THESIS

# CHANGES IN THE SNOWPACK OF THE UPPER COLORADO RIVER BASIN IN A WARMER FUTURE CLIMATE

Submitted by

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# ABSTRACT

## CHANGES IN THE SNOWPACK OF THE UPPER COLORADO RIVER BASIN IN A WARMER FUTURE CLIMATE

Water is a crucial factor to sustaining life on Earth. Snow acts as a reservoir for water, providing storage during the cold seasons and freshwater resources throughout the warmer months. Streamflow in the upper Colorado River Basin is primarily contributed by seasonal mountain snowmelt that provides critical freshwater resources to humans and wildlife, effectively connecting ecological, hydrological, and atmospheric systems. Global Climate Models (GCMs) and regional climate models do not represent the complex processes that can impact snowpack growth, evolution, and melting, thus they often rely on parameterizations to represent such processes. SnowModel is a high-resolution snowpack-evolution modeling system that can simulate processes such as blowing snow redistribution and sublimation, forest canopy interception, and snow-density evolution. To investigate how snowpack in the Upper Colorado Basin may change in a future warmer climate, high-resolution convection-permitting regional climate atmospheric model simulations at 4-km horizontal grid spacing are used to provide input conditions to drive SnowModel at 100-m in the current and future climate for 13 years. Results show that the average snow season will be shorter in the future, reducing the days that the snowpack can accumulate. In addition, analysis of the characteristics of precipitation in the simulations shows a 150% increase in convective precipitation frequencies in the winter months, indicating shifts in the character of precipitation in a future climate. Liquid precipitation in winter increases 200% in a future climate as a result of warmer air temperatures. In contrast, solid precipitation stays roughly the same in the winter, but decreases about 25 percent in the fall and spring. A case study analysis of the high-impact snowstorm on 17-19 March 2003 that delivered between 30-70 inches of snow along the Colorado Front Range in a current and future climate shows a shift from a snow-dominant to a rain-dominant event, as well as increases in moisture and convective precipitation frequencies. The simulated changes in the snowpack of the Upper Colorado River Basin will likely have detrimental impacts on freshwater resources and food production in a future climate that will undoubtedly impact a multitude of humans and ecosystems in the western United States.

# ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to my advisor, Kristen Rasmussen, for her patience, feedback, and for pushing me out of my comfort zone. You have taught me so much and helped me to grow as a scientist and as a person. I'm extremely grateful to my defense committee for helping me reach this milestone with their time and invaluable expertise.

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I would be remiss in not mentioning my professors, department faculty and staff, and my fellow students for creating a welcoming and constructive environment where I felt comfortable to make mistakes and learn from them.

Last but not least, I would like to thank my family and friends for supporting me through my highs and lows, keeping my spirits up, listening to me cry on the phone, and for being my biggest cheerleaders.

# DEDICATION

*This thesis is dedicated to my family for always encouraging, supporting, and praying for me even while facing their own struggles. I love you all, and this would not have been possible without you. Thank you guys!*

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# Chapter 1

# Introduction

The importance of snowpack ranges from storing critical water resources through the winter and connecting hydrological, ecological, atmospheric, and human systems. Snow is the dominant precipitation type across most high-latitude and mountainous regions of the world and accounts for 41% of annual precipitation falling over land north of 30° N latitude (Nace et al. 1975). In addition, mountains are Earth's water towers, covering 30 million km2 or 23% of global land area, with over 40% of global mountainous areas maintaining a seasonal snowpack (Viviroli et al. 2007). A dependable snowpack in the Rocky Mountains is a major reason why such large populations can be sustained in the relatively dry western United States. Through the colder months, the snowpack acts as a reservoir. Snow water equivalent (SWE) is the amount of water that is stored in the snowpack and is a rough estimate of how much water will be released when the snow begins to melt and runoff into streams and rivers in the spring and summer months. In the Upper Colorado River Basin (UCRB), nearly 85% of the total stream flow is a result of the snowmelt (Butler et al. 2015; Rasmussen et al. 2011).

The UCRB plays a major role in supplying water to the west during the drier summer months. A dry snow season in this region can influence water security for millions of people from Denver to Tijuana. The Colorado River provides water for industry, municipalities, agriculture, recreation, and more and supports an annual economy of over $1 trillion (James et al. 2015). With a growing population in the UCRB, increased demand for water resources often exceeds the supply, particularly under severe drought conditions (Viviroli and Weingartner 2008). The historic low water levels in Lake Mead and Lake Powell during 2022 are prominent signs of the level of water distress the west is facing. An extended period of snow drought can be detrimental and can lead to water rationing like what was recently seen in California in 2022[1]

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[1] State of California, 2022: Statewide emergency water conservation regulations. California drought action, https://drought.ca.gov/state-drought-response/statewide-emergency-water-conservation-regulations/

Given the importance of snow resources for atmospheric, human, and hydrologic systems, some studies using coarse resolution global climate models (GCMs) looking at how snowpack may change in a future climate in mountainous regions in the western U.S. were conducted (Cayan et al. 2008; Houghton et al. 2001; Maurer, 2007; Solomon et al. 2007). These studies showed that as temperatures in the intercontinental mountain ranges increase, there is an inconsistent pattern in the snow estimates for a future climate with results ranging from no change to slight decreases in snow amounts (Hoerling and Eischeid 2006). GCMs are useful in looking at large areas over long time periods with relatively low computational cost, but the finer mesoscale and land-surface processes that heavily influence snow amounts are often parameterized. When compared to snowpack telemetry (SNOTEL) sites, the models were found to either consistently over or underestimate snow amounts at various elevations (Ikeda et al. 2010). In addition, these coarse models smooth the topography, so important processes in complex terrain like orographically induced updrafts and downdrafts that are important for accurate predictions of snow amounts are poorly represented (Garvert et al. 2007).

Recent advances in computing power have allowed for higher resolution convection-permitting models ( 4-km grid spacing) to be run on long timescales to more accurately represent detailed synoptic through mesoscale processes associated with precipitating systems in the U.S. (Liu et al. 2017; Rasmussen et al. 2011; Rasmussen et al. 2023). A study from Ikeda et al. (2010) found that SWE observed at SNOTEL sites in the intermountain West have good agreement with model derived SWE when the horizontal grid spacing is 6 km or less. In addition to using higher grid spacing, the convection-permitting models do not rely on a convection parameterization to initiate and build clouds, but instead allow precipitating systems to evolve naturally in their environment (Ikeda et al. 2010; Prein et al. 2015; Rasmussen et al. 2011; Rasmussen et al. 2017). The diurnal cycle of precipitation and mesoscale organization are two examples of important aspects of convection that are improved when moving from a GCM to a convection-permitting modeling framework (Prein et al. 2017; Rasmussen et al. 2017). High-resolution models provide much better estimates of snowpack as well and the consensus from researchers using this approach is that snowpack will generally decrease at lower elevations while higher elevations would not be as drastically impacted, if at all (Fyfe et al. 2017; Ikeda et al. 2021; Rasmussen et al. 2011; Siirila-Woodburn et al. 2021). Ikeda et al. (2021) found that future SWE reduction in the ranges of the intermountain west was 50% and the smallest reductions were found at the highest peaks in Colorado and Wyoming (< 20% reduction). While these models were able to provide a clear understanding of how snow in the region may change, the land surface schemes still only represent several layers of snow that are missing detailed processes associated with the evolution of snowpack, blowing snow, and many other important processes. These missing snowpack processes limit the ability of the convection-permitting regional climate modeling frameworks to accurately represent the life cycle of the snowpack and its impacts on water resources in a future climate.

This study uses a high-resolution convection-permitting regional climate model at 4-km grid spacing to provide input conditions to drive SnowModel, a specialized snow process model, at 100-meter resolution to understand how snowpack and snow processes may change in a future, warmer climate. A recent study by Hammond et al. (2023) used the same model simulations to analyze the hydrologic impact of climate change in the region by calculating surface water input (SWI), the sum of both rainfall and snowmelt that is available to enter the surface. They found that future peak SWI is expected to increase, but that snow-derived SWI will be reduced for all elevations. This indicates an increase in total precipitation, but decreases in the amount of precipitation received as snow.

