VARIATIONS IN SNOW DEPTH IN THE COLORADO ROCKY MOUNTAINS

by

JENNIFER ELLEN JACOBS

(Under the Direction of Andrew J. Grundstein)

ABSTRACT

This study examines snow depth trends by elevation in the Southern Rocky Mountains of Colorado. Using cooperative data, trends for accumulated seasonal snow depth, snowfall, snow days, and melting degree days were computed. The relationship of snow depth and meteorological variables versus elevation is assessed. When only the negative trends were plotted by elevation, both snow depth and snowfall have statistically significant relationships ($p \leq 5\%$). However, there is a distinct geographic pattern with negative trends in snow depth to the west of the Continental Divide and positive trends to the east. Regression analysis identifies snowfall as the primary influence on the snow depth trends. The spatial variability of trends in snowfall and snow depth may be explained by Pacific climate variability since correlations with the NPI and the PDO show strong spatial coherence. Melting degree day trends show broad warming across the region, consistent with anthropogenic greenhouse warming.

INDEX WORDS: Snow, snow depth trends, climate change, southern Rocky Mountains, Colorado, Pacific climate variability

VARIATIONS IN SNOW DEPTH IN THE COLORADO ROCKY MOUNTAINS

by

JENNIFER ELLEN JACOBS

ABJ, University of Georgia, 2003

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment

of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2008

VARIATIONS IN SNOW DEPTH IN THE COLORADO ROCKY MOUNTAINS

by

JENNIFER ELLEN JACOBS

Major Professor:	Andrew J. Grundstein
Committee:	Thomas W. Hodler Thomas L. Mote

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
August 2008

DEDICATION

I dedicate this work to my dad, Bernard Stewart Jacobs. I was in Jackson Hole, Wyoming when he called to tell me I was accepted into the graduate program. He said, "Break up with that ski bumb, come home and get your Master's." So that is what I did.

ACKNOWLEDGEMENTS

Thank you Dr. Grundstein for your encouragement, optimism, patience, and knowledge. God knew I could not have done it without you. Thank you mom for more than I can write in words. Thank you Dave for cooking me dinner and getting me double-shot caramel lattes. And thank you both for still loving me when it was all over.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Snow is a fundamental component of the Earth's water cycle and has an important influence upon water availability for irrigation, hydropower, domestic consumption, and recreation. Meltwater from mountain snowpacks is the primary source of water for much of the western United States, which consists of several mountain ranges, including the Cascade, Coastal, Sierra Nevada, and Rocky Mountains (Figure 1.1). Indeed, it has been estimated that up to 70% of streamflow in the region is generated from mountain snowpacks (Hamlet et al. 2005).

Figure 1.1. A map of the mountain ranges in the western United States. The four mountain ranges include the Cascade, Coast, Sierra Nevada, and Rocky. The yellow circle highlights the southern Rocky Mountains, which exist mostly in the state of Colorado (from Mote 2006).

Because snow is one of the major sources of water in the western United States, it is important to consider its vulnerability to climate change. Studies have documented a widespread increase in temperature across the western United States over the past 50 years (IPCC 2007). There have been both hydrological and ecological changes in response to the increasing temperatures. Plants such as lilacs and honeysuckles are blooming and leafing earlier, salmon fry (baby salmon) are emerging earlier; and there has been an increase in wildfire activity in some areas linked to warming temperatures and earlier spring snowmelt (Cayan et al. 2001, Westerling et al. 2006, Jackson and Dittmer 2007). Streamflow derived from melting snowpack is occurring earlier in the season (Regonda et al. 2005, Stewart et al. 2005). An increase in early spring streamflow due to earlier snowpack ablation would reduce streamflow in late summer and, therefore, accentuate seasonal summer droughts for portions of the western United States (Stewart et al. 2005).

Not only is the snow melting earlier, but also many areas are experiencing less total snow accumulation (Mote et al. 2003a, 2005). Widespread declines in spring snow water equivalent (SWE) have occurred in much of the North American West over the period 1925-2000. SWE is the amount of liquid water contained within the snowpack (Doesken and Judson 1996). There is an elevation pattern to trends in snow (Regonda et al. 2005, Mote et al. 2005). The largest reductions in SWE occur at relatively low to moderate elevations where average winter temperatures are near the freezing point (Mote et al. 2005, Regonda et al. 2005). Spatially, the areas with the largest reductions in SWE are in the Pacific Northwest, which has been documented to be particularly sensitive to warming temperatures. Mote et al. (2005), for example, found losses in excess of 50-75% in 1 April SWE in western Washington, western Oregon, and northern California. Smaller loses in 1 April SWE of 15-30% were found in the northern Rockies. Many of these changes have been associated with a combination of an increasing frequency of mid-winter melt events and a decrease in snowfall as more of the precipitation occurs as rain (Karl et al. 1993, Mote et al. 2005, Knowles et al. 2006). A few studies have suggested that climate indices such as the Pacific Decadal Oscillation (PDO), the North Pacific Index (NPI), and the Southern Oscillation Index (SOI) could influence SWE on decadal time scales (Clark et al. 2001, Mote et al. 2005, 2006).

Nearly all the above studies, however, have relied on either snow course observations or data from the National Resource Conservation Service (NRCS) snowpack telemetry (SNOTEL) network. One downside to both sets of data is that in particular regions of the West there are few sites located in the transient snow zone below 2500 m where snow is ephemeral (Hamlet et al. 2005). This is a particularly noteworthy deficiency for climate change studies because these areas are especially sensitive to warming (Hamlet et al. 2005). Transient zones, which are low to moderate elevations sites, are represented in the Pacific Northwest because of the generally lower elevation of the Cascades. Table 1.1 shows the elevations that Mote et al. (2005) define as low to moderate versus high elevation sites.

Table 1.1. Elevation categories for the western United States used in Mote et al. (2005).

Category	Mean Snow Course Elevation (m)	Maximum Snow Course Elevation (m)	Example Locations (from Mote et al. 2005)
Low to Moderate	1900	2600	Cascades Coastal Range northern Sierra Nevadas
High	2600	3500	southern Rocky Mountains southern Sierra Nevadas

Studies in the southern Rocky Mountains, however, have relied on data sources that only have high elevation stations (Mote 2003a, Mote et al. 2005, Regonda et al. 2005). The undersampling of lower elevations in this area makes their claims about a lack of snow trends with elevation questionable.

This study seeks to examine snow depth trends by elevation in the Colorado Rocky Mountains using data from cooperative observing stations (Figure 1.1). This dataset provides a wider range in elevation than the snow course or SNOTEL datasets and allows for an examination of snow depth trends in both the highly sensitive transitional zones and the higher elevation sites. The Colorado Rocky Mountains were selected as the study area for this research project because the topography there has a diverse range in elevation unlike the lower elevation mountain ranges in the Pacific Northwest. Also, variations in snow in Colorado are of interest because meltwater from watersheds within Colorado is particularly important hydrologically (Clark et al. 2001). This research will examine a variety of research questions related to snow in the Colorado Rocky Mountains:

- What are the spatial patterns of snow depth, snowfall, melting degree day, and snow day trends across Colorado?
- Is there a relationship between snow depth, snowfall, melting degree day, and snow day trends and elevation?
- What are the meteorological factors that contribute to the trend in snow depth?
- How does Pacific climate variability affect snow depth trends?

This research is unique because of the use of cooperative observing stations, which provide stations with a wider range in elevation. It will examine stations that range from 1300-

3450 m in the Colorado Rocky Mountains versus the stations used by Mote et al. (2005) and Regonda et. al (2005), which start at 2500 m. This research is also unique because unlike previous studies it uses stations on both sides of the Continental Divide (Mote et al. 2005, Regonda et al. 2005).

CHAPTER 2

LITERATURE REVIEW

2.1 Temperature Variations

Winter and spring temperatures have increased in western North America during the Twentieth Century (Folland et al. 2001; Scott and Kaiser 2004; Knowles et al. 2006). The sites that have warmed the most tend to have relatively cold climates (Knowles et al. 2006). These cold, usually higher elevation areas, warmed more than 4°C, whereas, most other sites warmed between 0°C and 3°C from 1949-2004 (Knowles et al. 2006). A study using tree-ring based temperature reconstructions from the central Canadian Rockies indicates that summer and spring temperatures in the last half of the twentieth century are higher than any equivalent period over the last 900 years (Luckman 1998).

Similar anomalies have been found worldwide. Beniston et al. (1997) also reveal that the warming in the Alps since the early 1980s, while synchronous with the global warming, is of far greater amplitude than the average global temperature increase. In the high elevations, temperature increases reaches are near 1°C on average for the Alps and up to 2°C for individual sites, such as the highest observed site in the Alps, Santis, at 2500 m. Similar studies for the Austrian Alps (e.g., Auer and Boehm, 1994) and the Bavarian Alps lead to broadly similar conclusions (Beniston et al. 1997). Figure 2.1.1 illustrates that the high elevation site temperature anomalies are roughly a five-fold amplification of the global signal.

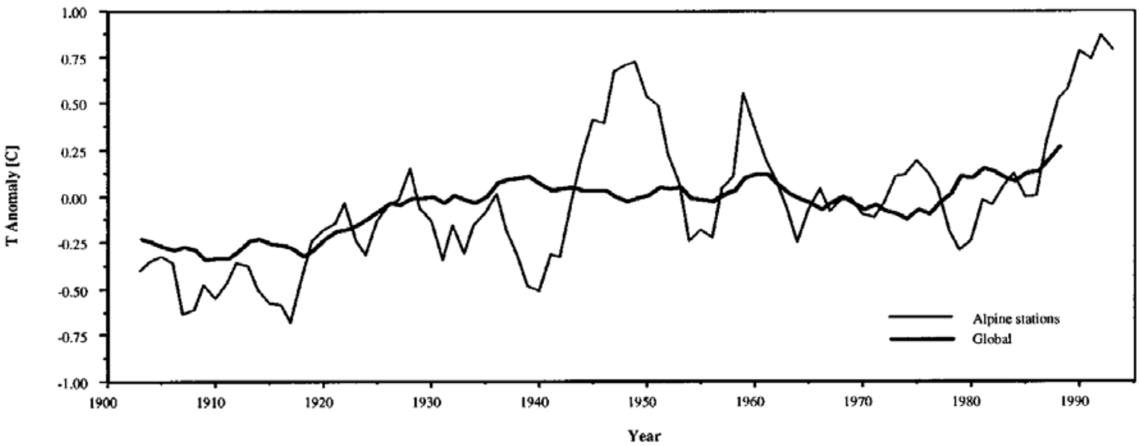


Figure 2.1.1. Yearly-mean surface temperature anomalies averaged for eight high elevation sites in the Swiss Alps, ranging in elevation from 569 m to 2500 m above sea level. The change in global mean temperatures is given for comparison purposes. Data have been smoothed with a five-year filter (from Beniston et al. 1997).

Investigations also indicate that, in all regions and at all elevations, the warming trend is more notable in terms of rising minimum temperatures than increasing maximum temperatures—a pattern consistent with anthropogenic warming. Karl et al. (1993) show this on a global scale. Over much of the continental land masses, minimum temperatures have risen on the order of 0.84º since the 1950s, while maximum temperatures have only risen 0.28ºC (Karl et al. 1993). In the Alps, climate change has been characterized by increases in minimum temperatures of about 2°C, with a more modest increase in maximum temperatures (Beniston et al. 1997). In the United States, Brown et al. (1992) have observed this asymmetry between minimum and maximum temperature trends in the Colorado Rocky Mountains and neighboring Great Plains locations.

2.2 Ecological and Hydrological Variations

Rising temperatures in the West have been associated with a number of observed ecological and environmental changes. Cayan et al. (2001) used data from the Western Regional

Phenological Network (WRPN) to measure the ecosystem response to climate change. The results suggest that, because of pervasive warming across the West, plants such as honeysuckles and lilacs are now blooming and leafing out earlier in the year (Cayan et al. 2001). Across the Pacific Northwest, the warming temperatures have affected fisheries (Jackson and Dittmer 2007). In the winter, salmon fry are emerging earlier and this may lead to food shortages later in the season. Additionally, higher summer water temperatures may damage salmon populations. Since the 1940s, a critical temperature threshold for salmon has occurred more frequently and is now exceeded more than half the time. Another environmental impact linked to warming temperatures is associated with increased wildfire activity. In the western United States, there has been a higher frequency of fires, a greater duration in the life of fires, and a longer wildfire season since the mid-1980s (Westerling et al. 2006). Westerling et al. (2006) found the greatest increases in fire activity in the mid-elevation, Northern Rocky forests. They associate the increase with an earlier spring snowmelt, which may lead to an earlier and longer dry season conducive to wildfires.

Hydrologic changes related to the temperature increases include earlier and reduced snowmelt-derived water supply (Cayan et al. 2001; McCabe and Clark 2005; Mote et al. 2005; Regonda et al. 2005; Stewart et al. 2005). In fact, since the late 1940s a trend toward earlier spring snowmelt-derived streamflow has been documented for numerous regions across the West (Hamlet et al. 2005; Stewart et al. 2005). In addition, during the past half-century (1950-2000), the spring streamflow has shifted to such an extent that the primary April—July streamflow peak now occurs one or more (up to four) weeks earlier than it did in 1948, with consequent declines in spring and early-summer river discharge (Stewart et al. 2005). Regonda et al. (2005) examined the spatial pattern of trends in the timing of peak snowmelt-driven streamflow across the West. They found that peak spring flows are occurring earlier for the majority of stations across the West, but that statistically significant trends toward earlier peak streamflow occur principally in the Pacific Northwest. A small number of stations in the interior west and the Sierra Nevada region show later occurrences in peak streamflow. Regonda et al. (2005) note that these stations are located in higher elevation locations, which are less sensitive to temperature changes that would affect snowmelt timing. The shift in timing of peak streamflow is closely linked to elevation. Earlier peak flows of 10 to 20 days occurred in basins less than 2500 m in elevation (Regonda et al. 2005).

