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Winter Snowpack Evolution and Precipitation Patterns Related to Cyclone Activity in the Western United States

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WINTER SNOWPACK EVOLUTION AND PRECIPITATION PATTERNS RELATED TO CYCLONE ACTIVITY IN THE WESTERN UNITED STATES

by

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The water supply in the western United States is in large part derived from runoff originating from mountain snowpacks. Temperature and precipitation control snowpack growth, both which are sensitive to climate change. This study uses daily snow telemetry (SNOTEL) observations and reanalysis-based cyclone center locations and pressures to correlate snowpack changes with cyclone activity. The results indicate that while a quarter of the stations used in this study indicate significant shifts toward lower peak snow water equivalent (SWE) amounts, the snowpack conditions differ between regions. Stations in the Utah region experience earlier peak SWE dates, shorter accumulation seasons, and fewer total snowcover days, indicating delayed snowpack initiation and multiple melt events. Other regions, such as the Middle and Southern Rockies, do not show changes toward less continuous snowcover, yet have lower peak SWE amounts. Unlike previous studies, only 5% of the stations indicate significant shifts toward shorter melt seasons. The direct effects of increasing temperatures does impact the type of precipitation events and the initiation of snowpack accumulation However, the indirect effects related to the timing and amount of precipitation events, in connection to the frequency and intensity of winter storms, are also critical. Variations in cyclone activity, occurring at the beginning of the snow season or closer to the date of peak SWE, correspond to significant correlations of decreasing monthly precipitation totals. The likely scenario is that peak SWE amounts will decrease in the future due to increased temperatures, though altered precipitation patterns may enhance or offset SWE amount losses.

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CHAPTER 1: INTRODUCTION

The western United States is a semiarid to arid region in which most of the annual precipitation occurs during late fall through early spring (November through March) and between 40% and 70% of the precipitation falls in the form of snow (Avanzi et al. 2014). Winter snowpacks play an important role in the hydrologic cycle of this region Snowpacks act as natural reservoirs, in many watersheds the snow water equivalent (SWE) of the snowpacks exceeds the storage capacity of constructed reservoirs (Clow 2009). Runoff from melting winter snowpacks accounts for 70% of streamflow volume during the spring and summer (Avanzi et al. 2014), which is then collected and stored in a system of over 700 constructed reservoirs (Nijhuis 2014). The combination of natural and constructed reservoirs provide water resources during the summer dry season, when demand is heavy for agriculture, industry, and drinking water for large metropolitan areas.

The growth, persistence, and decline of a winter snowpack is dependent on many factors, particularly precipitation and temperature. Snowpack SWE increases through snowfall events and decreases through sublimation and melting. The frequency and intensity of snowfall events are linked to the occurrence of winter storms; extratropical cyclones contribute close to 60% of all precipitation north of 30°N latitude in the western United States (Oakley and Redmond 2014). The sum of all the snowfall events during one snow season is reflected in the timing and amount of peak SWE. The date of peak SWE also designates the onset of the snowmelt season. It is generally thought that the initiation of snowmelt is more likely to be sensitive to temperature, although the occurrence of rain events can accelerate snowmelt (Knowles et al. 2006). Runoff forecasts use SWE measurements to predict streamflow patterns;

peak SWE amounts indicate potential peak streamflow volume, and the length of the melt season relates to the timing and amount of peak streamflow (Clow 2009). However, the timing and amount of peak SWE, when compared with the timing of snowpack initiation and disappearance, can also provide insights on snowpack conditions throughout the snow season.

Increased concentrations of greenhouse gases are generally thought to increase average minimum temperatures and intensify the hydrological cycle, leading to less frequent and more intense precipitation events (Barnett et al. 2005). Wet regions, such as the Pacific Northwest, will likely become wetter while drier regions, such as the Southwest, will become drier. However, unlike temperature predictions, there is little agreement among climate models relating to the magnitude of precipitation changes (Barnett et al. 2005). With as much as 75% of the water supply in the western United States originating from mountain snowpacks (Nijhuis 2014), significant changes in precipitation patterns and winter temperatures related to climate change will likely strain water resources and have dire consequences for the economy of the western United States.

The focus of this study is to investigate winter snowpack evolution in the western United States and determine how long-term snowpack changes relate to cyclone activity. Changes in peak SWE timing and amount, as well as other snowpack properties, will be used to indicate how snowpacks are varying through time. SWE variations will be ascribed to changes in monthly average temperature and monthly precipitation. Lastly, precipitation will be compared to changes in cyclone frequency, intensity, and track. To accomplish these goals, snowpack data for the western United States will be collected and analyzed for the 1981-2008 period. Reanalysis data will be used to determine atmospheric conditions and statistical analyzes will be used to identify relationships among the parameters.

CHAPTER 2: BACKGROUND

Snowpack conditions in the western United States are monitored by snow telemetry (SNOTEL) stations, which consist of several instruments that collect hourly and daily measurements. When stations were first installed in the early 1960s, the only instruments available were snow pillows, which derives SWE by measuring the weight of the snow. The original purpose of SNOTEL stations was to collect high temporal resolution SWE data at higher elevations and more remote locations, where manual measurements were too dangerous or cost prohibitive. Precipitation gauges were then added in the early 1980s, followed by thermistors to measure temperature in the late 1980s. All stations were later retrofitted with sonic sensors to measure snow depth while select "enhanced" stations were outfitted with sensors to measure solar radiation, barometric pressure, wind speed, and soil moisture and temperature. Data are transmitted at midnight by using meteor burst technology, where the regional data center sends out a radio wave that is reflected off of the ionized molecules of meteor trails in the upper atmosphere and the station responds to the signal (Schaefer and Paetzold 2000). Yearly cumulative measurements, such as precipitation accumulation, are reset at the beginning of the water year, which is defined by the United States Geologic Survey as starting on 1 October of one year and ending on 30 September of the next year. The water year is designated by the calendar year it ends in.

Earlier climate studies of SWE relied on data from manual snow course sites (Cayan 1996; Mote 2006). These archived snow course measurements largely go back to the 1930s when SWE measurement techniques were standardized and primarily conducted by the Soil Conservation Service (later the Natural Resources Conservation Service); however measurements were collected by individual state cooperatives as early as the 1910s and 1920s. Measurements were taken once or twice a month with the largest number of measurements being around the expected time of peak snow accumulation in order to create runoff forecasts. The time of peak accumulation varied by location, though measurements made around 1 April were used as a proxy for the peak SWE amount. Many SNOTEL stations were installed after 1980, so even though these stations provide greater temporal resolution, climate studies continued to use snow course SWE measurements. Serreze et al. (1999) was one of the first to use SNOTEL measurements to map regional differences in SWE, precipitation, and temperature, as well as compare 1 April SNOTEL SWE values with those of co-located snow courses. Later studies focused on specific regions such as the Great Salt Basin (Bedford and Douglass 2008) and the Intermountain West (Harpold et al. 2012), and connected them with streamflow patterns (Clow 2009). In some cases, SNOTEL data were used in conjunction with snow course measurements to lengthen the record, as some snow courses have been abandoned in preference to the automated sites. Other uses for SWE data have been to compare snowfall versus rainfall (Knowles et al. 2006) and large snowfall events over time (Serreze et al. 2001; Lute and Abatzoglou 2014). Some climate studies still use snow course records instead of SNOTEL records, though the reliance on snow course data has lessened in recent years.

Though the methods of analyses differ somewhat, many of the conclusions of past studies are similar: the peak in SWE is occurring earlier, snowmelt is initiated earlier, and the melt season is shorter in length (Serreze et al. 1999; Barnett et al. 2005; Mote 2003; Clow 2009; Harpold et al. 2012). Also, the impacts of temperature and precipitation changes are not equal. The Cascades, Sierra Nevada, and Arizona regions are strongly impacted by warming throughout the winter and spring, while the Rockies are predominantly sensitive to precipitation changes during the winter and, to some extent, warming in late spring (Hamlet et al. 2005). Higher elevation sites may see an increase in SWE, as more extreme snowfall events may occur due to the intensification of the hydrological cycle, which may partially offset losses from enhanced snowmelt attributed to increased temperatures (Lute and Abatzoglou 2014; Kumar et al. 2012).

The main conclusions of most studies are primarily focused on warming temperatures in the future and only provide conjectures in relation to precipitation. That is not surprising, as changes in precipitation are not as easily predicted or understood. While climate models are more consistent on the sign , and to some degree the magnitude, of temperature change, there is little agreement on both the magnitude and sign of regional precipitation changes (e.g. Barnett et al. 2005). Precipitation variations cannot be ignored, as the number of winter storm events is linked with peak SWE (Pederson et al. 2010) and extreme snow events can be the difference between a drought or a water surplus in many areas (Lute and Abatzoglou 2014; Oakley and Redmond 2014). Thus, while the direct effects of increasing temperatures on snowpack persistence are important to consider, the indirect effects relating to changes in precipitation could exacerbate or offset SWE losses (Kumar et al. 2012).

Much work has been done on identifying trends in cyclone activity with connotations to climate change (Lambert 1995; McCabe et al. 2001; Oakley and Redmond 2014), as well as the connection between winter cyclones and precipitation (Myoung and Deng 2009; Hawcroft et al. 2012). Other studies have focused on the contribution of large snow events on SWE (Serreze et al. 2001; Knowles et al. 2006; Kumar et al. 2012). While the frequency and intensity of snowfall events are a function of both temperature and precipitation, which in turn are linked to the frequency and intensity of mid-latitude winter cyclones (Lute and Abatzoglou 2014), little work has focused on connecting cyclone activity directly with changes in snowpack evolution over time. Studies that do connect large scale circulations with SWE either have limited spatial coverage (e.g. the northern Rocky Mountains, Pederson et al. 2010) or use 1 April SWE from snow course data (McCabe and Legates 1995). Though many past studies have used snow course data to investigate teleconnections between long term climate and SWE, some caution must be used with regard to their conclusions. Comparisons of 1 April SWE and peak SWE have shown that 1 April SWE amounts tend to underestimate peak SWE amounts (Bohr and Aguado 2001), which could potentially result in misleading conclusions about trend estimates (Montoya et al. 2014). Thus, comparing snowpack conditions as a whole, not just the timing and amount of peak SWE, with changes in cyclone activity would be beneficial in understanding the possible consequences of precipitation shifts due to climate change.

CHAPTER 3: DATA AND METHODS

3.1 SNOTEL Data

Daily SNOTEL data including SWE accumulation, precipitation (accumulation and increment), and air temperature (maximum, minimum, average) measurements were obtained from the Natural Resources Conservation Service (NRCS) archive (NRCS 2015). SNOTEL stations were chosen using several criteria; the stations: had to be installed and functional by 1 Oct 1981, have continuous SWE and precipitation measurements for the desired time period, and had to be located within close proximity of other SNOTEL stations. The 307 SNOTEL stations that were selected were then grouped into eight regions (Figure 1 and Table 1). The eight regions — Cascades, Sierra Nevada, Blue Mountains, Northern Rockies, Middle Rockies, Utah, Southern Rockies, and Arizona/New Mexico — are organized to largely represent distinct mountain ranges in the western United States and are similar to those used by Serreze et al. (1999). Cumulative SWE measurements were used to calculate several snowpack property indicators, which are dependent on the date and amount of peak SWE (Figure 2). The snow season is divided into two distinct parts: the accumulation season and the melt season. For this study, the length of the accumulation and melt season measures the number of continuous days with snowcover before and after peak SWE. Other snowpack indicators, such as the first and last days with snowcover, the total number of days with snowcover (SWE > 0), and the number of days for half of the snowpack to melt (SM50) were also calculated. Precipitation accumulations were totaled for each month, the winter season, and the water year. Quality control measures are applied by the NRCS to precipitation and SWE measurements when they are received and again at the end of the water year; however, temperature measurements are more prone to missing data, as

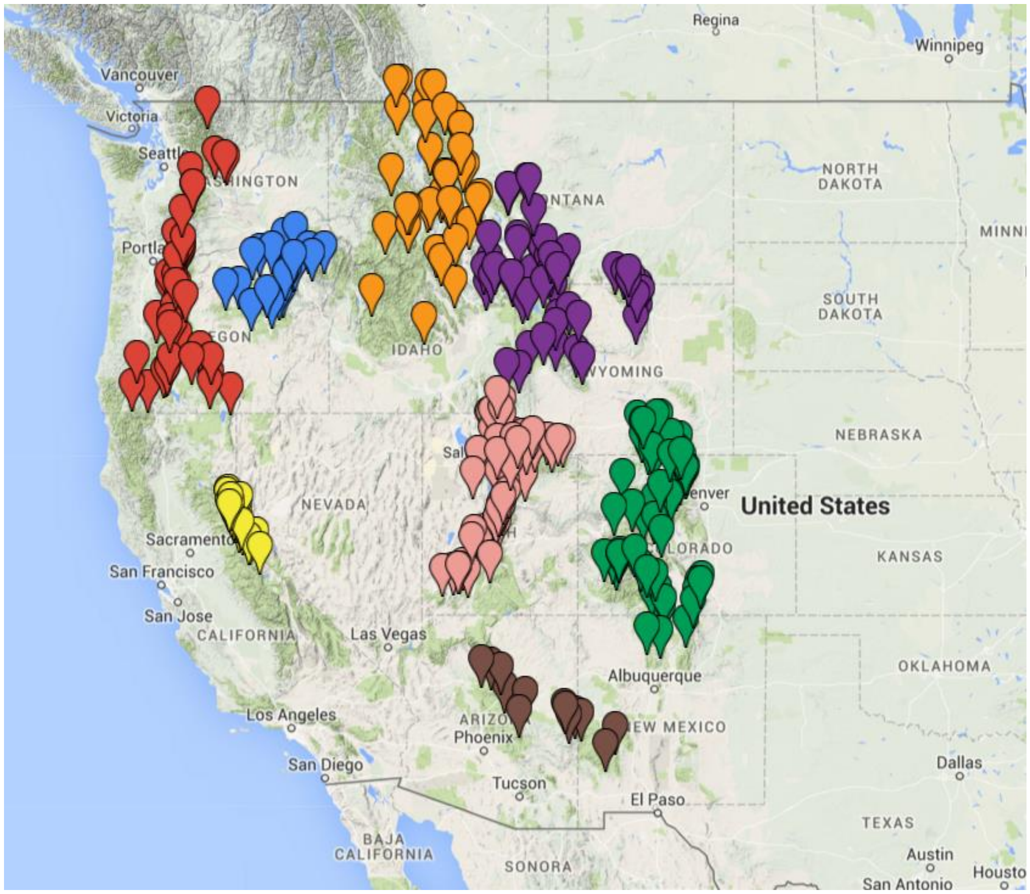

Figure 1. Map of snow telemetry (SNOTEL) sites used in this study, grouped by region: Cascades (red), Sierra Nevada (yellow), Blue Mountains (blue), Northern Rockies (orange), Middle Rockies (purple), Utah (salmon), Southern Rockies (green), Arizona/New Mexico (brown).

Table 1. Region Characteristics.