The current study builds upon Hammond et al. (2023) by investigating integrated atmospheric and hydrologic processes leading to changes in snowpack in the UCRB in a future climate. The main objectives of this study are to:

1. Investigate how the snowpack characteristics and snow season in the UCRB may change in a future climate
2. Use a high resolution, snow process model to explore the timing and magnitude of snow in the UCRB

3. Consider how future extreme snowfall events may differ with a warmer climate

With improved understanding of how the snowpack characteristics, seasonality, and extreme events contributing to seasonal snowpack may change in a future climate, mitigation efforts related to preserving water resources in the UCRB can be developed and implemented to continue to sustain human, plant, and animal populations in the region.

# Chapter 2

# Data and Methods

## 2.1 Study Area

The region of focus is the Upper Colorado River Basin (UCRB) that includes portions of Wyoming, Colorado, Utah, Arizona, and New Mexico. This region was chosen because of the importance of the snowmelt-dominated basin to water resources in the western United States and its recent designation as the second Next Generation Water Observing System (NGWOS) focus by the United States Geological Survey (USGS). The study domain spans 382 km in both the north-south and east-west directions and includes the cities of Telluride, Aspen, and Grand Junction as well as the Rocky Mountains in western Colorado (Figure 2.1). The elevation in the domain ranges from 1312 to 4385 meters above sea level (ASL). The domain consists of federally owned lands like national parks, cities, farmland, and many winter recreation zones. The tree line in Colorado is typically about 11,500 feet (3,500 meters) above ground level (AGL) and, based on input from SnowModel, the breakdown of different vegetation types is forest, shrub, grasslands, bare, ice/snow, and human development, with forest making up around half of the total area of the UCRB.

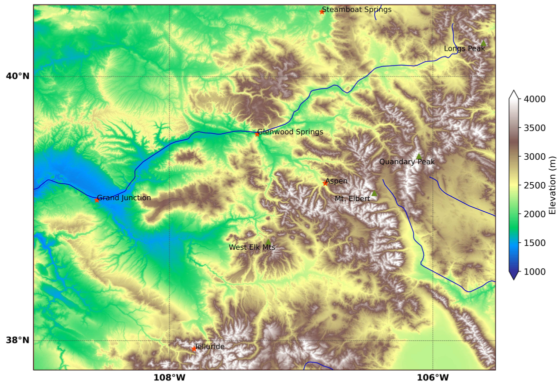

**Figure 2.1:** Topographic map of the domain area at 100-meter grid spacing showing altitude in meters above sea level. The red stars denote central locations for cities and large populated areas. The green triangles denote famous and/or popular mountains.

The climate in the UCRB is cool and dry due its location in the mid latitudes, having high elevation, and being surrounded by land with no large water source nearby. The mountains of Colorado make up a large portion of the domain and temperatures are often cooler than the lower elevation plains to the east. Due to the high elevation, the effects of solar radiation are greater and on clear days, snow can melt rapidly. The continental interior geography also leads to there being a significant diurnal cycle with warm dry temperatures during the day and the temperature dropping significantly during the night (Doesken et al. 2003).

The snow season is defined from October to April, but the UCRB often has snow outside of these months. The peak snow date is usually in early spring and the snowiest months are in winter. The higher elevations experience snow cover for a longer period than the Front Range, but can still be described as being between intermittent and transitional snow zones (Richer et al. 2013). The rivers in the UCRB are at their greatest capacity in May and June when the snowmelt is at its peak and this water is utilized by those living within the state of Colorado and those in states where the Colorado River flows through.

## 2.2 Convection- Permitting Simulations

Novel convection-permitting regional climate simulations at 4 km resolution are utilized in order to study the future precipitation features in the Upper Colorado River Basin. The Weather Research and Forecasting (WRF) model v3.4.1 was used to conduct these high-resolution climate simulations (WRF-CONUS) at the National Center for Atmospheric Research (NCAR) (Liu et al. 2017). WRF-CONUS covers the entirety of the contiguous U.S. (CONUS), along with parts of Canada and Mexico. As stated previously, WRF-CONUS has a horizontal grid spacing of 4km with a 1360 x 1016 grid point domain and 51 stretched levels in the vertical extending up to 50 hPa (Liu et al. 2017). The planetary boundary scheme from Yonsei University (YSU) (Hong et al. 2006), the Rapid Radiative Transfer Model for GCMs (RRTMG) (Iacono et al. 2008), the Thompson aerosol-aware microphysics (Thompson and Eidhammer 2014), and the Noah-MP land surface model (Niu et al. 2011) are some of the parameterizations utilized in the simulations.

ERA-Interim 6-hourly reanalysis data was used to force the WRF-CONUS simulations for a thirteen-year period in the current climate (2000-2013). The current climate (CTRL) simulation was run along with a future climate simulation using the Pseudo-global warming (PGW) approach (Liu et al. 2017; Rasmussen et al. 2011; Schär et al. 1996). For the PGW approach, the climate delta forcing term is added to the original ERA Interim reanalysis data and is calculated with the following equation:

$$PGW = ERA - I + \Delta CMIP5_{RCP8.5}. \tag{2.1}$$

A monthly mean difference between the historic and future climates for the 19-model ensemble mean variables was determined under the "business as usual" Representative Concentration Pathway (RCP) 8.5 emissions scenario and is represented in the equation above as $\Delta CMIP5_{RCP8.5}$. The PGW simulation was conducted over the same time period (2000-2013) using the modified forcing term shown in Eq.(2.1) above.

Synoptic patterns over 2000 km in horizontal extent are well replicated in the PGW simulation due to the use of spectral nudging which helps reduce the effects of climatic drift. Sub-synoptic features are allowed to freely evolve allowing for the ability to investigate how individual storms will differ in the future climate. The large-scale nudging does result in the imitation that changes in storm track and synoptic features cannot be well investigated but despite this, there have been many studies that have successfully utilized the PGW approach to explore how storm processes will change in a future climate (Lackmann 2013, Mahoney et al. 2018, Prein et al. 2017) .

## 2.3 SnowModel

SnowModel is a complex high-resolution process-based snowpack model composed of a suite of sub-models created to represent a variety of geographic and climatic conditions (Liston and Elder 2006b). It can resolve very fine scale snow processes such as blowing snow, sublimation, and more. By specifically representing snowpack processes at a fine scale, more realistic simulations of the temporal and spatial distribution of SWE and snowpack in the complex terrain of the UCRB is possible. SnowModel has been used in a wide variety of research studies since its development, including many ecological and hydrologic projects (Cunningham et al. 2022; Greaves et al. 2023; Loe et al. 2021). It has also been shown to do exceedingly well in replicating the conditions in areas similar to the UCRB study region (e.g., Greene et al. 1999; Hiemstra et al. 2006; Liston and Elder 2006a, 2006b; Liston et al. 2008; Prasad et al. 2001; Sexstone et al. 2018).

This spatially distributed snow evolution modeling system is comprised of four sub- models: MicroMet, EnBal, SnowTran3D, and SnowPack. The meteorological forcing conditions are defined by MicroMet (Liston and Elder 2006a), surface energy exchanges are calculated by EnBal (Liston 1995), SnowPack simulates SWE and snow depth evolution (Liston and Hall 1995), and SnowTran3D is the model that handles snow redistribution (Liston and Sturm 1998). In this study, meteorological conditions from the convection-permitting regional climate simulations are used as input to SnowModel. The submodels use this information and process it to provide information on the fine scale processes within the snowpack. SnowModel was run with a daily time step for the UCRB domain and a grid spacing of 100 m for 13 years for both the CTRL run (2000-2013) and the PGW run. These simulations were run by the Snow Hydrology team at the United States Geological Survey (USGS) (Hammond et al. 2023).