2.3 Variations in Snow

Changes in the persistence and amount of snow have been documented in mountainous regions around the world. Most notably, Europe has the longest and most useful records. A decline in spring snow cover has been found for mountainous regions of the world including ones in Austria, Switzerland, and Germany (Beniston et al. 1997), and the former Soviet Union and China (Brown 2000). In the Swiss alpine, the number of snow days (the number of days with snow on the ground each year) has decreased since the late 1980s and 1990s (Scherrer et al. 2004).

In the United States, many studies have documented significant decreases in snow water equivalent (SWE) and snow depth over large portions of the West during the last five decades (Mote 2003a, 2006; Hamlet et al. 2005; Mote et al. 2005; Regonda et al. 2005; Dyer and Mote 2006). In the Pacific Northwest, Mote (2003a) found negative trends in 1 April SWE obtained from snow course surveys during the 1950-2000 period. A broader study by Regonda et al. (2005), relying on snow course measurements from 1950-1999, found negative trends in March, April, and May SWE across the Pacific Northwest, and the northern parts of Idaho, Utah, Wyoming, and the Sierra Nevada region. Mote et al. (2005) performed a similar analysis of trends in spring SWE in the western United States, augmenting the snow course data with automated SNOTEL observations. They found strong downward trends in 1 April SWE over most of the domain. The largest changes are found in Washington, Oregon, and northern California with 50-75% losses (relative to the 1950 starting value). Decreases in the northern Rockies were smaller in magnitude ranging from 15%-30%. In contrast, increases (some greater than 30%) in 1 April SWE were observed in the southern Sierra Nevadas of California and in other areas of the Southwest. The state of Colorado has both increasing (mostly in southern Colorado) and decreasing (mostly in northern Colorado) trends in 1 April SWE (Figure 2.3.1).

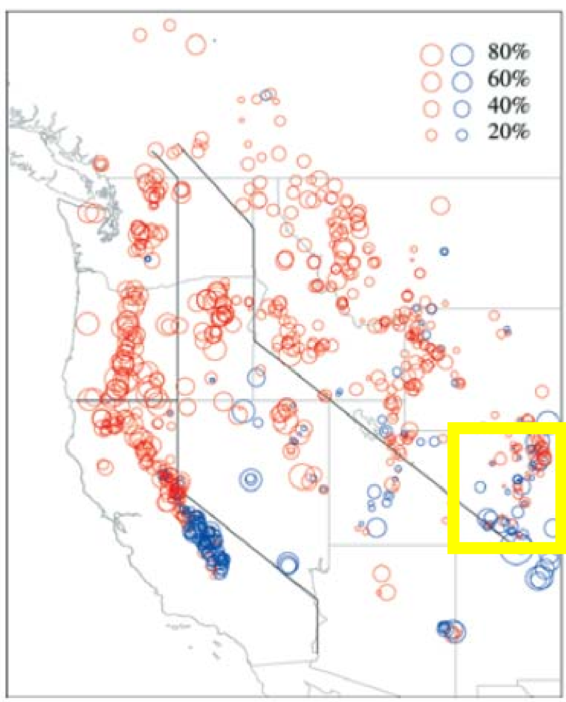


Figure 2.3.1. Linear trends in 1 Apr SWE at 824 snow course locations in the western United States and Canada for the period 1950–97, with negative (positive) trends shown by red (blue) circles. Lines on the maps divide the West into four regions: Cascades, California, Dry Interior, and the Rockies. The yellow box highlights the state of Colorado (from Mote et al. 2005).

While trends in spring SWE are negative in many areas, the changes are not entirely monotonic. Mote et al. (2005) aggregated snow course data and produced regional time series maps for the Cascades, California, the Dry Interior region, and the Rockies. They found interdecadal variations that were similar among regions. Spring SWE declined from 1915 to the 1930s, increased in the 1940s and 1950s, and decreased since mid-century except for a peak in the 1970s. The peak in the 1970s is believed to be in response to a shift in the Pacific Decadal Oscillation from a cool phase to a warm phase (Mantua et al. 1997).

2.4 Variations in Snow by Elevation

Elevation is an important physiographic characteristic that helps explain the spatial patterns in SWE. The largest reductions in SWE occur at relatively warm, low to moderate elevations where winter temperatures are typically nearer to the melting point (Table 1.1). Regonda et al. (2005) found that low-elevation basins (<2500 m) showed strong decreasing SWE trends, but little or no trend in the higher elevation stations. Similarly, they also found that changes in the timing of snowmelt are also most pronounced in stations below 2500 m where even modest temperature changes may be associated with large changes in snow conditions.

To illustrate the dependence on elevation, or more generally on mean winter temperature, Mote et al. (2005) binned 1 April SWE trends for four mountain areas in the West (Cascades, Rockies, California, and the Dry Interior) by mean winter temperature (Figure 2.4.1). The strongest relationships are found in the Cascades and mountains of California where the warmer mean winter temperatures (December to February) correspond with the largest decreases in SWE. The Rockies and the Dry Interior with colder mean winter temperatures (most below 0ºC) showed less correlation. The sensitivity to temperature is illustrated looking at the correlation between SWE and temperature with elevation in California. The percent change in SWE is virtually zero above 2500 m but grows increasingly negative at lower elevations with correlations exceeding -0.5 below 1800 m (Mote 2006). Regonda et al. (2005) also illustrates the dependence on elevation using a scatter plot of 1 April SWE trends versus snow course elevation (Figure 2.4.2).

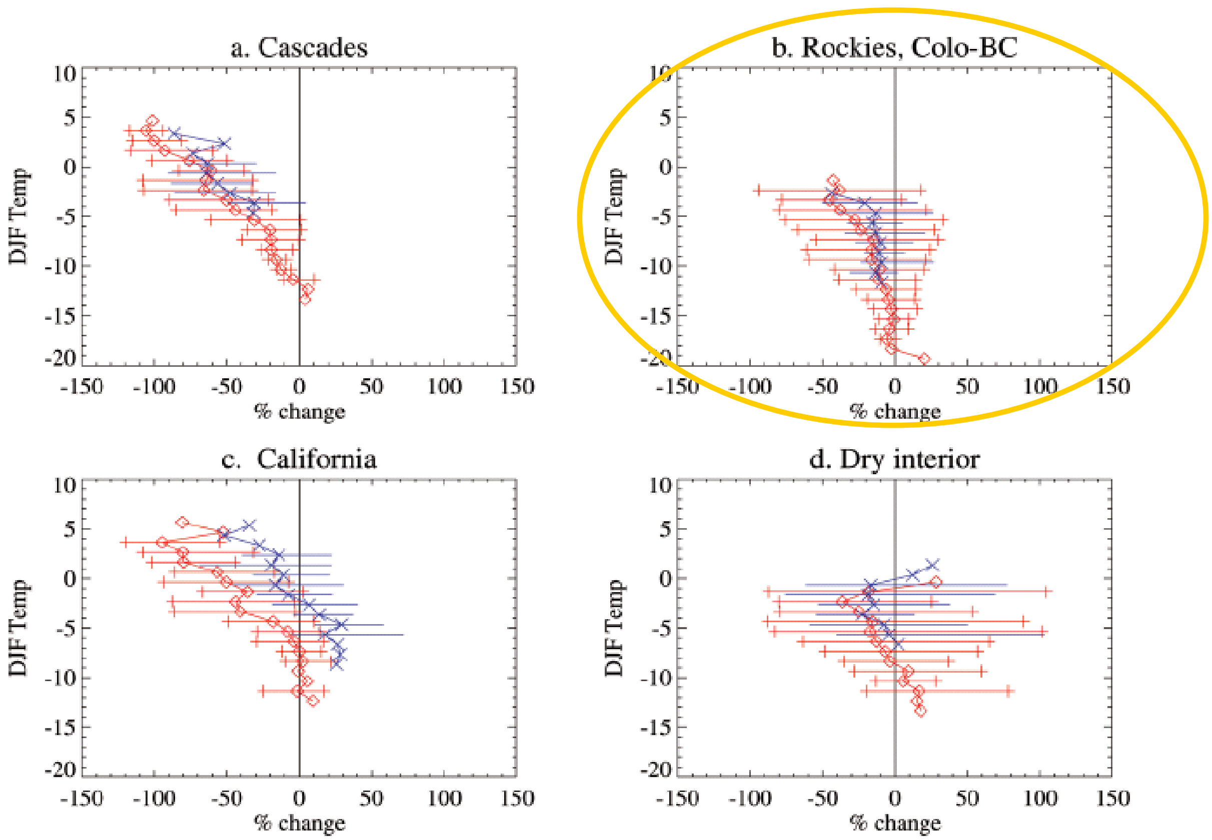


Figure 2.4.1. Mean 1 April SWE trends stratified by December-February temperature for the (a) Cascades, (b) Rockies, (c) California, and (d) Dry interior. Blue pluses represent observations and red diamonds represent model results. For any bin with at least 10 values, the span from the 10th to 90th percentiles is shown (from Mote et al. 2005).

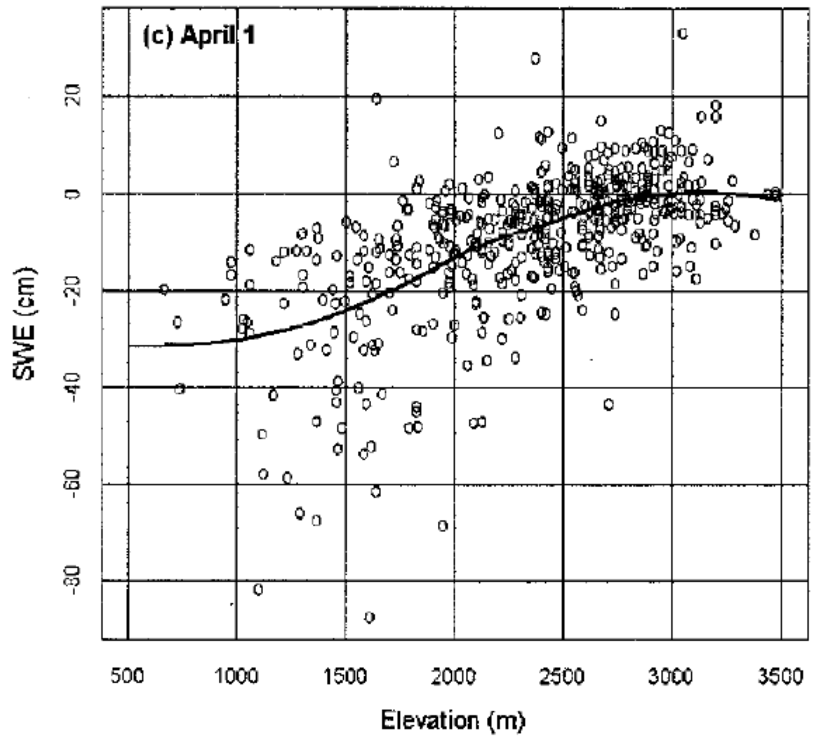


Figure 2.4.2. Scatter plot comparing the trends in SWE (cm) against snow-course elevation (m) for measurements taken on 1 April (from Regonda et al. 2005).

Because both latitude and elevation may affect temperature, temperature sensitivity of SWE, and spring SWE trends, Mote (2006) examined latitude-altitude transects across the Western United States. He noted that elevation of snow courses decrease with latitude. In addition, trends in 1 April SWE are generally negative north of 40°N with positive trends only at the highest elevation stations. South of 40°N, trends in SWE are mostly positive with negative trends limited to the lowest elevation stations. Latitude-altitude transects were also used to examine the correlations of SWE with November-March precipitation and temperature. At most latitudes, low elevation locations (e.g. average temperatures ≥0°C) have high negative correlations between SWE and temperature (very temperature sensitive), but weak correlations between SWE and precipitation. In contrast, the SWE at higher elevation locations have weak correlations with temperature with much stronger correlations to precipitation.

2.5 Meteorological Explanations for Observed Snow Trends

Snow is a variable that is sensitive to both temperature and precipitation. A variety of studies have investigated their respective roles in explaining trends in spring SWE. The sensitivity of different sites to meteorological variables such as temperature and precipitation may be assessed using correlations between 1 April SWE with November-March average temperature and accumulated precipitation. Low elevation sites are highly sensitive to temperature changes with strong negative correlations between November-March average temperature and 1 April SWE (Mote et al. 2005). Thus, it is expected that lower elevation sites would respond strongly to temperature changes and, in the absence of precipitation increases, lead to less accumulated SWE.

Trends in both precipitation and temperature have been examined across the western United States (Mote et al. 2005). During the 1950-1997 period, temperature trends were almost uniformly positive (Mote et al. 2005). Many stations had statistically significant trends exceeding 1.6^{o}C per century. Precipitation trends are more variable. Negative trends are evident across the western portions of Oregon and Washington, and parts of the northern Rockies. Positive trends occur across eastern Oregon, Washington, and the Southwest.

Several studies have tried to isolate the relative importance of precipitation versus temperature on spring SWE trends. Mote (2006) used a multiple regression model to isolate the influence of the two variables. Nearly all sites showed that the warming has had a negative contribution toward the trend in SWE (Figure 2.5.1a). The values were especially large, ranging from 5-10 cm over the 1960-2002 period, in the Cascades and mountains of northern California. The pattern of the SWE trend contributed by precipitation alone is more variable across the region with equal numbers of sites with positive and negative values (Figure 2.5.1b). When combining both influences, it is clear that the negative SWE trends in the Cascades and northern California were due to a combination of increased temperature and decreased precipitation.

