., McBoyle, G., & Mills, B. (2003). Climate change and the skiing industry in southern Ontario (Canada): exploring the importance of snowmaking as a technical adaptation. *Climate Research, 23*, 171-181.

Siirila-Woodburn, E. R., Rhoades, A. M., Hatchett, B. J., Huning, L. S., Szinai, J., Tague, C., et al. (2021). A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth & Environment, 2*(11), 800-819.

Steiger, R., Scott, D., Abegg, B., Pons, M., & Aall, C. (2017). A critical review of climate change risk for ski tourism. *Current Issues in Tourism, 22*(11), 1343-1379.

Sturm, M., Goldstein, M. A., & Parr, C. (2017). Water and life from snow: A trillion dollar science question. *Water Resources Research, 53*(5), 3534-3544.

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research, 53*(3), 2404-2418.

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., & Weingartner, R. (2007). Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resources Research, 43*(7).

Wiesnet, D. (1981). Winter Snow Drought. *EOS, 62*, 137.

APPENDIX A

Table A-1. Contingency table of peak SWE and winter precipitation percentiles for SNOTEL stations.

		Winter Precipitation Percentile				
		Very High	High	Medium	Low	Very Low
Peak SWE Percentile	Very High	123	49	3	0	0
	High	45	199	91	2	0
	Medium	9	80	473	107	2
	Low	1	8	105	193	45
	Very Low	0	0	8	41	133

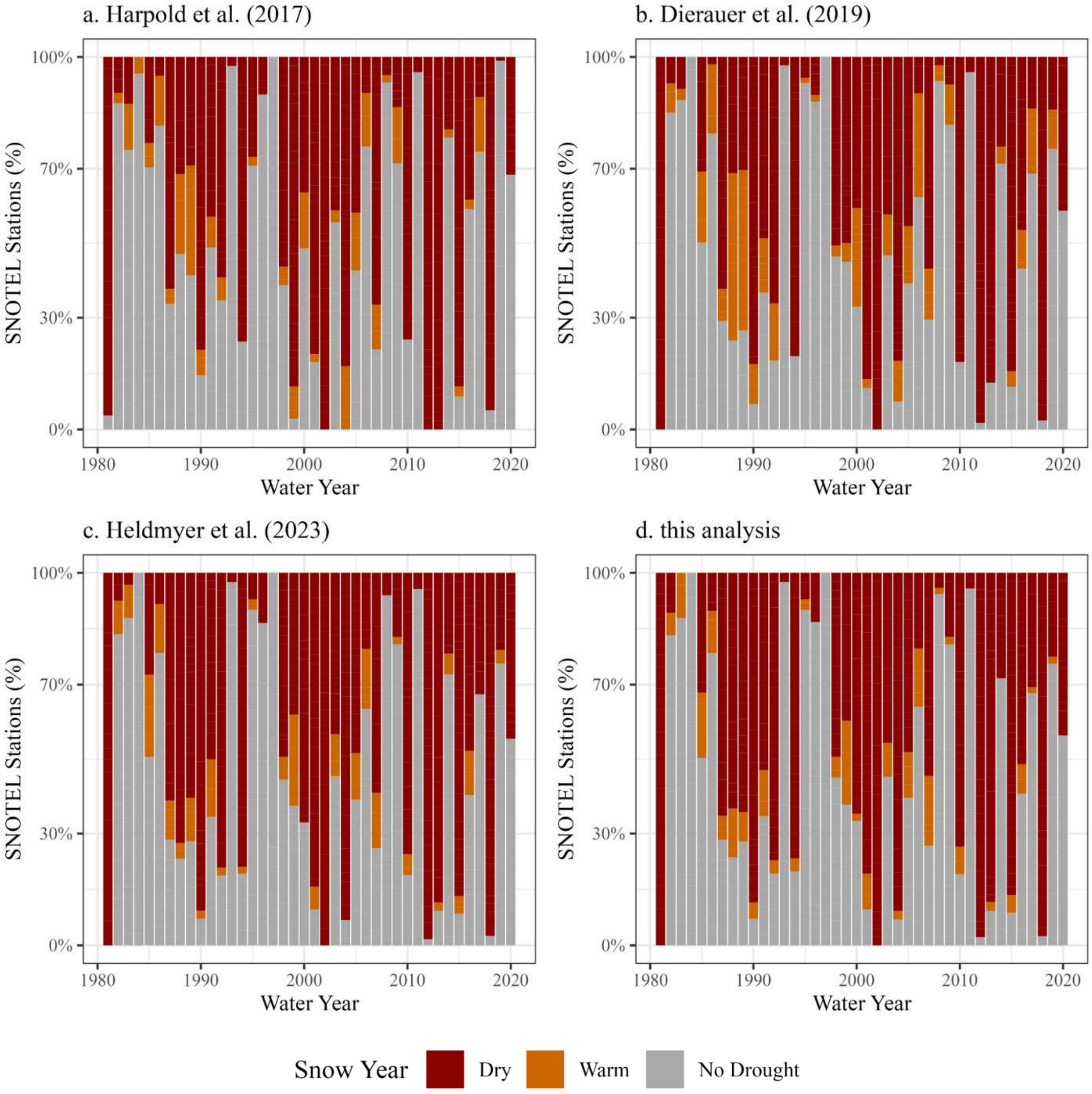


Figure A-1. Snow drought occurrence for different methods of SWE/P ratios from SNOTEL stations.

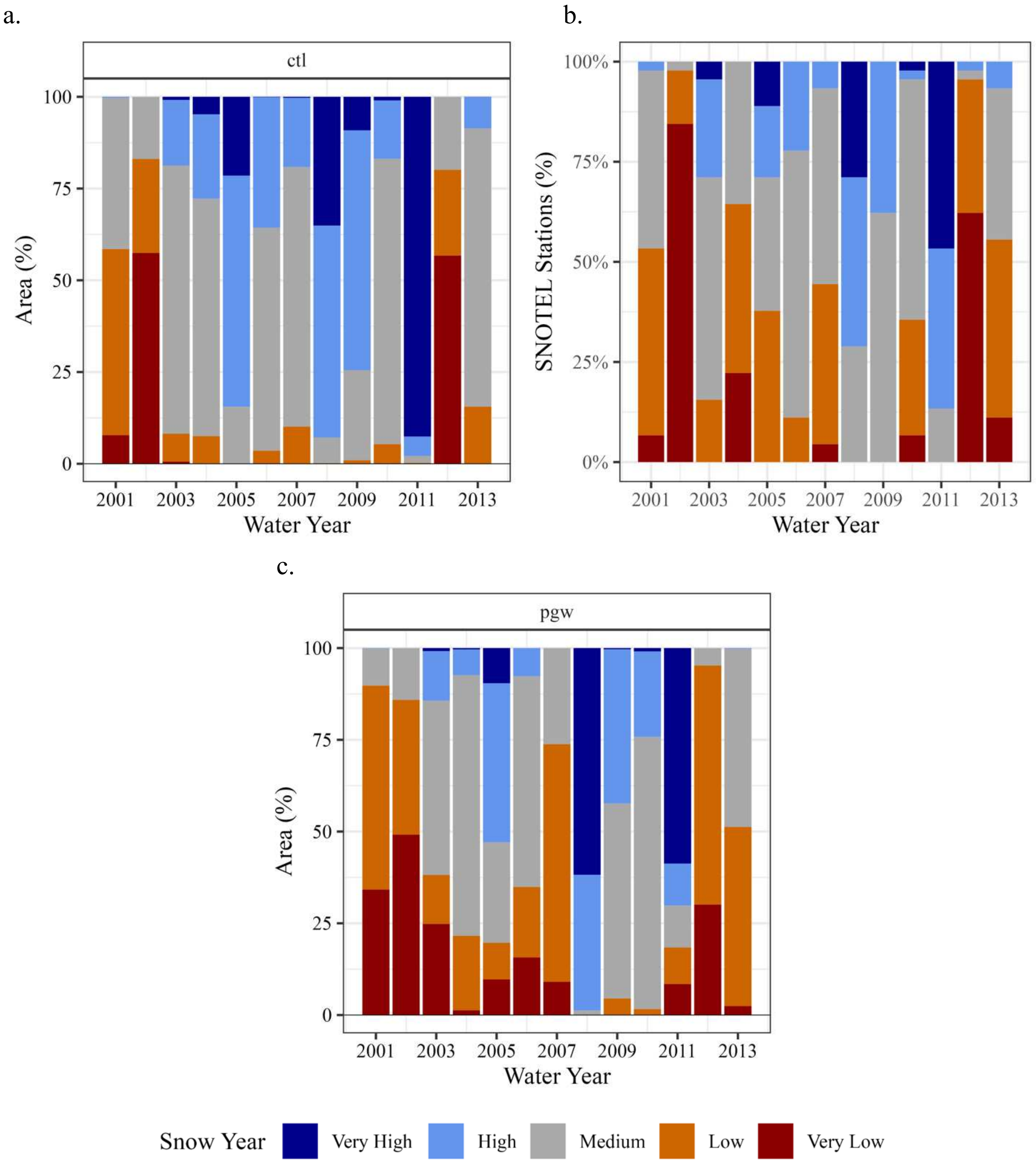


Figure A-2. Snow year classifications for peak SWE using WRF-SM dataset for a) the CTL scenario, b) SNOTEL stations from 2001 to 2013, and c) the PGW scenario.