SnowModel has the ability to simulate many complex processes associated to snow. A few of the variables from SnowModel that this study utilizes are snow water equivalent (SWE), blowing snow transport, sublimation (blowing snow, canopy, and static surface), snow depth, snow density, runoff, and rain precipitation. For domain changes in SWE, April 1st SWE is used due to it being a consistent date that has been historically used as a surrogate to represent peak snowpack (Pagano et al. 2004). While April 1st SWE has been found to slightly underestimate peak SWE in the Rocky Mountain region, it was found to provide a reasonably estimate of total seasonal precipitation so it is used as a proxy in this study to understand seasonal SWE changes (Bohr and Aguado 2001). These variables are used to investigate shifts in precipitation types, timing of snowfall and snow melt, and changes in snowpack processes in a warmer climate.

## 2.4 Convective and Stratiform Partitioning

A commonly-used convective/stratiform partitioning method (Steiner et al. 1995) is used to understand how the character of precipitating systems that bring snow to the UCRB may change in the future and whether they differ between the two precipitation modes. The method uses simulated radar reflectivity values from WRF in order to classify whether the storm area is convective or stratiform. A storm mode climatology was developed for the entire CONUS (Yu et al. 2023) and these data are used for the UCRB snow season storm mode analysis. Sigma level 12 is used in the terrain-following coordinates of the WRF model in order to capture the reflectivity approximately 2 km above the ground level across the domain, including over complex terrain. The moderate threshold was utilized over the strong threshold because this climatology was developed primarily to describe warm season storms. Snow storms are characteristically less intense and have lower reflectivity values compared to severe thunderstorms due to a combination of different storm dynamics, slower precipitation rates, and the physical properties of snow. This partitioning method has been used in numerous previous studies across the United States using radar observations (Houze et al. 2007; Steiner et al. 1995; and many more) and model simulations (Yu et al. 2023).

This study uses convective and stratiform partitioning to investigate whether there is a shift in the nature of winter time storms in the UCRB. At each timestep of the model run, the precipitating areas are classified as either a convective or stratiform pixel. In the future climate, the extent of the precipitating areas can change both spatially and temporally, so for a simple comparison between the two climate runs, the total number of convective and stratiform pixels were used to determine the change in frequency which would include the combined effects from storms increasing/decreasing in size and/or duration. By using this partitioning method over the domain for the snow season, a foundation is being built to make connections between the precipitation mode that the snow is received and snowpack characteristics of the layer that is deposited during that mode.

# Chapter 3

# Results and Discussion

## 3.1 Upper Colorado River Basin

### 3.1.1 Snow Season Climatology

The entire UCRB domain shows large changes in snowpack characteristics in the cool season (October to April of the following year) in a future climate. The average snow season in the CTRL climate shows that the region receives snow from September to May and sometimes even through June with the heaviest snow months being about equal from December to March (Figure 3.1). Significant runoff is present starting in March and continuing through October, with runoff exceeding snow input from April to October. In the PGW climate, the region receives snow in a much shorter time period from October to May. In all months during the snow season, there is an increase in the amount of liquid precipitation received. Liquid precipitation received during these months is indicative of warmer temperatures and can lead to increased runoff and destabilization of the snowpack (Colbeck 1982; Conway and Raymond 1993; McCabe et al. 2007). The increased runoff can be seen in Figure 2b where there is significant runoff throughout the entire year and the runoff either exceeds or balances the snow received in the months of March to November.

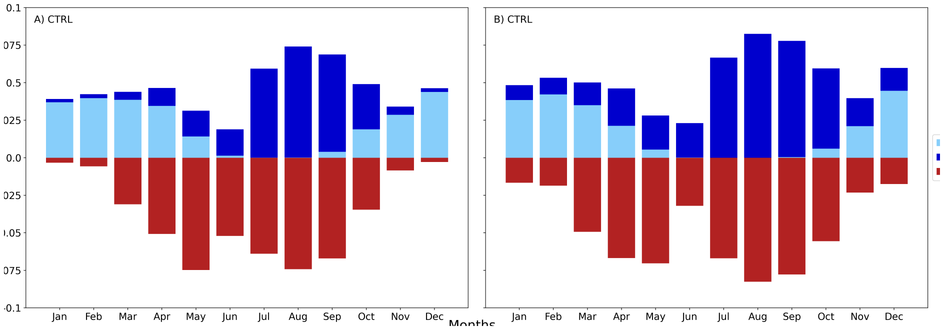

**Figure 3.1:** Bar charts showing solid and liquid precipitation and runoff amounts by month averaged over the 13-year CTRL (a) and PGW (b) simulations.

Examining the individual water years, there is a notable difference between the amount of SWE received in the CTRL and PGW simulations (Figure 3.2). In nearly every year, the average amount of SWE received in the PGW simulation is noticeably less than that of the CTRL. When calculating the SWE amount and peak SWE date using the median of the domain, essentially the same pattern is displayed. The years of 2003 and 2012 show decreased peak SWE amounts when compared to the CTRL but only by a few millimeters. The only year where the CTRL and PGW had the same peak SWE amount is 2010 where the accumulation part of the season is very similar in the CTRL and PGW cases but sees a faster melting period in the PGW simulation. In addition, the date of peak SWE in days since the beginning of the snow season and the PGW peak SWE dates are either the same day (as in the years 2001, 2002, 2003, 2004, 2005, 2007, 2010, 2012, and 2013) or before the day (as in the years 2006, 2008, 2009, and 2011) of peak SWE in the CTRL simulations.

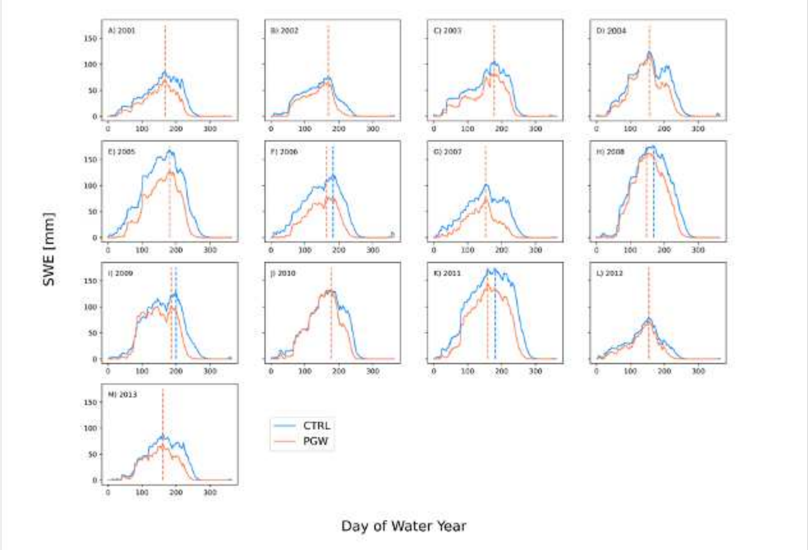

**Figure 3.2:** SWE amount for each of the 13 simulation years (A-M) in mm for CTRL simulation shown in blue and PGW shown in red. The dashed horizontal lines show the day of the water year that has peak SWE.

The average snow season is shorter in length from an average of 210 days in the CTRL simulation to approximately 185 days in Figure 3.3. This is an average decrease of 25 days that can greatly impact how much snow can accumulate during the snow season and ultimately how much

SWE will be stored for the summer months. The shortening of the snow accumulation period along with the decrease in annual SWE and an earlier peak SWE date all point to a scenario where the timing and amount of stored water resources from snow in the future may decrease and will likely impact human use and recreation.