	Elevation, m			Latitude		Longitude		
Region	Max	Min	Median	Max	Min	Max	Min	N
Cascades	2243	789	1487	48.44	41.99	-120.18	-123.34	46
Sierra Nevada	2879	1864	2370	39.49	38.07	-119.23	-120.31	21
Blue Mountains	2411	1158	1649	45.70	43.95	-117.17	-120.33	23
Northern Rockies	2697	1311	1920	48.91	43.63	-111.15	-115.66	39
Middle Rockies	3078	1966	2512	46.79	42.51	-106.98	-112.06	51
Utah	3335	1777	2715	41.90	37.49	-109.54	-113.40	57
Southern Rockies	3487	2560	3048	41.33	35.92	-105.07	-108.20	57
Arizona/New Mexico	2804	2103	2438	35.14	32.92	-107.83	-112.15	13

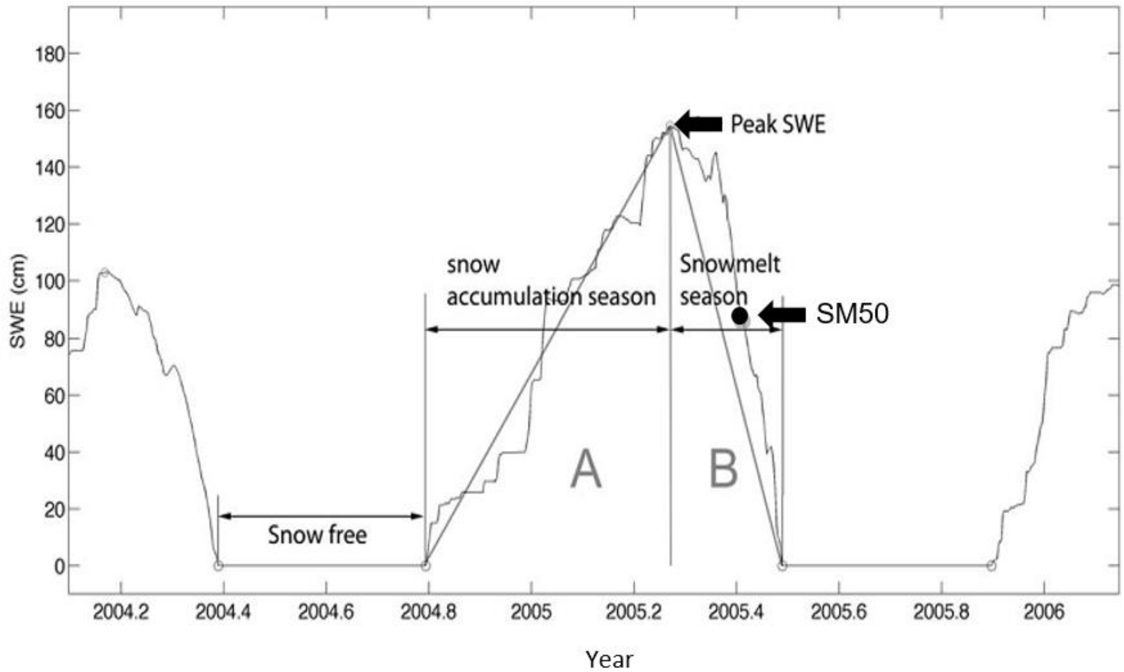

Figure 2. Example SWE curve, indicating the separation of the snow accumulation season and the snowmelt season by peak SWE and the halfway point in the snowmelt season (SM50). Adapted from Trujillo and Molotch (2014).

well as obviously false readings, as the height of the instrument in relation to the snow surface changes throughout the snow season. Data points were excluded if: i) the temperature measurements were above 40°C (104°F) or below -40°C (-40°F), ii) the absolute difference of the daily high and low temperature was greater than 25°C (45°F), or iii) the daily high/low temperatures were the same as the average. Monthly average temperatures were computed only when there were more than fifteen days of good data available.

3.2 Cyclone Data

The cyclone data were derived from the Northern Hemisphere cyclone locations and characteristics dataset from the National Snow and Ice Data Center (NSIDC 2015). The original dataset was created using six-hour interval Sea Level Pressure (SLP) data from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) Reanalysis I data set and applying the updated Serreze et al. (1997) algorithm to isolate centers of low pressure (Serreze and Barrett 2008). The NSIDC dataset consists of a 50-year record (1958 to 2008) of extratropical cyclone coordinates and characteristics, including central pressure, pressure tendency, and indications of cyclogenesis or cyclolysis events, at a resolution of 250 km. For this study, the primary focus was concentrated on cyclones that make landfall over the western United States, between 30° and 50° N latitude and 125° and 100° W longitude. However, the NSIDC dataset focuses solely on the centers of the low pressure systems and gives no indications of the size of the cyclone or the associated frontal positions. Two additional analyses were conducted by simultaneously increasing the areal boundaries farther north and west and east for analysis 3 (Figure 3) to accommodate frontal

Figure 3. Boundaries for the cyclone activity statistical analyzes: analysis 1 (black), analysis 2 (dark gray, dashed), analysis 3 (light gray, dashed).

positions and determine relationships which might occur due to an artifact of the boundary conditions. Only the reanalyzes at 12-hour intervals were used (0Z and 12Z) as those at 6Z and 18Z were often a reflection of changes in the cyclone central pressure and not distance traveled. Monthly statistics were calculated for the total number of cyclones, average central pressure, maximum and minimum pressure of the cyclone, and average latitude.

3.3 Data Analysis

The aim of this study is to detect variations in the snowpack indicators, correlate the variations to changes in temperature and precipitation patterns, and then correlate with changes in the frequency, intensity, and location of extratropical cyclones. To identify relationships over time, all of the data were analyzed using simple linear regression. A linear relationship between each variable and time was established by minimizing the Chi-squared statistic; the correlation coefficient (r-value) was calculated and converted to a p-value with the use of a t-statistic. Of particular interest was whether the slope of the regression line or the correlation coefficient differed significantly from zero, an indication that either the magnitude or the strength of the linear relationship is sufficiently significant over the specified time frame. The cutoff for statistically significant results was set at the 90% level ($\alpha = 0.1$) due to the considerable variability of conditions typical of mountainous regions. Results significant at the 95% level were also specified for comparing the difference in the two significance levels.

Originally, both the slope and the correlation coefficient were to be utilized. However, preliminary analyses of the slopes for the SNOTEL and cyclone data indicated no statically significant trends at either the 90% or 95% level from the regression analysis, which is consistent with the null hypothesis that the true slope is zero. The lack of statistically significant slope values is due to the considerable variability of SWE and precipitation from year to year, in part related to the influence of interannual and interdecadal circulations (McCabe and Dettinger 2002). One or two years with unusually high or low peak SWE amounts can alter the slope of the fitted line, and thus the magnitude of the long term trend. For example, in the case of the Beaver Dams, UT station, (Figure 4), removing two years with unusually high peak SWE amounts would change the trend from a decrease of 22.3 cm over 27 years to a decrease of only 9.6 cm over the same time period. Considering that the average peak SWE for the Utah region is close to 50 cm (Table 2), the difference between the two trends could be substantial. In other regions there is considerable variability in peak SWE amounts, so much so that there are no clear outliers. For example, at the Cascade Summit, OR station (Figure 5), there are no clear outliers

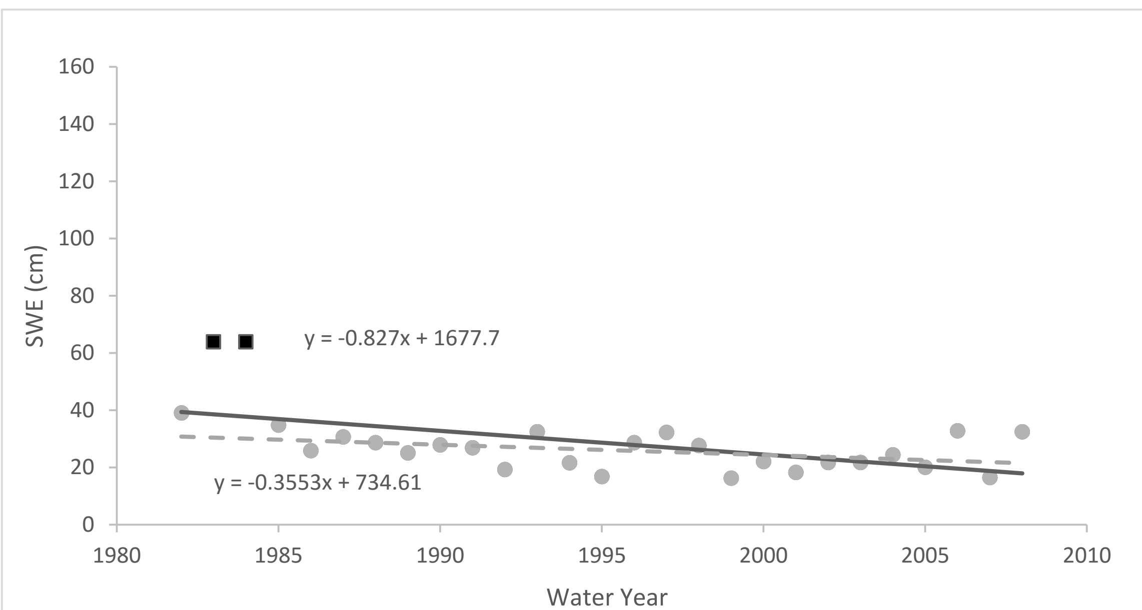

Figure 4. Trendline and equations of peak SWE amounts for Beaver Dams, UT (station number 329). Solid trendline and the top equation include all peak SWE values, dashed line and bottom equation excludes years of abnormally high peak SWE (square points).

Table 2. Typical range of First, Peak, and Last dates (±one standard deviation from the regional mean date); average length of accumulation and melt seasons; average number of days for half of the snowpack to melt (SM50); average number of snowcover days; and average peak SWE amount (cm). Standard deviations are within the parentheses.

Region	First		Peak		Last		Acc	Melt	SM50	Total	SWE
Cascades	19-Oct	16-Nov	26-Feb	12-Apr	2-May	3-Jun	125 (29.1)	54 (18.9)	37 (15.9)	188 (23.3)	67.7 (25.7)
Sierra	12-Oct	16-Nov	5-Mar	14-Apr	4-May	7-Jun	129 (27.9)	51 (15.2)	37 (13.5)	190 (25.3)	70.9 (31.0)
Blue Mtns	22-Oct	20-Nov	25-Feb	3-Apr	16-Apr	15-May	119 (24.9)	41 (15.1)	28 (12.7)	167(21.5)	35.9 (11.9)
N Rockies	4-Oct	27-Oct	28-Mar	25-Apr	22-May	18-Jun	164 (19.7)	46 (12.7)	34 (11.6)	220 (17.1)	50.7 (13.7)
M Rockies	1-Oct	23-Oct	5-Apr	4-May	25-May	5-Jun	181 (20.8)	41 (12.3)	30 (11.4)	231 (19.2)	46.5 (12.5)
Utah	5-Oct	5-Nov	20-Mar	21-Apr	7-May	5-Jun	153 (23.0)	40 (12.1)	29 (11.2)	201 (22.5)	48.2 (15.9)
S Rockies	5-Oct	4-Nov	29-Mar	29-Apr	13-May	8-Jun	167 (23.2)	40 (11.9)	29 (10.4)	213 (21.2)	49.8 (12.9)
AZ/NM	25-Oct	16-Dec	1-Feb	20-Mar	14-Mar	23-Apr	73 (33.4)	29 (15.6)	19 (12.1)	116 (32.0)	18.8 (9.3)

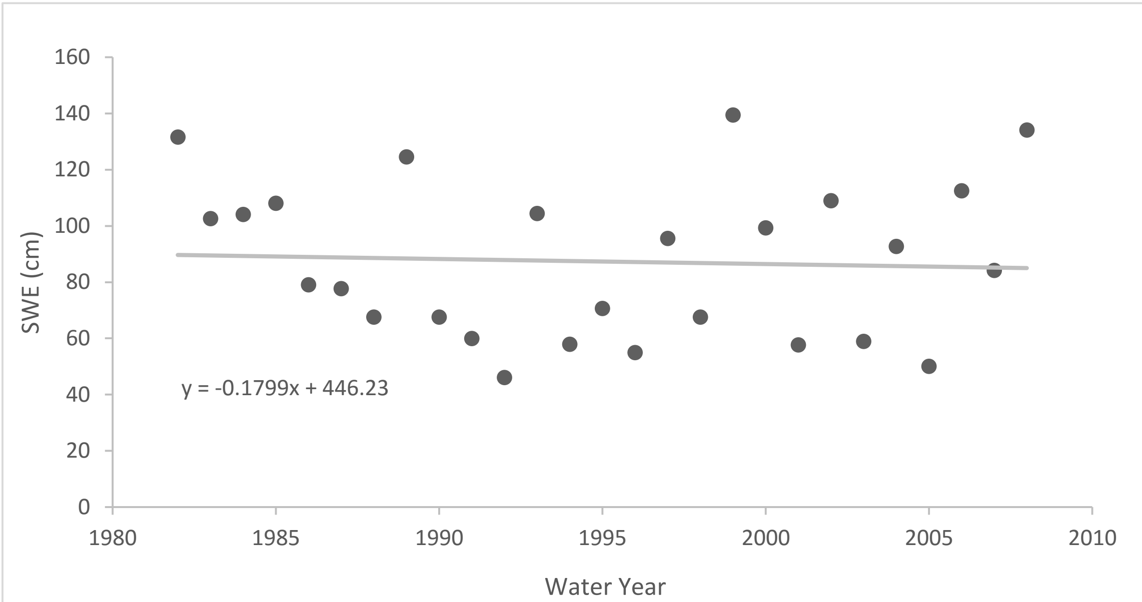

Figure 5. Trendline and equations of peak SWE amounts for Cascade Summit, OR (station number 388). No data points were removed.

in the data. Outlying SWE values also may not be due to instrument error, so removing such points to create a better fitting curve for the remaining data could also result in a relationship that does not reflect actual conditions.

The results of the linear regression analyzes could be interpreted two ways: that there truly are no trends related to snowpack conditions, precipitation, and cyclone activity, or that the magnitudes of the trends are small compared to interannual variability. For example, a 5 cm decrease in the amount of peak SWE over the time frame of the study would likely not be noticeable at a location where peak SWE amounts can vary up to 30 cm from one year to the next. Since the magnitude of the trend is highly influenced by the method of analysis, the slope is not a very reliable number in and of itself. However, while the slope values are not statistically significant, the sign of the correlation coefficient is the same as the sign of the slope (except in cases of highly skewed slopes or r-values very close to zero). The correlation coefficient represents the strength and the sign of the linear relationship, a sort of "normalized" slope. A significant positive or negative relationship may not equate to a substantial overall change in magnitude of a value. However, the r-value is a good indicator of whether the change in a parameter is a likely event, and thus a reflection of normal climate variability instead of climate change. Thus further analysis will focus on correlation coefficients, though not on the magnitude of the r-values themselves. Instead the number of stations that have statistically significant r-values in each region are totaled and converted to percentages. Patterns in the signs of the correlations for the snowpack indicators will be compared with the sign of the correlations for monthly precipitation and maximum/minimum temperature to indicate which snowpack variations are attributed to precipitation shifts and which are related to temperature changes. Precipitation patterns will then be contrasted against changes in cyclone frequency, intensity, and location in order to identify possible correlations between snowpack conditions and winter storms.

CHAPTER 4: RESULTS

Before examining similarities between cyclone activity and snowpacks, more information about snowpack physical processes is required. Previous studies have focused on variations in peak SWE (using 1 April SWE) and the length of the melt season, primarily due to the application of these measures in runoff forecasts. For this study, it is also important to detail the changing state of winter snowpacks, to identify whether the fluctuations are related to temperature and/or precipitation variations, and to associate cyclone activity with precipitation patterns.

4.1 Snowpack Indicators

The patterns of peak SWE timing and amount, as well as the other snowpack indicators, vary by region. Generally, SNOTEL stations in the Cascades and Sierra Nevada regions experience shorter accumulation seasons, longer melt seasons, fewer snowcover days, and higher peak SWE amounts than regions such as the Northern and Middle Rockies (Table 2). Typical dates of peak SWE occur within a one or two month period, of which 1 April can either be located at the beginning or the end of that range. For the Middle Rockies and Arizona/New Mexico regions, the range of typical peak SWE dates does not include 1 April. Considering the variability of both peak SWE dates and amounts, 1 April SWE therefore is not a suitable proxy for peak SWE values, as 1 April could be a part of the accumulation season for some years or a part of the melt season for other years.

The tendency in many regions is toward shorter snow accumulation seasons, lower peak SWE amounts, and earlier peak SWE dates. However, the length of the melt season is not drastically changing in many places. Positive r-values (Table 3a) are less common than negative r-values (Table 3b) in terms of the timing and duration of snow accumulation, the total number of days with snowcover, and the timing and amount of peak SWE, which reinforce conclusions from earlier studies (Serreze et al. 1999; Barnett et al. 2005; Mote 2003; Bedford and Douglass 2008; Clow 2009; Harpold et al. 2012). Conversely, with the exception of the Arizona/New

Table 3. Percentage of stations within each region with positive or negative r-values that are statistically significant at the 90% level for the snowpack indicators. The stations within each region meeting the significance level are given within the parentheses.

a. Positive SWE r-value percent (frequencies).