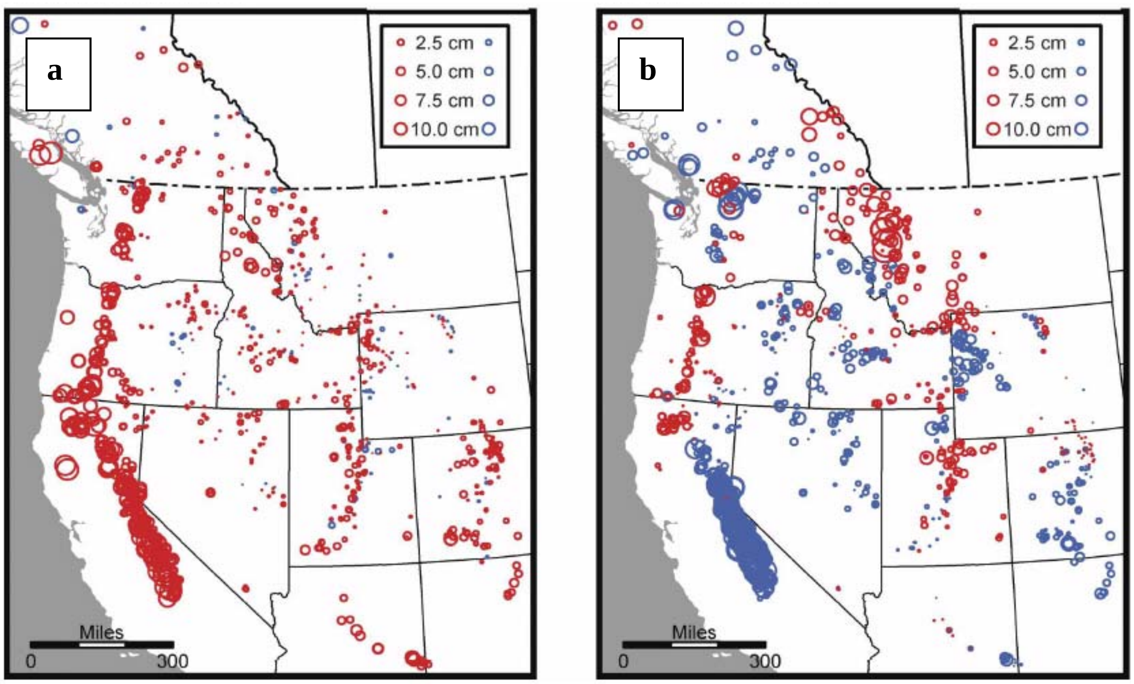


Figure 2.5.1. The estimated trends in SWE computed through the multiple regression model used to isolate the roles that temperature versus precipitation play in estimating trends in SWE. (a) Temperature-derived and (b) precipitation-derived trends in 1 April SWE over the 1960-2002 period of record. Positive (negative) trends are shown in blue (red)(from Mote 2006).

Hamlet et al. (2005) used a hydrologic model to simulate the changing snowpack. They conducted fixed temperature and fixed precipitation simulations to see the effects of each on snowpack accumulation. Their study indicates that, in areas with warmer winter temperatures (average winter temperatures >-5^{o}C), the effect of warming tends to overwhelm the effects of increasing precipitation. Trends in colder areas are mainly driven by variations in precipitation with temperature effects relatively small.

Changes in snowfall have a direct effect on snow mass accumulation, but changes in temperature may affect both melt events and whether precipitation falls as rain or snow. Several studies have investigated how temperature may physically impact SWE accumulations. The influence of changes in the fraction of rain to snow on spring snowpacks has also been studied (Knowles et al. 2006). Knowles et al. (2006) found decreased snowfall (water equivalent) in response to warming across the region. Snowfall showed a strong negative relationship with elevation when precipitation trends were controlled. That is, lower elevations showed the greatest decrease in snowfall accumulation. Knowles et al. (2006) note that these elevations tend to have average temperatures above -5^{o}C on days with precipitation. These results suggest that the warming temperatures contribute to reduced snow amounts because increasing temperatures during precipitation events reduce the snow deposited.

Mote et al. (2005) examined the role of melt events on spring SWE. Their results show that increasing frequency of melt events also plays an important role in 1 April SWE at sites in Oregon, Washington, Nevada, California, and the Southwest. These melt events, however, are not important at higher elevation sites in the Rockies prior to 1 April. These results suggest that warming produces less SWE largely because of an increase in melt events, not simply by increasing the likelihood of rain over snow.

2.6 Pacific Climate Variability and Western Snow

The observed negative trends in snowpack are not entirely monotonic. Rather, there have been documented variations in snowpack in the Western United States related to teleconnections such as the Pacific Decadal Oscillation (PDO), the North Pacific Index (NPI), and El Niño Southern Oscillation (ENSO). A teleconnection is a linkage between changes in atmospheric or oceanic circulation occurring in widely separated parts of the globe such as the PDO, which links variations in sea surface temperature in the North Pacific to circulation patterns across the western United States (Figure 2.6.1a; Mantua et al. 1997). The PDO is a low-frequency

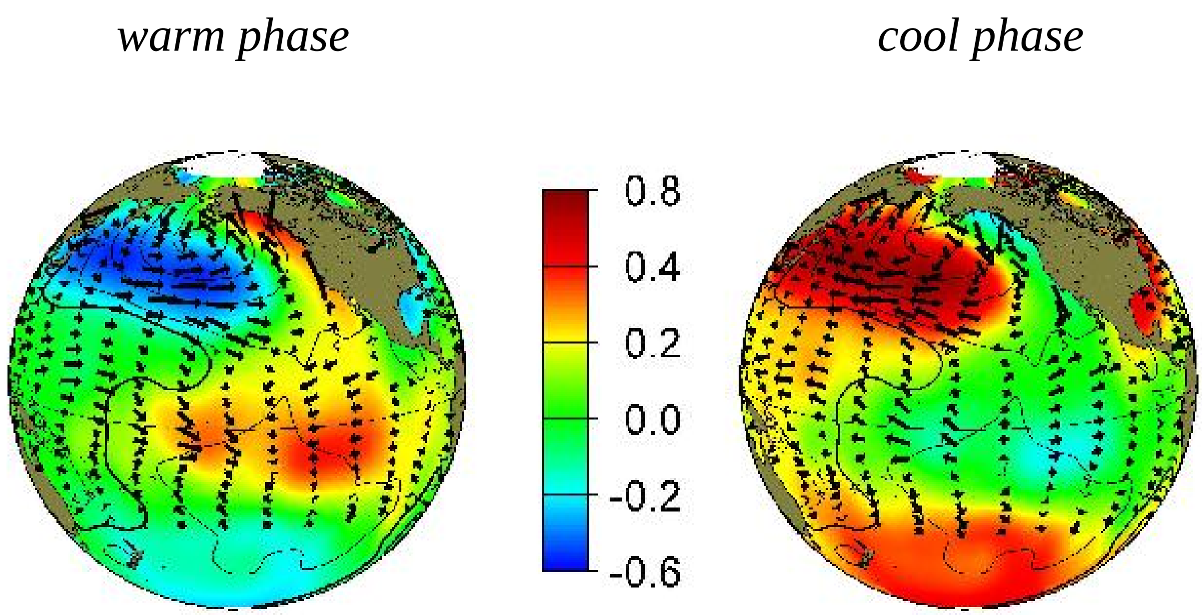


Figure 2.6.1. (a) Typical wintertime Sea Surface Temperature (colors), Sea Level Pressure (contours) and surface wind stress (arrows) anomaly patterns during warm and cool phases of PDO (from http://jisao.washington.edu/pdo/)

teleconnection that operates on decadal time scales. The Aleutian low deepened after the 1976/77 climate regime shifted to a positive PDO phase. Figure 2.6.2 shows the inverse relationship between the PDO phase and sea-level pressure over the North Pacific. A deeper Aleutian Low is associated with advection of warmer and moister air into the North American west coast and colder air over the North Pacific along with a southward shift in the storm track (Hidalgo and Dracup 2003; Trenberth and Hurrell 1994). The influence of the PDO varies by

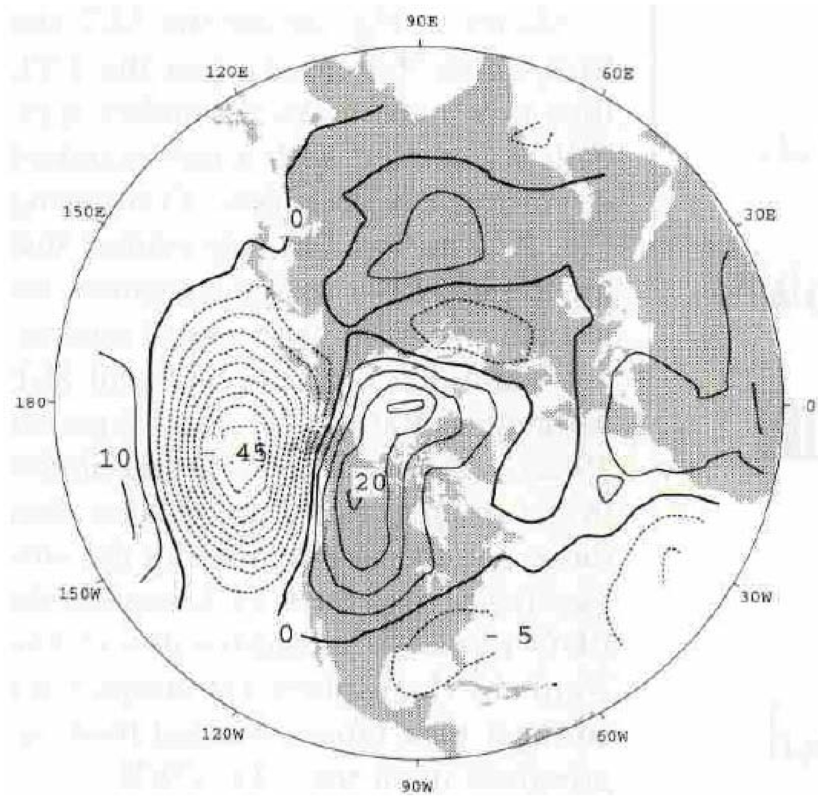


Figure. 2.6.2. Wintertime Northern Hemisphere 500 mb heights regressed upon the PDO index for the period of record 1951-90. Contour interval is 5 m, positive (negative) contours are solid (dashed) (from Mantua et al. 1997).

region (Mantua et al. 1997). There is a distinct relationship with precipitation in the Pacific Northwest, where the conditions shifted from wet to dry as the PDO changed from a warm to cool phase (1925-1976) and from dry to wet during a period where the PDO changed from the cool to the warm phase (1947-2003; Figure 2.6.3; Hamlet et al. 2005). Other areas such as the Colorado River basin, however, do not show similar relationships (Hidalgo and Dracup 2003). Overall, PDO does explain decadal-scale precipitation variability quite well and thus winter precipitation trends over shorter periods of the record (Hamlet et al. 2005). Yet, it is unclear the degree to which the moderately increasing trend in precipitation across the western United States is associated with the PDO versus the influences of anthropogenic warming (Hamlet et al. 2005).

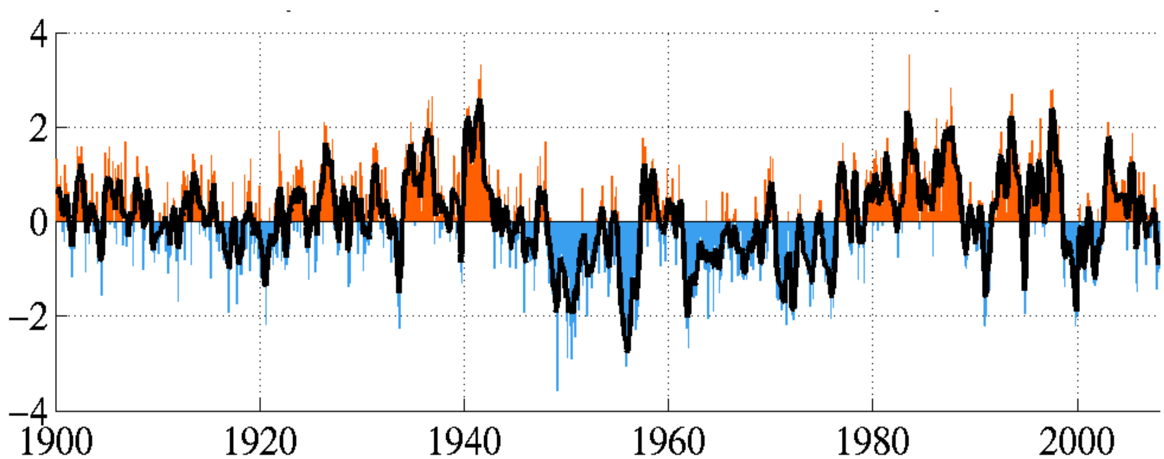


Figure 2.6.3. Monthly values for the PDO index: 1900—January 2008 (from http://jisao.washington.edu/pdo/)

Temperature variations have also been associated with the PDO, which in turn affects the percentage of precipitation falling as snow. The 1947-1976 cool phase was associated with cooler temperatures and greater percentages of the precipitation as snow than during the warm phases (1925-1946 and 1977-1998; Knowles et al. 2006). Nevertheless, the widespread regional warming trend is not well explained by the decadal-scale variability associated with the PDO (Hamlet et al. 2005). In terms of snow, cool (warm) phases are linked with higher (lower) snowpacks and streamflow values in the Pacific Northwest and the opposite effects in the Southwest (Mote 2006). The dividing line between positive and negative correlations runs diagonally from northern California through central Idaho to the Montana–Wyoming border (Mote 2006).

Another measure of Pacific climate variability is the North Pacific Index (NPI), which is an atmospheric index that measures variations in sea-level pressure in the North Pacific (Trenberth and Hurrell 1994). The NPI is weakly correlated with the PDO (Mote 2006). There is a trend in the index since 1930, which corresponds with a pattern towards a deeper Aleutian low (Figure 2.6.4; Mote 2006). SWE is positively correlated with the NPI in the Pacific Northwest and negatively correlated with it in the Southwest where the dividing line extends runs more east–west from central California (Mote 2006). Mote (2006) notes that the NPI can only explain about half of the negative trend in SWE in the Pacific Northwest, with the remaining portion attributed to anthropogenic warming.