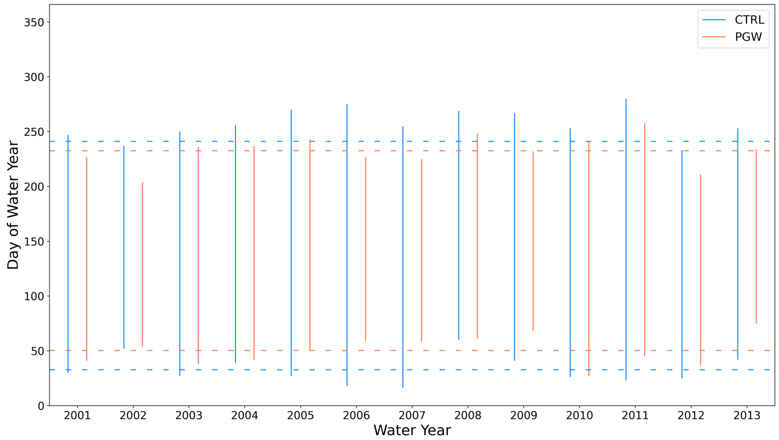

**Figure 3.3:** The dates of first and last snowfall in the water year for CTRL (blue) and PGW (red) simulations. Horizontal dashed lines show average snow season length of the CTRL and PGW runs.

### 3.1.2 Melting Level

The point in elevation where the temperature changes from positive to negative degrees Celsius is the melting level (also known as the freezing level). The melting level can also be thought of as the point where precipitation received above this altitude is snow and below is rain. The average melting level for the CTRL snow season falls below the average height of the topography in the region at every latitude (Figure 3.4). In contrast, in the snow season in the PGW simulations, we see that the melting level increases in altitude so much that at every latitude, the melting level is above the average topographic height.

The PGW melting level being above the average topographic height does not mean that all mountain regions do not receive snow, but instead indicates that on average, there is a large decrease in the elevated areas that can consistently support snowpack. Reliable snowpack that con-

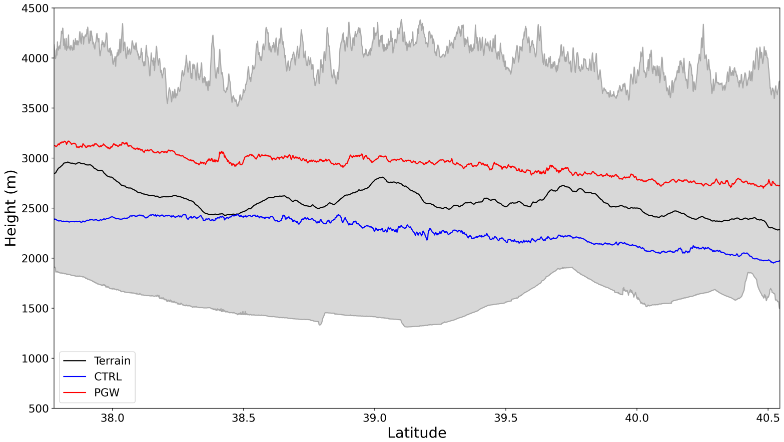

**Figure 3.4:** Gray shaded area shows the range of altitudes at each latitude. The black line is the average topographic height at each latitude. The blue and red lines show the elevation of the 0°C line for the CTRL and PGW simulations, respectively.

tinues to accumulate could be limited significantly in area, particularly at higher elevations due to warming temperatures in a future climate. Abatzoglou (2011) also described how the decreasing snowpack in the western U.S. can be partially attributed to changing melting level elevations. This could also have large ecological ramifications that should be investigated across the UCRB (and beyond) given the potential shift in the climatological conditions supporting animal and plant habitats in a changing climate.

### 3.1.3 Snow Water Equivalent

Snow water equivalent is one of the most important and well observed snowpack properties due to its usefulness as a hydrologic variable in assessing the total water content of the snowpack. In the UCRB, the majority of SWE stored in the snowpack melts and feeds into the Colorado River. It is extremely important to understand the ways in which SWE may change in the future given the importance of water resources in the Colorado River and those who depend on them throughout the drier summer season.

Many studies have estimated the possible change in SWE in the UCRB and most have come to the conclusion that it is expected for SWE to decrease across the region in a future climate

(Brown and Mote 2009; Peacock 2012; Pierce and Cayan 2012). Similarly, this study shows that on average, there will be large decreases in April 1st SWE across the UCRB domain with mid to high elevations experiencing slight increases of April 1st SWE. In Figure 3.5, April 1st SWE is expected to decrease by at least 50% in a majority of the lower elevations in the UCRB. This decrease could potentially be due to the shift from frozen to liquid hydrometeors that would accompany the melting level increasing in altitude that was explored in the previous section. This decrease in SWE might also be explained by the shortening of the snow season where in the PGW simulations there is already a large runoff signal throughout the winter as was seen in Figure 3.1. The increases that are seen at mid to high elevations are likely due to the temperature being cold enough to sustain snow despite warming temperatures (Ikeda et al. 2021).

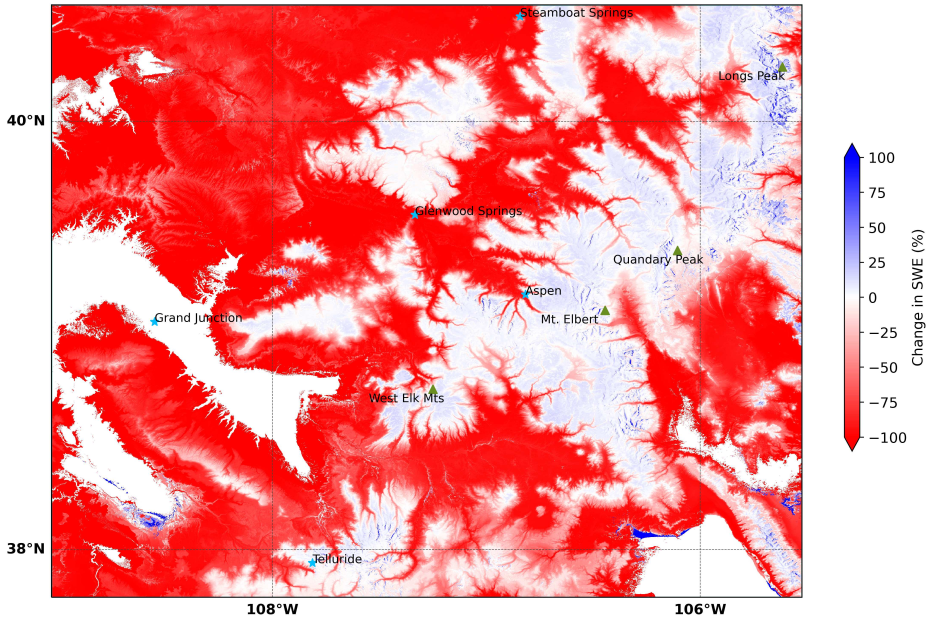

**Figure 3.5:** Spatial map of average percentage change of April 1st SWE from the CTRL to PGW at 100-meter resolution. Blue stars denote popular and large cities and areas. Green triangles denote famous/popular mountains.

The average SWE change with respect to elevation above sea level (ASL) in Figure 3.6 reveals a similar pattern. The largest decreases in April 1st SWE are at lower elevations from about 2750–3400 m. At elevations lower than 2750, like in valleys and western Colorado, the average

April 1st SWE is 0 mm in both the CTRL and PGW cases so there is no change between the two. From tree line and up, the average change in SWE shows small increases (less than 10%) and the highest elevations show roughly no average change in April 1st SWE. At the highest elevations, it is reasonable to assume that temperatures will still be cold enough in the future climate to support a persistent snowpack (Rasmussen et al. 2011). At the highest elevations above 4000 m, the nearly net zero change in SWE can likely be attributed to smaller scale snow processes.