Region	First	Peak	Last	Acc	Melt	SM50	Total	SWE
Cascades	4 (2)	7 (3)	7 (3)	7 (3)	0 (0)	7 (3)	4 (2)	7 (3)
Sierra	0 (0)	0 (0)	0 (0)	0 (0)	10 (2)	5 (1)	0 (0)	0 (0)
Blue Mtns	0 (0)	0 (0)	0 (0)	0 (0)	13 (3)	9 (2)	0 (0)	0 (0)
N Rockies	3 (1)	0 (0)	5 (2)	0 (0)	5 (2)	3 (1)	0 (0)	3 (1)
M Rockies	0 (0)	0 (0)	4 (2)	0 (0)	4 (2)	6 (3)	0 (0)	0 (0)
Utah	0 (0)	0 (0)	0 (0)	0 (0)	9 (5)	9 (5)	0 (0)	0 (0)
S Rockies	0 (0)	0 (0)	0 (0)	0 (0)	4 (2)	4 (2)	0 (0)	0 (0)
AZ/NM	0 (0)	15 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

b. Negative SWE r-value percentages (frequencies).

Region	First	Peak	Last	Acc	Melt	SM50	Total	SWE
Cascades	11 (5)	7 (3)	2 (1)	15 (7)	2 (1)	7 (3)	11 (5)	4 (2)
Sierra	0 (0)	0 (0)	0 (0)	14 (3)	10 (2)	5 (1)	33 (7)	0 (0)
Blue Mtns	0 (0)	13 (3)	9 (2)	9 (2)	4 (1)	17 (4)	0 (0)	39 (9)
N Rockies	8 (3)	8 (3)	3 (1)	13 (5)	8 (3)	3 (1)	15 (6)	3 (1)
M Rockies	10 (5)	8 (4)	4 (2)	16 (8)	4 (2)	2 (1)	18 (9)	24 (12)
Utah	0 (0)	23 (13)	4 (2)	49 (28)	7 (4)	7 (4)	46 (26)	39 (22)
S Rockies	0 (0)	19 (11)	23 (13)	16 (9)	5 (3)	7 (4)	14 (8)	40 (23)
AZ/NM	0 (0)	0 (0)	0 (0)	8 (1)	54 (7)	38 (5)	8 (1)	46 (6)

Mexico region, significant positive and negative r-values related to snowmelt are localized to just a few stations. The proportion of stations indicating shifts towards shorter melt seasons is also roughly equal to, or less than stations indicating shifts towards longer melt seasons, which contradicts previous conclusions that the melt seasons are becoming shorter over time.

Changes in the length and timing of the snow season differ between regions. Several regions have a similar percentage of stations indicating shifts toward lower peak SWE, though the proportions of other snowpack indicators (such as the timing of peak SWE or the length of the snow accumulation season) differ widely. For example, the percentage of stations indicating shifts toward lower peak SWE amount are similar in the Blue Mountain and Utah regions (Table 3b), though the percentages indicating shorter accumulation seasons differ by 40%.

The implication of the snowpack indicator relationships is that lower peak SWE amounts are the result of many factors, in which different combinations could provide the same end result. Air temperature, the frequency and intensity of snowfall events, and the rate of sublimation vary from region to region, however, snowpacks in different regions are subject to comparable constraints. The relationships between the date of peak SWE and the amount of peak SWE (Figure 6) are similar for all stations within the study regions: earlier peak dates correspond with lower SWE amounts. The relationship between the date and amount of peak SWE is almost identical to that between the length of the accumulation season and the amount of peak SWE (Figure 7). This makes sense when considering that there is a limit on how early in the water year snow can begin to accumulate, so an earlier date of peak SWE would result in a shorter accumulation season and lower SWE. However, later peak dates can range between lower or higher SWE amounts. Longer accumulation seasons and later peak SWE dates do not

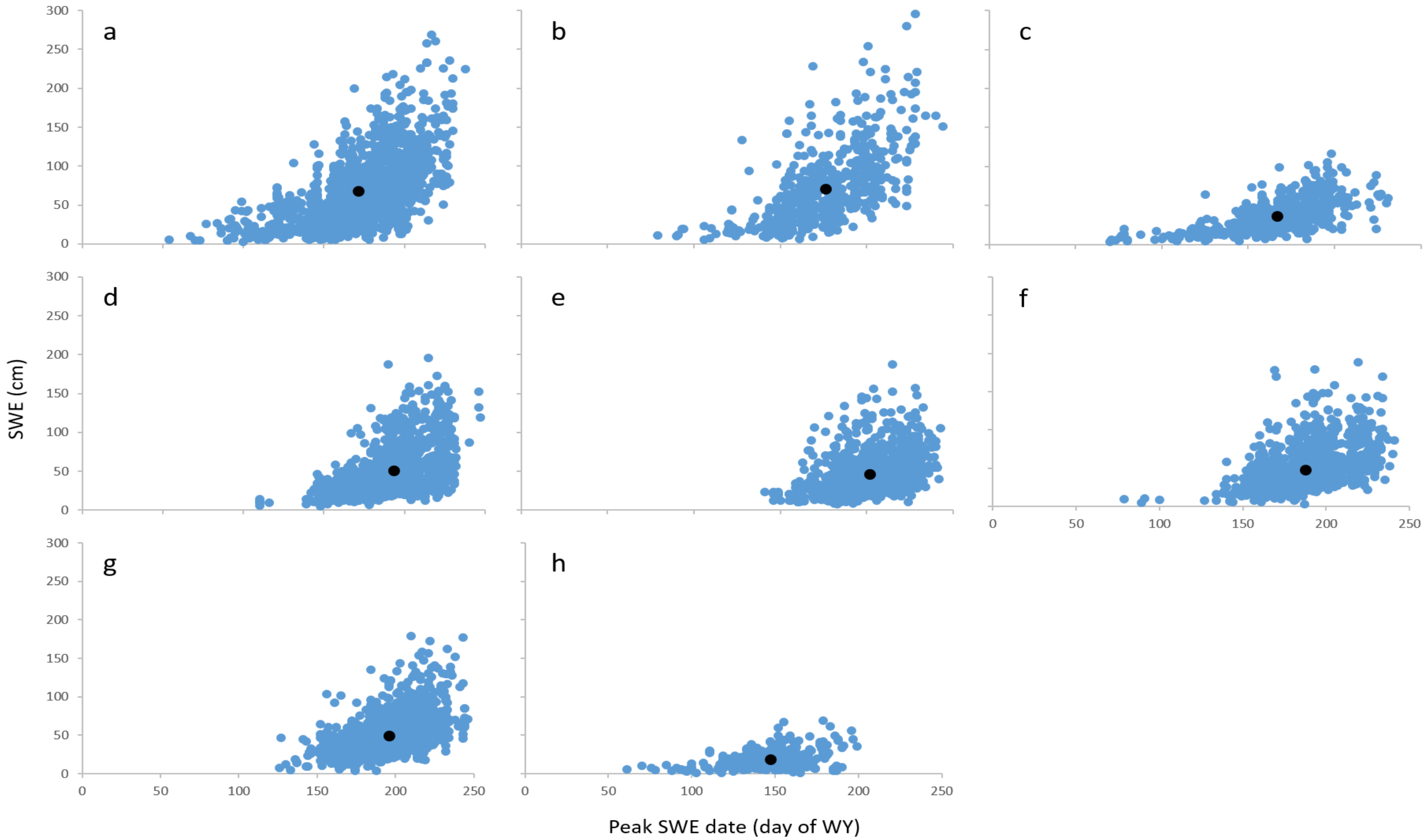

Figure 6. Scatterplots comparing peak SWE date vs. peak SWE amount by region: (a) Cascades, (b) Sierra Nevada, (c) Blue Mountains, (d) Northern Rockies, (e) Middle Rockies, (f) Utah, (g) Southern Rockies, (h) Arizona/New Mexico. Black dot indicates position of the regional average values.

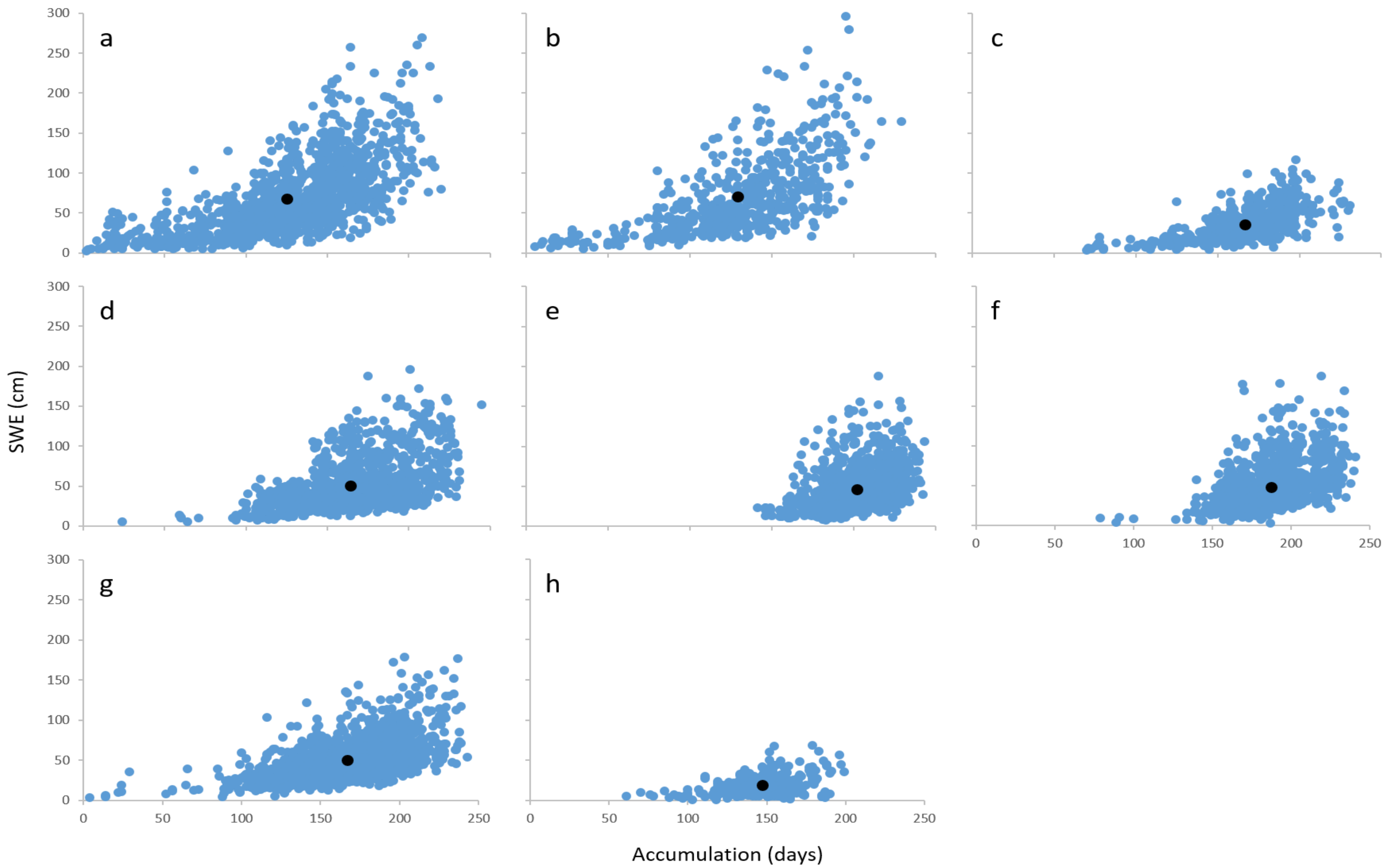

Figure 7. Comparison of length of accumulation season vs. peak SWE amount by region: (a) Cascades, (b) Sierra Nevada, (c) Blue Mountains, (d) Northern Rockies, (e) Middle Rockies, (f) Utah, (g) Southern Rockies, (h) Arizona/New Mexico. Black dot indicates position of the regional average values.

guarantee higher peak SWE amounts, though the potential for higher peak SWE amounts is greater.

While relationships between peak SWE dates and amounts as well as accumulation season lengths are similar for all regions, the patterns for each region do differ. Peak SWE dates and amounts and accumulation season lengths in the Cascades and Sierra Nevada regions (Figure 6a and b) vary considerably as compared to other regions, which could account for the lack of discernable statistical trend patterns for the snowpack indicators (Table 3a and b). The Blue Mountains region (Figure 6c) experiences variability in date of peak SWE similar to that seen in the Cascades region (Figure 6a). However, the amount of peak SWE in the Blue Mountains is typically half of that in the Cascades and does not vary as much from year to year. The same is also true for the Arizona/New Mexico region (Figure 6h), with even lower average peak SWE amounts (Table 2). A change in the amount of peak SWE over time would be much easier to identify in the Blue Mountains or Arizona/New Mexico regions than a change in the date of peak SWE, which could account for the greater percentage of stations in the Blue Mountains, Middle Rockies, and Southern Rockies regions indicating shifts towards decreasing peak SWE amounts than stations indicating shifts towards shorter accumulation seasons and earlier peak SWE dates (Table 3b).

The length of the melt seasons (Figure 8) varies less than that of the accumulation seasons (Figure 7), which suggests greater likelihood of identifying changes in the lengths of the melt season. However, relationships between melt season lengths and peak SWE amounts (Figure 8) differ: higher peak SWE amounts corresponds with melt seasons of moderate length while shorter or longer melt seasons correspond with lower peak SWE amounts. This pattern is more apparent in the Cascades and Sierra Nevada regions (Figure 8a and b), though there are

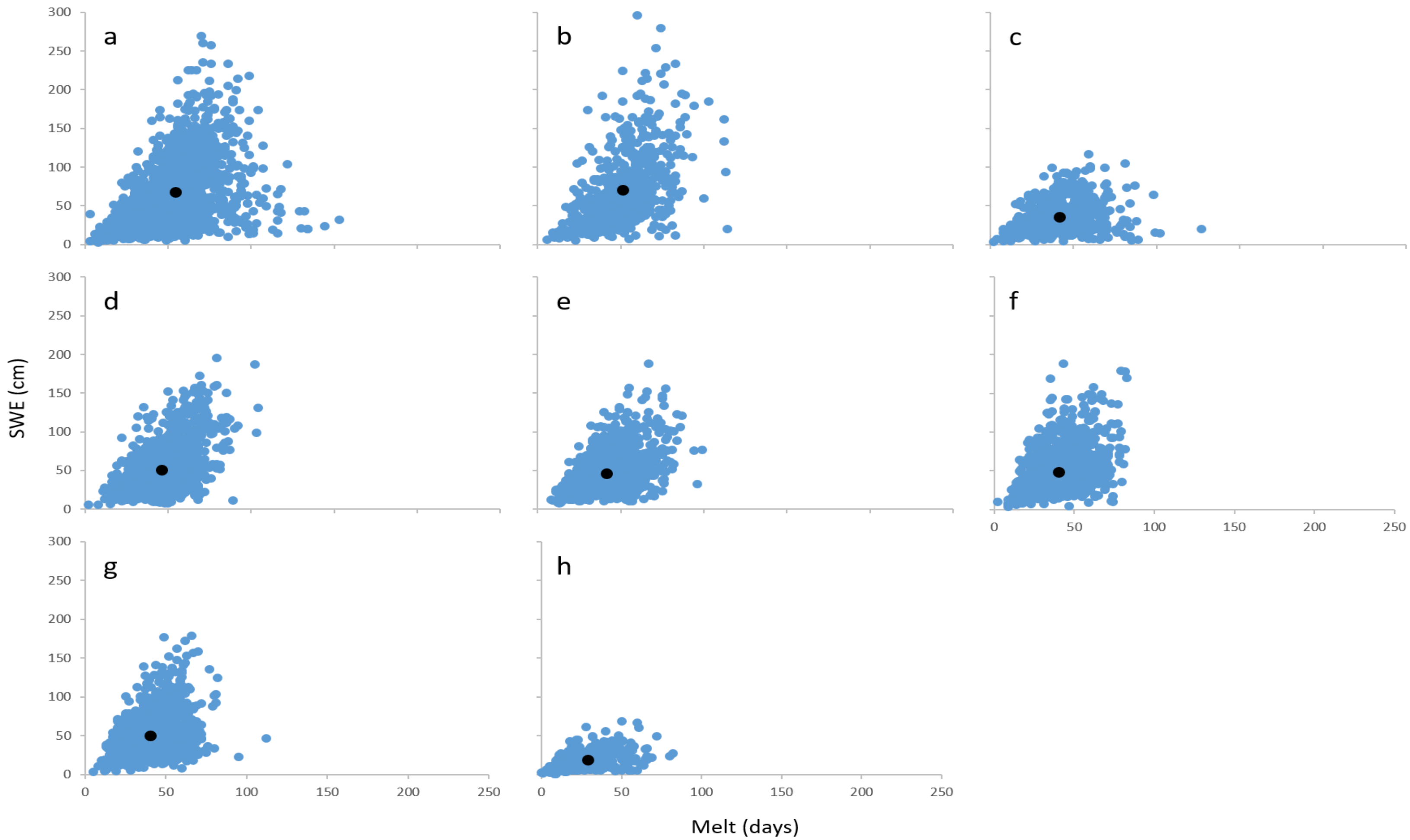

Figure 8. Comparison of length of melt season vs. peak SWE amount by region: (a) Cascades, (b) Sierra Nevada, (c) Blue Mountains, (d) Northern Rockies, (e) Middle Rockies, (f) Utah, (g) Southern Rockies, (h) Arizona/New Mexico. Black dot indicates position of the regional average values.

similar patterns associated with the other regions. The average melt season length, indicated by the black dots on the scatterplots, is also fairly consistent for all regions, despite the considerable variability in peak SWE amounts between regions. Unlike SWE amounts and accumulation season lengths, the length of the melt seasons are less dependent on peak SWE dates, though there is a slight negative correlation (Figure 9). Melt season lengths vary more in the Cascades, Sierra Nevada, and Blue Mountains regions (Figure 9a, b, and c), particularly for earlier peak SWE dates, yet the general pattern is almost identical for all regions.