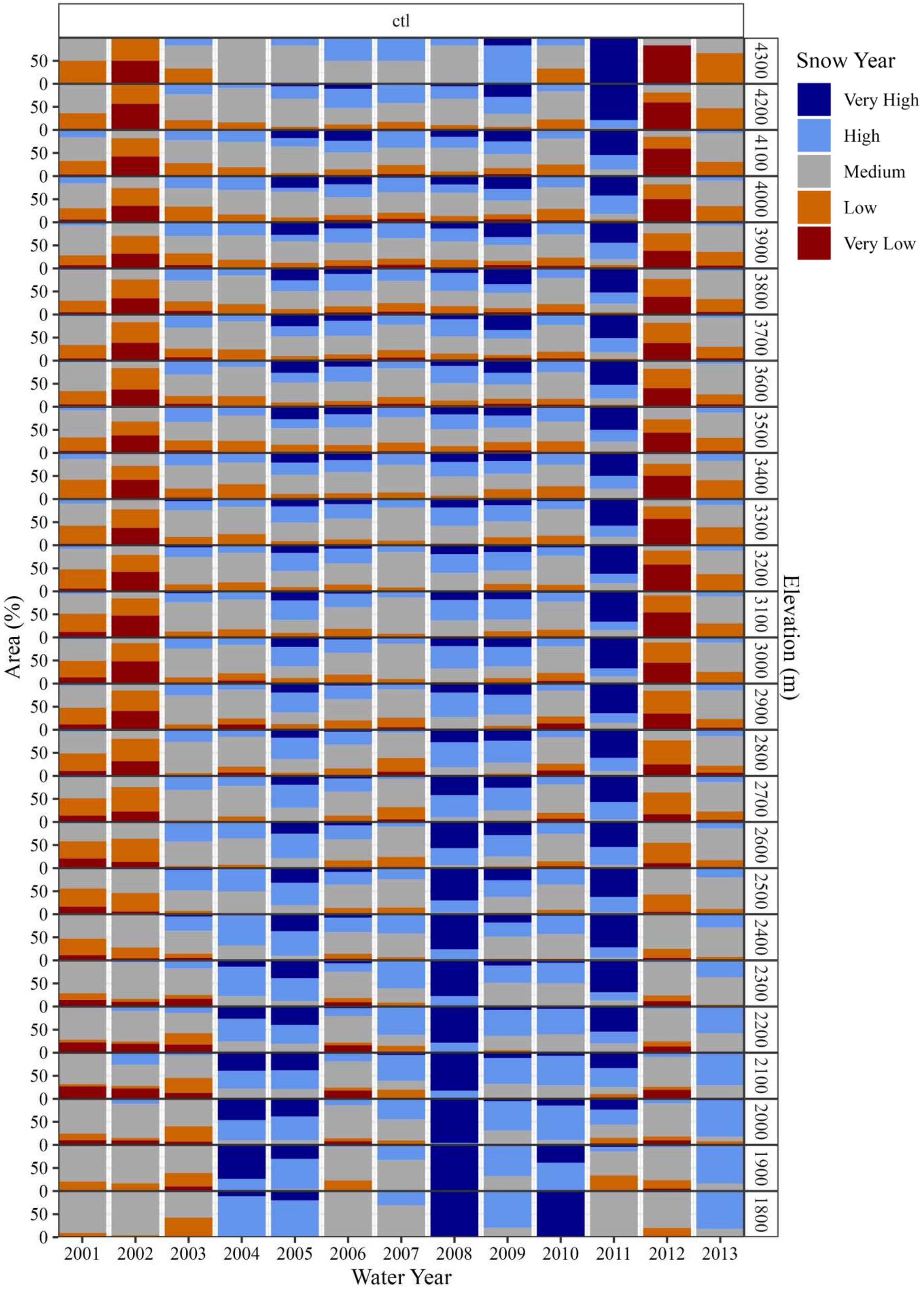


Figure A-3a. Snow year classifications for peak SWE by elevation band using WRF-SM dataset.

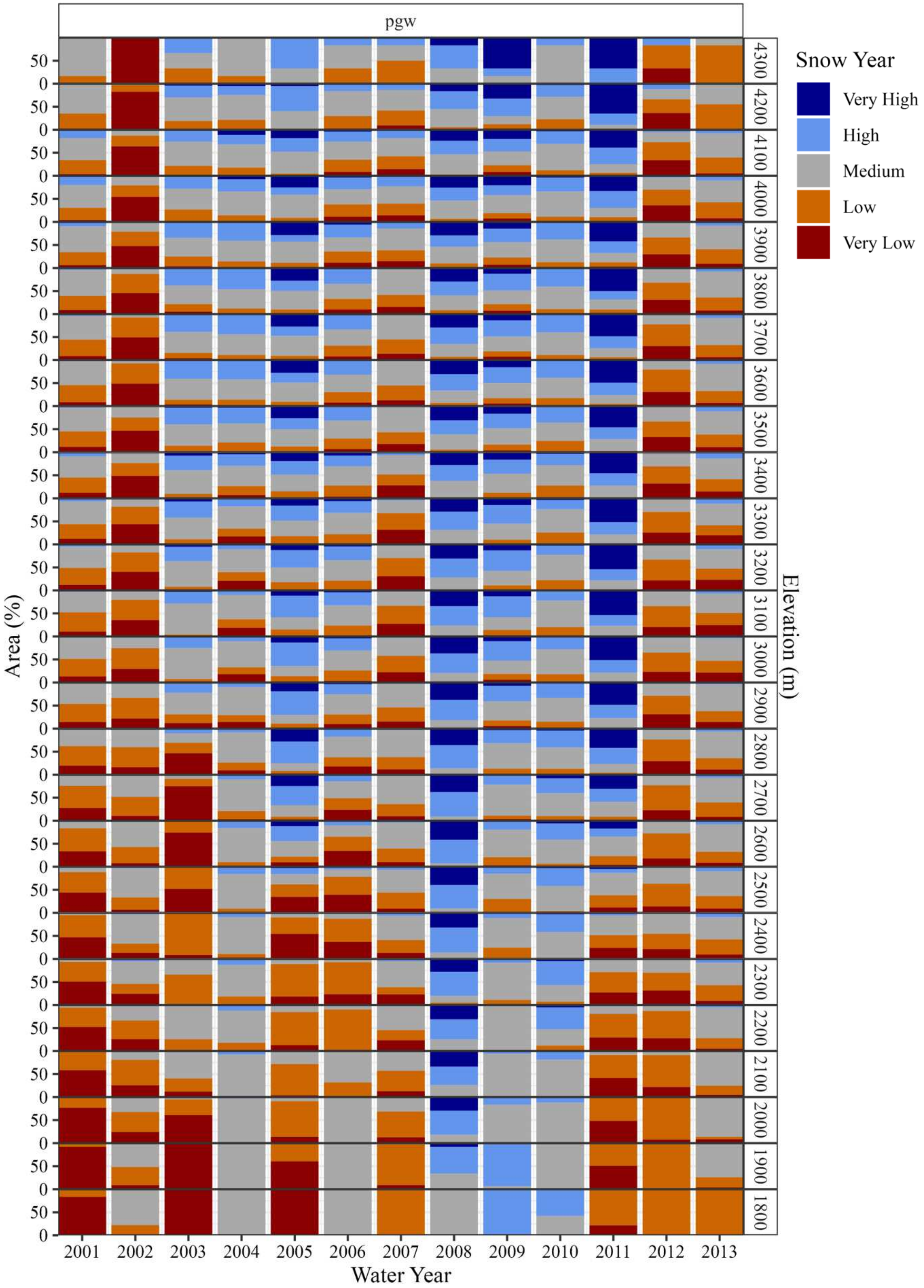


Figure A-3b. Snow year classifications for peak SWE by elevation band using WRF-SM dataset.