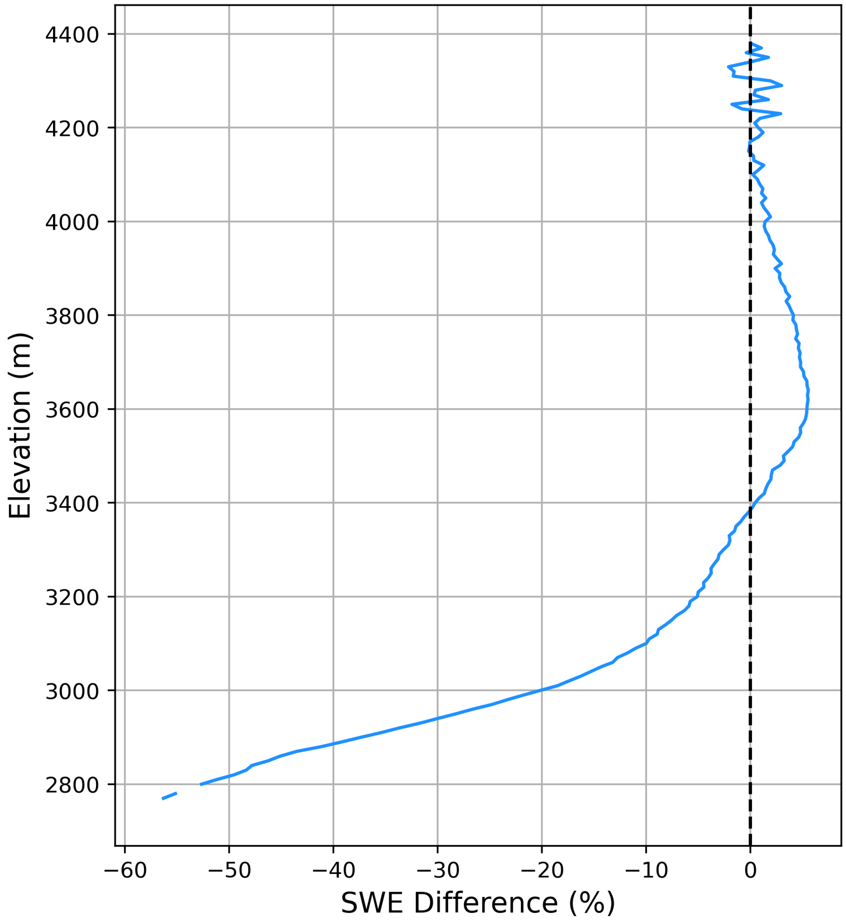

**Figure 3.6:** Average percent change of April 1st SWE with respect to elevation above sea level.

While the mid to high elevations experience increases in April 1st SWE and the lower elevations experience decreases, there is not a noticeable change when calculating the total amount of precipitation across the entire domain and snow season when comparing the CTRL and PGW simulations. This is suspected to be due to the increases and decreases roughly canceling each other out. These results are consistent with past literature done on this region (Ikeda et al. 2021, Rasmussen et al. 2011). Rasmussen et al. (2011) found a similar pattern where the lower elevations saw increased melting and the higher elevations saw increases in SWE while not seeing any major change in the peak snow mass.

### 3.1.4 Sublimation

Sublimation is a process that describes the transition from the vapor phase to the solid phase and vice-versa. In the context of snowpack, sublimation is mainly used to describe the loss process of snow by transitioning directly into water vapor. Sublimation loss (hereafter referred to as sublimation) can be increased with extremely dry conditions and higher wind speeds (Harpold and Brooks 2017; Sexstone et al. 2016). When defining sublimation, it includes the combined impacts from the processes of blowing snow sublimation, static surface sublimation, and canopy sublimation that are all products from SnowModel.

In Figure 3.7, the difference between the CTRL and PGW runs shows a positive change in the water vapor mixing ratio and a decrease in sublimation with respect to the current climate. The correlation between air moisture and decreased sublimation suggests that the more moisture in the air, the less sublimation there is. This is supported by the empirical Clausius-Clapeyron correlation, which states that at warmer temperatures the air is able to hold about 7% more moisture (Trenberth et al. 2003). With more moisture in the air, the vapor pressure gradient between the atmosphere and snow decreases, making sublimation less likely to occur in these conditions and our findings are consistent with this. SnowTran3D is the submodel that handles sublimation and the required inputs are spatially distributed fields of vegetation and topography as well as spatially distributed and temporally varying air temperature, humidity, wind speed and direction, and precipitation (Liston and Elder 2006b).

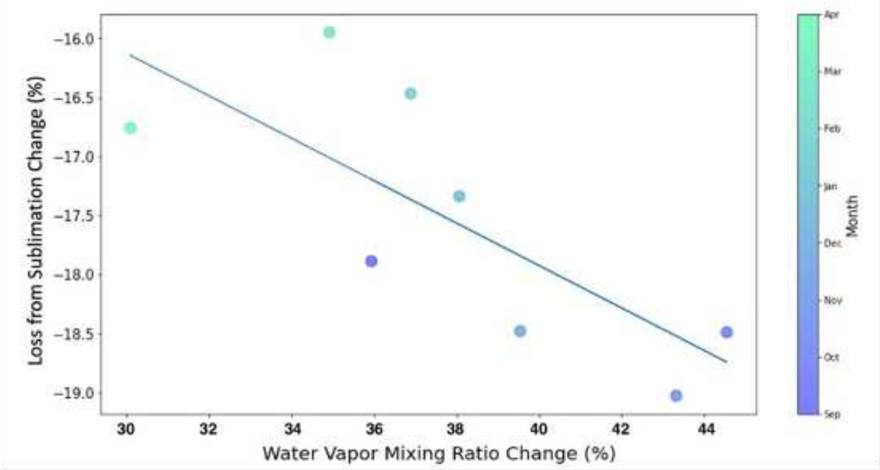

**Figure 3.7:** Percent change of sublimation loss with respect to percent change in water vapor mixing ratio. The shading of the markers is the month of the snow season. Blue diagonal line is the best fit line.

Decreased sublimation could be a positive factor for maintaining snowpack in the future assuming that sublimated snow in a CTRL scenario would not sublimate in the PGW scenario due to increased humidity. While this work suggests that sublimation in the future changes just on the basis of changing atmospheric water vapor, it is important to include additional context on other factors that could be influencing the sublimation decrease. Sublimation, especially at lower elevations, could be largely influenced by the shortening of the snow season. Sexstone et al. (2018) found that in climate warming simulations total sublimation decreased to 6% due to a reduction in snow covered area and duration. A decrease in the duration the snow is on the ground would lead to a decrease in the amount of sublimation and the case is the same if the snow cover extent is decreased as well. As stated before, the sublimation calculation in SnowModel also depends on wind speed and direction so storm scale changes in wind could also have a small impact on sublimation. However, the relative impact of decreased sublimation compared to the possible shrinkage of snow-covered area, duration, wind speed, and direction in the future need to be further investigated to determine the overall impact of reduced sublimation loss in a future climate.

With respect to elevation, lower elevations experience the greatest sublimation decrease in the future as can be seen in Figure 3.8. The difference in sublimation between the CTRL and PGW simulations slowly decreases and at the highest elevations, the sublimation actually increases slightly. These elevations are above the tree line so the impacts from canopy sublimation are very small. Static surface sublimation and blowing snow sublimation would be the biggest factors resulting in the increased sublimation. This increase at the top of the highest peaks has not been attributed to anything but is suspected to be due to increased winds or reduction in snow cover duration.