To understand relationships between the dates and amounts of peak SWE and the rate of snow accumulation and melting, cumulative SWE curves for one station (Beaver Dams, UT) are investigated. To illustrate several possible conditions, four years are analyzed: 1983, 1984, 1995 and 2007 (Figure 10). Two years chosen are low peak SWE years (1995 and 2007), while the other two years had much larger SWE amounts (1983 and 1984). In the case of these four years, the relationship for peak SWE timing and amount as well as the length of the accumulation season are straightforward: the years with higher peak SWE amounts had longer accumulation seasons and later peak SWE dates, while the years with lower peak SWE had shorter accumulation seasons and earlier peak SWE dates. However, the melt season length does not correspond to a particular accumulation season length, peak SWE date or amount. For example, Beaver Dams, UT had shorter melt seasons during 1984 and 2007 while 1983 and 1995 were longer (Figure 10). The pattern of shorter and longer melt seasons associated with similar peak dates is apparent in all regions (Figure 9), which suggests that the lengths of the melt seasons are dependent on something other than SWE. Earlier peak SWE dates associated with lower peak SWE amounts and shorter accumulation seasons holds when considering an

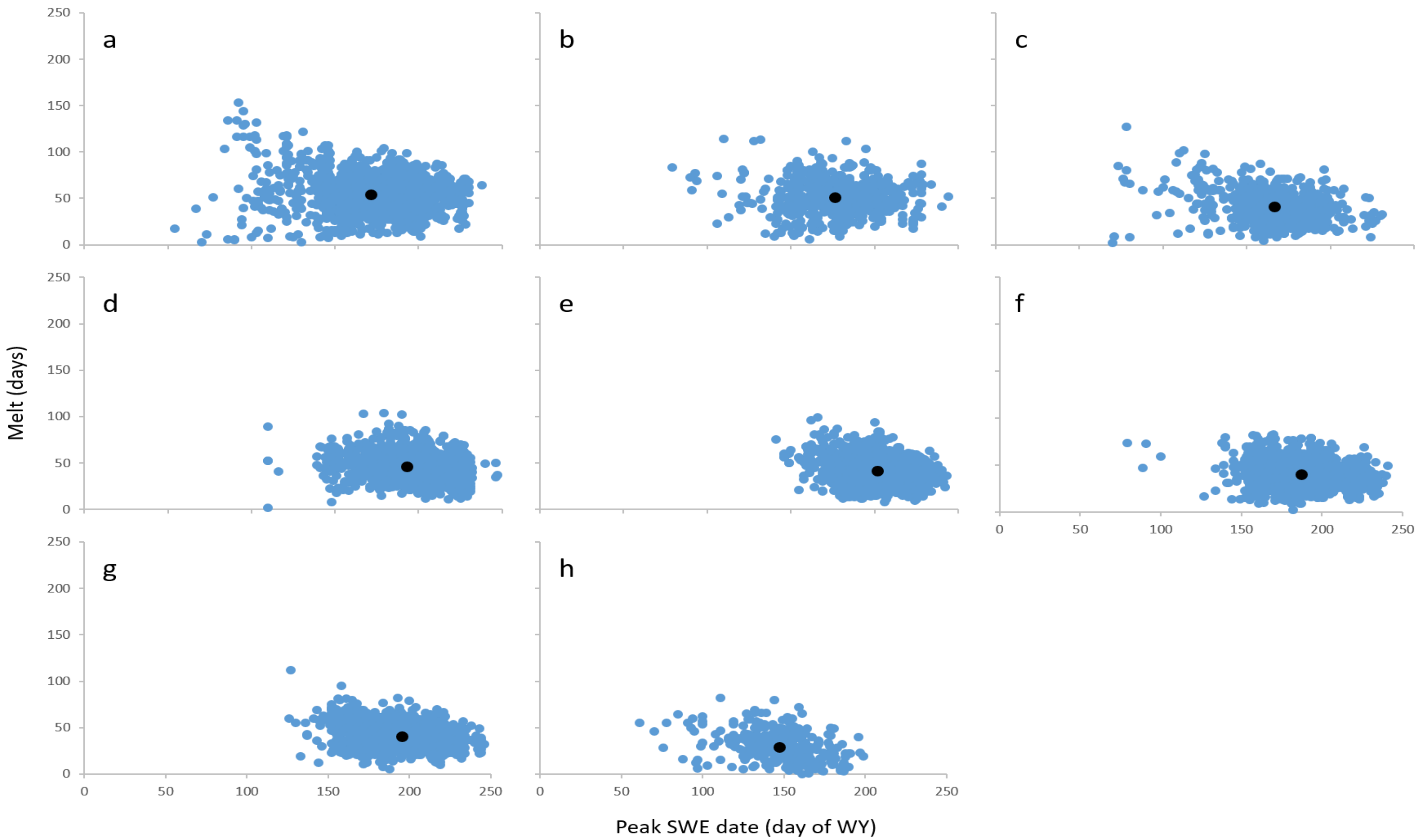

Figure 9. Comparison of peak SWE date vs. length of melt season by region: (a) Cascades, (b) Sierra Nevada, (c) Blue Mountains, (d) Northern Rockies, (e) Middle Rockies, (f) Utah, (g) Southern Rockies, (h) Arizona/New Mexico. Black dot indicates position of the regional average values.

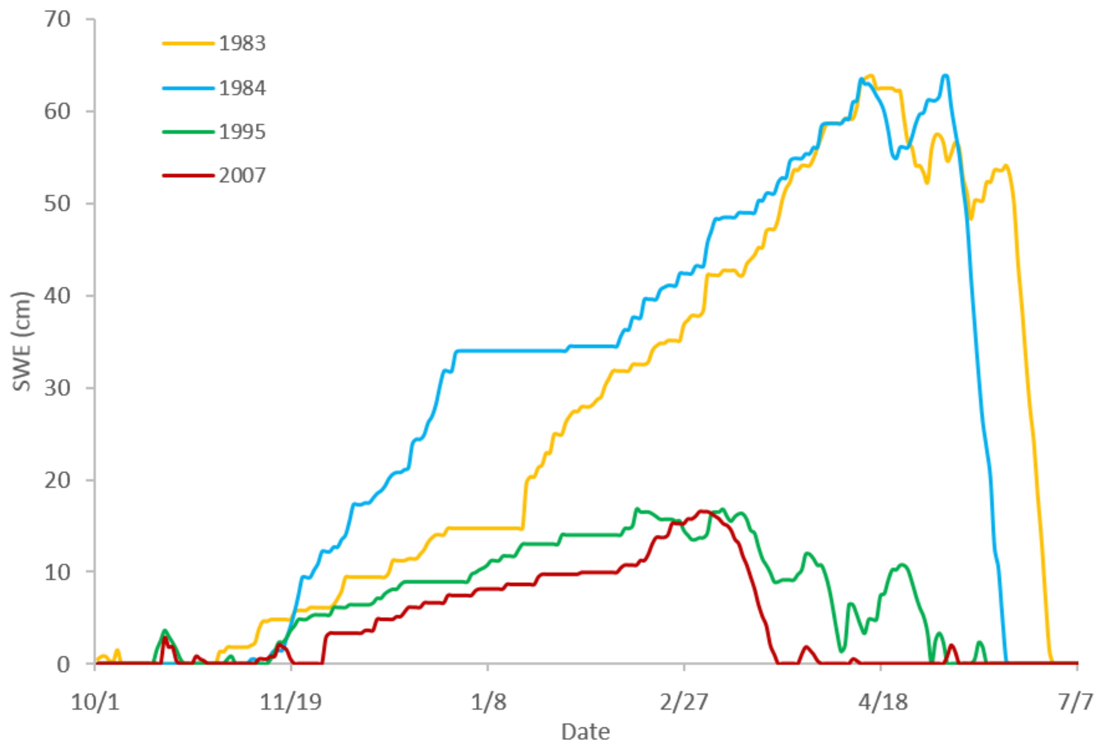

Figure 10. Cumulative SWE curves of four years for Beaver Dams, UT (station number 329).

individual station or a whole region, however, the characterization of early SWE peaks always equaling shorter melt seasons does not appear to be true.

4.2 Temperature

Temperature is one of the main factors that influences snowpacks. In particular, increased spring temperatures are indicated as a key factor for earlier onsets and shorter durations of the snowmelt seasons (Clow 2009; Harpold et al. 2012). Monthly average minimum temperatures reflect an increase in temperature; for seven of the twelve months of the year, more than half of all of the stations have positive r-values associated with monthly average minimum temperature (Table 4a). Negative r-values are less prevalent than positive r-values and are predominantly related to the monthly average maximum temperatures (Table 4b). Thus it appears as though the average minimum temperatures have increased more than the average maximum temperatures, leading to a reduction in the diurnal temperature range similar to the results of Favre and Gershunov (2006). However, in the present study, widespread increases in minimum temperature do not coincide with peak SWE or the beginning of the melt season. Instead, the months with the greatest percentages of stations indicating increases in minimum temperatures are May through December. In contrast, the increases in minimum temperatures in January through April are not as pronounced and are isolated to regions that typically have later peak SWE dates, such as the Southern Rockies (Table 4a). The absence of temperature changes does not mean that temperatures are not increasing. Instead, a temperature change over time could not be pronounced enough to rule out normal climate variability. The standard deviation for both maximum and minimum temperatures are from 1.5°C to 3.0°C, depending on the region and the time of year (Table 5), so an increase of 0.5°C over the time frame of the study may not register. A half-degree increase could make all the difference in the Cascades, Sierra Nevada, and Arizona/New Mexico regions, where the average minimum temperatures are already close to freezing during the winter. However, the stations in these three regions do not indicate significant shifts towards earlier peak SWE dates (Table 3b). Furthermore, the Arizona/New Mexico region is the only region indicating shifts towards lower peak SWE amounts and shorter melt seasons. The regions that do indicate substantial shifts toward earlier peak SWE dates are the regions that have average minimum

Table 4. Percentage of stations within each region with positive or negative r-values that are statistically significant at the 90% level for maximum (X) and minimum (N) temperature. The number stations within each region meeting the significance level are given within the parentheses.

a. Positive Temperature r-value percent (frequencies).

	Oct		Nov		Dec		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep	
Region	X	N	X	N	X	N	X	N	X	N	X	N	X	N	X	N	X	N	X	N	X	N	X	N
Cascades	2	22	17	17	11	52	2	4	4	9	2	11	2	2	2	15	9	24	54	70	15	26	0	9
	(1)	(10)	(8)	(8)	(5)	(24)	(1)	(2)	(2)	(4)	(1)	(5)	(1)	(1)	(1)	(7)	(4)	(11)	(25)	(32)	(7)	(12)	(0)	(4)
Sierra	0	14	10	71	19	76	0	5	10	10	14	10	5	10	24	62	48	76	52	100	33	71	24	33
	(0)	(3)	(2)	(15)	(4)	(16)	(0)	(1)	(2)	(2)	(3)	(2)	(1)	(2)	(5)	(13)	(10)	(16)	(11)	(21)	(7)	(15)	(5)	(7)
Blue	0	17	26	0	17	57	0	4	0	0	0	4	0	0	4	13	17	22	74	91	9	35	0	4
Mtns	(0)	(4)	(6)	(0)	(4)	(13)	(0)	(1)	(0)	(0)	(0)	(1)	(0)	(0)	(1)	(3)	(4)	(5)	(17)	(21)	(2)	(8)	(0)	(1)
N Rockies	28	67	79	44	87	87	56	21	26	36	10	31	18	18	8	74	3	90	90	97	15	67	10	59
	(11)	(26)	(31)	(17)	(34)	(34)	(22)	(8)	(10)	(14)	(4)	(12)	(7)	(7)	(3)	(29)	(1)	(35)	(35)	(38)	(6)	(26)	(4)	(23)
M	27	78	86	75	78	94	43	33	18	20	18	18	27	43	12	76	6	80	76	98	12	27	10	53
Rockies	(14)	(40)	(44)	(38)	(40)	(48)	(22)	(17)	(9)	(10)	(9)	(9)	(14)	(22)	(6)	(39)	(3)	(41)	(39)	(50)	(6)	(14)	(5)	(27)
Utah	4	51	16	58	19	74	11	28	5	16	9	11	5	14	16	51	5	67	37	91	9	75	5	33
	(2)	(29)	(9)	(33)	(11)	(42)	(6)	(16)	(3)	(9)	(5)	(6)	(3)	(8)	(9)	(29)	(3)	(38)	(21)	(52)	(5)	(43)	(3)	(19)
S Rockies	11	72	61	72	35	84	40	70	19	14	23	44	25	47	40	54	25	47	67	98	25	88	16	75
	(6)	(41)	(35)	(41)	(20)	(48)	(23)	(40)	(11)	(8)	(13)	(25)	(14)	(27)	(23)	(31)	(14)	(27)	(38)	(56)	(14)	(50)	(9)	(43)
AZ/NM	0	38	38	69	15	38	8	62	0	31	0	54	0	23	8	54	8	46	0	62	0	54	0	69
	(0)	(5)	(5)	(9)	(2)	(5)	(1)	(8)	(0)	(4)	(0)	(7)	(0)	(3)	(1)	(7)	(1)	(6)	(0)	(8)	(0)	(7)	(0)	(9)

b. Negative Temperature r-value percent (frequencies).