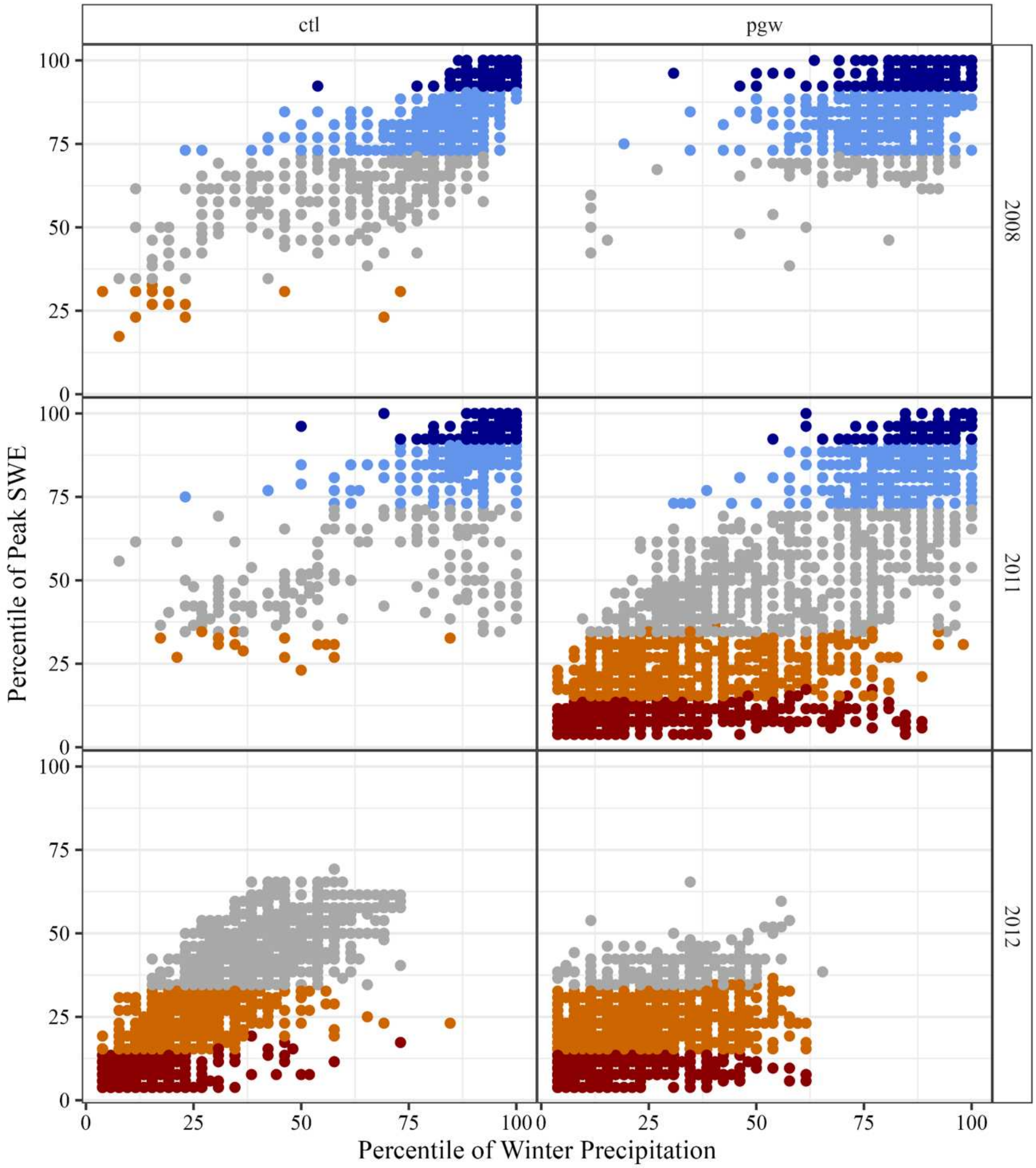


Figure A-4. Winter precipitation percentile compared to peak SWE percentile for random sample of WRF-SM data (n = 9000 out of 428570).

APPENDIX B

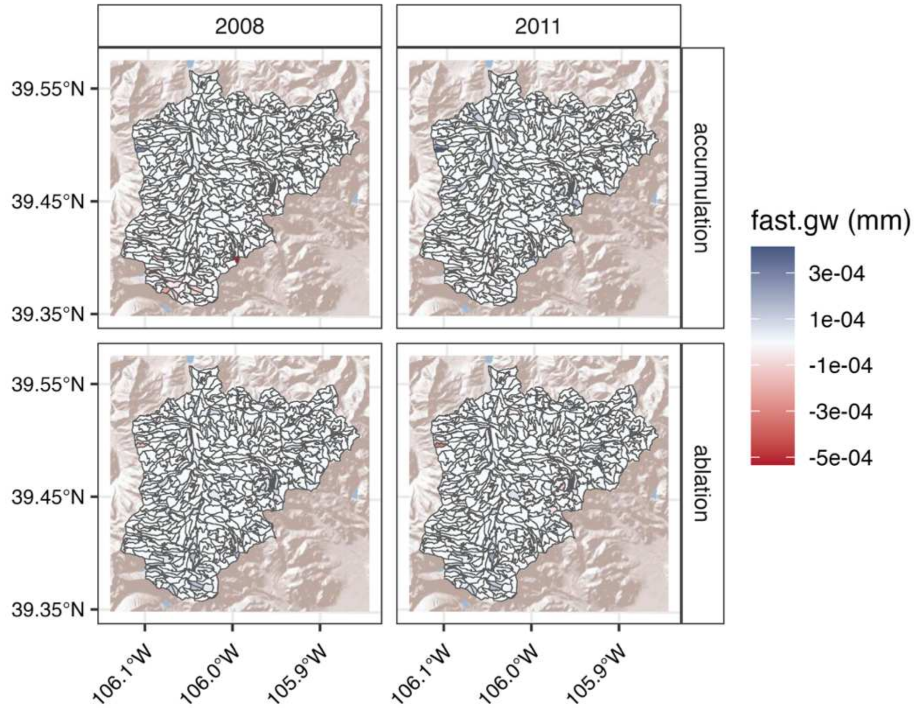


Figure B-1. Difference in fast moving groundwater between PGW and CTL from Ages model.

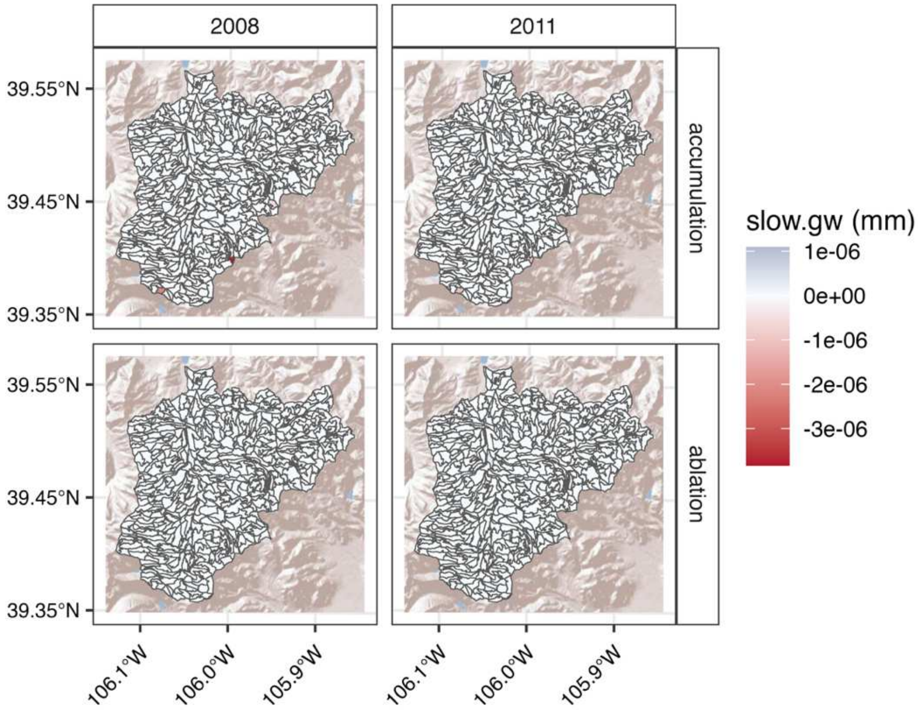


Figure B-2. Same as above but for slow moving groundwater.

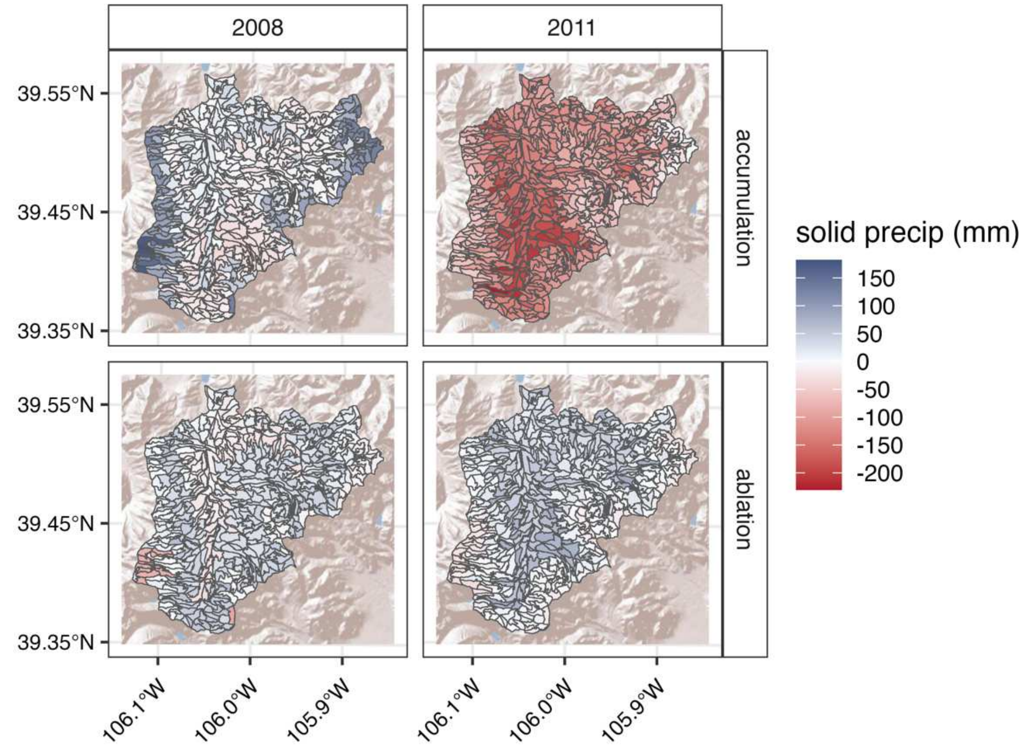


Figure B-3. Difference between PGW and CTL for solid precipitation from the WRF-SM dataset.