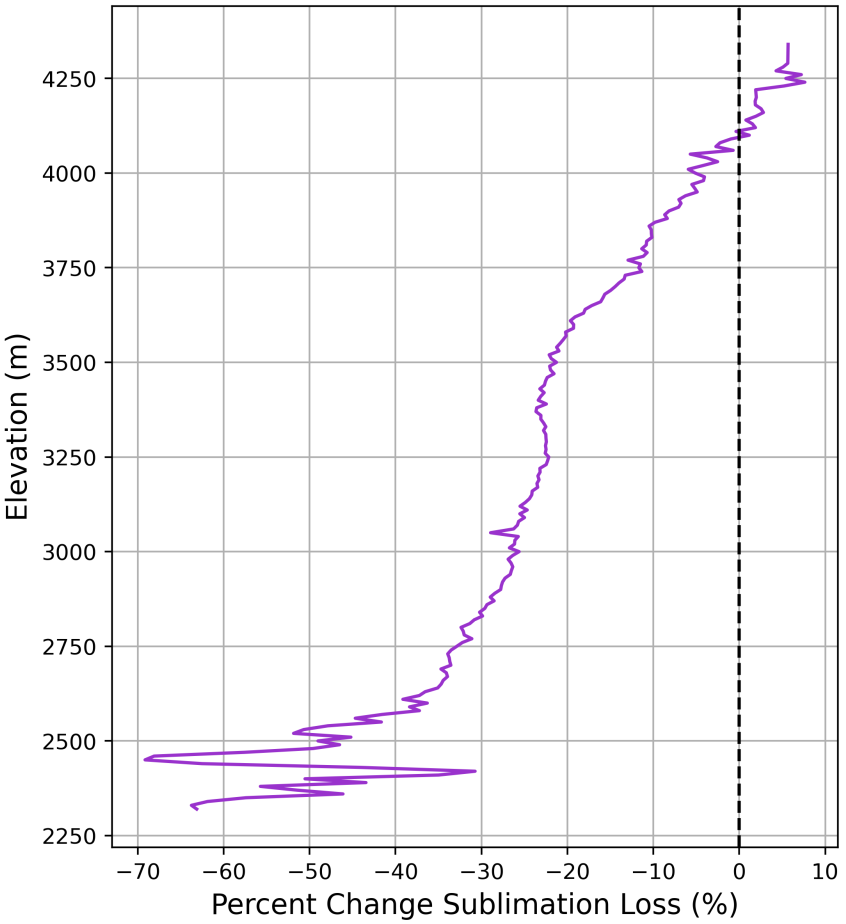

**Figure 3.8:** Average percent change of sublimation loss with respect to elevation.

### 3.1.5 Convective and Stratiform

The classification of precipitation modes has been of interest for many years as it allows for greater understanding of the nature of precipitation in different environmental regimes, rainfall intensities and microphysics, and storm dynamics (Houze 1997). Convective and stratiform storm modes associated with winter storms are analyzed as the characteristics and intensity of the precipitation can impact the snowpack evolution through the deposition of snow particle types or habits, snow density, and deep snow layers deposited over short timescales. Both convective and stratiform precipitation types can occur within extratropical cyclones that produce many snowstorms in the cool season across the UCRB. For example, convection often occurs along the leading edge of strong cold fronts, while stratiform precipitation is commonly associated with warm frontal regions (Browning 1990). Convective precipitation associated with winter storms is often shorter-lived and smaller in area compared to stratiform precipitation, but are associated with hazards such as mesoscale snow bands and blizzard conditions that impact visibility and create dangerous situations for transportation and aviation. Most winter precipitation is contributed by stratiform storm types (Poujol et al. 2021), so a shift to more convective precipitation associated winter storms in the future could potentially change characteristics, density, and snow particle types associated with typical snowpack.

In the PGW simulation, there is an increase in the average number of convective precipitation grid points in nearly all of the snow season months compared to the CTRL simulation (Figure 3.9). The largest increases in convective precipitation are seen in October to February with all these months exhibiting a doubling or more of convective pixels. The average number of stratiform grid points in the domain stays about the same throughout the snow season in a future climate. From December to February, there is a slight increase in stratiform grid points meaning that on average, the stratiform snow events in the domain are either increasing slightly in duration or area. In May, there is no change in convective events and a decrease in stratiform snow events so this is likely due to a decrease in snow events in total in May.

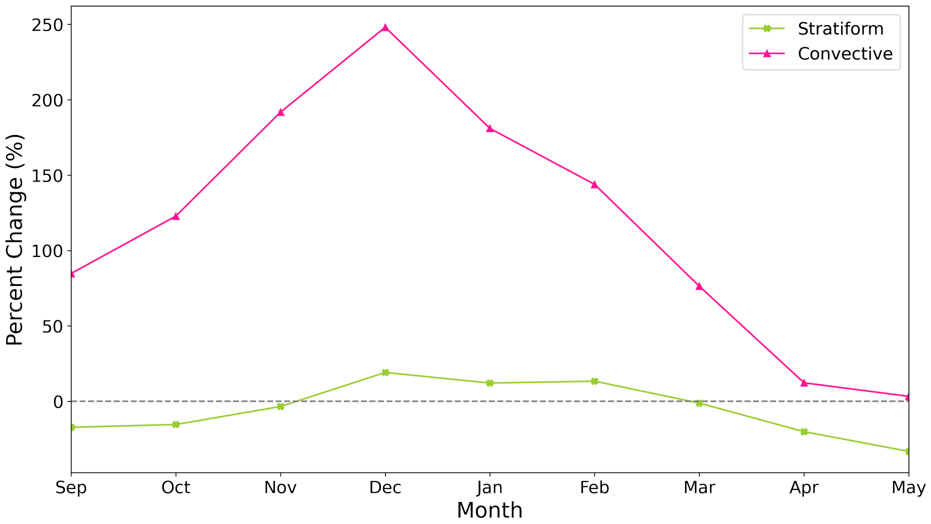

**Figure 3.9:** Average percent change in convective (pink) and stratiform (green) precipitation frequencies from meteorological fall to the end of meteorological spring.

The stratiform precipitation frequency decreases in SON and MAM and increases in DJF table 1. The change is never more than ±20% so the shift is not as dramatic as in the convective precipitation frequencies. All seasons experience an increase in convective frequency but the largest increase by far is in meteorological winter. There is an increase of 167% in the convective precipitation grid points, but this large increase is likely exaggerated by how few convective storms were present in the CTRL run so even a small increase in the actual number of convective events can appear significant when compared to the CTRL. This likely plays some part in the large increase seen in SON as well. However, the increase in convective snow events in the winter still indicates the atmospheric conditions in the PGW differ from what is typically seen in the CTRL climate and this could result in a difference of future snowpack characteristics and evolution.

**Table 3.1:** Shows the average percent change in stratiform and convective frequencies in SON, DJF, and MAM from the CTRL to the PGW simulations.

| Season | Storm Type | Change (%) |
|---|---|---|
| SON | Stratiform | -12.6 |
| SON | Convective | 99.72 |
| DJF | Stratiform | 15.11 |
| DJF | Convective | 166.96 |
| MAM | Stratiform | -16.78 |
| MAM | Convective | 19.15 |

## 3.2 Case Study: March 2003 Upslope Snowstorm

### 3.2.1 Overview

On 17-19 March 2003, there was an extreme snow event that produced multiple feet of snow and prompted closures across the Front Range of Colorado. Storm total snow accumulations in Denver were about 31 inches, but got as high as 87.5 inches in Gilpin County. The major synoptic feature that was credited with causing this event was a low-pressure area in the four corners region. The upper levels displayed a deep cut off low pressure trough moving incredibly slowly causing the surface level low to virtually stall over the southern Rockies. The flow associated with this low-pressure system began funneling warm and moist air from the Gulf of Mexico and into the Colorado Front Range producing an upslope event. On 17 March 2003, cities in the Front Range began experiencing rain that transitioned to snow as the temperatures continued to get colder and a full-fledged snow storm lasted from Monday night to Wednesday. The snow to liquid ratio was nearly 5:1 meaning the snow was extremely dense and almost slushy in texture and fell at an intense rate of about 0.2 inches of SWE per hour[2] This slow-moving system and the amount of snow that was deposited along the Front Range in such a short amount of time is what led to one of the most memorable Colorado snow storms to date.