	Oct		Nov		Dec		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep	
Region	X	N	X	N	X	N	X	N	X	N	X	N	X	N	X	N	X	N	X	N	X	N	X	N
Cascades	15	7	0	0	2	0	4	2	7	0	9	2	11	20	0	2	4	2	0	0	4	0	30	7
	(7)	(3)	(0)	(0)	(1)	(0)	(2)	(1)	(3)	(0)	(4)	(1)	(5)	(9)	(0)	(1)	(2)	(1)	(0)	(0)	(2)	(0)	(14)	(3)
Sierra	10	0	0	0	5	0	14	0	5	0	0	0	19	0	0	0	0	0	0	0	5	0	14	0
	(2)	(0)	(0)	(0)	(1)	(0)	(3)	(0)	(1)	(0)	(0)	(0)	(4)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(1)	(0)	(3)	(0)
Blue Mtns	0	0	0	0	0	0	0	0	0	0	0	0	4	9	0	0	0	0	0	0	0	0	22	0
	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(1)	(2)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(5)	(0)
N Rockies	0	0	0	0	0	0	0	0	0	0	3	0	5	0	3	0	8	0	0	0	3	0	10	0
	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(1)	(0)	(2)	(0)	(1)	(0)	(3)	(0)	(0)	(0)	(1)	(0)	(4)	(0)
M Rockies	0	0	0	0	0	0	0	0	0	0	4	0	6	0	2	0	2	0	0	0	0	0	2	0
	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(2)	(0)	(3)	(0)	(1)	(0)	(1)	(0)	(0)	(0)	(0)	(0)	(1)	(0)
Utah	9	0	0	0	2	0	4	0	11	2	7	0	14	0	0	0	0	2	0	0	12	0	28	0
	(5)	(0)	(0)	(0)	(1)	(0)	(2)	(0)	(6)	(1)	(4)	(0)	(8)	(0)	(0)	(0)	(0)	(1)	(0)	(0)	(7)	(0)	(16)	(0)
S Rockies	5	0	0	0	4	2	2	2	7	0	2	2	4	0	2	0	0	0	0	0	4	0	0	0
	(3)	(0)	(0)	(0)	(2)	(1)	(1)	(1)	(4)	(0)	(1)	(1)	(2)	(0)	(1)	(0)	(0)	(0)	(0)	(0)	(2)	(0)	(0)	(0)
AZ/NM	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	15	0	31	8	8	0
	(1)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(1)	(0)	(2)	(0)	(4)	(1)	(1)	(0)

Table 5. Monthly average maximum and minimum temperatures (°C), standard deviations given within the parentheses.

	Oct		Nov		Dec		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep	
Region	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Cascades	11.7 (2.1)	1.1 (1.4)	4.7 (2.2)	-2.5 (2.1)	1.8 (2.1)	-4.8 (2.0)	2.2 (1.8)	-4.8 (1.8)	3.9 (2.4)	-4.6 (2.1)	6.4 (2.1)	-3.5 (1.7)	9.0 (2.0)	-1.8 (1.4)	13.1 (2.7)	1.3 (1.6)	17.2 (2.1)	4.1 (1.4)	22.7 (2.5)	7.8 (1.8)	22.5 (2.0)	7.7 (1.5)	19.1 (2.2)	5.4 (1.4)
Sierra	13.3 (2.5)	-0.2 (1.7)	7.1 (2.6)	-4.4 (2.2)	3.5 (2.1)	-7.3 (2.2)	3.7 (2.3)	-7.4 (2.2)	4.3 (2.7)	-7.4 (2.2)	7.1 (3.1)	-5.8 (2.2)	9.0 (2.3)	-4.0 (1.9)	13.5 (2.7)	-0.1 (1.9)	18.4 (2.3)	3.6 (1.9)	23.1 (1.9)	7.5 (2.0)	22.7 (1.7)	7.2 (1.6)	19.1 (1.8)	4.1 (1.2)
Blue Mtns	11.4 (1.7)	0.2 (1.3)	3.8 (2.2)	-4.1 (2.1)	0.4 (2.0)	-7.1 (2.2)	0.9 (1.5)	-6.9 (1.8)	3.2 (2.0)	-6.5 (2.3)	6.5 (1.8)	-4.5 (1.6)	9.2 (1.9)	-2.3 (1.5)	13.7 (2.3)	1.4 (1.5)	17.9 (1.8)	4.2 (1.3)	24.2 (2.6)	8.4 (1.9)	23.9 (1.8)	8.1 (1.3)	19.4 (1.9)	5.1 (1.5)
N Rockies	8.1 (2.1)	-2.2 (1.8)	0.9 (2.5)	-7.0 (2.9)	-2.5 (2.4)	-10.3 (2.9)	-1.9 (2.1)	-10.0 (2.8)	0.2 (2.4)	-10.0 (3.0)	3.9 (2.2)	-7.4 (2.3)	7.7 (1.8)	-4.2 (1.7)	12.4 (2.2)	-0.3 (1.4)	16.4 (2.2)	3.1 (1.5)	22.1 (3.0)	6.6 (2.1)	21.4 (2.3)	6.0 (1.6)	15.8 (2.4)	2.3 (1.6)
M Rockies	7.3 (2.1)	-3.6 (1.9)	0.0 (2.7)	-9.3 (3.0)	-3.7 (2.3)	-12.7 (2.6)	-3.3 (2.1)	-12.6 (2.5)	-1.4 (2.2)	-12.3 (2.5)	2.7 (2.1)	-9.5 (2.2)	6.5 (2.0)	-6.1 (2.0)	11.3 (2.0)	-1.5 (1.4)	15.9 (2.3)	2.3 (1.5)	21.3 (2.8)	6.1 (2.2)	20.6 (2.0)	5.6 (1.6)	14.7 (2.0)	1.5 (1.7)
Utah	10.7 (2.2)	-1.9 (1.7)	3.9 (2.7)	-7.8 (2.8)	0.0 (2.0)	-11.4 (2.2)	0.4 (2.1)	-11.2 (2.3)	1.9 (2.3)	-10.7 (2.2)	5.6 (2.4)	-8.0 (2.3)	8.7 (2.1)	-4.7 (2.1)	13.6 (2.1)	-0.1 (1.7)	18.8 (2.4)	4.0 (1.8)	23.3 (2.0)	8.1 (1.9)	22.1 (1.6)	7.4 (1.4)	17.2 (1.8)	3.1 (1.5)
S Rockies	9.3 (2.4)	-3.7 (1.8)	2.3 (2.9)	-9.7 (2.6)	-1.7 (1.9)	-13.7 (1.9)	-1.6 (2.0)	-13.8 (2.1)	0.2 (1.9)	-12.8 (2.0)	4.1 (2.2)	-10.1 (2.0)	7.8 (2.1)	-6.4 (1.9)	12.7 (1.9)	-1.9 (1.4)	17.9 (2.2)	2.2 (1.5)	21.0 (2.2)	5.4 (1.7)	19.5 (1.8)	4.9 (1.5)	15.4 (2.1)	1.1 (1.7)
AZ/NM	16.4 (2.5)	1.8 (1.9)	10.6 (2.5)	-3.0 (2.4)	6.5 (1.9)	-6.5 (1.9)	6.7 (2.2)	-6.5 (1.9)	8.1 (2.1)	-5.5 (2.1)	11.0 (2.1)	-3.6 (1.8)	14.5 (2.3)	-0.8 (1.9)	19.7 (2.4)	3.3 (1.7)	24.9 (2.6)	7.6 (2.2)	25.9 (2.4)	10.3 (1.7)	24.3 (2.3)	9.7 (1.6)	21.7 (2.2)	7.0 (1.6)

temperatures between -5°C and -10°C around the date of peak SWE (Table 5). It is unlikely that an increase in temperature is the sole reason for an earlier or lower SWE peak.

The initiation of snowmelt is related to the sun angle and the availability of energy to melt large snowpacks. The presence of a deep snowpack affects the surface energy balance, resulting in net radiational cooling at the surface. An earlier peak date around mid-February would likely correspond to a lower peak SWE amount (and thus less snow to melt) than a later peak date in early April, however, the sun angle would also be lower at the earlier peak. There would be less energy available to melt the snowpack, resulting in a longer snowmelt season than if the peak date was later. Once the snowpack has melted, the energy available goes into latent and sensible heating of the surface, hence the coherent signal of increasing temperatures in every region during the summer. However, temperature can still play a role in the length of the snowmelt season. Stations in the Cascades and Sierra Nevada regions are more likely to experience temperatures near or above freezing during the winter, thus they are more prone to rain-on-snow events and shifts from large snow events to large rain events (Knowles et al. 2006), which accelerate snowmelt over a short period of time. Nonetheless, snowpack conditions varied considerably from year to year, so there are few overall changes in peak SWE amounts at the coastal stations.

The change in minimum temperature has likely had a greater impact on snowpack accumulation instead of snowmelt. At Beaver Dams, UT (Figure 10), one or more accumulation and melt events sometimes occur before the winter snowpack is formed. The snow from these events does not contribute to peak SWE. The average minimum temperatures in October and November are below freezing in the Utah region (Table 5), however, the average maximum temperatures are above freezing, which could result in more melting during the day. An increase in temperature could also result in increased sublimation losses even for temperatures below freezing (Harpold et al. 2012). In either case, snowpack initiation could be delayed by days or weeks, ultimately resulting in a shorter accumulation season and lower peak SWE amounts. However, temperature variations alone did not account for all of the changes shown by the snowpack indicators, such as the differences in peak SWE amounts for the Blue Mountains or the Middle Rockies, as well as the lack of stations indicating shifts toward shorter melt seasons.

4.3 Precipitation

One difficulty of using SNOTEL data is that the years when many stations were installed happened to also be anomalously wet years, resulting in higher than average peak SWE amounts (Bedford and Douglass 2008; Harpold et al. 2012). Thus it comes as no surprise that there are more negative r-values associated with monthly, winter, and yearly precipitation (Table 6b) than positive r-values (Table 6a). The regions that indicate shifts toward lower peak SWE amounts at many stations (Table 3b) also indicate shifts toward decreasing winter and total precipitation (Table 6b). However, the percentage of stations indicating decreasing monthly precipitation is not equal for all months. Larger percentages of stations indicate decreasing monthly precipitation in November and March, which is around the time of the first snowfall and peak SWE in most regions (Table 2). Highly variable conditions, or few noticeable changes, are present from December through February as well as April and May.

Table 6. Percentage of stations within each region with positive or negative r-values that are statistically significant at the 90% level for precipitation. The number of stations within each region meeting the significance level are given within the parentheses.

a. Positive Precipitation r-value percent (frequencies).

Region	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Winter	Total
Cascades	0 (0)	0 (0)	4 (2)	7 (3)	0 (0)	0 (0)	0 (0)	7 (3)	0 (0)	0 (0)	2 (1)	0 (0)	0 (0)	0 (0)
Sierra	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Blue Mtns	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	9 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
N Rockies	0 (0)	0 (0)	3 (1)	3 (1)	0 (0)	0 (0)	3 (1)	0 (0)	23 (9)	0 (0)	0 (0)	0 (0)	3 (1)	0 (0)
M Rockies	2 (1)	0 (0)	0 (0)	8 (4)	6 (3)	0 (0)	2 (1)	0 (0)	4 (2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Utah	0 (0)	0 (0)	0 (0)	7 (4)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
S Rockies	0 (0)	0 (0)	0 (0)	5 (3)	4 (2)	0 (0)	0 (0)	0 (0)	0 (0)	2 (1)	5 (3)	7 (4)	0 (0)	0 (0)
AZ/NM	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

b. Negative Precipitation r-value percent (frequencies).

Region	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Winter	Total
Cascades	0 (0)	4 (2)	2 (1)	0 (0)	13 (6)	17 (8)	2 (1)	2 (1)	22 (10)	70 (32)	11 (5)	30 (14)	2 (1)	2 (1)
Sierra	48 (10)	100 (21)	0 (0)	0 (0)	0 (0)	29 (6)	0 (0)	0 (0)	48 (10)	33 (7)	10 (2)	95 (20)	5 (1)	10 (2)
Blue Mtns	0 (0)	30 (7)	0 (0)	0 (0)	35 (8)	43 (10)	0 (0)	0 (0)	22 (5)	57 (13)	26 (6)	35 (8)	22 (5)	48 (11)
N Rockies	0 (0)	3 (1)	3 (1)	0 (0)	3 (8)	18 (7)	5 (2)	3 (1)	0 (0)	46 (18)	13 (5)	8 (3)	3 (1)	0 (0)
M Rockies	0 (0)	41 (21)	6 (3)	4 (2)	2 (1)	22 (11)	10 (5)	0 (0)	10 (5)	57 (29)	4 (2)	45 (23)	18 (9)	18 (9)
Utah	2 (1)	75 (43)	0 (0)	0 (0)	0 (0)	72 (41)	9 (5)	16 (9)	2 (1)	39 (22)	9 (5)	19 (11)	28 (16)	44 (25)
S Rockies	0 (0)	40 (23)	0 (0)	0 (0)	2 (1)	53 (30)	2 (1)	12 (7)	37 (21)	32 (18)	2 (1)	0 (0)	21 (12)	26 (15)
AZ/NM	0 (0)	69 (9)	8 (1)	0 (0)	8 (1)	38 (5)	0 (0)	0 (0)	15 (2)	8 (1)	0 (0)	23 (3)	23 (3)	69 (9)

There are a few relationships that do not fit, such as how all of the stations in the Sierra Nevada region indicate patterns of decreasing precipitation for November despite showing no changes in peak SWE amounts (Table 3). Also, the Blue Mountain and Utah regions indicate similar proportions of stations indicating lower peak SWE amounts, yet a greater proportion of stations in the Utah region indicate decreasing precipitation in November and March than in the Blue Mountains (Table 6b). Since the timing and duration of the accumulation and melt seasons differs among regions (Table 2), a decrease in precipitation during one specific month would likely have a different impact on peak SWE timing and amount for different regions.

For Beaver Dams, UT, the timing of winter precipitation has a noticeable impact. Except for 2007, a continuous snowpack began to accumulate at the beginning of each November (Figure 10). More precipitation fell during November in 1984 than for the other three years (Figure 11) which results in a steeper accumulation SWE curve (Figure 10). Individually, precipitation totals for December, January, and February vary by year, as did the timing of peak precipitation, which occurred as early as October in 2007 and as late as March/April for 1983 and 1995 (Figure 11). Grouping the monthly precipitation totals into three-month sets (Figure 12) demonstrates the differences in SWE accumulations and melt season lengths. In regions with typical SWE peaks in March and April, such as the Utah region where Beaver Dams is located in, DJF precipitation contributes to snowpack accumulations and the peak SWE amounts while precipitation from March to May (MAM) either contributes to peak SWE amounts or offsets losses due to snowmelt. The years with lower peak SWE (1995 and 2007) received less precipitation in DJF and had earlier/lower SWE peaks. The difference between the two years is that in 1995, precipitation in MAM is similar to the years with higher peak SWE

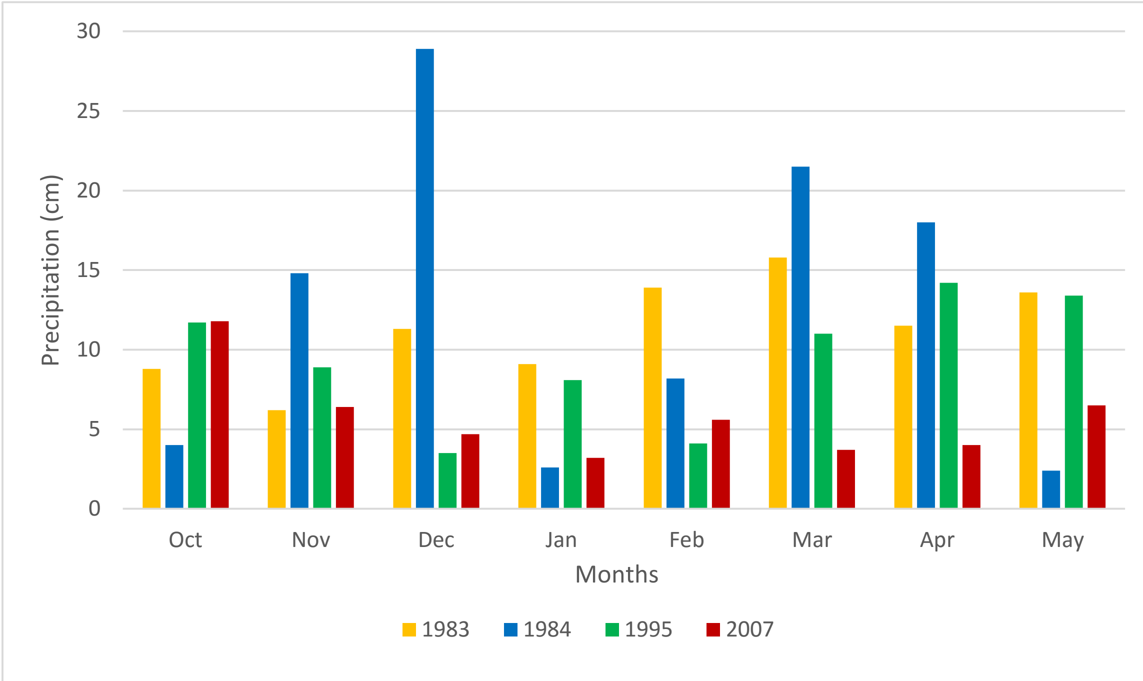

Figure 11. Monthly precipitation totals for Beaver Dams, UT for select years.