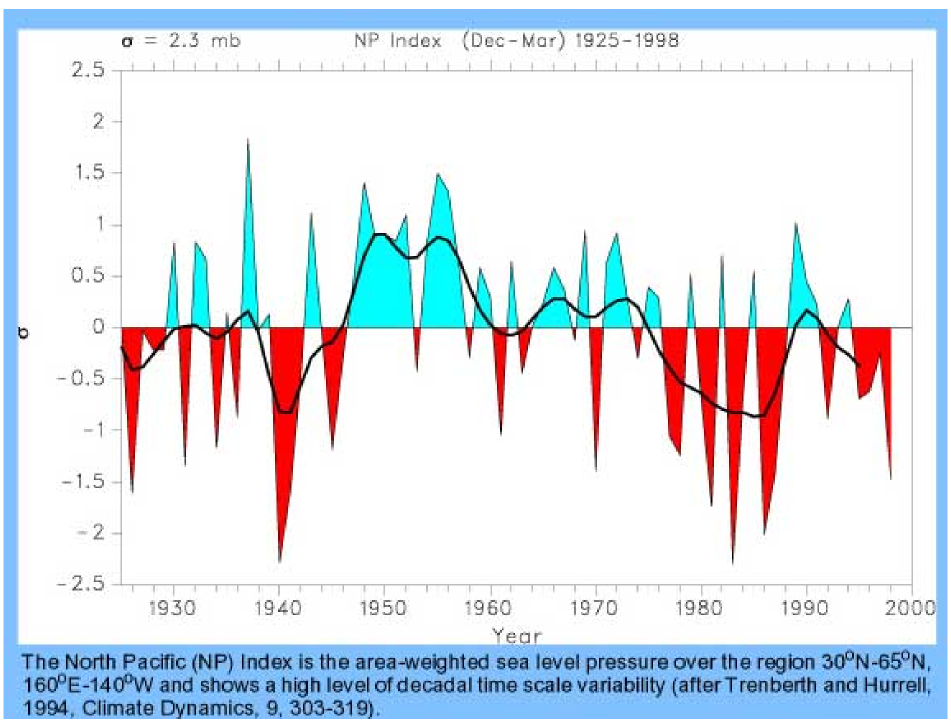


Figure 2.6.4. Time series of the NPI. Positive (negative) values of the NPI correspond to years with a deepened (weakened) Aleutian low (from www.ncdc.noaa.gov/paleo/ctl/clisci100b.html).

A third climate index that is associated with climate changes in the western United States is the El Niño Southern Oscillation (ENSO) (Clark et al. 2001). The warm phase (El Niño) is associated with lower snowpack in the Northwest and higher snowpack in the Southwest (Clark et al. 2001). This phase is characterized by above normal sea surface temperatures (SSTs) in the eastern tropical Pacific Ocean, which leads to higher temperatures over the northwestern United States and Canada. It also influences precipitation patterns by shifting storm systems northward toward Alaska, which subsequently reduces precipitation over the Pacific Northwest. At the same time, a strengthened subtropical jet entrains more moisture from the Pacific Ocean, increasing precipitation over the Southwest. As a result, SWE and annual runoff decrease in the Northwest and increase in the Southwest. The cold phase (La Niña) is characterized by below normal sea surface temperatures (SSTs) across the eastern tropical Pacific Ocean. It is associated with a southward shift in the Pacific storm track that increases precipitation over the Pacific Northwest while the weakened subtropical jet decreases the likelihood of precipitation in the Southwest (Clark et al. 2001). During the cold phase, SWE and annual runoff increase in the Northwest and decrease in the Southwest.

The strength of ENSO can be measured with an atmospheric index called the Southern Oscillation Index (SOI; Kiladis and van Loon 1988, Trenberth 1997). The Southern Oscillation Index (SOI) is one measure of the large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific during El Niño and La Niña episodes (www.cpc.noaa.gov/ensocycle). The calculations for this index are based on the differences in air pressure anomaly between Tahiti and Darwin, Australia. Below-normal air pressure at Tahiti and above-normal air pressure at Darwin is represented by the negative phase of the SOI.

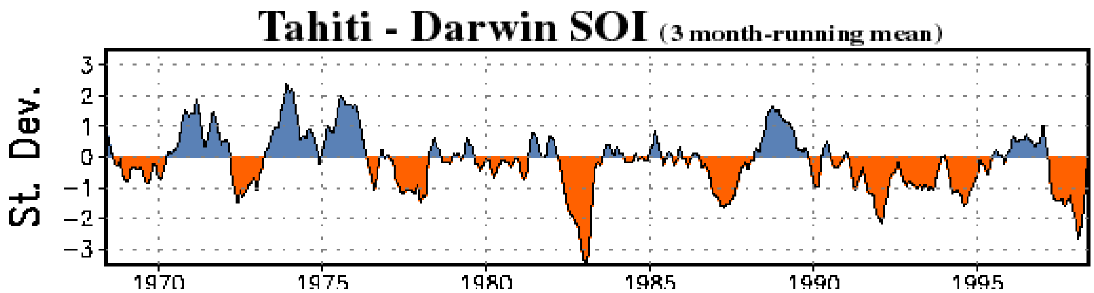


Figure 2.6.5. Time series of the SOI. Negative (positive) values are associated with the warm (cold) phase of ENSO (from www.cpc.noaa.gov/ensocycle).

The time series of the SOI and sea surface temperatures in the eastern equatorial Pacific indicates that the ENSO cycle has an average period of about four years, although in the historical record the period has varied between two and seven years (Figure 2.6.5). Therefore this index differs from the PDO and the NPI, which have more consistently decadal shifts. Historically, there is considerable variability in the ENSO cycle from one decade to the next. For example, there are decades in which the cycle was relatively inactive, and decades in which it was quite pronounced.

The SOI is positively correlated with SWE and annual runoff in the Pacific Northwest and negatively correlated in the Southwest because the negative (positive) values of SOI are associated with the warm (cold) of ENSO phase. ENSO influences are limited in the Colorado region, which is typically regarded as the midpoint of a see-saw with strong opposing ENSO associations to the north and south, but no associations in Colorado itself (Clark et al. 2001).

ENSO has a distinct influence upon snow accumulations in some areas. Clark et al. (2001) assessed SWE data from hundreds of montane sites in the Columbia and Colorado River Basins to investigate effects of El Niño and La Niña events on the seasonal snowpack. The Columbia watershed encompasses portions of Oregon, Idaho, and Washington, while the

Colorado watershed and its tributaries drain southwestern Wyoming and western Colorado, parts of Utah, Nevada, New Mexico and California, and almost all of Arizona. Analyses of the data indicate that in the Columbia River Basin, there is a general trend for SWE increases during La Niña years and SWE declines during El Niño years. In the Colorado River Basin, SWE and annual runoff tend to be smaller in the northern half of the basin and greater in the south during El Niño years. The opposite influences tend to occur during La Niña years.

Overall, the cyclical climate variations due to ENSO or the PDO do play an important role in affecting temperature, precipitation, and snow on year-to-year and decadal time scales. However, they do not explain the consistent warming trend that has occurred across the West. Further, Mote (2006) concludes that even considering these known patterns of climate variability, the negative trend in snowpack is consistent with anthropogenic warming.

2.7 Summary

There are several interesting conclusions from the previous research. First, temperatures are increasing monotonically and are most influential in low to moderate elevation areas. Precipitation, however, does not show a similar monotonic change. Precipitation trends are more the result of decadal-scale fluctuations in Pacific Climate and have been associated with variations in Pacific Climate indices such as the PDO and NPI. Snow pack is influenced by both precipitation and temperature. An area that is low to moderate in elevation is mostly influenced by temperature. Consequently, areas in lower elevation mountains of the Pacific Northwest are most sensitive to temperature changes and, therefore, have seen the largest declines in SWE. Higher elevations, located in the Southwest and the interior West are influenced more by precipitation than temperature because their average mean winter temperatures are still well below freezing.

Despite the intriguing conclusions provided by much of the research, there are clearly a number of areas, which deserve further attention. Of particular concern is the limited quality of the data used in many studies, both in terms of time frame and elevational distribution. Studies that use the automated observations of SWE via the Natural Resources Conservation Service Snowpack Telemetry (SNOTEL) network cannot provide useful information about long-term trends in patterns of snow accumulation and melt because the longest records available for these observations are only slightly more than 20 years (Hamlet et al. 2005). Many of the above studies on SWE trends have relied on data from snow course surveys. This network of observations does not tend to cover the transient zone where snow is highly sensitive to temperature changes (Hamlet et al. 2005). An examination of stations used in Regonda et al. (2005) and Knowles et al. (2006) shows that snow course stations are nearly all above 2500 m in areas like Colorado, Utah, and northern New Mexico. Finally, the snow course data lack temporal resolution with observations typically taken monthly after midwinter (Hamlet et al., 2005).

Previous research suggests that trends in snow pack vary by region, elevation, and their response to variations in Pacific Climate. A critical question, then, is whether the elevation trends of the previous research would be evident in a region such as the Colorado Rocky Mountains if lower elevation stations where included in the analysis?

This study will build upon previous investigations of snow trends by examining trends in snow depth by elevation using the cooperative observing dataset. The cooperative observing station network provides snow depth data at a greater range in elevation than is offered by the snow course dataset and at a superior temporal resolution (i.e. daily). No study has used this dataset to examine trends in snow by elevation. A superior understanding of the amount of change in snow with elevation is particularly important in light of anthropogenic warming. Even using conservative projections of the expected winter warming rate for western mountains, Mote (2006) suggests that by the start of the next century the majority of the westernmost mountains on the continent would lie in the transient snow zone, where snow accrues and melts repeatedly during the snow season, so that, even at higher elevations, the spring SWE would grow increasingly sensitive to temperature.

CHAPTER 3

DATA AND METHODOLOGY

The objective of this study is to utilize a higher density cooperative data set, which will incorporate stations at a large range in elevations and a larger spatial extent including stations east and west of the Continental Divide. In addition, the meteorological forcing mechanisms that explain snow depth variability will also be examined. The following sections will describe the snow depth and meteorological datasets as well as the methodologies for computing temporal trends, analyzing the relationship between meteorological variables and snow depth trends, and for evaluating the role of Pacific climate variability on snow depth trends.

3.1 Data

Daily snow depth, as well as meteorological data (snowfall, and maximum and minimum temperatures), from 1949-2004 were obtained from cooperative observing stations in the Rocky Mountains of Colorado (United States Department of Commerce 2003). All observations were subjected by Dyer and Mote (2006) to a quality control routine following a methodology by Robinson (1989). Stations were selected geographically within the Southern Rocky Mountains with an observation record start year of at least 1950. These 120 stations are plotted in Figure 3.1.1 and listed in table format in Appendix A.

Two methods were used to fill in missing data. A cubic spline routine was used for variables that were not zero bounded (temperature) or generally not zero bounded (snow depth).

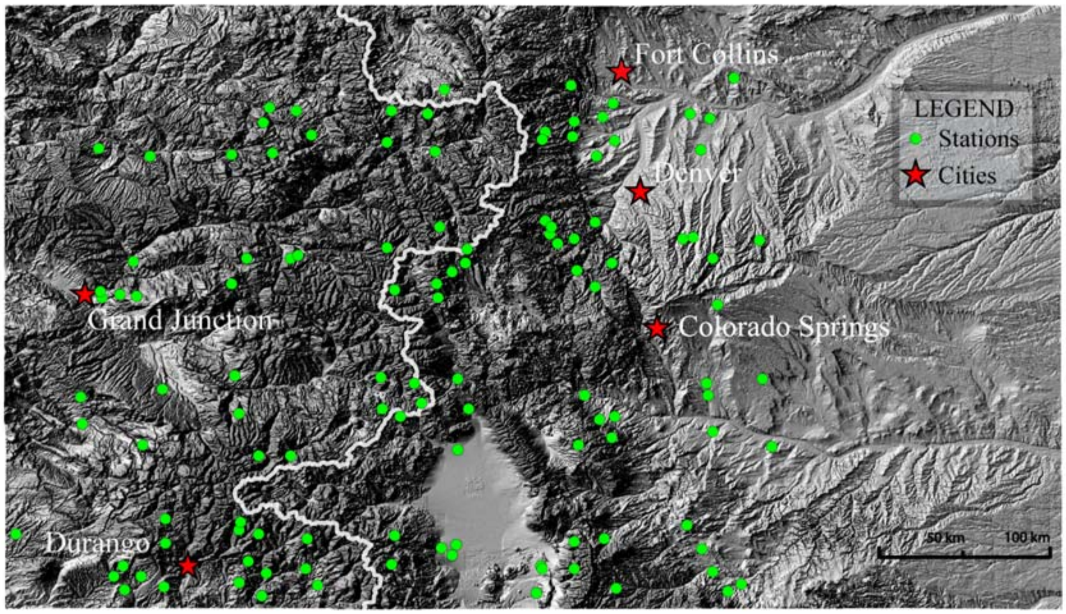


Figure 3.1.1. Cooperative observing station distribution for the Colorado Rocky Mountains.

Only years that had no more than 15% of the values interpolated and gaps in data of no more than 4 days for snow depth and 5 days for temperature were retained for use in this study. Slightly less stringent restrictions were used for temperature because it is not zero bounded. For zero bounded data such as snowfall, only years that were 90% complete with data gaps of less than or equal to 4 days were retained. These thresholds were subjectively determined to balance data quality with the need to maximize the number of years available for the study.

Accumulated seasonal values for snow depth, snow days, snowfall, and melting degree days from 1 November through 31 March were used. The accumulated value was computed by summing the daily values of a particular variable over the 151 days of the season. These seasonal values were then compiled into an annual time series for trend analysis. Accumulated values were used because they integrate both time and magnitude. Also, the use of accumulated values allows for comparison between stations where temporal patterns in snow depth accumulation may vary by elevation. Two derived variables were computed from the original snow depth and temperature datasets. Melting degree days were calculated from the daily maximum and minimum temperature data sets and represent the number of degrees the average daily temperature is above the freezing point. Melting degree days are a useful measure of the energy available for snowpack ablation. Accumulated snow days were computed from the snow depth dataset and included any day with snow present.

This project used snow depth rather than SWE as was examined in most other studies (Mote 2003a, 2006; Mote et al. 2005, Hamlet et al. 2005, Regonda et al. 2005) in order to include greater range in elevation. The cooperative station data used for this study have a 2150 m range in elevation (1300-3450 m). The available NRCS SWE, in contrast, has only a 250 m range in elevation (2377-2627 m).

Many geographic (latitude and longitude) and physiographical (elevation and aspect) variables that may affect the snow and meteorological data are interrelated in the complex terrain of the mountains. For instance, an increase in latitude may also coincide with a change in elevation of the mountain ranges. Thus, to scrutinize some of the major geographic influences on the trends, the study considered elevation, latitude, longitude and aspect. The elevation, latitude and longitude data were provided in the cooperative station dataset. Aspect data for each cooperative station were obtained from the United States Geological Survey (http://rockyags.cr.usgs.gov/ESA/getESA.aspx).