This event caused widespread impacts, including closing the Denver International Airport and Interstate 70, a major U.S. highway running east-west that many winter recreationalists use to access ski towns, essentially stranding thousands in the state. The snow was uncharacteristic for Colorado, being extremely dense and wet making the snow immensely heavy. This caused downed power lines, trees, and branches resulting in many people losing power for up to several days. Furthermore, the roofs of many businesses and homes collapsed from the weight making this an extraordinarily hazardous snow event[3]

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[2] Doesken, N., 2003: Colorado climate: water year, https://ccc.atmos.colostate.edu/pdfs/wy2003.pdf.

[3] Sneeringer, B., 2021: LOOKING back: 82 inches of snow and $93 million in damages during 2003 blizzard. The Denver Gazette, July 5, 2023, https://ccc.atmos.colostate.edu/pdfs/wy2003.pdf.

An event such as this had not occurred in the area since 1913 and while the storm totals were similar, the cost of the damage caused by the storm increased substantially with hundreds of structures sustaining damage, thousands of people losing power, and the National Guard deploying dozens of soldiers to rescue stranded motorists[4]. NOAA recently reported that the amount and cost of weather disasters in the United States are on an upward trend (Hayhoe et al. 2018). There are a multitude of factors contributing to increased costs, including businesses having to shut down for multiple days, transportation coming to a halt and stranding travelers, damage to infrastructure, insurance claims, and more people living in the area in general. It is important to know the impacts a similar snow event would have in a future, warmer climate as Colorado continues to grow (Hayhoe et al. 2018; Wesley et al. 2013).

### 3.2.2 Future Event

One unique aspect of the PGW methodology is the ability to examine specific high-impact weather events in the current climate and how those specific events might be different in a future warmer climate. This methodology well represents the thermodynamic aspects of climate change and even allows for sub-monthly variability of mesoscale and smaller-scale features to evolve naturally in their environment. Changes in large-scale climate dynamics (i.e., shifts in the jet stream) are not represented in this framework that would likely impact the frequency and characteristics of extratropical cyclones in a future climate. The PGW framework has been used to examine high-impact weather events in a future climate (Dougherty and Rasmussen 2021, 2020; Dougherty et al. 2020; Gutmann et al. 2018) and has led to important understanding of how the full spectrum of convective storms may change (Rasmussen et al. 2017). It provides a way to recreate an event that is almost identical to the past scenario, but includes the thermodynamic impacts from warming. With major synoptic features being the same between the CTRL and PGW simulations, it is easier to isolate the specific changes that occur due to climate change.

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[4] Mann, R., 2021: Blizzard of 2003 left 4000 stranded at partially collapsed denver airport. The Weather Network, July 5, 2023,https://www.theweathernetwork.com/en/news/weather/severe/this-day-in-weather-history-march-20-2003-colorado-blizzard..

In a future climate, warmer air temperatures will allow for a greater holding capacity for water vapor associated with the Clausius-Clapeyron empirical relationship. Thus, if the 2003 March upslope snow storm had occurred toward the end of the current century, it would have had a lot more moisture (Figure 11). Colorado's normally dry climate usually results in relatively dry snow with low density (often 10-12 to 1 snow to liquid ratio), but in the 2003 case, there was an influx of moisture from the Gulf driven by easterly and southeasterly winds associated with the cut-off low pressure system (Wesley et al. 2013). Given that the PGW methodology preserves large-scale synoptic features of scales greater than 2,000 km above the boundary layer, this cut-off low is also present in the PGW simulation. In the PGW simulation, air from the Gulf is even more moist relative to the CTRL simulation, creating the potential for the snow to be even more dense than the CTRL event. In the times leading up to the snow event, the amount of precipitable water increases along the Front Range (Figure 3.10). The PGW case also shows a higher overall amount of precipitable water than in the CTRL case, likely due to the overall warmer air temperatures and greater availability of moisture in the PGW simulation.

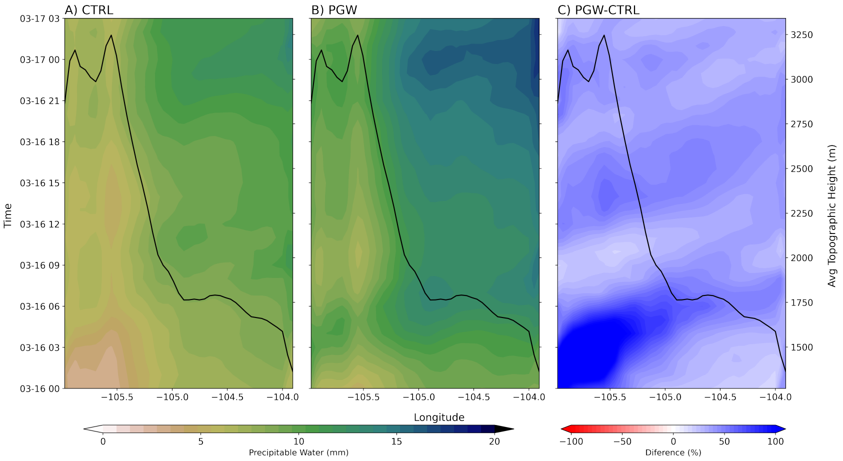

**Figure 3.10:** Precipitable water (mm) with respect to latitude starting 27 hours before the extreme snow event March 17, 2003 to March 19, 2003.m Panel A) shows the CTRL panel, B) shows the PGW, and panel C) shows the percent difference between the PGW and CTRL.

Figure 3.11 shows that temperatures were notably warmer in the PGW simulation as it can be seen that during the entire event, the average temperature in the Front Range is warmer than 0°C while for the majority of the storm event in the CTRL case, the temperature is below 0°C. While the total precipitation for this event in the CTRL and PGW simulations was 66.77 mm and 71.23 mm, respectively, a major shift from the dominant precipitation type of this storm from snow to rain or freezing rain is notable.

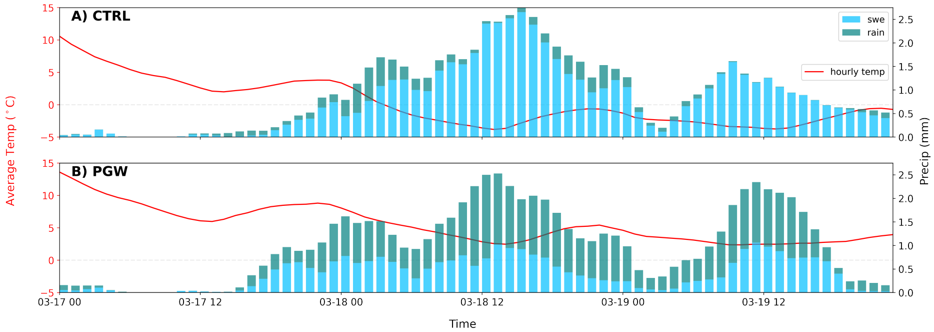

**Figure 3.11:** Hourly rates of SWE (light blue) and rain (teal) in mm during the 17-19 March extreme snow event for the CTRL (a) and PGW (b) simulations. Temperature is plotted on the left y-axis by the red line.

Spatial maps of SWE amounts across the UCRB show increases in SWE at higher elevations and decreases at the lower elevations along the Front Range (Figure 3.12). The increased SWE at the highest elevations is likely due to the increased moisture availability and the ability to produce more snow (Rasmussen et al. 2011). At that altitude, the temperatures are still below 0°C, so it can sustain snow. In the lower elevations where temperatures are warmer, the decrease in SWE is likely attributed to warmer temperatures and the change in partitioning of hydrometeors to more liquid precipitation and less solid precipitation.