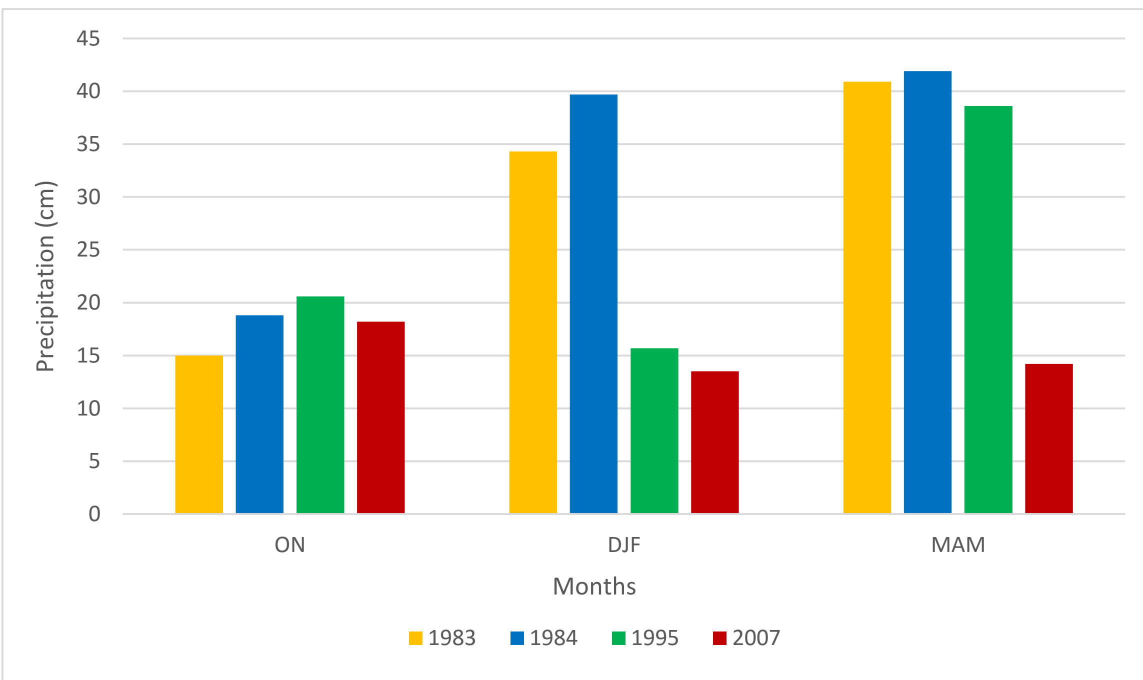

Figure 12. Grouped monthly precipitation totals for Beaver Dams, UT for select years.

amounts. Thus the additional precipitation (in the form of snow) somewhat offset SWE losses from snowmelt, allowing the snowpack to persist and results in a longer snowmelt season. In this case, the timing and amount of precipitation are key factors in determining peak SWE amount and date and the length of the melt season.

The general pattern of snowfall events throughout the snow season is likely the deciding factor in why certain regions show shifts toward lower peak SWE amounts, and indicate earlier peak SWE dates and shorter accumulation seasons while others do not, as well as why some regions indicate no changes in peak SWE amount and date. The growth and decline of a snowpack depends on its sources and sinks: precipitation in the form of snow increases SWE, while sublimation and the drainage of meltwater decreases SWE. During the accumulation season there is a net gain in SWE, then during the melt season there is a net loss. The timing of peak SWE is then related to the seasonal precipitation pattern and the availability of energy at the surface.

For most of the western United States, more of the yearly precipitation falls during the winter in the form of snow than as rain during the summer. The timing of the winter peak in precipitation varies: regions farther to the west (Cascades, Sierra Nevada, Blue Mountains) have their peak earlier in the snow season around DJF, while regions farther east (Middle and Southern Rockies) have peaks in MAM (Figure 13). There is a lag between the peak in precipitation and the peak in SWE (Table 2) as the balance of mass input versus energy input shifts. A decrease in precipitation around the time of peak SWE would likely shift peak SWE to an earlier date, as some of the stations in the Utah and Southern Rockies regions indicate (Table 3b). Any subsequent precipitation would either offset snowmelt losses or hasten the rate

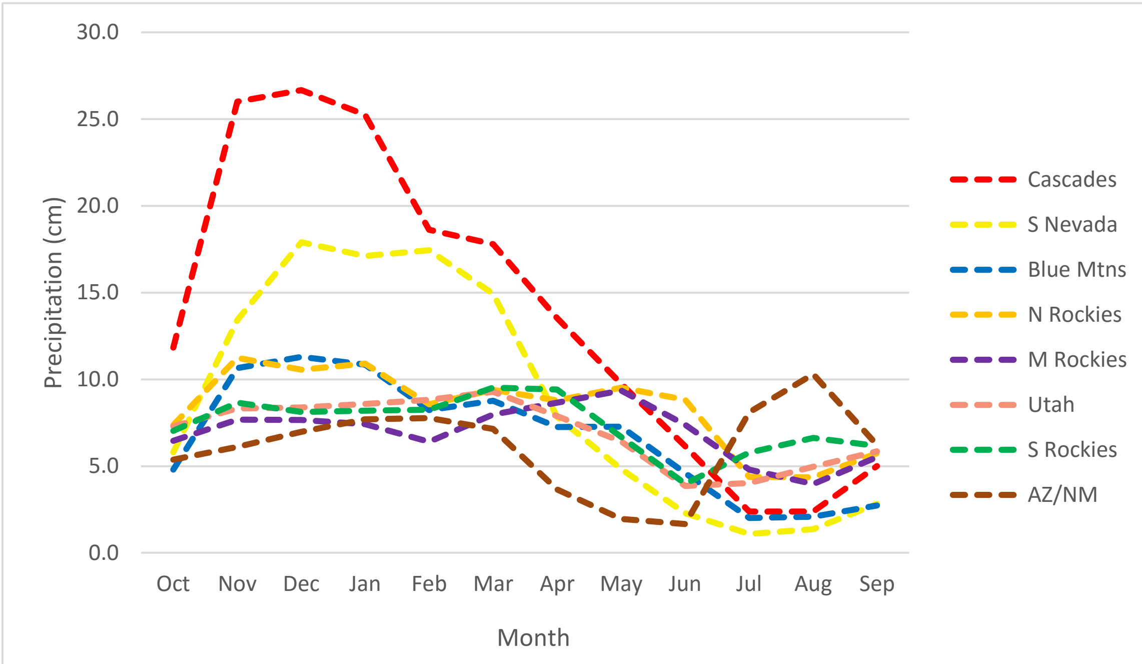

Figure 13. Regional monthly average precipitation curves.

of snowmelt, depending on the type of precipitation. As for the beginning of the snow season, changes in temperature and precipitation can either reinforce or cancel out possible impacts. For example, all of the stations in the Sierra Nevada region indicate a shift towards less precipitation in November (Table 6b). However, monthly precipitation totals for this region vary significantly in comparison to other regions (Table 7), as much of the precipitation falls during heavy snowfall events. With average temperatures close to freezing, some of the heavy precipitation events could be in the form of rain. Thus, less precipitation during November would likely not impact the peak SWE amount at a location already prone to extreme snowfall and melt events, at least not on the time scale of this study.

Taking into consideration variations in the snowpack indicators, temperature, and precipitation, some of the regions can be grouped together by similar environments. Few

Table 7. Monthly, winter, and yearly average precipitation (cm). Standard deviations given within the parentheses.

Region	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Winter	Total
Cascades	11.8 (7.3)	26.0 (12.7)	26.7 (13.5)	25.3 (11.4)	18.6 (9.7)	17.8 (7.8)	13.5 (5.2)	9.7 (5.0)	6.2 (3.5)	2.4 (2.6)	2.4 (2.7)	5.0 (4.4)	114.4 (30.9)	165.4 (36.1)
Sierra	5.8 (4.8)	13.4 (10.7)	17.9 (14.3)	17.1 (12.8)	17.4 (12.4)	14.9 (11.9)	7.9 (5.6)	4.8 (4.0)	2.3 (2.2)	1.1 (1.3)	1.4 (1.8)	2.8 (3.5)	80.8 (31.8)	106.8 (39.0)
Blue Mtns	4.8 (2.8)	10.6 (4.9)	11.3 (5.5)	10.8 (4.7)	8.2 (4.1)	8.8 (3.6)	7.3 (2.9)	7.3 (3.8)	4.6 (2.6)	2.0 (2.1)	2.1 (2.2)	2.7 (2.3)	49.8 (12.7)	80.5 (17.0)
N Rockies	7.4 (3.9)	11.2 (5.3)	10.6 (4.7)	10.9 (4.5)	8.6 (4.1)	9.4 (4.0)	8.8 (3.1)	9.5 (3.8)	8.8 (4.1)	4.4 (3.5)	4.4 (3.2)	5.7 (3.6)	50.7 (12.4)	99.6 (7.3)
M Rockies	6.5 (3.4)	7.7 (3.5)	7.7 (4.2)	7.4 (3.6)	6.4 (3.5)	8.0 (3.5)	8.7 (3.5)	9.4 (3.9)	7.4 (3.6)	4.8 (3.3)	4.0 (2.5)	5.5 (3.2)	37.1 (9.6)	83.3 (16.3)
Utah	7.3 (4.5)	8.3 (4.3)	8.4 (5.1)	8.6 (5.2)	8.8 (5.2)	9.3 (4.5)	7.9 (3.3)	6.4 (3.3)	3.8 (2.8)	4.0 (2.7)	5.0 (2.8)	5.9 (4.1)	43.4 (11.9)	83.7 (19.9)
S Rockies	7.0 (3.7)	8.7 (3.9)	8.1 (4.6)	8.2 (4.2)	8.3 (4.2)	9.5 (3.6)	9.4 (3.8)	6.7 (3.8)	4.0 (2.6)	5.8 (3.2)	6.6 (3.1)	6.2 (3.3)	42.8 (9.1)	88.4 (15.8)
AZ/NM	5.4 (4.4)	6.1 (4.6)	7.0 (5.8)	7.7 (6.8)	7.8 (6.8)	7.1 (5.1)	3.7 (2.8)	2.0 (2.8)	1.7 (1.7)	8.1 (4.7)	10.3 (4.5)	6.2 (4.4)	35.7 (17.5)	73.0 (21.0)

stations in the Cascade and Sierra Nevada regions indicate significant changes in peak SWE (Table 3), though it is likely high variability in temperature and precipitation patterns inherent to those regions that may mask any signal. There are also few stations in the Northern Rockies that indicate changes in peak SWE amounts, though this is likely attributed to low variability in precipitation and subfreezing temperatures despite temperatures increasing over time. Patterns pointing toward decreasing winter precipitation (Table 6b), particularly in November and March, are likely the reason for lower peak SWE in the Blue Mountains as well as the Middle and Southern Rockies. However, changes in number of days with snowcover are not as noticeable as changes in peak SWE amount (Table 3b), so while the snowpacks may have less mass and water equivalence, the snowcover is still continuous throughout the snow season. A few degrees in temperature is one reason for the difference: average maximum and minimum temperatures are 1°C to 3°C higher in the Utah region compared to the Middle and Southern Rockies regions (Table 5). All three regions indicate peak SWE is decreasing over time (Table 3b) and average minimum temperatures are increasing at the beginning of the water year (Table 4a), however, only stations in the Utah region indicate shorter accumulation seasons (Table 3b). Thus stations in Utah are likely shifting towards patchy snowcover, particularly at the beginning of the snow season, as a result of both decreasing precipitation and increasing temperatures. Both precipitation and temperature are also factors in lower peak SWE and shorter melt seasons for the stations in the Arizona/New Mexico region. So while increasing minimum temperatures are a factor in lower peak SWE, the timing and the direction of precipitation changes in relation to snowpack accumulation and melting patterns are also crucial. This reinforces the importance of relating patterns in cyclone activity with SWE.

4.4 Cyclone Activity Statistics

In the previous sections, correlations between changes in the snowpack indicators, particularly the amounts and timings of peak SWE, and monthly precipitation totals were identified. The next step is to relate these changes with cyclone activity, thus possibly establishing a relationship between winter snowpacks and cyclone activity. Overall, there are shifts towards decreasing cyclone frequency and increasing average latitude from October to March (Table 8), which is consistent with the results of previous studies (e.g. McCabe et al. 2001; Favre and Gershunov 2006). That translates to about eight fewer cyclones in October and cyclone tracks shifted two degrees latitude north (Table 9). Using different areas (Figure 3), several area analyses were conducted to identify which patterns may be the result of the size of the analysis area. The r-values for the number of cyclones for October, November, and February and the average latitude for October are statistically significant or close to significant for all of the area analyses (Table 8), which indicates that these relationships could possibly be independent of the size of the analysis area. The relationships also correspond to similar parts of the snow season with negative r-values, which indicate a decreasing precipitation (Table 6b) at the beginning of the snow season and close to the date of peak SWE (for some regions). For instance, the shift toward decreasing cyclone frequency in November (Table 8) could account for the shifts toward decreasing precipitation for the Sierra Nevada, Utah, Southern Rockies, and Arizona/New Mexico regions (Table 6b).

Some of the changes in cyclone activity that do not correspond to the precipitation results of this study or the results of previous studies. In response to increasing temperatures, evaporation rates would increase and the more available moisture could result in more intense

Table 8. R-values for the number of cyclone, the average pressure, and the average latitude for each month. Analyzes correspond to the areal boundaries given in Figure 3. Values in dark gray are significant at the 95% level and light gray at the 90% level.

	Number			Average Pressure			Average Latitude		
	1	2	3	1	2	3	1	2	3
Oct	-0.41	-0.39	-0.37	0.26	-0.04	0.14	0.47	0.55	0.45
Nov	-0.27	-0.29	-0.34	0.1	0.08	0.12	0.07	0.06	0.22
Dec	-0.24	-0.15	-0.17	0.3	0.28	0.51	0.09	0.25	0.15
Jan	-0.13	-0.15	-0.25	0.42	0.35	0.06	0.16	0.07	0.11
Feb	-0.4	-0.36	-0.31	-0.15	-0.19	-0.21	0.14	0.19	0.25
Mar	-0.26	-0.2	-0.13	-0.16	-0.33	-0.16	0.09	0.23	0.44
Apr	0.16	0.16	0.14	0.09	0.2	0.15	0.52	0.34	0.24
May	0.08	-0.01	0.28	0.43	0.3	0.15	0.17	0.03	-0.08
Jun	-0.26	-0.34	-0.34	0.09	0.02	-0.04	0.03	-0.03	-0.38
Jul	-0.21	-0.22	-0.09	0.19	0.23	0.15	0.34	0.28	-0.03
Aug	0	-0.07	-0.08	0.4	0.48	0.5	0.08	0	-0.08
Sep	0.17	0.18	-0.21	-0.04	0.12	0.05	-0.01	-0.2	0.31

Table 9. Average number of cyclones, average central pressure (hPa), and average latitude for each month, standard deviations given within the parentheses. Values from first areal analysis (black box in Figure 3).