3.2 Trend Computation

For each station, standardized temporal trends for accumulated seasonal snow depth, snowfall, snow days, and melting degree days were computed. The number of stations available for use in the study depended on the particular variable. There were 109 stations for snow depth and snow days, 119 for snowfall, and 60 for melting degree days. The number of cooperative stations available to compute temporal melting degree day trends was limited to 60 due to the need for stations with both minimum and maximum temperature values. Prior to the trend analysis, each time series was visually inspected for outliers. Questionable data were evaluated by comparison with neighboring stations and for consistency with other variables for that station. For instance, an extremely large accumulated snow depth value for a given season would be compared with the snowfall dataset to insure that the season had a large quantity of snowfall. Data for any of the four variables that could not be verified were removed from the trend analysis.

Temporal trends were computed in a manner similar to that used by Lu et al. (2005). A regression line was fit to each time series and the slope of the regression line was computed. The slopes were then standardized for each station by dividing by the standard error. The advantage of using the standardized trend is that the standard error accounts for missing data. A large number of missing values will inflate the standard error. In addition, the standardized values make it easy to compare stations, which have variables of different magnitudes.

The relationship of temporal trends in snow depth and meteorological variables versus elevation was investigated using scatter diagrams. Here, the temporal trends were plotted against elevation and a regression line was fit through the data to access the elevation trend. The level of significance of the elevation trend was determined using a test of correlation:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \tag{3.2.1}$$

where r is the correlation coefficient and n is the number of years of data. Relationships were considered statistically significant for $p \leq 0.10$. Scatter diagrams were plotted with all data as well as with only negative and positive temporal trends.

Finally, the standardized temporal trends for the snow depth and the meteorological variables were plotted on maps to assess the spatial patterns. All temporal trend values were plotted, but statistically significant ones (i.e. $p \leq 0.05$ and $p \leq 0.10$) were accentuated. Latitude, longitude, elevation, and aspect are important geographic and physiographic variables that influence snow depth, snowfall and MDD in mountainous terrain. A stepwise linear regression model with the temporal trend (snow depth, snowfall or MDD) as the output and geographic and physiographic variables as inputs was used to identify the key variables in explaining the spatial variability. The stepwise regression was run using backward elimination where each variable was tested for statistical significance and eliminated if not significant (Hamilton 2004). For each variable a t-statistic was computed from a ratio of the regression coefficient divided by the standard error. A hypothesis test was then conducted to test the null hypothesis that the coefficient equals zero. A level of significance for a two-tailed test of $p \leq 10\%$ was used.

3.3 Meteorological Analysis of Trends

The relationship between snow depth and the meteorological variables was explored using a methodology similar to Mote (2006). Only stations with statistically significant snow depth trends were considered for use in the analysis. In addition, the number of stations used in this portion of the analysis is limited because it requires that the stations have data for both melting degree days and snowfall. Even if the station has data for both meteorological variables, some snow depth data years may be missing. Thus, the time series of data is often a subset of the original datasets. An example is provided in Table 3.3.1, which shows data for the period from 1949-1961 for one station. The years 1949-1957 would not be used in the analysis because of missing snow depth and/or MDD data but 1958-1960 would be used because data for all three variables is available. Trends for the subset datasets (snow depth, snowfall, and MDD) were compared with the original ones to insure that the loss of some data does not affect the sign or magnitude of the original trend.

Table 3.3.1. Original data sets for accumulated snow depth, snowfall and MDD for Gateway (5324602). Years that did not have a recorded value for any of the three variables are not included in the table. Gray shaded rows are years that were not included in the regression analysis because of incomplete data.

Year	Accumulated Snow Depth (cm)	Accumulated Snowfall (cm)	Accumulated MDD (ºC)
1949	408.9	99.6	
1950	149.9	62.0	
1951		45.2	
1953	5.1	21.1	
1954		33.5	
1955		19.6	
1957		56.6	505.7
1958	43.2	26.7	491.8
1959	35.6	0.0	643.2
1960	119.4	82.3	466.5
1961	5.1	22.9	579.9

The multiple regression models were constructed using accumulated seasonal snow depth as the dependent variable and accumulated melting degree days and snowfall as independent variables for each station. Multiple regression models were constructed because they are valuable for quantifying the impact of various simultaneous influences upon a single dependent variable. First, the estimated snow depth trends were compared with the observed snow depth trends. If the model did a poor job of reproducing the observed trend (i.e. the estimated diverges from the observed trend in either magnitude or sign) the station was excluded from further analysis. For the stations that were retained, the regression

coefficients allow the variables such as melting degree days and snowfall to be converted into units of snow depth. Next, the regression coefficients for snowfall and melting degree days were used in an equation to estimate the snow depth trend from the trends in the meteorological variables:

$$SNWD_{derived} = a_{mdd} \times slope_{mdd} + a_{snof} \times slope_{snof} \qquad \textbf{(3.3.1)}$$

(Mote 2006) where $SNWD_{derived}$ is the estimated snow depth trend (cm yr^{-1}), $slope_{mdd}$ is the trend in melting degree days (^{o}C yr^{-1}) and $slope_{snof}$ is the snowfall trend (cm yr^{-1}). This model allows an assessment of the relative importance of snowfall versus melting degree days on the snow depth trend. For instance, the quantity α_{mdd}*$slope_{mdd}$ is the estimated snow depth trend if the variable melting degree days was the only climatic variable influencing the accumulated snow depth trend. The percentage of the estimated snow depth trend explained by snowfall or melting degree days is computed by dividing the quantities α_{mdd}*slope$_{mdd}$ and α_{snof}*slope$_{snof}$ by the derived snow depth trend (SNWD$_{derived}$) and multiplying by 100. The results were examined to see the relative importance of thermal factors versus precipitation on sites with negative and positive trends.

3.4 Pacific Climate Variations

Several studies have identified the importance of Pacific climate variations on the climate across the Western United States. Three indices of Pacific climate were used in the study. The Pacific Decadal Oscillation (PDO) is a low frequency teleconnection based on North Pacific Ocean temperatures. It was obtained from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) at the following web address: http://jisao.washington.edu/pdo/PDO.latest. The monthly index values were derived as the leading principal component of monthly sea surface temperature anomalies in the North Pacific Ocean, poleward of 20^{o}N (Mantua et al. 1997). The North Pacific Index is an atmospheric index that measures the strength of the Aleutian Low (Trenberth and Hurrell 1994). Monthly data were obtained from the Climate Analysis Section of the National Center for Atmospheric Research (NCAR) at the following web address: http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html#nam. Finally, the Southern Oscillation Index (SOI) is a measure of the pressure variations between the eastern and western tropical Pacific Ocean (Trenberth 1997, Walker 1924; Kiladis and van Loon, 1988). The index is computed as standardized differences in pressure between Tahiti and Darwin, and is obtained from the National Center for Environmental Predication:

http://www.cpc.ncep.noaa.gov/data/indices/soi. For this study, the monthly index values are averaged over the November-March season. Each index was correlated against time series data for snow depth, snowfall, and MDD. Only stations that have statistically significant trends ($p \leq 10\%$) will be analyzed.

CHAPTER 4

RESULTS

The objective of this study is to examine the temporal trends in snow depth, snowfall, melting degree days, and snow days, and how the temporal trends of these stations vary with elevation over space. In addition, the meteorological factors that explain the trends are examined. First, the role of temporal trends in MDD and snowfall in explaining snow depth trends are investigated. Second, the influence of Pacific climate variables on snow depth, snowfall, and MDD are examined.

4.1 Temporal Trends

Temporal trends in seasonal accumulated snow depth, snowfall, MDD, and snow days were computed for each station (Appendix A). The slope of the regression line was used to determine the temporal trend. Examples of snow depth time series for two stations, Shoshone (west of the Continental Divide) and Boulder (east of the Continental Divide), are used to illustrate this methodology (Figure 4.1.1). The trends in Appendix A and of the two examples in Figure 4.1.1 show that the temporal trends vary both in sign and magnitude. The following two sections will examine whether there is a pattern either by elevation or over space to these temporal trends.

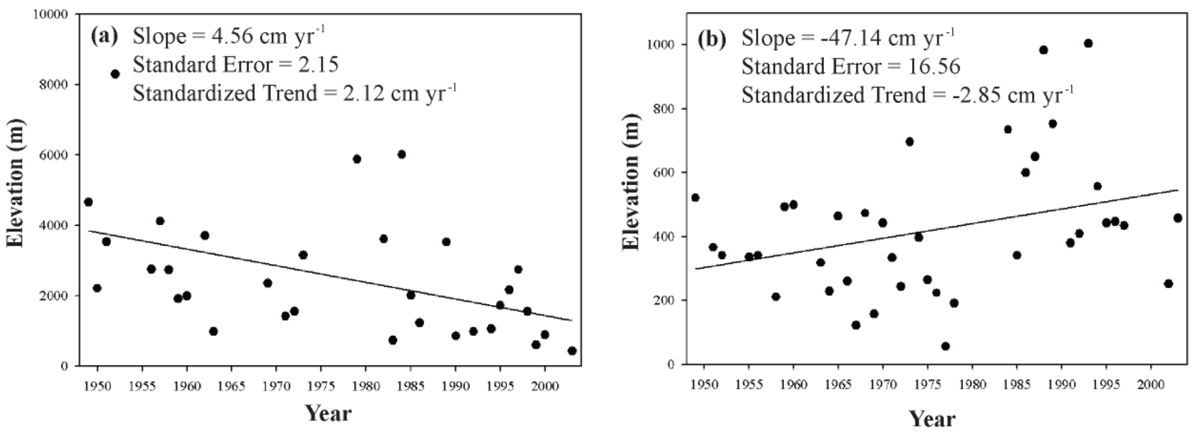


Figure 4.1.1. Examples of snow depth time series for two stations: (a) Shoshone (5761802) is west of the Continental Divide at 1,808 m (b) and Boulder (5084804) is east of the Continental Divide at 1,672 m. The slope of the regression line is shown along with the standard error value that was used to compute the final standardized snow depth trend.

4.2 Temporal Trends with Elevation

The relationship between trends in snow depth and meteorological variables was examined by elevation. As noted in Chapter 2, past research has suggested that there are differences in trends of snow depth (Regonda et al. 2005, Mote et al. 2005) and meteorological variables (Knowles et al. 2006, Beniston et al. 1997) with elevation.

Accumulated seasonal snow depth as well as MDD, snowfall and snow days are examined for trends with elevation (Figure 4.2.1). However, only the accumulated snowfall trend exhibits a statistically significant relationship (at $p \leq 5\%$) with elevation (Figure 4.2.1b). There is a positive relationship between snowfall trends and elevation as seen in Figure 4.2.1b. The accumulated snowfall trend becomes less negative with increasing elevation. In other words, the low elevation stations have a decreasing trend in snowfall while the higher elevations are experiencing an increasing trend in snowfall over the study period (1949-2004). The threshold for negative versus positive trends is between 2000 m and 2500 m, which is near a threshold that has defined high versus low elevations in previous studies (Mote et al. 2005, Regonda et al. 2005). Mote et al. (2005) define high elevations as having a mean elevation of 2600 m and Regonda et al. (2005) regard high elevations as those above 2500 m.

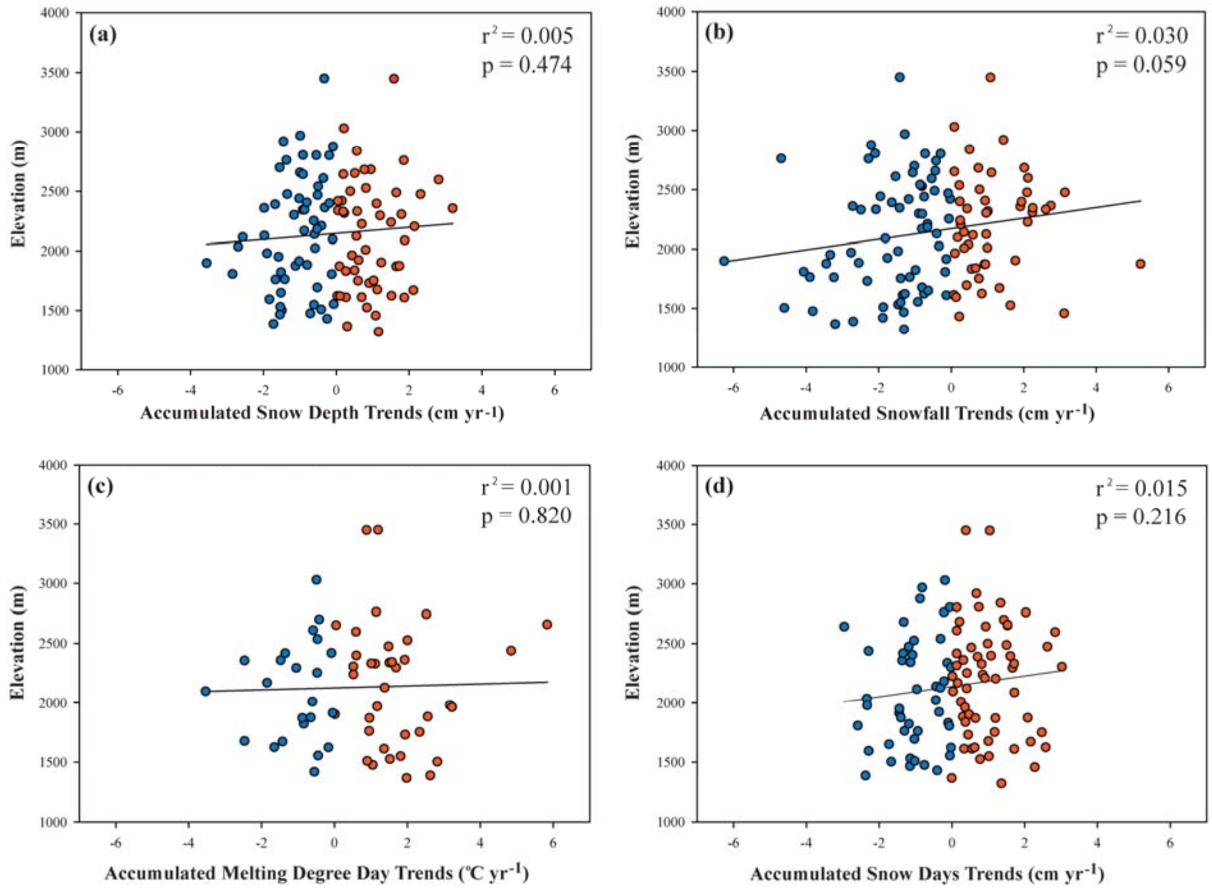


Figure 4.2.1. Standardized accumulated temporal trends versus elevation for: (a) snow depth, (b) snowfall, (c) melting degree day, and (d) snow days. Blue (red) points are negative (positive) temporal trends.