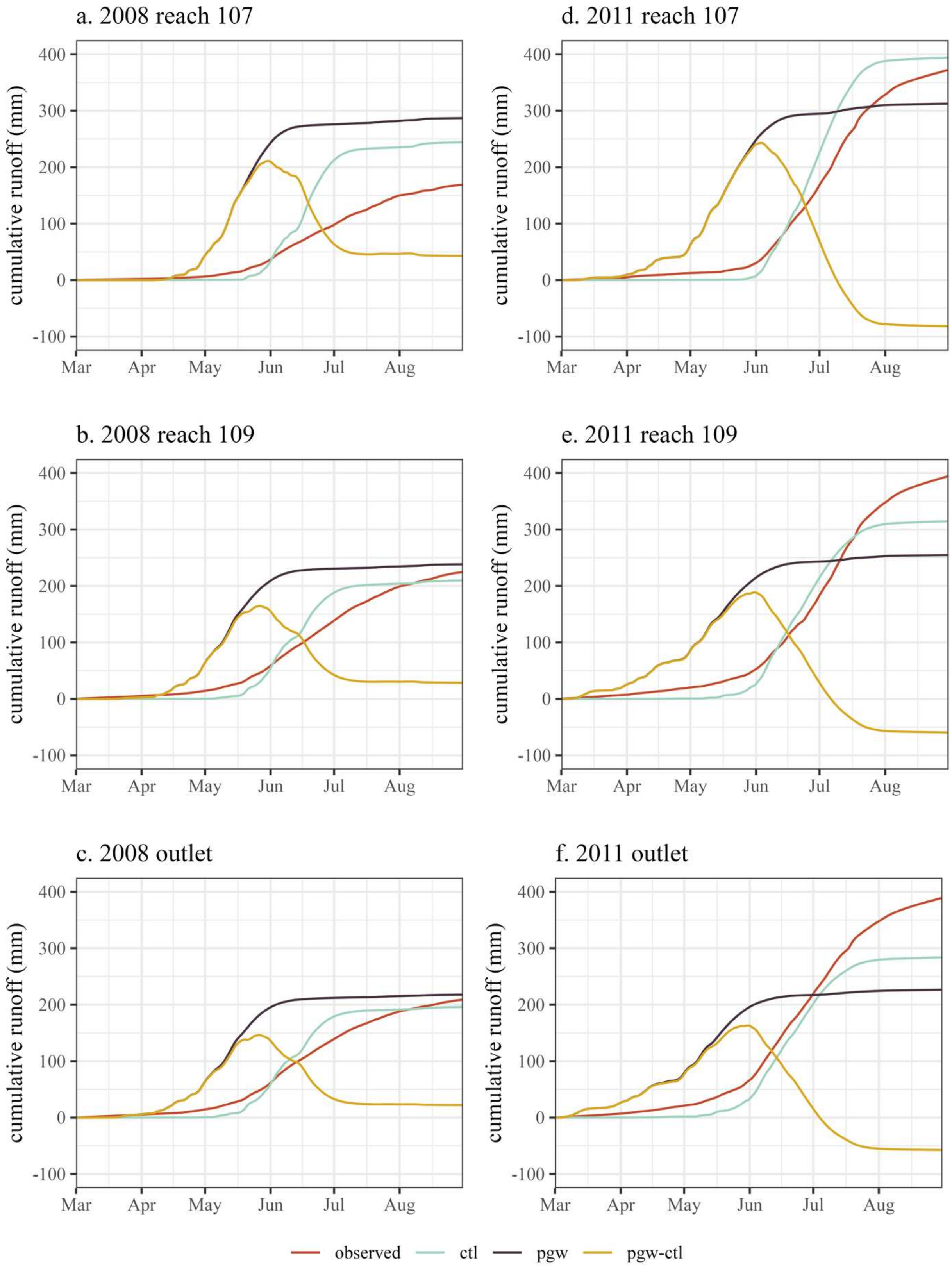


Figure B-4. Observed, modeled, difference (PGW-CTL) cumulative hydrographs for 2008 for a) Reach 107, b) Reach 107, and c) outlet; and d) through f) are the same but for 2011.

APPENDIX C

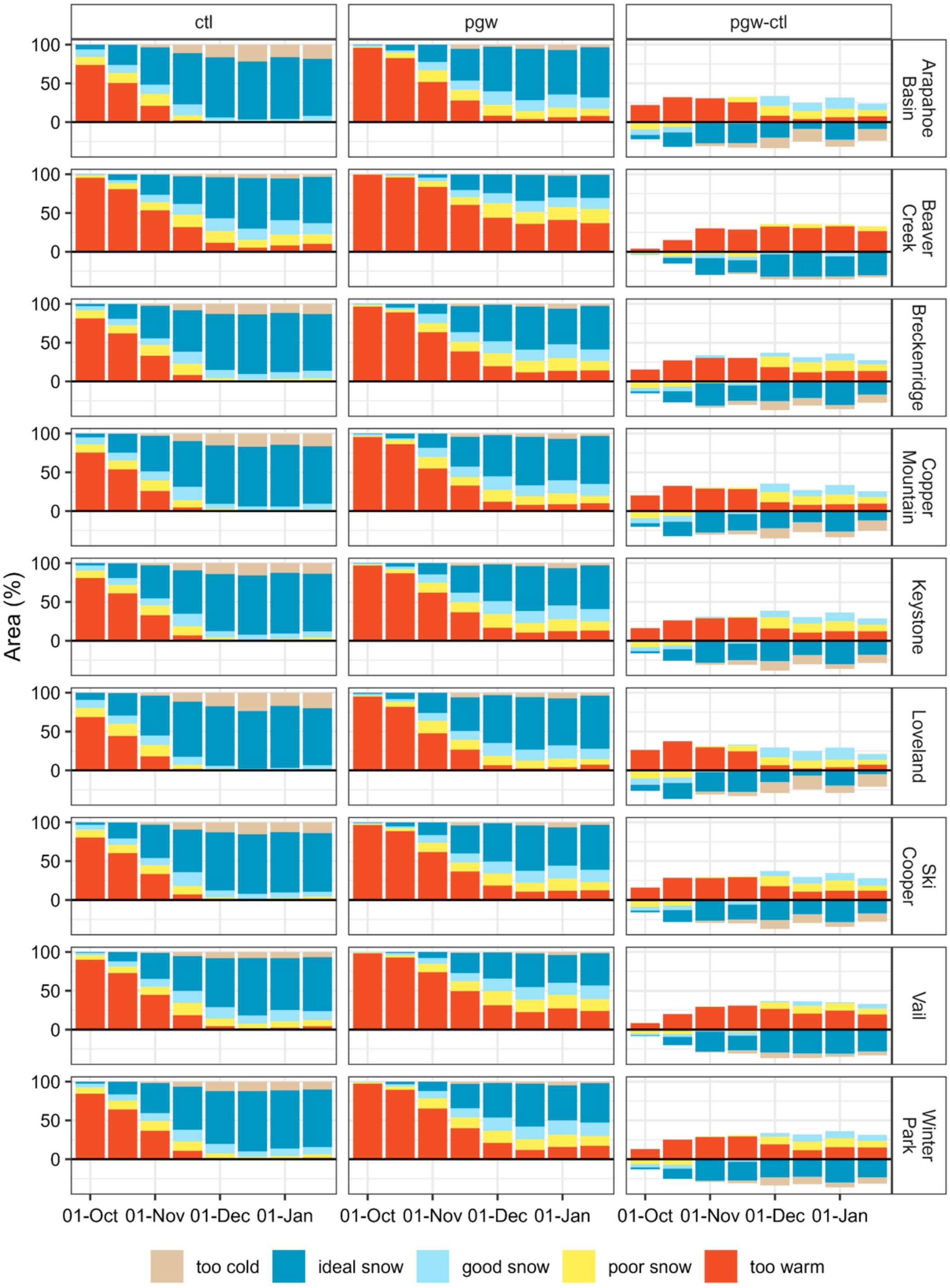


Figure C-1. Sub-monthly opportunities for snowmaking at all ski resorts over the 13-year (CTL, PGW, and PGW-CTL).