Figure 3.13 also supports the notion that the lower elevations would receive more rain in this storm in a future warmer climate. In the CTRL simulation, there is very little to almost zero percent of the precipitation received as rain during this event. In the PGW simulation, however, the percent of precipitation received as rain increases dramatically from contributing about 14% of the CTRL event precipitation to contributing over 55% of the total PGW event precipitation. Klos

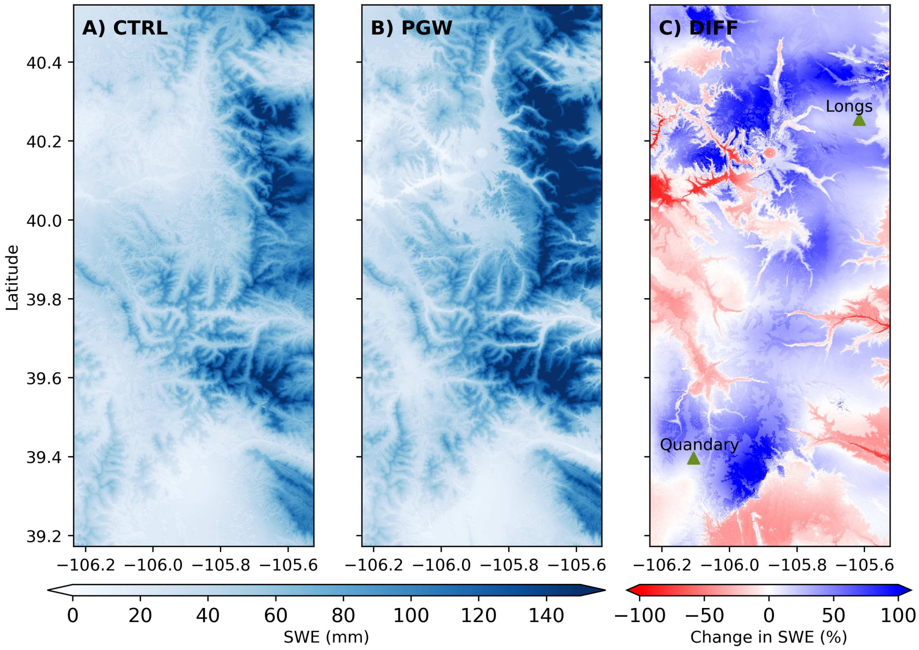

**Figure 3.12:** Spatial maps of SWE in mm in the CTRL (panel A) and PGW (panel B) simulations in the Front Range during the extreme snow event. Panel C is a difference plot between the two simulations and shown in percentages.

et al. (2014) utilized an empirical probabilistic precipitation phase model to estimate snow versus rain occurrence in the western U.S. and found that in a future climate, there is a transition to a more rain dominant regime from a snow dominant regime on a widespread scale that is consistent with the results from this study. This transition is especially highlighted in the lower elevation areas, where in many places the percentage of precipitation received as rain is around at least 50% and goes as high as about 85%. It would be beneficial to look at this specific event in further detail to understand the risk that rain on snow could have in the Front Range area in a future warmer climate.

The March 2003 snowstorm was a late winter, early spring event and from Figure 3.9 we know that in March the convective frequency increases. Figure 3.14 shows that the stratiform frequencies in March stay relatively the same on average which this event may not be entirely representative of. For this event, the stratiform frequencies increase along the Front Range (Figure 3.14a, c). The convective frequencies increase as well but not significantly. Increases in both the stratiform and convective frequencies and the changing nature of the precipitation to a more rain-dominant phase

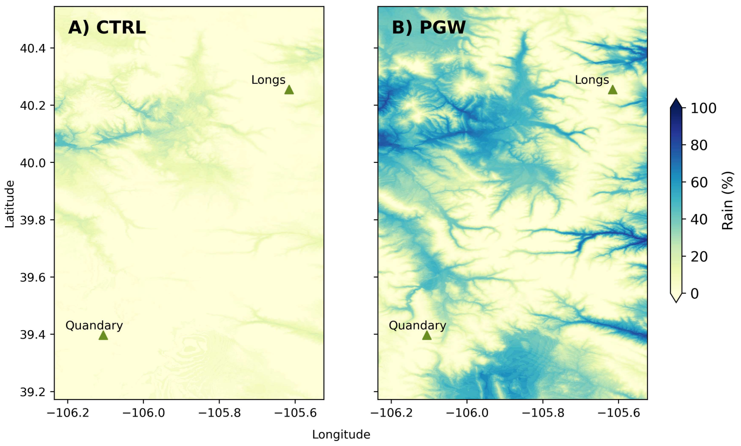

**Figure 3.13:** Percentage of precipitation that is received as rain during the extreme snow event of March, 2003 in the CTRL (panel a) and PGW (panel b) simulations.

indicates the societal impacts of this memorable event would likely be different in a future climate and should be further studied in more detail.

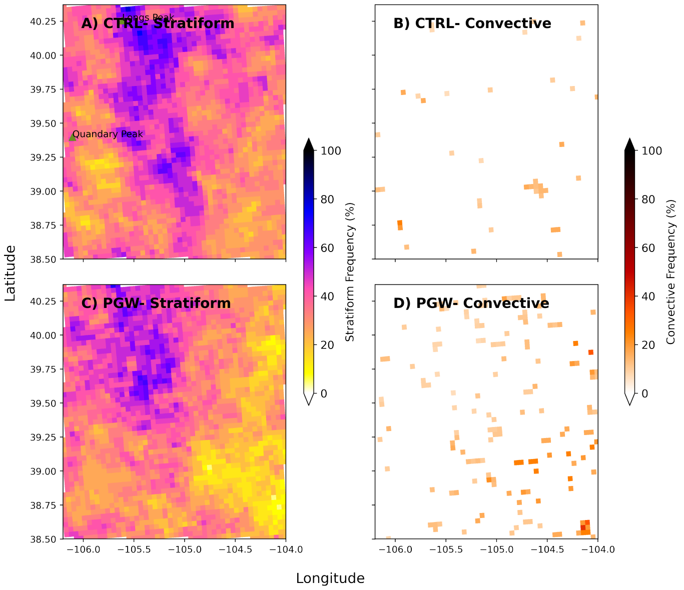

**Figure 3.14:** The spatial frequency of stratiform (left column) and convective (right column) storm modes in the CTRL (top row) and PGW (bottom row) simulations for the March 17-19, 2003 case study.

# Chapter 4

# Conclusions

Snow is incredibly important to the delicate water balance in Colorado and the intermountain West. With so many people, governments, and industries depending on a predictable snowpack, it is of utmost importance to understand how the snowpack in the Upper Colorado River Basin will change in a future, warmer climate and the potential impacts it will have. High-resolution convection-permitting regional climate simulations in a 13-year period in the current and future climate were used to provide input conditions to a complex process-based snowpack model to understand how changes in atmospheric conditions may impact the life cycle of snowpack in the UCRB. From the simulations that were run, it is expected that the UCRB region will experience many changes to the snow season and snowpack. The main conclusions from this research are as follows:

1. The snow season shortens, reducing the amount of time that the snow can accumulate.
2. There are broad decreases in SWE across the region and at nearly every altitude.
3. Cool season precipitation shifts from a snow-dominant to rain-dominant mode in a future climate.
4. Convective storm mode frequencies increase in all months of the snow season, potentially increasing hazards.
5. The percentage of precipitation received as rain during the snow season increases in an early spring extreme snowfall case.

The implications of these conclusions are concerning and should be taken into account in future water resource planning and allocations. By providing new understanding of how high-impact snow events may have differed in a future warmer climate, water managers can more carefully consider how impacts of such extreme events may change.

Future work on this topic could include using a longer simulation period than 13 years so that patterns on multiyear or decadal time scales can be examined in the context of a changing snow season and snowpack evolution. In addition, the framework used herein primarily considers impacts of thermodynamic aspects of climate change, but changing storm tracks and other large-scale climate dynamics will likely impact the occurrence and locations of future extratropical cyclones and associated snow events.

While the findings of this paper are not overwhelmingly positive in terms of the outlook for future water resources connected with snowpack in the UCRB, there is still a lot of hope for a better situation. In using RCP8.5, the simulations accounted for a future that represents the worst-case scenario. If sufficient progress is made in climate change policy and reductions in greenhouse gas emissions, it is possible that reality will not be as extreme. Nevertheless, a better plan for water management can be developed using informed research to prepare the western United States for a warmer, future climate with a significantly different snowpack.

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