Next, stations were stratified into groups with positive and negative temporal trends of snow depth, snowfall, melting degree day, and snow day. The negative and positive trends for each of the four variables were plotted against elevation since it was possible that a pattern was only evident for negative or positive trends. When only the negative temporal trends were plotted by elevation, both snow depth and snowfall temporal trends show statistically significant relationships with elevation (at p≤5%; Figure 4.2.2). The trend between the negative snow depth

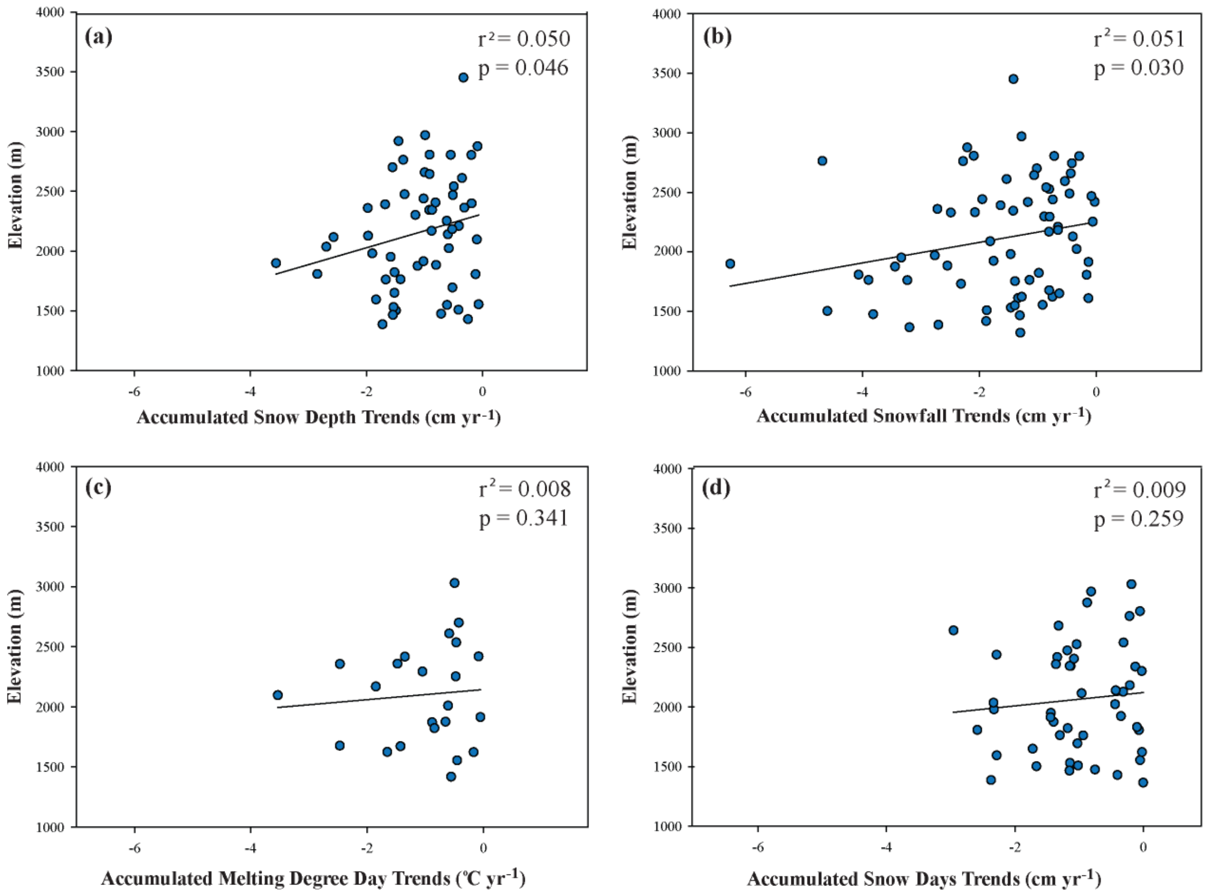


Figure 4.2.2. Standardized accumulated negative temporal trends versus elevation for: (a) snow depth, (b) snowfall, (c) melting degree day, and (d) snow days.

temporal trends and elevation show a direct relationship, meaning that as elevation decreases the snow depth trend becomes more negative. This supports the hypotheses of previous studies that lower elevation stations are experiencing larger decreases in snow depth than those at a higher elevation. The relationship between temporal snowfall trends and elevation is also a direct relationship confirming that the lower elevations are experiencing the largest decreases in snowfall over the study period. The temporal MDD trends show no relationship with elevation. Scatter diagrams of only positive trends showed no statistically significant patterns (Figure 4.2.3).

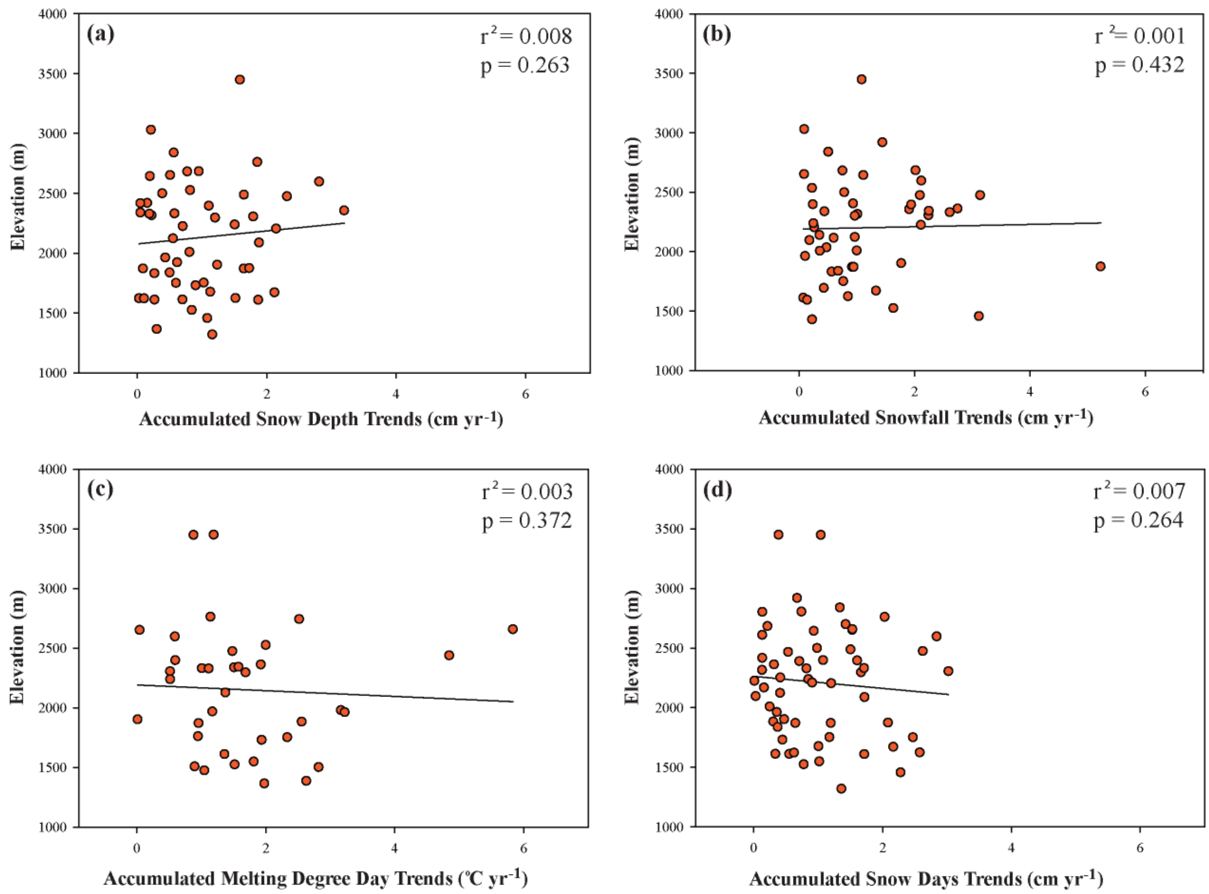


Figure 4.2.3. Standardized accumulated positive temporal trends versus elevation for: (a) snow depth, (b) snowfall, (c) melting degree day, and (d) snow days.

4.3 Spatial Trends

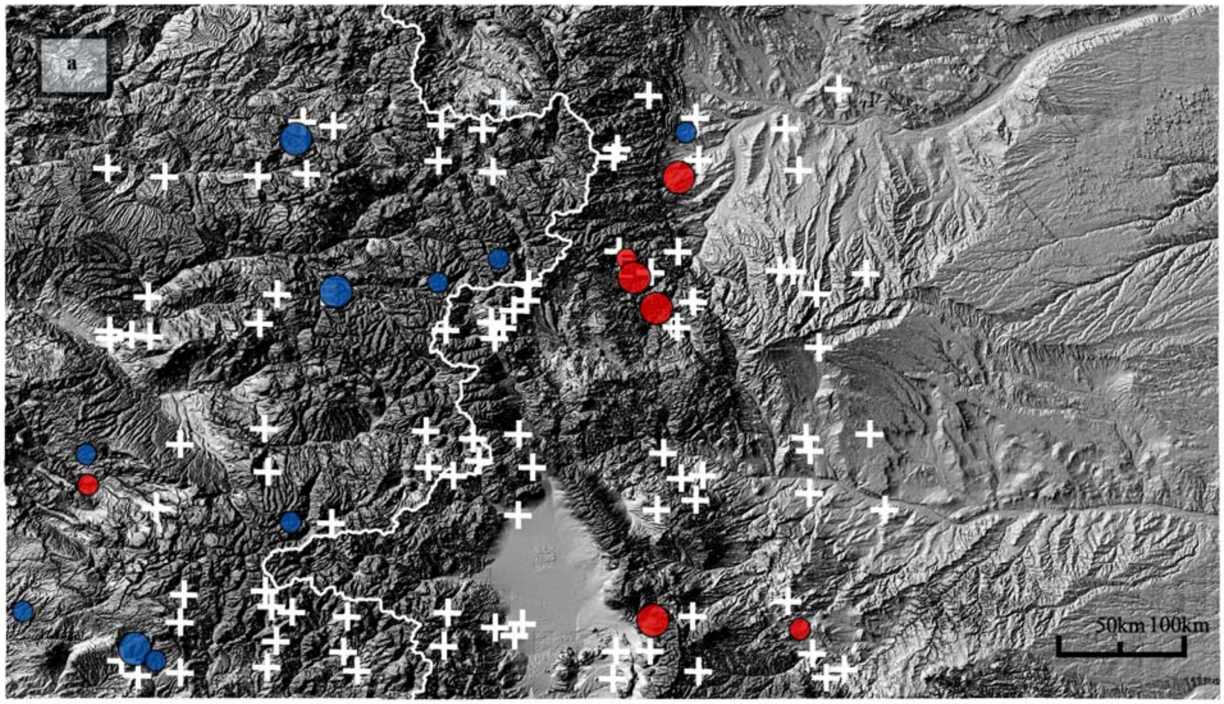
The spatial patterns of trends in snow depth, MDD, snowfall, and snow days were investigated (Figure 4.3.1). As mentioned in Chapter 3, the number of stations differs by variable due to data availability and the small number of MDD stations was due to the limited availability of stations with both the minimum and maximum temperatures needed to compute

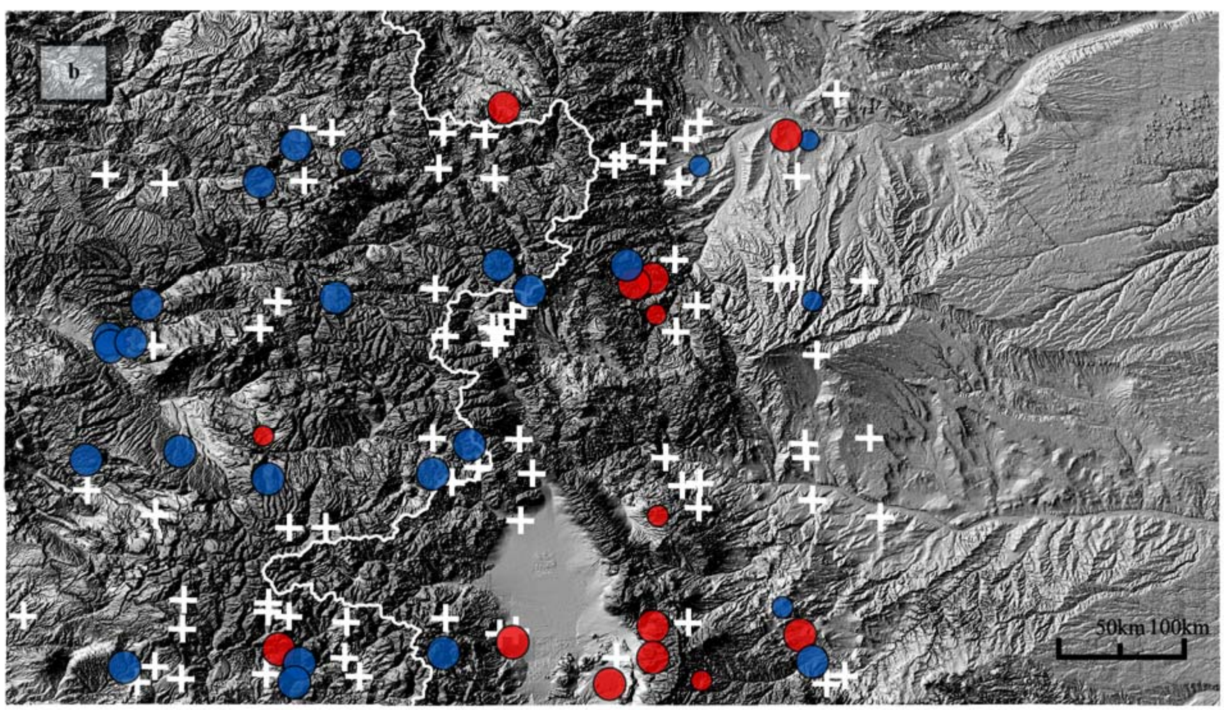
MDD. Consequently, temporal snow depth and snow day trends were computed at 109 of the 120 cooperative observing stations, snowfall trends were computed at 119 of the stations, and MDD trends at only half (60) of the stations.