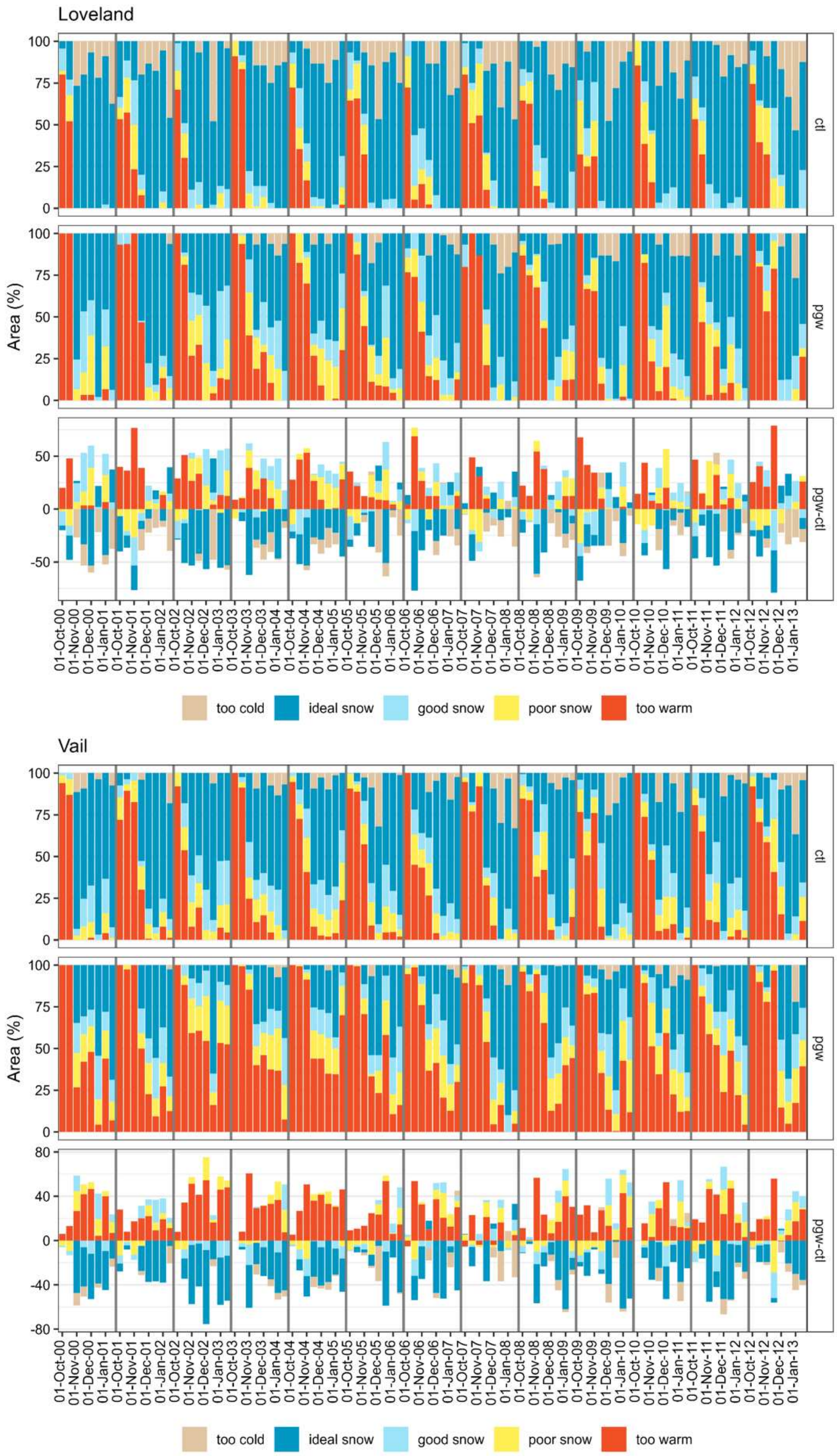


Figure C-2. Snowmaking days at Loveland (high elevation) and Vail (low elevation).

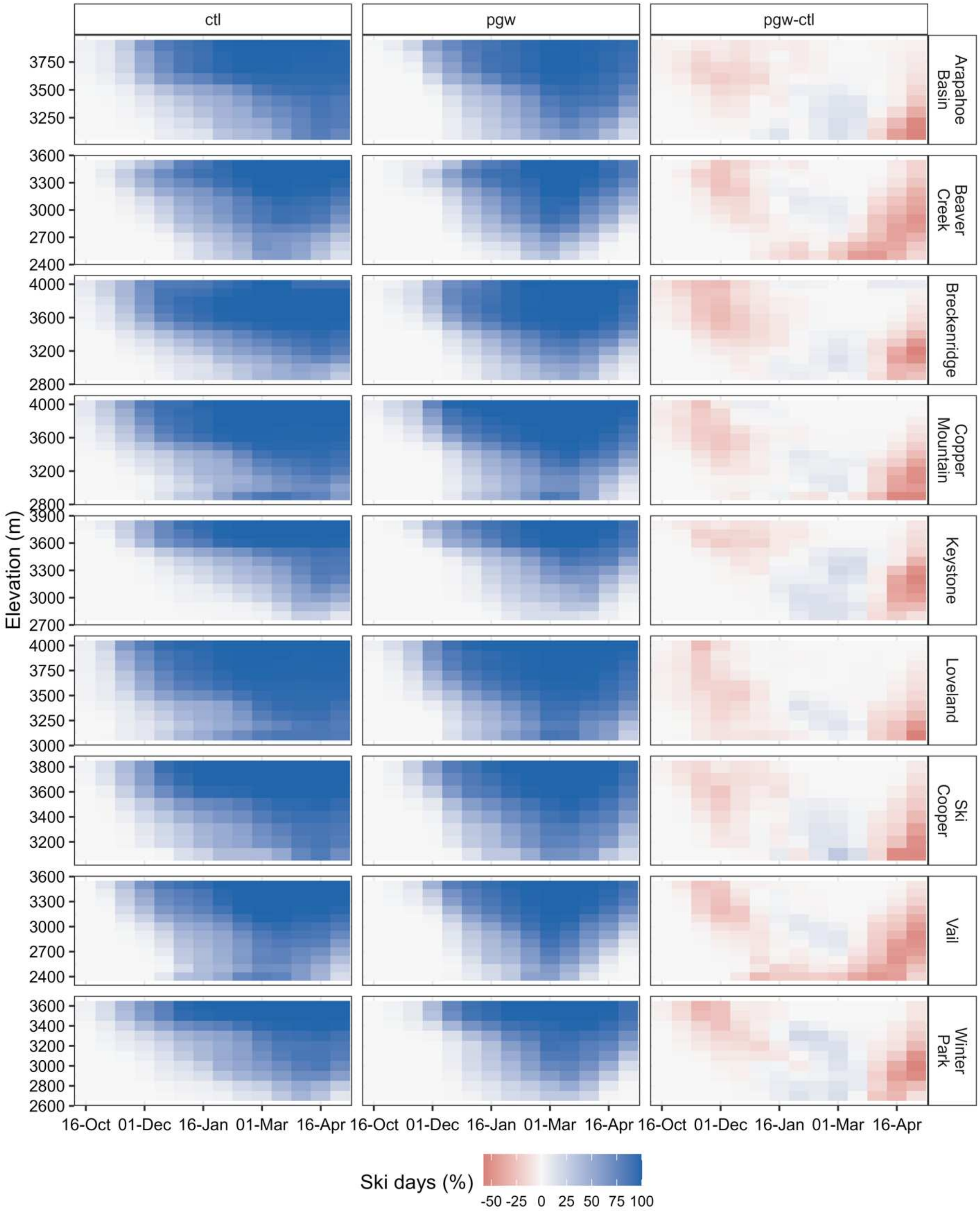
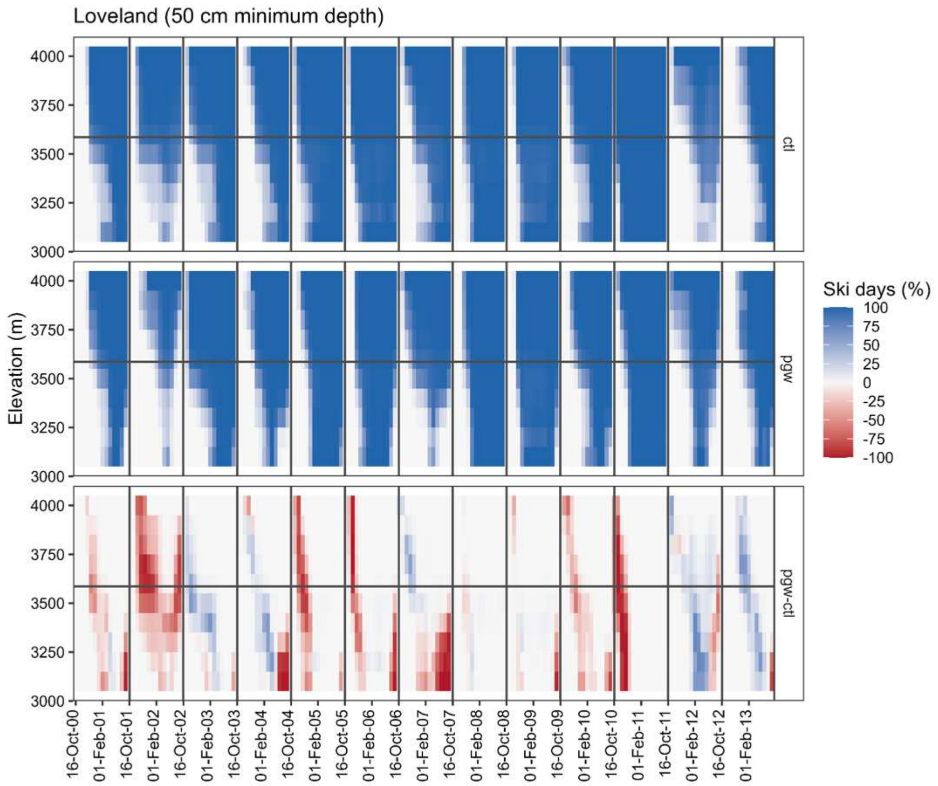


Figure C-3. Mean ski days over the 13-year period (CTL, PGW, and PGW-CTL) for each resort across elevation bands.