	Number	Pressure	Latitude
Oct	20 (5.8)	1013.6 (2.2)	39.8 (1.2)
Nov	21 (6.0)	1013.7 (1.5)	39.6 (0.9)
Dec	20 (5.0)	1013.7 (2.4)	38.8 (1.5)
Jan	23 (5.3)	1013.3 (1.7)	37.9 (1.4)
Feb	25 (4.3)	1010.6 (2.5)	37.7 (1.5)
Mar	30 (5.5)	1008.8 (1.9)	38.0 (1.1)
Apr	24 (5.5)	1007.3 (1.6)	39.1 (1.1)
May	19 (5.1)	1005.5 (2.0)	40.2 (1.8)
Jun	21 (3.5)	1002.6 (2.0)	41.1 (1.8)
Jul	23 (6.0)	1000.5 (2.1)	39.2 (2.5)
Aug	24 (6.2)	1002.6 (1.7)	39.5 (1.8)
Sep	19 (5.5)	1007.6 (1.9)	39.3 (1.2)

storms. The central pressure of a low is often used as an indicator of intensity, so the average central pressure of the low should decrease. However, the average central pressure of cyclones for October through January appear to be increasing (Table 8), which would suggest that the storms are becoming less intense over time instead of more intense. Furthermore, the winter months with statistically significant positive r-values (December and January), do not indicate corresponding changes in precipitation (Table 6). Though the cyclone activity and monthly precipitation changes correspond to similar time frames during the snow season, significant shifts do not correspond to the exact same months. For example, significant r-values indicate less frequent cyclones and more northerly cyclone tracks for October (Table 8), yet the only region indicating a change in precipitation for October is the Sierra Nevada region (Table 6b). Also, it is likely that any change in precipitation in October would not be very large in comparison to winter months, since October is considered part of the dry season in the Sierra Nevada region. Similarly, the Blue Mountains region is the only region with a larger fraction of stations indicating shifts towards less precipitation in February, another month indicating less frequent winter storms (Table 8). The results of all three area analyses together indicate that the significance, and in a few cases the sign, of some relationships, are dependent on the area of interest. For example, the statistical significance of the cyclone activity changes in March vary considerably between the area analyses (Table 8), so the changes for this month are likely an artifact of the size of the analysis area. While the cyclone activity pattern are overall consistent with the results of this and previous studies, there are precipitation patterns at stations in some regions for which the cyclone activity patterns do not account.

4.5 Discussion

Many possible reasons can explain in part or in whole why the patterns of cyclone activity, precipitation, and SWE do not match up as was hypothesized. One of the main reasons is that the length of time covered by this study is relatively short for discerning patterns related to climate change. The normal NWS climate averaging period is 30 years, during which it is assumed that the climate system is in a state of quasi-equilibrium. For example, yearly precipitation totals averaged over 30 years describe the general climate of an area. Fluctuations between wet and dry years over a decade may be the result of interannual events like El Niño, though these distinctions are attributed to climate variability. A change in precipitation patterns over a much longer period would reflect a shift in the local climate, or climate change. The data collected for this study covers a span of 27 years, which is slightly shorter than the climate averaging period. If conditions vary considerably on an interannual basis, then smaller changes on longer time scales may not be discernable.

Peak SWE amounts vary considerably among stations in the Cascades region, sometimes upwards of 30 cm from the regional average for just one year (Figure 14a). A decrease in peak SWE of 5 or 10 cm over 10 or 20 years would be hard to distinguish from the variability already inherent to the region. For regions where peak SWE varies less on an annual basis, such as the Arizona/New Mexico region (Figure 14g), 27 years may be a long enough period to identify trends related to climate change. However, for some regions it is still difficult to separate the long term trend “signal” from the annual background “noise”. In addition, the years covered by this study include two very strong El Niño events (1982-1983 and 1997-1998) as well as one strong La Niña event (1988-1989). In the Cascades and Sierra Nevada regions, these events

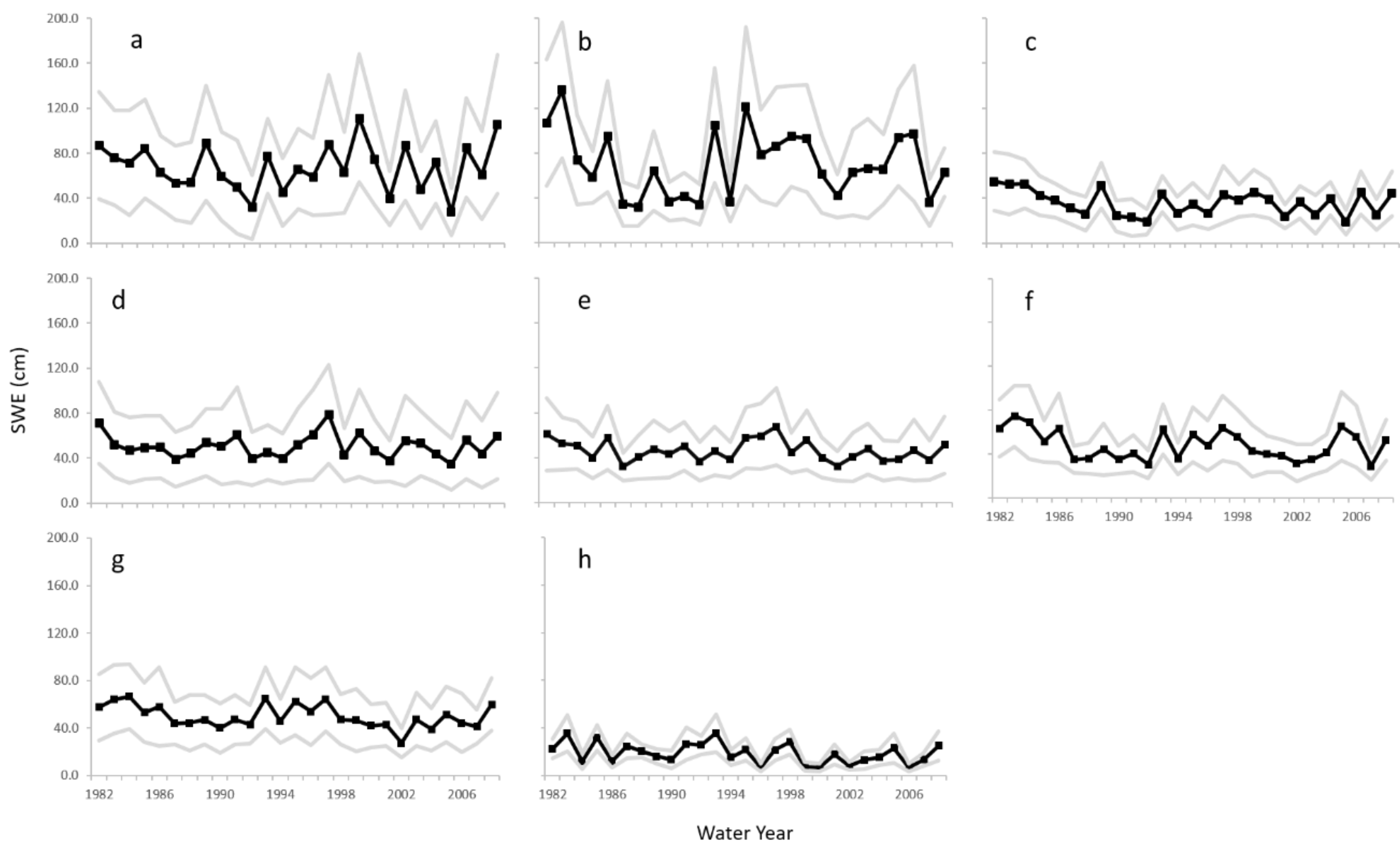

Figure 14. Regional average (black line) and range (gray, one standard deviation) of peak SWE amount by year: (a) Cascades, (b) Sierra Nevada, (c) Blue Mountains, (d) Northern Rockies, (e) Middle Rockies, (f) Utah, (g) Southern Rockies, (h) Arizona/New Mexico.

contribute to higher than average or lower than average peak SWE values and greater variability in region peak SWE values (Figure 14a and b). The occurrences of these events are a normal part of the climate for the area of this study, however the events from one or two years can further obfuscate long term trends by introducing more “noise”. Ideally the data collected would have spanned a longer time period to minimize the influence of individual years, though due to constraints set by the cyclone dataset and installation dates of SNOTEL stations that is not possible. Thus establishing what is considered “statistically significant” and then relating it in terms of this study has proven to be rather difficult.

A key factor in the differences between cyclone activity and SWE patterns is likely related to the source of the data. While the precipitation, temperature, and SWE patterns originate from actual measurements, the locations of the low pressure systems are based on reanalysis SLP data. It should be remembered that while reanalysis data are often used as if they are real measurements, they are actually results from a constrained model. Furthermore, the resolution of the NCEP/NCAR reanalysis data used to isolate cyclone center locations is 250 km. To put it into perspective, one 250 km by 250 km grid square would encase the entire Sierra Nevada region, where the distance between the two farthest SNOTEL stations is around 200 km. The coarse resolution of the reanalysis data could introduce some uncertainty to the cyclone center locations and the area analyzes. However, archived locations for cyclones are few and far between and do not cover a long span of time, so the reanalysis dataset was used. Needless to say, the patterns for cyclone activity were generally consistent with the monthly precipitation patterns, despite the shorter time frame. Future studies could use a regional reanalysis and expand the time frame to include more recent years, both of which would improve the results of the analyzes.

Precipitation and temperature changes will have consequences beyond peak SWE. The timing and volume of runoff is also dependent on precipitation and temperature. Water demands, particularly for agriculture, are greatest during the summer dry season. Current water allocation relies on mountain snowpacks to act as natural reservoirs, storing winter precipitation and allowing runoff volume to gradually increase. Much of the western United States is characterized by this snow dominant streamflow pattern (Figure 15c), particularly snowpacks at higher elevations and higher latitudes. With a projected warming of 0.8-1.7°C by 2050 (Barnett et al. 2005), the pattern of streamflow in many locations will shift from snow dominant to a mixture of rain and snow (Figure 15b), as snow events are replaced by rain events. Runoff volume will then peak in conjunction with both the yearly precipitation peak as well as snowmelt. Once rain events become the dominant form of precipitation, the peak in runoff will correspond with the yearly precipitation peak; Figure 15a shows what a rain dominant streamflow pattern looks like the runoff peak when the yearly precipitation peak is in early winter. With greater runoff volumes over a short period of time, constructed reservoirs will quickly fill in response to precipitation events. Water management practices dictate that reservoirs be kept slightly below capacity in order to prevent dam overflow from large precipitation events (Nijhuis 2014), so water would then be released and flow downstream, resulting in less water stored in reservoirs and available for use during the summer (Barnett et al. 2005). However, the exact timing and amount of peak runoff will depend heavily on the precipitation patterns of each region.

For the Cascades and Sierra Nevada regions, increasing temperatures will likely result in earlier peak SWE dates as well as a peak in runoff in early winter. Average maximum temperatures are at or above freezing during the winter in these regions, so many stations

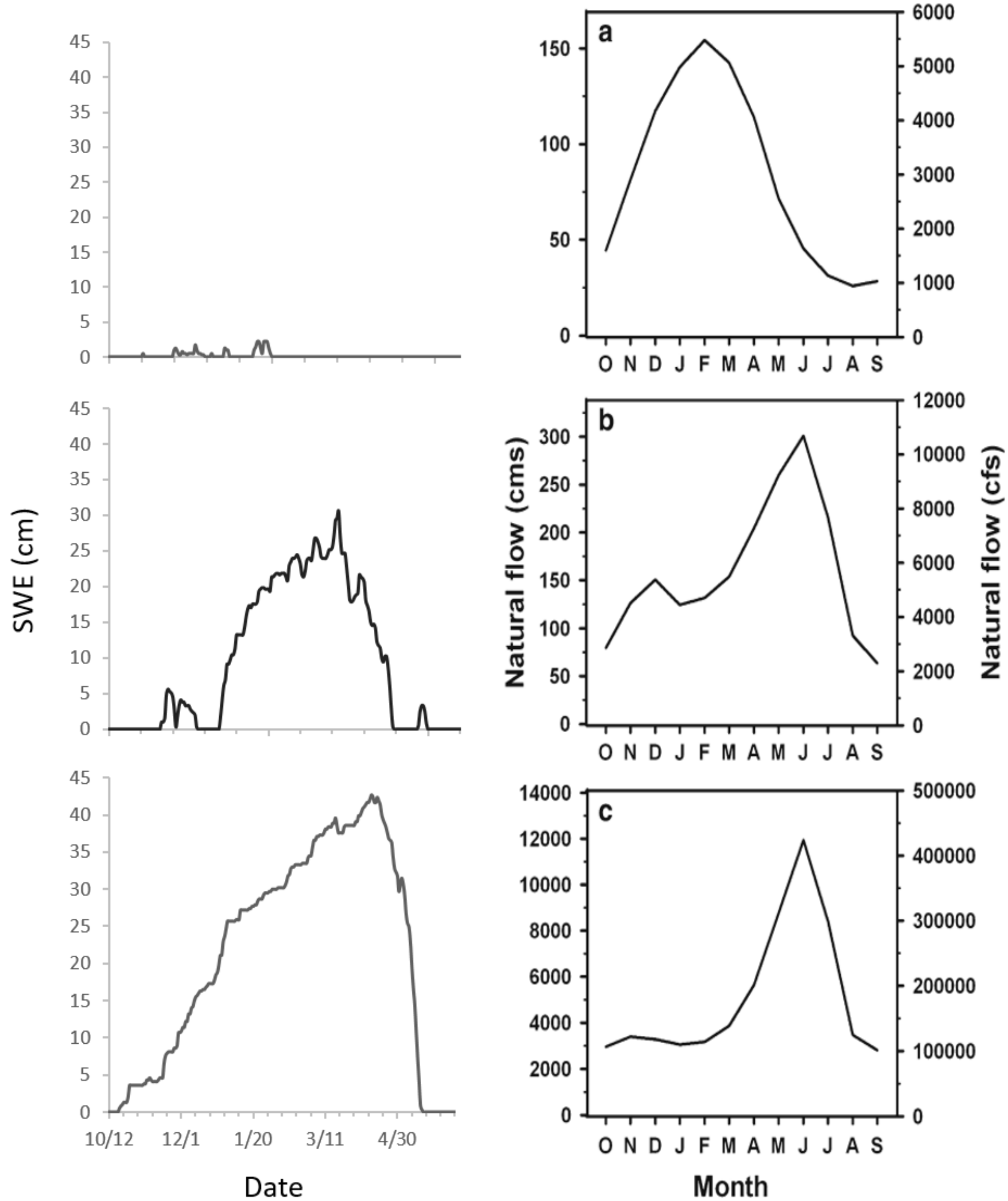

Figure 15. Cumulative SWE curves (left) and corresponding runoff regimes: (a) rain dominant streamflow corresponding with a yearly precipitation peak in December/January, (b) rain snow streamflow with peaks corresponding to precipitation peak and snowmelt, (c) snowmelt dominant streamflow. Hodographs courtesy of Elsner et al. (2010).

already experience a mixture of heavy snow and rain events. Peak SWE timing and amount (Figure 6ab and Figure 14ab) as well as the length of the accumulation (Figure 7a and b) and melt seasons (Figure 8a and b) vary considerably, particularly for stations at lower elevations. One example is King Mountain, OR (Figure 16). At this station, years with lower peak SWE amounts tend to have earlier peak SWE dates. The yearly precipitation total is within the normal range for the Cascades region, except for 1992, the lowest peak SWE amount. Lower peak SWE amounts and earlier peak SWE dates would result in a rain dominant runoff pattern similar to Figure 15a. Thus the SWE patterns for King Mountain, OR are a good example of the scenario in which precipitation amounts in the Cascades and Sierra Nevada regions do not significantly change, though the phase of the precipitation does. A similar pattern in peak SWE amount and timing would also come as a result of both increasing temperatures and decreasing precipitation amounts. At Tahoe City Cross, CA, just prior to and during the 2014-2015 drought (Figure 17), the peak SWE generally occurred at earlier dates when peak SWE amounts were lower, though the timing of the few snow events would heavily influence the date of peak SWE. For either precipitation scenarios for the Cascades and Sierra Nevada regions, the peak in runoff would likely occur closer to the yearly precipitation peak during the winter.