There are distinct spatial patterns between areas with increasing and decreasing trends. In particular, the snow depth, snowfall, and snow day trends are predominately positive to the east of the Continental Divide and predominately negative to the west of the Continental Divide (Figure 4.3.1a, 4.3.1b, 4.3.1d). MDD trends are mostly positive across the region except for a small pocket of stations with negative trends in the east central portion of the state (Figure 4.3.1c).

4.3.1 Stepwise Regression

A stepwise linear regression model was used to isolate the important geographic variables that explain the spatial pattern of the snow depth, snowfall, and MDD trends. The results of the stepwise regression suggest that longitude is the most important variable for explaining the snow depth and snowfall patterns (Table 4.3.1). Longitude is statistically significant at the at $p \leq 1\%$ level for both snow depth and snowfall trends. This supports the findings from a visual analysis of the data in the previous section. Other variables were of secondary importance and are different for each individual trend. Aspect shows up as a statistically significant influence on snow depth trends at $p \leq 10\%$, while latitude shows up as a statistically significant influence on snowfall at $p \leq 10\%$. For MDD trends, none of the variables were statistically significant at $p \leq 10\%$.


a
50km 100km


b
50km 100km

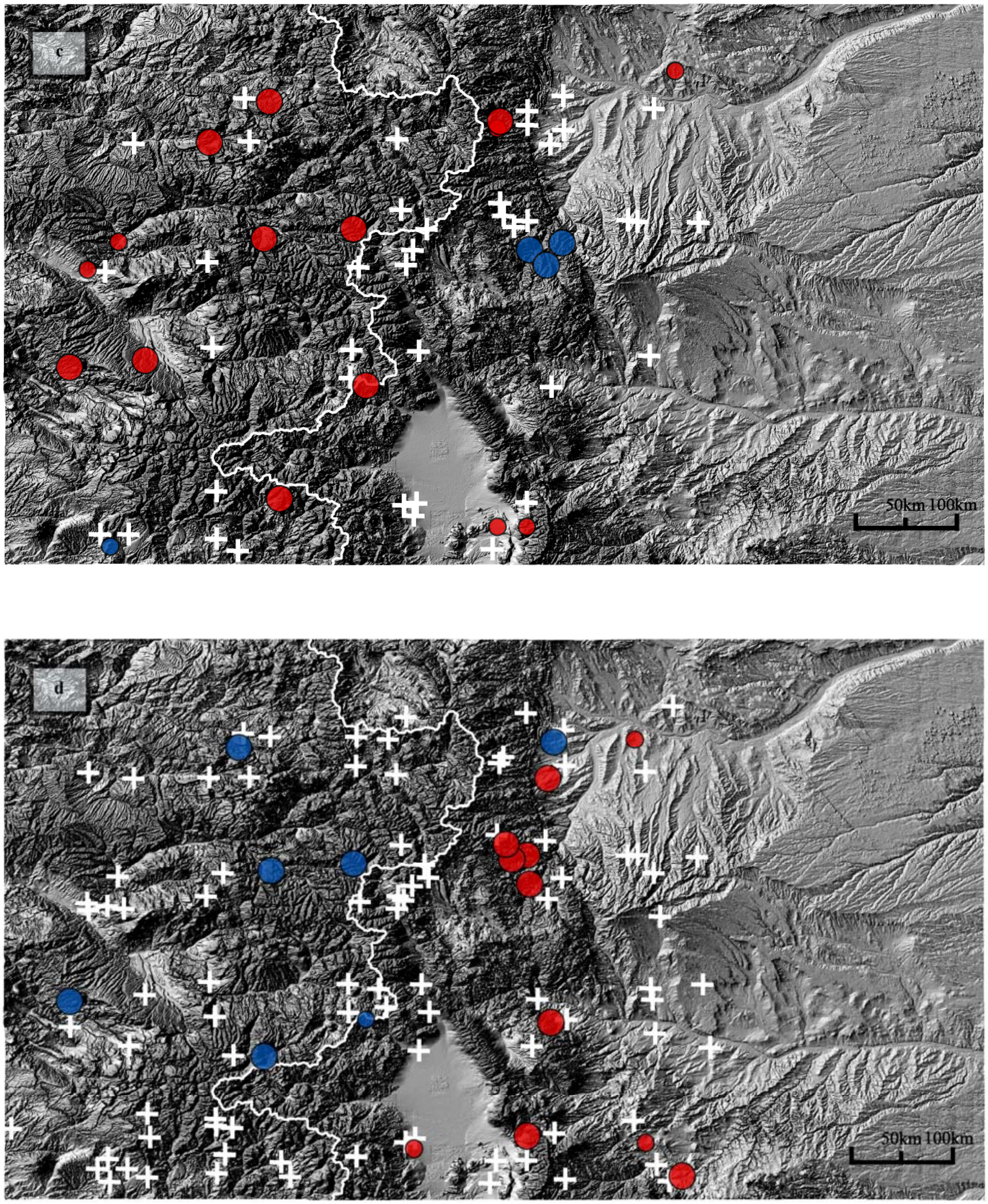


Figure 4.3.1. Accumulated (a) snow depth, (b) snowfall, (c) melting degree days and (d) snow day trends. Blue (red) circles are negative (positive) trends, large (small) circles are statistically significant at p≤5% (10%) level. The pluses represent insignificant trends.

Table 4.3.1. Stepwise linear regression results for snow depth, snowfall, and melting degree days (MDD). The t-value is a statistical value computed from the ratio of the regression coefficient divided by the standard error. The p-value is the level of significance for a two-tailed test. An X indicates the variable was insignificant (p>10%) and not included in the model.

	Snow Depth		Snowfall		MDD	
	t	**p**	**t**	**p**	**t**	**P**
Latitude	X	X	-1.73	0.092	X	X
Longitude	3.04	0.007	3.80	0.001	X	X
Aspect	-2.04	0.056	X	X	X	X
Elevation	X	X	X	X	X	X

4.4 Meteorological Influences

A multiple regression model using MDD and snowfall to predict snow depth was used to examine the relationships among the different variables. The number of stations for this portion of the analysis was initially limited to nine because of the need for corresponding snow depth, snowfall, and MDD data sets. However, the stations represent a sample of stations with both positive and negative snow depth trends, and a range in elevations (1387-2475 m). Of the stations that were retained for analysis, only a subset of the total years were available (i.e. merged dataset) for use in the regression analysis because of missing data within the input datasets (for example Table 3.3.1). The following sections will provide an assessment of how representative the subset datasets are of the original data, an assessment of the model estimates of accumulated snow depth, and finally an investigation of the climate factors influencing the snow depth trend.

4.4.1. Evaluation of Trends in Subset Years

The degree to which temporal trends in the subset of years matched the complete dataset was examined to insure that the loss of some data in the subset did not affect the sign or magnitude of the original trend. Only stations with greater than 20 years of data were retained in the analysis. Thus, three stations: Georgetown (5326104), Idaho Springs (5423404), and Mancos (5532702) with between seven and 13 years were not examined further. Green MT Dam (5359202) was also removed because the regression did poorly (further explanation is below in section 4.4.2). For the remaining five stations, the trends for each variable (snow depth, snowfall, and MDD) were computed for the subset and complete dataset (Table 4.4.1). The statistical significance of each slope was determined using a test of correlation.

Overall, the sign and magnitude of the temporal trends of the merged and complete datasets match. For complete and merged snow depth, all but one of the merged trends are significant at $p \leq 10\%$ and most are significant at $p \leq 5\%$. For snowfall, the statistical significance of the complete versus merged trends corresponds for two stations. Eagle County AP (5245402) was not originally significant in the complete data set, but became statistically significant ($p \leq 10\%$) in the merged data set. Gateway 1 SE (5324602) was highly significant ($p \leq 1\%$) in the complete data set, but became insignificant with the loss of 13 years in the merged data set. For MDD, the stations with significant trends ($p \leq 10\%$) in the original dataset also had significant trends of the same magnitude in the merged dataset. Three stations did not have significant trends in either dataset.

4.4.2. Observed and Estimated Snow Depth Trends

A regression model was constructed where MDD and snowfall were used to predict snow depth. The results indicate that the model performs well because the trends are similar in both magnitude and sign at four of the six stations (Table 4.4.2). At Bailey (5045404), the estimated trend is similar in sign, but too low in magnitude. In contrast, at Green MT Dam (5359202), both the magnitude and sign are different between the observed and predicted snow depth trends. This station will be removed from further analysis since the regression estimate so poorly matches the observed trend.

Table 4.4.1. Comparison of temporal trends (cm yr^{-1}) for the complete dataset and for the merged dataset. Merged dataset only includes years that are available for all three datasets. The asterisks correspond to *p≤10%, **p≤5%, ***p≤1%.

Station ID	Name	Years	Complete		Years	Merged	
Snow Depth							
5045404	**Bailey**	24	55.73	***	23	62.28	***
5084804	**Boulder**	39	4.56	**	38	4.87	**
5245402	**Eagle County AP**	43	-26.05	*	42	-29.63	**
5324602	**Gateway 1 SE**	36	-3.94	*	31	-4.23	
5354105	**Great Sand Dunes N M**	26	26.16	**	25	26.58	**
Snowfall							
5045404	**Bailey**	47	0.65	*	23	0.87	*
5084804	**Boulder**	49	0.58		38	0.54	
5245402	**Eagle County AP**	43	-0.81		42	-0.93	*
5324602	**Gateway 1 SE**	44	-0.60	***	31	-0.54	
5354105	**Great Sand Dunes N M**	45	0.96	***	25	1.03	**
MDD							
5045404	**Bailey**	47	-1.54	**	23	-1.84	**
5084804	**Boulder**	47	-1.65		38	-0.36	
5245402	**Eagle County AP**	42	1.96	***	42	1.96	***
5324602	**Gateway 1 SE**	41	3.61	**	31	3.79	**
5354105	**Great Sand Dunes N M**	48	1.10		25	0.55	

Table 4.4.2. Comparison of observed and estimated temporal snow depth trends. Positive (negative) trends are in red (blue). Trends are in cm yr^{-1}.

Station ID	Name	Years	Observed	Estimated
5045404	**Bailey**	23	**62.28**	**35.97**
5084804	**Boulder**	38	**4.87**	**2.14**
5245402	**Eagle County AP**	42	**-29.63**	**-24.22**
5324602	**Gateway 1 SE**	31	**-4.23**	**-2.77**
5354105	**Great Sand Dunes N M**	25	**26.58**	**21.87**
5359202	**Green MT Dam**	22	**-53.11**	**5.19**

4.4.3. Influence of Climate Variables on Snow Depth

The multiple regression coefficients were used to convert MDD and temporal snowfall trends into units of snow depth, allowing one to determine the relative importance of MDD versus snowfall on temporal snow depth trends (Table 4.4.3). The results show that MDD and snowfall may work in concert or oppose each other in affecting the trend in snow depth. Snowfall was the primary influence on the temporal snow depth trend at four of the five stations. It is directly related to snow depth and explains 39% to 128% of the variability in the snow depth trend. A value over 100% is possible since MDD is inversely related to snow depth and may counterbalance the influence of snowfall. Thus, if one considers only the snowfall at Gateway (5324602), the snow depth would have been 28% greater than actually occurred. Snowfall exerted both positive and negative influences on snow depth depending on the station. The positive snowfall trends at three of these stations contributed to the overall increase in snow depth, while the negative trends at the other two stations lead to the overall decrease in snow depth.

MDD has an inverse relationship with snow depth and was the primary influence at only one station. The influence was small at two stations (3% and 6%), but more substantial at the remaining stations, explaining from 23%-61% of the snow depth trend. At Bailey (5045404), MDD explained 61% of the estimated snow depth trend. Here, the MDD lead to the overall increase in snow depth because of the cooling trend. This cooling trend coupled with an increasing snowfall trend lead to an increasing trend in snow depth.

Table 4.4.3. Percent explained variance of the estimated seasonal snow depth trend for melting degree days (MDD) and snowfall. All values are accumulated seasonal values.

Station ID	Name	Latitude	Longitude	Elevation (m)	Years	Snow Depth Trend	MDD (%)	Snowfall (%)
5045404	**Bailey**	39.2	-105.3	2356	23	36.0	61	39
5084804	**Boulder**	40.0	-105.2	1672	38	2.1	6	94
5245402	**Eagle County AP**	39.4	-106.6	1980	42	-24.2	23	77
5324602	**Gateway 1 SE**	38.4	-108.6	1387	31	-2.8	-28	128
5354105	**Great Sand Dunes N M**	37.4	-105.3	2475	25	21.9	-3	103

4.5 Pacific Climate Variability

Several indices of Pacific climate variability (PDO, SOI, and NPI) were examined to investigate the influence upon the spatial pattern of snow depth, snowfall, and MDD trends. Only stations with statistically significant trends were used in the analysis.