Loveland (50 cm minimum depth)

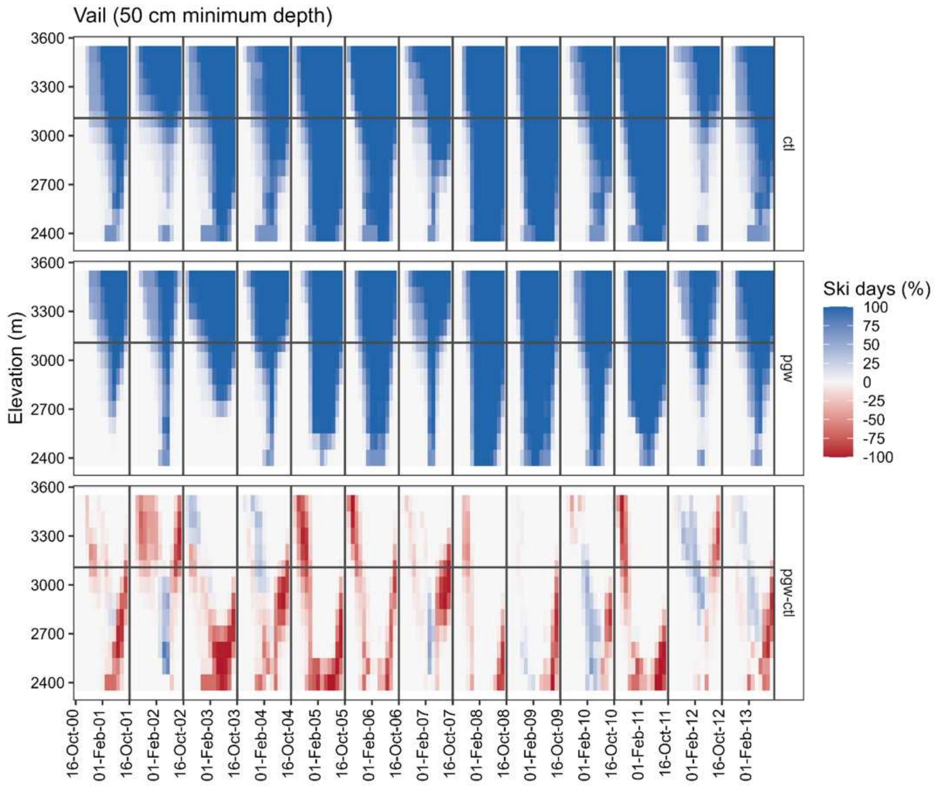

Vail (50 cm minimum depth)

Figure C-4. Ski days as a function of elevation and date for the 13-year period (CTL, PGW, PGW-CTL) for Loveland and Vail. The gray line represents the resort mean elevation.

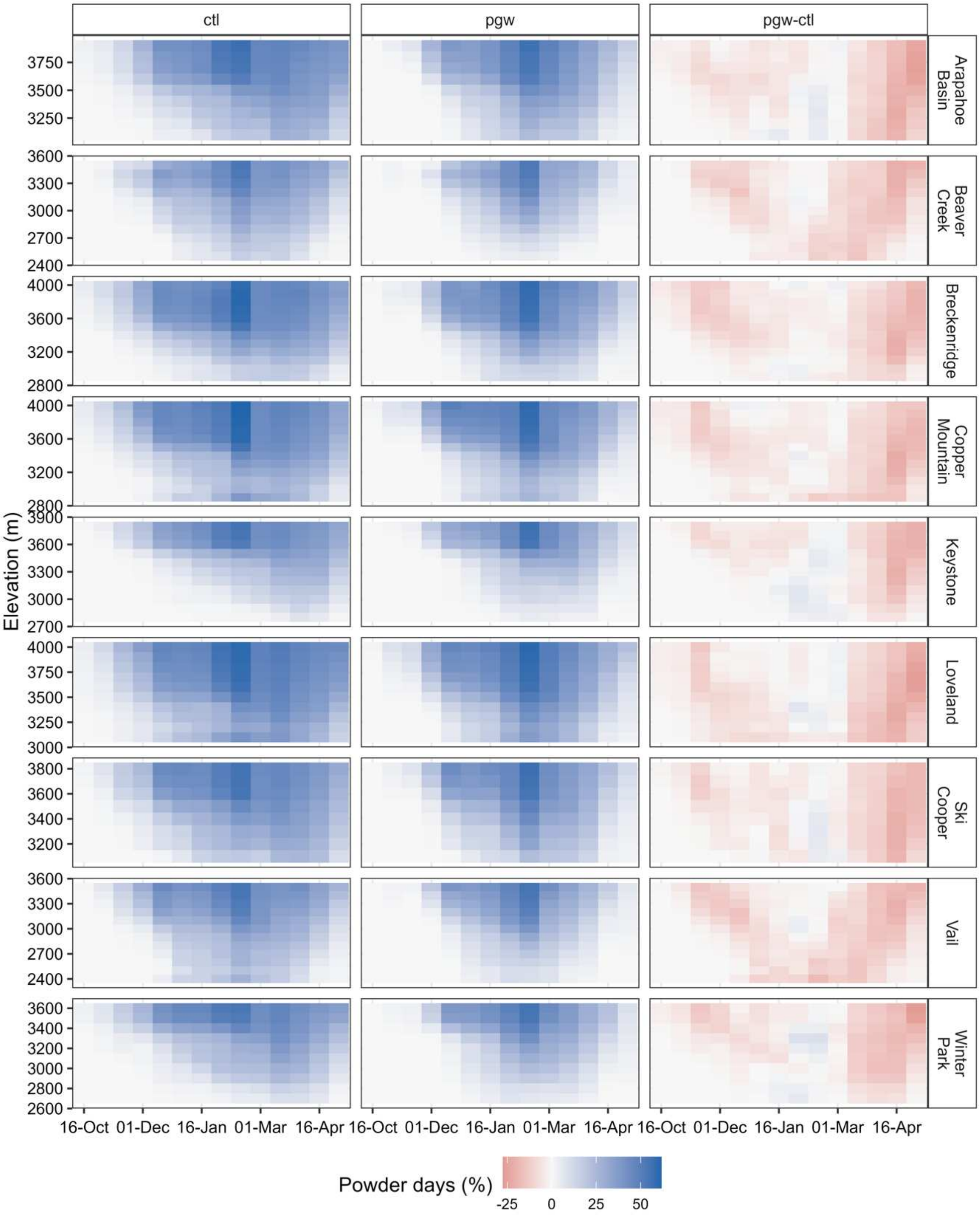
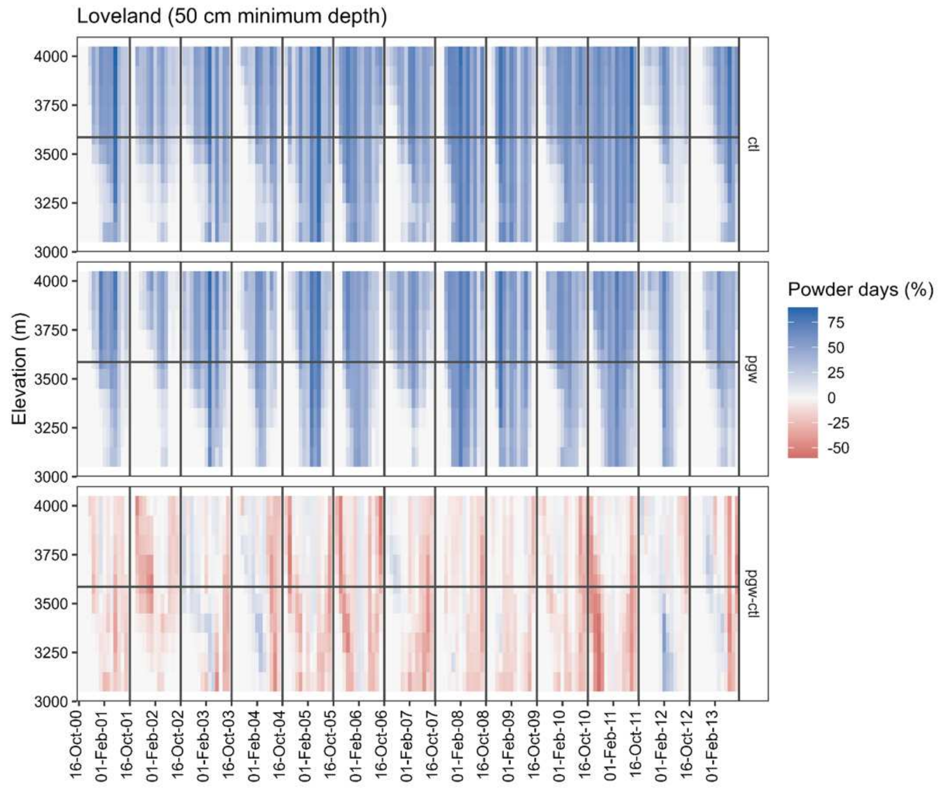


Figure C-5. Same as Figure 4-4 but for powder days (fresh snow depth greater than 15cm and fresh density 125 kg/m^3).