The amount and timing of both peak SWE and runoff in response to increasing temperatures will vary widely for the other regions and will be determined by precipitation pattern changes. Average minimum temperatures are -5°C to -10°C during the winter in the Rockies and Utah regions (Table 5), so most locations have not yet seen a shift from snowfall events to rainfall events. Stations at higher elevations and higher latitudes could benefit from an increase in temperature as long as it is still below freezing, as greater moisture availability for winter storms would lead to heavier snowfall events and higher peak SWE amounts. If monthly

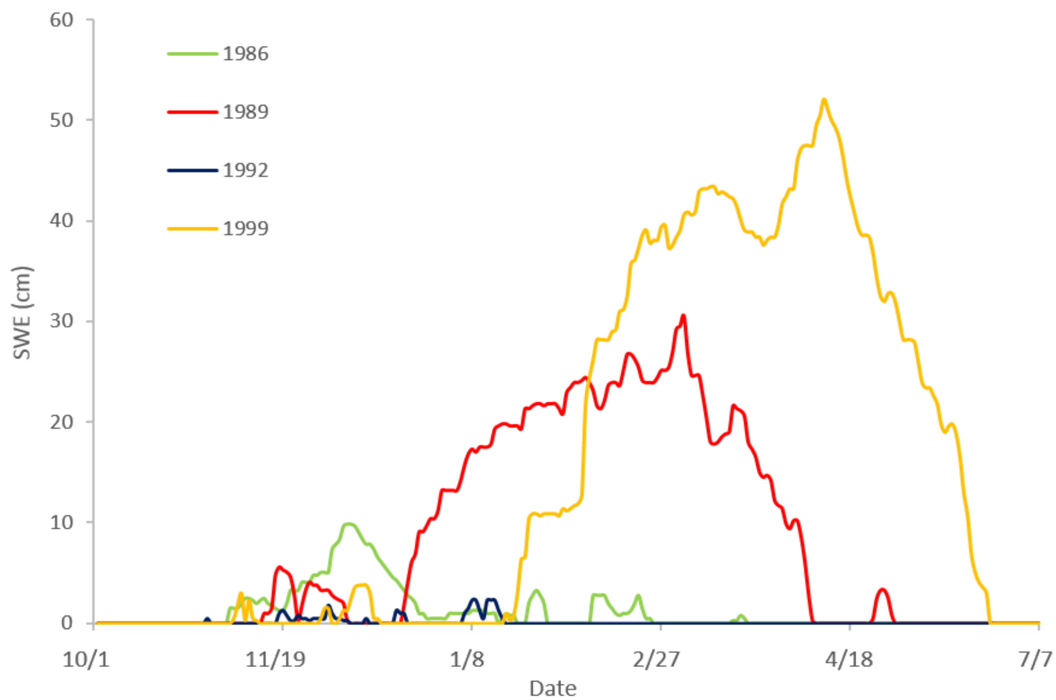

Figure 16. Cumulative SWE curves for King Mountain, OR (station number 558).

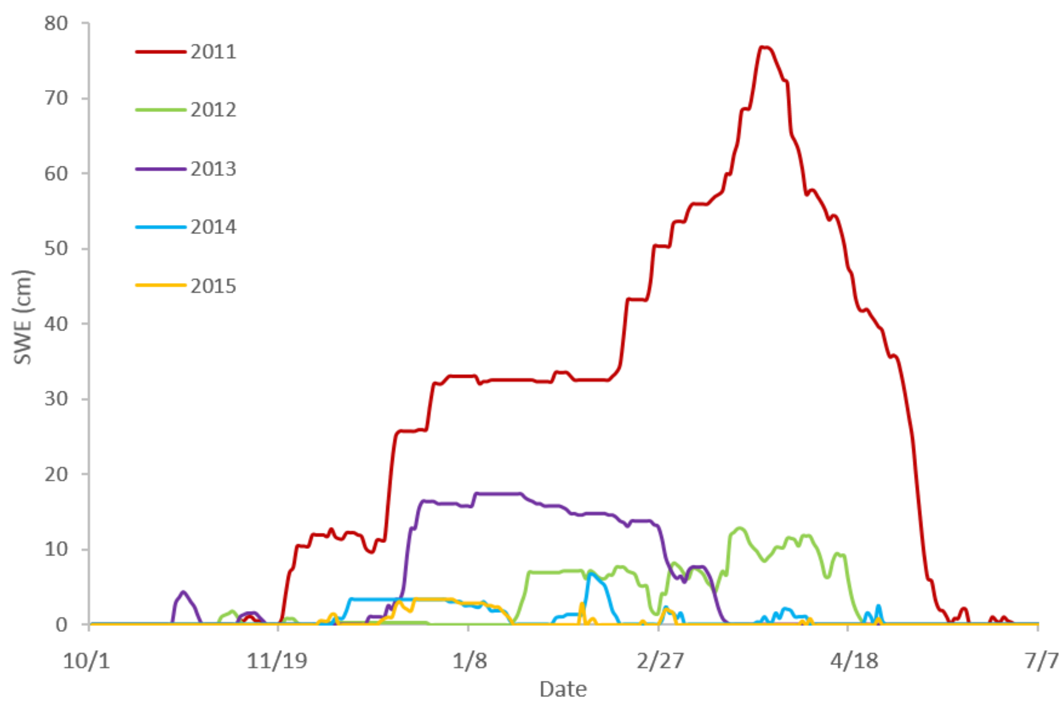

Figure 17. Cumulative SWE curves for Tahoe City Cross, CA (station number 809).

precipitation amounts stay the same while winter temperatures are still below freezing, then increased temperatures would first impact the initiation of a continuous snowpack, which the delay would shortening the accumulation season and decreasing peak SWE amounts. Decreased precipitation amounts, particularly around the date of peak SWE, would also lead to lower peak SWE amounts, as shown at Beaver Dams, UT. However, runoff timing and volume would still vary, depending on if precipitation after peak SWE decreased or not and the length of the snowmelt season. As shown by the snowpack indicator patterns at stations the Blue Mountains region (Table 3), the melt season could become longer, however, subject to large melt events (though the snowcover remains continuous) when rain events begin to replace snow events. The corresponding lower peak SWE amounts would lead to lower runoff volume, though the longer melt season would likely keep the runoff peak from shifting drastically earlier. However, the shift to more rain events during the melt season will eventually lead to a short initial melt season followed by one or more short accumulation and melt events, such as such as at Apishapa in southern Colorado (Figure 18). Eventually, decreased precipitation as well as increased temperatures could lead to shorter accumulation and melt seasons, as is the case at Baker Butte, AZ (Figure 19). Forecasting runoff could become more difficult, as runoff at lower elevations will correspond to the amount and timing of rain events.

The timing of runoff will vary from region to region, depending on the timing of peak precipitation and the relation of precipitation patterns before and after the date of peak SWE. However, as temperature increases, stations in all regions will likely have lower peak SWE amounts, as the changes in the snowpack indicators specify (Table 3). With less precipitation in the form of snow, there will be less delay between precipitation events and runoff. Streamflow

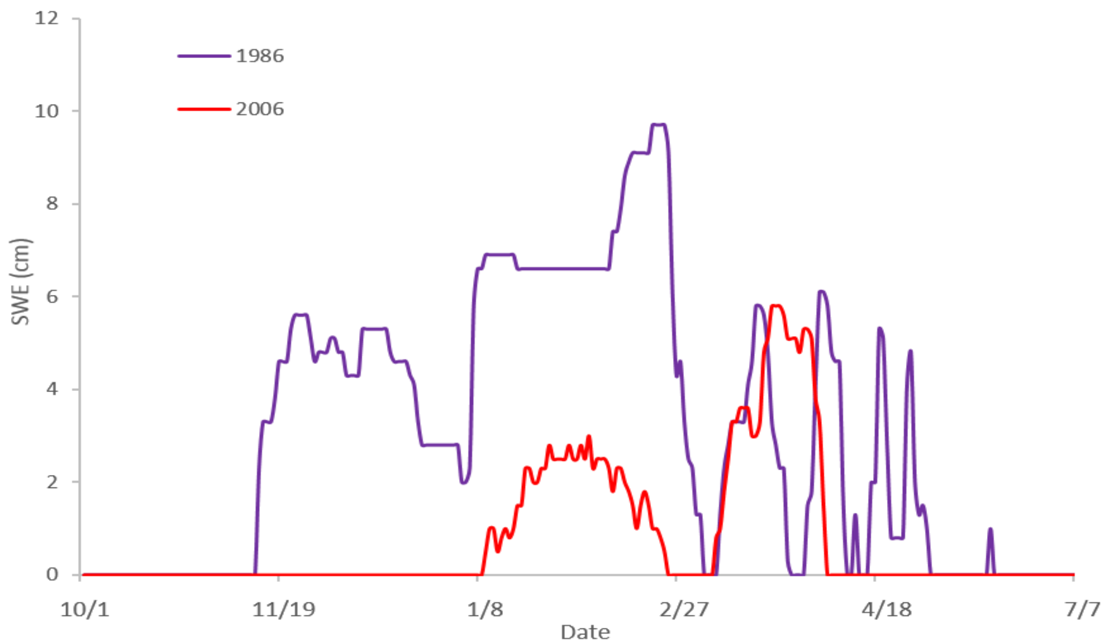

Figure 18 Cumulative SWE curves for Apishapa, CO (station number 303).

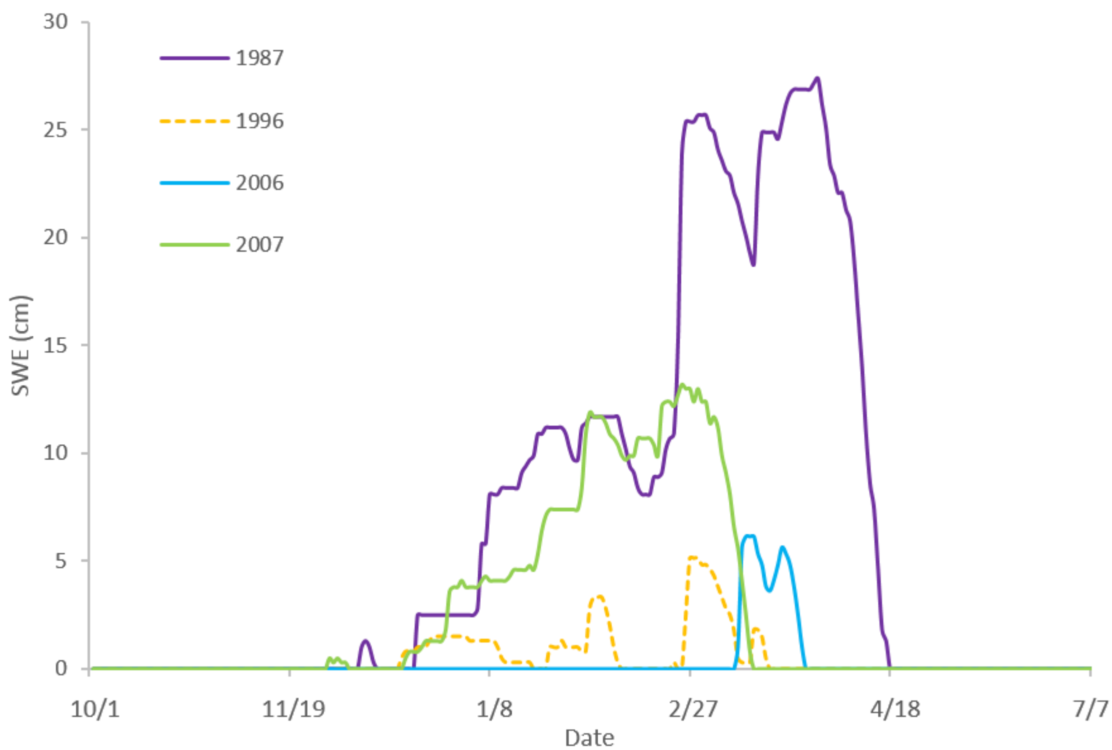

Figure 19. Cumulative SWE curves for Baker Butte, AZ (station number 308).

patterns will then reflect patterns in precipitation, leading to greater streamflow volume during the winter and lower streamflow during the summer.

CHAPTER 5: SUMMARY AND CONCLUSIONS

The purpose of this study was to investigate winter snowpack evolution in the western United States and determine what relationships might exist between the snowpack and cyclone activity using SNOTEL measurements and reanalysis data. Three main topics were investigated: how are the snowpacks changing through time, which variations within the snowpack can be attributed to temperature and precipitation, and to what degree do precipitation patterns and cyclone activity correlate. Between 25% and 50% of stations in the Blue Mountains, Utah, Arizona/New Mexico, Middle and Southern Rockies regions indicate shifts toward lower SWE. However, the snowpack conditions associated with lower peak SWE amounts vary between regions. For example, stations in the Utah and Southern Rockies regions show similar patterns of lower peak SWE amounts and earlier peak SWE dates, as well as no significant changes in the length of the melt season. However, while stations in the Utah region are experiencing shorter accumulation seasons and fewer snowcover days over time, stations in the Southern Rockies instead show a prevalence towards earlier dates in which the ground is completely snow free at the end of the snow season. Regions where few stations indicated any changes in peak SWE amounts either typically experience considerable variability in snowpack conditions from year to year (Cascades and Sierra Nevada regions), or conditions do not vary considerably (Northern Rockies region). The duration and timing of the snow season can be very different among regions, though the end result of lower peak SWE amounts is the same. Still, 1 April SWE should not be used to approximate peak SWE amounts, as typical peak SWE dates can fall within a range of up to two months for the Cascades region and as low as one month for the Northern, Middle, and Southern Rockies regions.

The primary impact of increasing temperatures is on the initiation of a continuous snowpack at the beginning of the snow season, not on peak SWE timing or the length of the melt season. Instead, precipitation type and amount is more often the driver of lower peak SWE amounts. The area analyzes indicate cyclones during the snow season are less frequent, particularly in October, November, and February, and on the order of three to five fewer cyclones per month over the 27 year time frame. Also, cyclones are shifting towards more poleward paths, by as much as two degrees latitude. However, with the exception of the Arizona/New Mexico region, fewer than 15% of stations in any one region indicate substantial changes in the length of the melt season. The melt seasons have not changed over the study period in response to lower peak SWE amounts or earlier peak SWE dates, therefore the length of the melt season is a function other factors. The frequency of snowfall events during the accumulation season alters the timing and amount of peak SWE while snowfall and rainfall events modify the length of the melt season. Instead of focusing only on peak SWE dates and amounts, future endeavors must consider the indirect effects of increasing temperatures related to cyclone activity, not just the direct effects on snowmelt and precipitation phase. The timing of snowfall events, as well as the amount, is crucial to understand how snowpacks are changing.

Building on the findings of this study, future work should focus on modeling different precipitation scenarios: how will more or less precipitation (snowfall or rainfall) prior to the date of peak SWE and during the melt season impact the timing and amount of peak SWE as temperatures increase. Peak SWE timing and the length of the melt season are influenced by precipitation patterns, so the frequency and intensity of snowfall events (earlier or later events, rain vs. snow events) will alter snowpack characteristics as well as the timing and volume of peak runoff. While direct impacts of temperature changes are a better understood aspect of climate change, precipitation shifts could accelerate or mitigate snowpack losses, generally affecting runoff patterns and water usage. Locations at higher elevations and latitudes, where average minimum temperatures during the winter are substantially below freezing, may benefit from increasing temperatures, which are still below freezing, since warmer air has a higher saturation mixing ratio, and more intense snow events could result in higher peak SWE amounts. However, less overall precipitation or a shift towards more rain events could result in lower peak SWE and a shorter snow season. Regardless, both precipitation and temperature changes will have implications toward future water resource and water management practices.

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