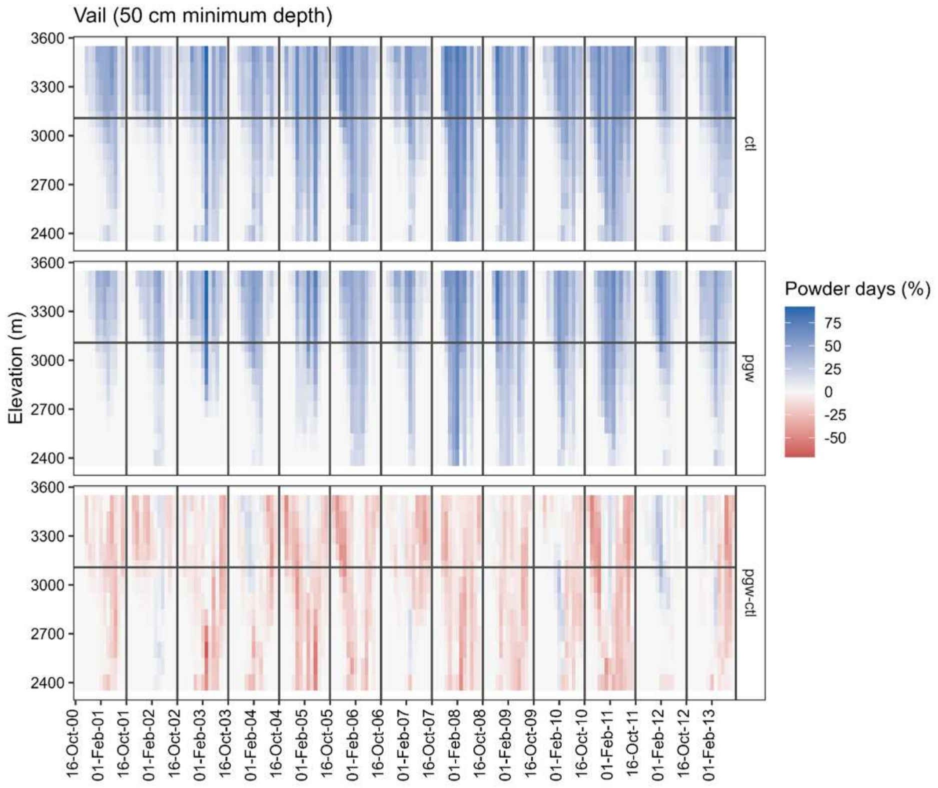


Figure C-6. Same as Figure 4-5 but for powder days.

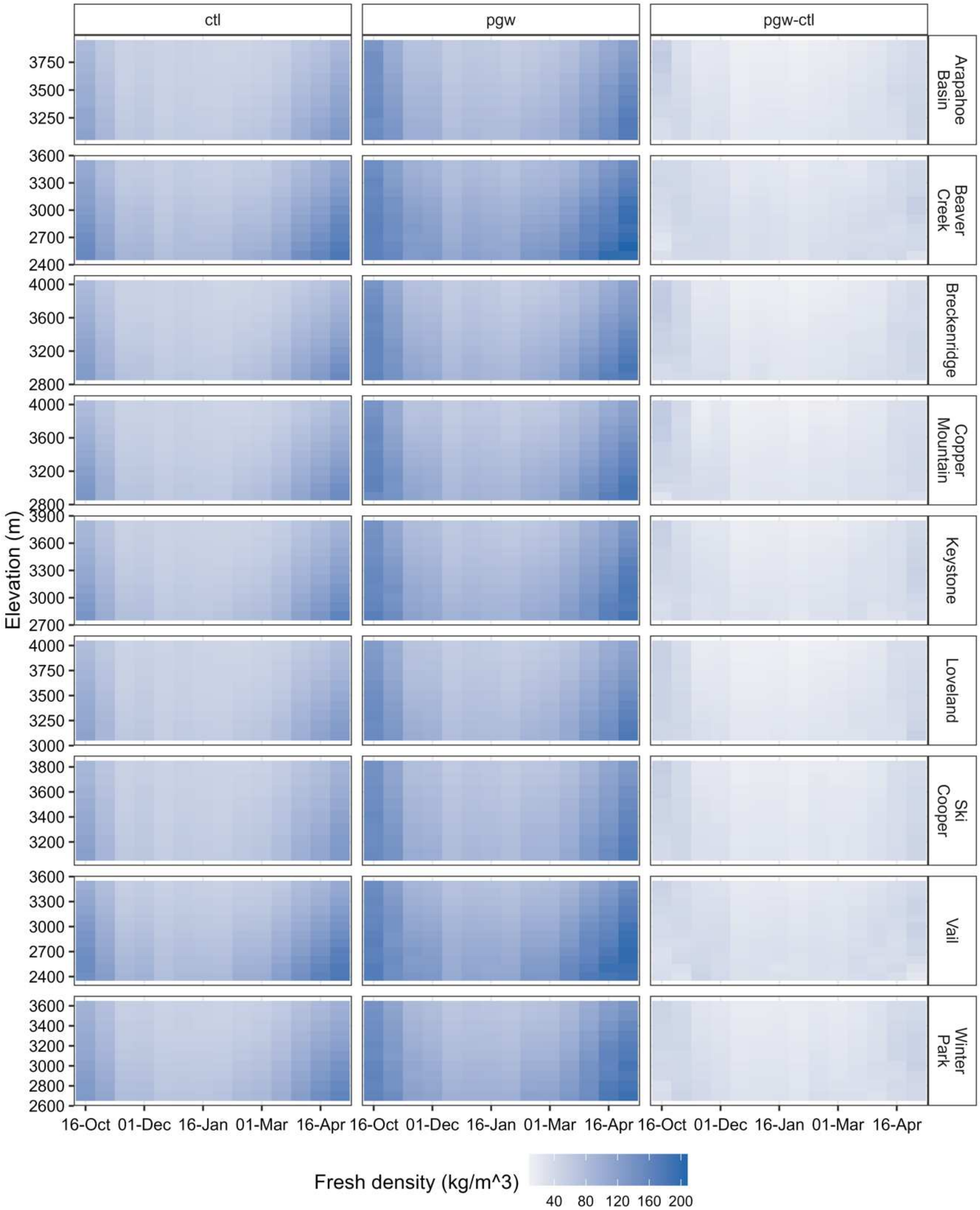


Figure C-7. Same as Figure 4-4 but for fresh snow density.

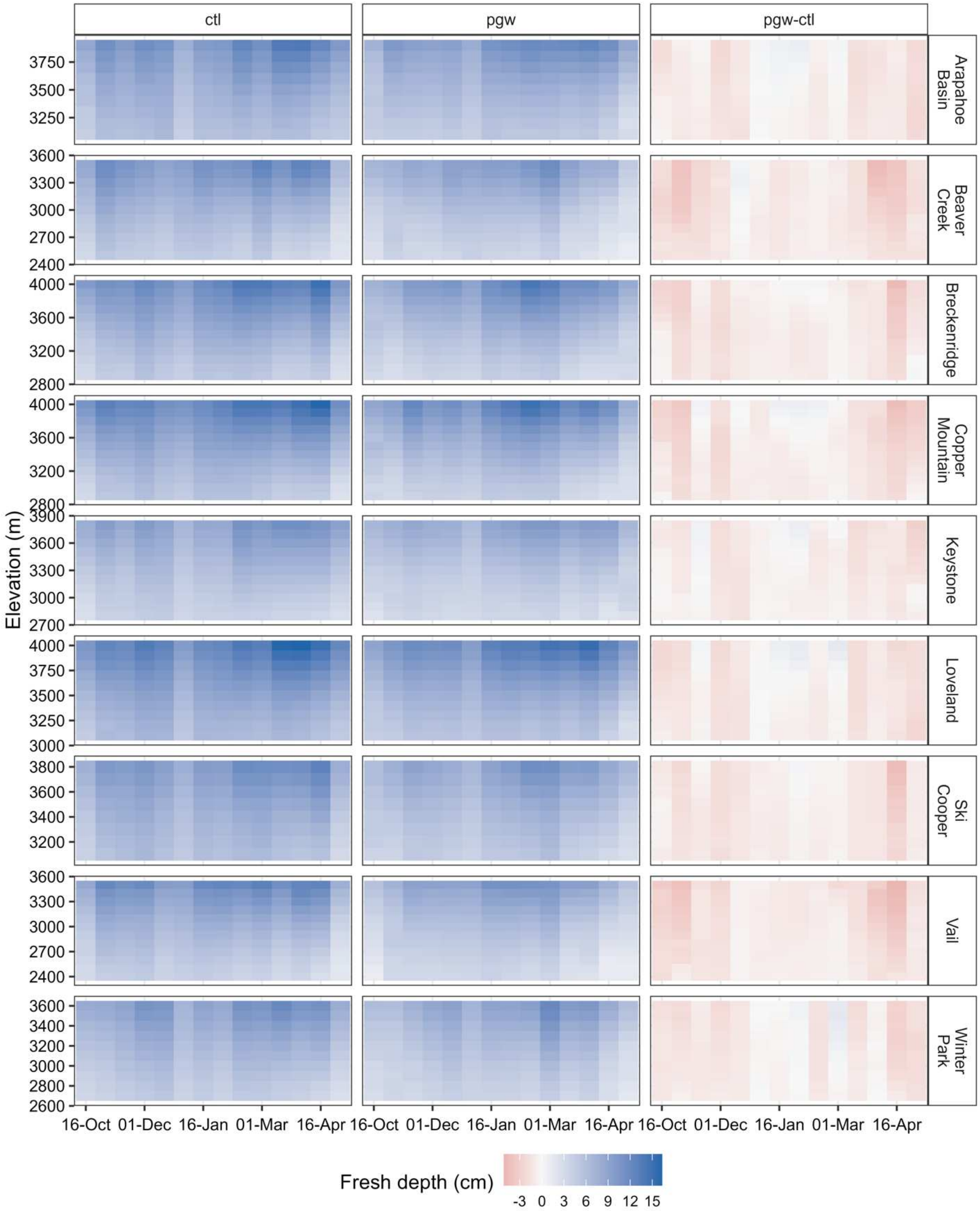


Figure C-8. Same as Figure 4-4 but for fresh snow depth.

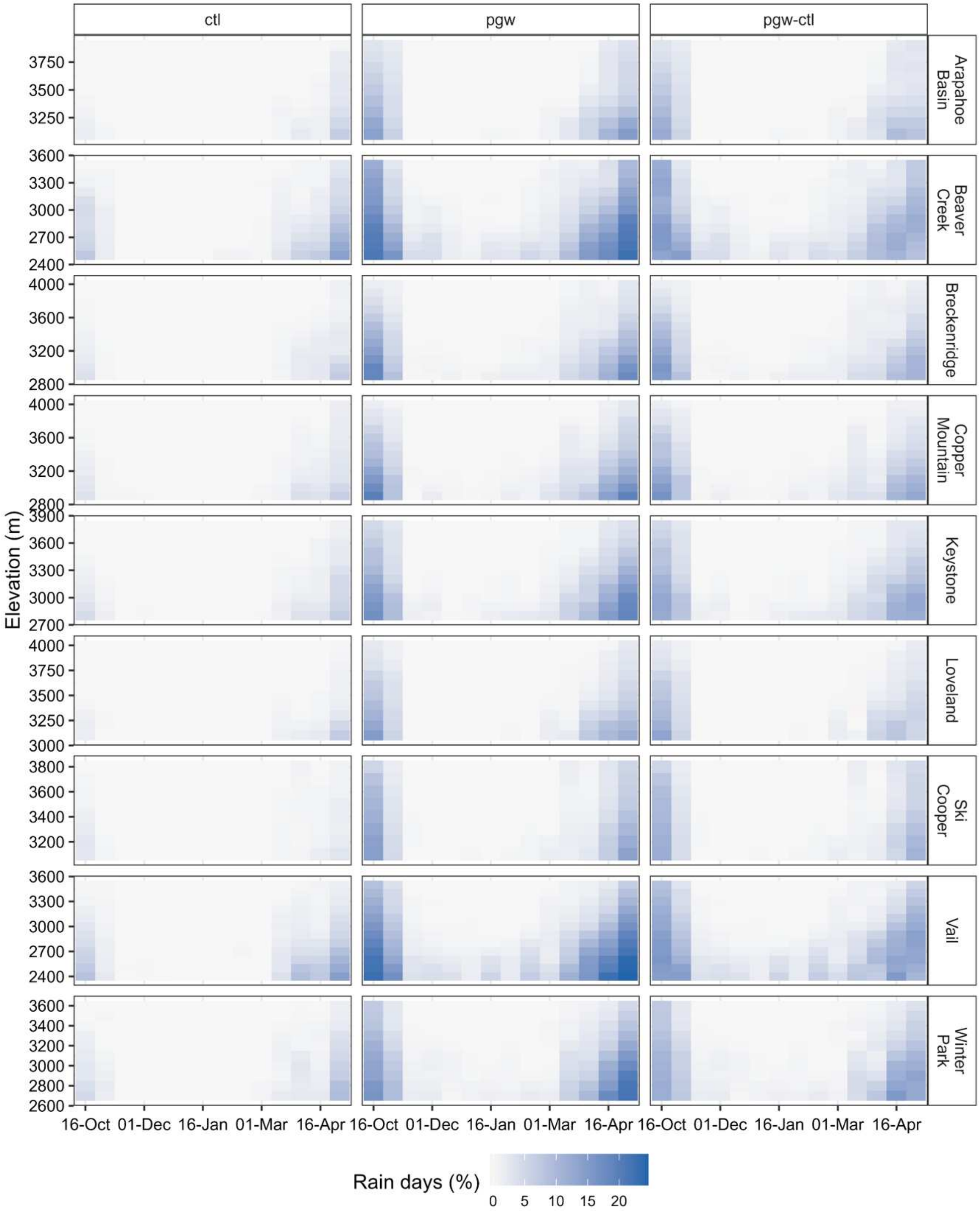


Figure C-9. Same as Figure 4-4 but for percentage of days with rain.

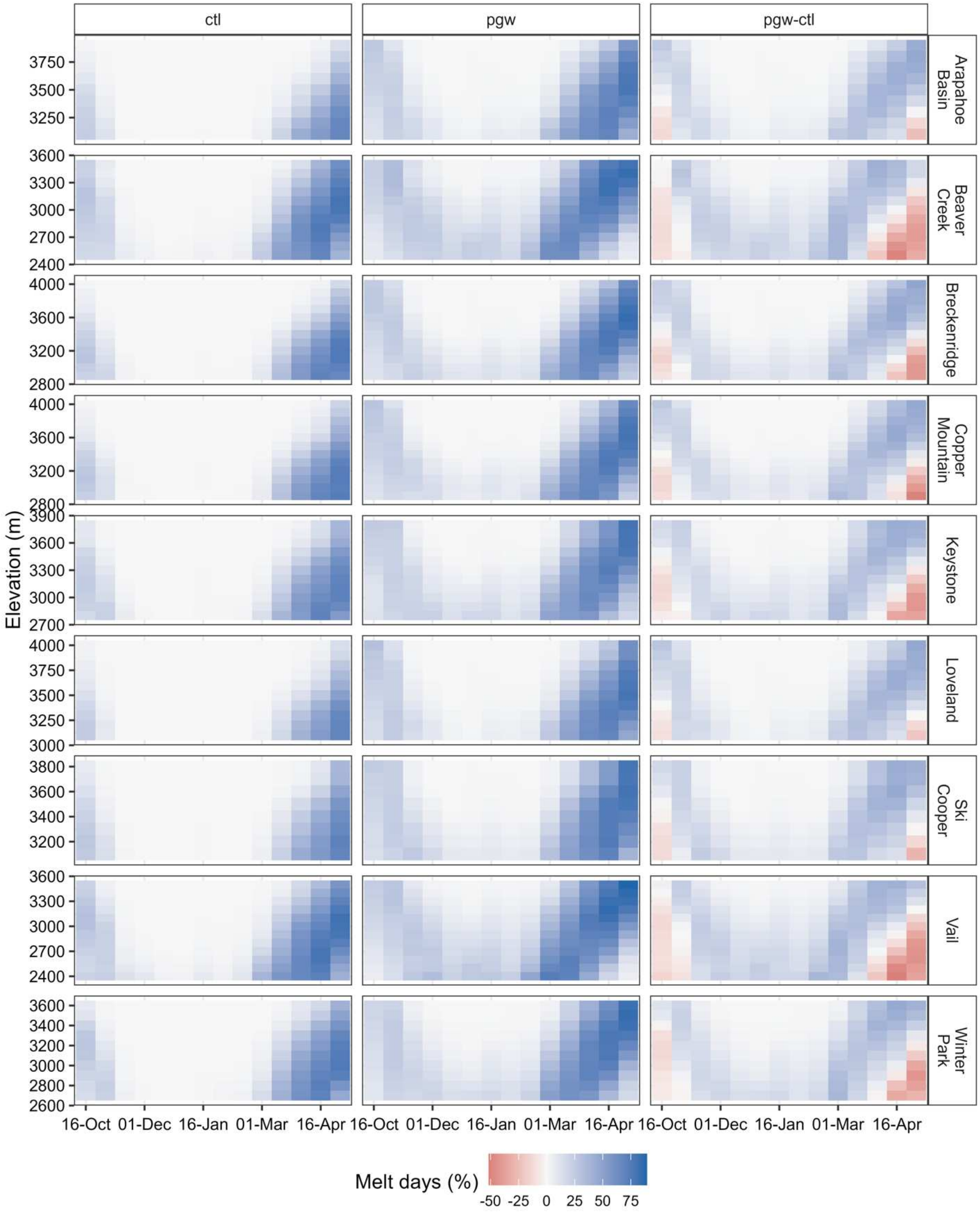


Figure C-10. Same as Figure 4-4 but for percentage of days with snowmelt.