The results show very distinct patterns in the correlations between snow depth and the climate indices (Table 4.5.1). To the east, The PDO Index is positively correlated with the snow depth trend while the NPI and the SOI are negatively correlated with the snow depth trend. Waterdale (5883904) is the only station that does not fit this pattern. This stations correlations are similar to the majority of the stations west of the Continental Divide. A possible explanation is that it has a west facing orientation, which is similar to most of the western stations. On the western side of the Continental Divide, the PDO Index is negatively correlated with the snow depth trend while the NPI is positively correlated with the snow depth trend. The only exceptions are stations that have very small correlations close to zero and eastern or southern orientations more similar to stations to the east. There is less consistency in sign with SOI with four stations having negative correlations and six with positive.

Table 4.5.1 PDO, NPI, and SOI Index correlations with Snow Depth Trends (cm yr^{-1}). Positive (negative) correlations are in red (blue).

Side of the Continental Divide	Station ID	Name	Years	Aspect	Elevation (m)	Snow Depth Trend	PDO	NPI	SOI
WEST	5232602	Dolores	17	W	2,115	-2.57	-0.15	0.21	-0.38
	5245402	Eagle County AP	43	SW	1,980	-1.90	-0.25	0.36	0.23
	5324602	Gateway 1 SE	36	N	1,387	-1.72	-0.40	0.22	0.40
	5359202	Green Mt Dam	28	W	2,359	-1.98	-0.27	0.26	0.18
	5373802	Hamilton	10	W	1,899	-3.56	-0.38	0.44	-0.59
	5532702	Mancos	9	E	2,128	-1.97	0.01	-0.02	-0.72
	5597002	Northdale	5	NW	2,036	-2.69	-0.36	0.27	0.11
	5620302	Ouray	50	NW	2,390	-1.68	-0.09	0.17	0.10
	5631502	Paradox	12	S	1,610	1.87	0.04	0.05	-0.12
	5761802	Shoshone	32	NW	1,808	-2.85	-0.22	0.35	0.11
EAST	5045404	Bailey	24	SE	2,356	3.20	0.50	-0.41	-0.34
	5084804	Boulder	39	NW	1,672	2.12	0.38	-0.18	-0.13
	5326104	Georgetown	13	S	2,597	2.81	0.74	-0.80	-0.21
	5354105	Great Sand Dunes	26	E	2,475	2.31	0.33	-0.34	-0.58
	5878101	Walsenburg	22	S	1,875	1.73	0.38	-0.15	-0.14
	5883904	Waterdale	26	W	1,594	-1.84	-0.36	0.31	0.06
	5917502	Winter Park	49	SE	2,761	1.85	0.13	-0.03	0.01

There are similar findings when examining snowfall trends versus the index values (Table 4.5.2). On the east side of the continental divide, correlations are mainly positive with the PDO and negative with the NPI and SOI. Indeed, 15 of 19 stations have positive correlations with PDO, 14 of 19 with the NPI, and 16 of 19 with the SOI. The sign of the correlations is reversed on the western side of the state. Correlations with the PDO are predominantly negative and positive for the NPI. The results are less consistent with the SOI.

Table 4.5.2. PDO, NPI, and SOI Index correlations with Snowfall Trends (cm yr^{-1}). Positive (negative) correlations are in red (blue).

Side of the Continental Divide	Station ID	Name	Years	Aspect	Elevation (m)	Snowfall Trend	PDO	NPI	SOI
WEST	5021402	Aguilar 1 SE	54	W	1,731	-2.31	**-0.27**	**0.37**	**0.07**
	5144002	Altenbern	45	N	1,903	1.77	**0.23**	**-0.21**	**-0.42**
	5177202	Bailey	47	NW	1,762	-3.23	**-0.38**	**0.36**	**0.05**
	5188602	Blanca	34	W	1,875	-3.44	**-0.34**	**0.21**	**0.17**
	5219202	Cedaredge	31	SE	1,503	-4.60	**-0.37**	**0.33**	**0.24**
	5228102	Colorado Nat'l Monument	51	W	2,763	-4.68	**-0.27**	**0.19**	**0.06**
	5314602	Cortez	36	E	1,366	-3.19	**-0.44**	**0.45**	**0.30**
	5324602	Delta	44	N	1,387	-2.70	**-0.45**	**0.38**	**0.33**
	5348802	Dillon 1 E	54	W	1,475	-3.82	**-0.31**	**0.35**	**0.16**
	5359202	Fruita 1 W	31	W	2,359	-2.72	**-0.41**	**0.30**	**0.42**
	5366202	Gateway 1 SE	46	W	2,329	-2.49	**-0.33**	**0.34**	**0.17**
	5373802	Georgetown	23	W	1,899	-6.26	**-0.52**	**0.44**	**-0.02**
	5425002	Grand Junction Walker Field	14	NW	1,969	-2.76	**-0.23**	**-0.04**	**0.14**
	5548402	Great Sand Dunes N M	26	S	1,884	-2.55	**-0.36**	**0.31**	**-0.02**
	5571702	Greeley	9	SW	1,764	-3.90	**-0.39**	**0.05**	**-0.43**
	5679702	Green Mt Dam	49	SE	2,441	-1.95	**-0.30**	**0.25**	**0.37**
	5761802	Gunnison 3 SW	26	NW	1,808	-4.06	**-0.45**	**0.43**	**0.07**
	5815402	Hamilton	32	SW	2,225	2.11	**0.06**	**0.02**	**-0.14**
	5818402	Idaho Springs	26	S	2,806	-2.09	**-0.36**	**0.24**	**-0.02**
	5858202	Ignacio 1 N	51	S	2,332	-2.07	**-0.08**	**0.13**	**-0.20**

Side of the Continental Divide	Station ID	Name	Years	Aspect	Elevation (m)	Snowfall Trend	PDO	NPI	SOI
EAST	5010201	Longmont 2 ESE	22	NE	1,951	-3.33	**0.42**	**-0.21**	**-0.38**
	5045404	Manassa	47	SE	2,356	1.91	**0.45**	**-0.44**	**-0.29**
	5077605	Meeker 3 W	47	SE	2,362	2.75	**0.48**	**-0.33**	**-0.17**
	5326104	Monte Vista 2 W	22	S	2,597	2.12	**0.36**	**-0.47**	**0.16**
	5354105	Montrose 1	45	E	2,475	3.14	**0.54**	**-0.43**	**-0.50**
	5354604	North Lake	15	NE	1,418	-1.88	**-0.05**	**0.12**	**-0.02**
	5423404	Parker 6 E	20	S	2,306	2.24	**0.18**	**-0.16**	**-0.08**
	5511604	Pyramid	46	W	1,509	-1.87	**0.06**	**-0.14**	**-0.01**
	5532205	Rye	30	S	2,344	2.25	**0.43**	**-0.27**	**-0.42**
	5570605	Shoshone	40	NE	2,332	2.61	**0.38**	**-0.20**	**-0.25**
	5599001	Tacoma	12	NW	2,684	2.02	**0.39**	**-0.18**	**-0.01**
	5632604	Taylor Park	42	NE	1,923	-1.76	**0.16**	**-0.30**	**-0.34**
	5731501	Vallecito Dam	18	S	2,088	-1.81	**0.00**	**-0.23**	**-0.06**
	5875604	Walden	53	S	2,475	2.09	**0.03**	**0.05**	**0.28**
	5878101	Walsenburg	53	S	1,875	5.22	**0.48**	**-0.34**	**-0.16**
	5893101	Westcliffe	50	S	2,396	1.94	**0.49**	**-0.34**	**-0.28**
	5914704	Windsor	19	E	1,457	3.12	**0.29**	**0.02**	**-0.01**
	5917502	Winter Park	54	SE	2,761	-2.28	**-0.22**	**0.26**	**0.06**
	5918302	Wolf Creek Pass 4 W	16	E	2,876	-2.21	**-0.45**	**0.26**	**-0.11**

Table 4.5.3. PDO, NPI, and SOI Index correlations with Melting Degree Day Trends (ºC yr^{-1}). Positive (negative) correlations are in red (blue).

Side of the Continental Divide	Station ID	Name	Years	Aspect	Elevation (m)	MDD Trend	PDO	NPI	SOI
WEST	5021402	Altenbern	42	W	1,731	1.94	-0.11	-0.06	0.27
	5219202	Delta	32	SE	1,503	2.82	0.20	-0.20	0.10
	5245402	Eagle County AP	42	SW	1,980	3.17	0.21	-0.21	-0.01
	5314602	Fruita 1 W	45	E	1,366	1.98	0.08	-0.13	0.13
	5324602	Gateway 1 SE	41	N	1,387	2.63	-0.03	-0.04	0.14
	5335902	Glenwood SPGS #2	31	N	1,753	2.33	0.30	-0.27	0.05
	5386702	Hayden	48	SE	1,963	3.22	0.17	-0.25	0.05
	5395105	Hermit 7 ESE	53	NW	2,743	2.52	-0.03	-0.03	0.23
	5548402	Meeker 3 W	29	S	1,884	2.56	0.05	-0.09	0.40
	5553102	Mesa Verde NP	51	NE	2,169	-1.85	-0.30	0.12	0.48
EAST	5013005	Alamosa Bergman Field	52	S	2,296	1.69	-0.15	0.11	0.39
	5045404	Bailey	47	SE	2,356	-2.47	-0.49	0.33	0.57
	5077605	Blanca	37	SE	2,362	1.92	-0.22	0.16	0.39
	5152804	Cheesman	49	NW	2,097	-3.54	-0.27	0.10	0.20
	5171302	Cochetopa Creek	52	E	2,438	4.85	0.14	-0.15	0.09
	5349602	Grand Lake 1 NW	51	E	2,658	5.83	0.12	-0.16	0.24
	5350002	Grand Lake 6 SSW	53	SE	2,526	2.00	-0.02	0.02	0.38
	5364304	Grover 10 W	14	E	1,549	1.81	0.18	-0.28	0.16
	5445204	Kassler	49	NW	1,677	-2.47	-0.50	0.22	0.44

Correlations between MDD and the Pacific Climate indices are less consistent than those for snowfall and snow depth (Table 4.5.3). The sign of the correlations for PDO show no pattern across the state. The correlations for NPI are nearly all negative on the western half of the state but have no pattern east of the continental divide. The SOI is positively correlated with MDD across the whole state. However, the strength of the correlations is generally greater on the eastern half of the state.

In summary, Pacific climate variability affects the snow depth trends. The response to climate variability differs from one side of the Continental Divide to the other. When the PDO is in its positive (negative) phase and the NPI is in its negative (positive) phase, snow depth and snowfall decreases (increases) on the western side of the Continental Divide and increases (decreases) on the eastern side. Melting degree days and SOI are mostly positively correlated across Colorado. A positive SOI corresponds to the cold phase of ENSO or La Niña. Thus, in the Rocky Mountains of Colorado, MDD values increase during La Nina years.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

This study examined trends in accumulated seasonal snow depth and associated meteorological variables across Colorado for the 1949-2004 period. Colorado is an area where previous studies have not found clearly identifiable spatial trends in seasonal snowpack (Regonda et al. 2005, Mote et al. 2005). In addition, previous studies only examined snow trends on the western side of the state. More broadly, the Rocky Mountains are a region where the role of elevation on the temporal trend in SWE is weak compared to other regions like the Pacific Northwest (Regonda et al. 2005, Mote et al. 2005). In part, these previous findings may be related to the reliance on observing stations that tend to be located at high elevation sites. This study attempted to address this problem by using cooperative observing stations that have a greater range in elevation and spatial coverage. The study explored several questions including:

- What are the spatial patterns of snow depth, melting degree day, and snowfall trends across Colorado?
- Is there a relationship between snow depth, snowfall, melting degree day, and snow day trends and elevation?
- What are the meteorological factors that contribute to the trend in snow depth?
- How does Pacific climate variability affect snow depth trends?

5.1 Spatial Variations in Snow Depth, Snowfall, and Melting Degree Day Trends

Unlike previous studies of snow trends, this study examined temporal snow depth trends across the southern Rocky Mountains of Colorado (both sides of the Continental Divide). Distinct spatial patterns in snow depth trends are evident. Declines in accumulated snow depth have occurred west of the Continental Divide in Colorado since 1949. This is consistent with previous research that suggests widespread declines in springtime SWE have occurred throughout much of the North American West (west of the Continental Divide) since the middle of the twentieth century (Mote et al. 2005, Regonda et al. 2005). However, the negative snow depth trends in Colorado would not be described as widespread in this study. The results show that over half (56%) of the stations with statistically significant snow depth trends in Colorado have negative trends. The ability to observe this spatial pattern was the result of including a larger spatial extent of stations with many east of the Continental Divide. Positive trends in snow depth occur primarily on the eastern side of the Continental Divide, an area that was not included in previous studies.

Temporal snowfall trends follow a similar pattern to snow depth trends with negative trends on the western part of the state and positive trends to the east. This result supports Knowles et al. (2006) who observed decreasing total winter precipitation and snowfall in the western half of Colorado and positive trends in precipitation and snowfall in eastern Colorado. Melting degree days have little spatial variation with most of the state showing positive trends. This warming pattern is consistent with results of Mote et al. (2005), who found positive linear trends in November-March temperatures across Colorado. Knowles et al. (2006) also observed increasing trends in winter minimum wet-day air temperatures, which may affect the partitioning of precipitation between rain and snow.

5.2 Variations in Snow Depth, Snowfall, and Melting Degree Days by Elevation

This study is unique in that it has been able to include stations with a greater range in elevation in the Colorado Rockies to better explore the relationship between snow depth and elevation. Previous studies in the region have focused only on the western half of the state. Accumulated seasonal snow depth, as well as snowfall, MDD, and snow days, was examined for trends with elevation (Figure 4.1.1). When the entire dataset was examined, only accumulated snowfall trends exhibited a statistically significant relationship ($p \leq 10\%$) with elevation. However, when the stations were stratified based on the sign of their trends, statistically significant trends ($p \leq 5\%$) were found between negative snow depth and snowfall trends and elevation. Both variables showed a positive (or direct) relationship with elevation (Figure 4.1.2a, b). The greatest decreases in snow depth and snowfall trends were at the lowest elevations. These findings are consistent with previous studies, but also suggest that the smaller trend values found for the Rockies in Regonda et al. (2005) and Mote et al. (2005) may underestimate the magnitude of change in snow depth by relying on higher elevation stations.

5.3 Meteorological Explanations for Observed Snow Trends

The results of the multiple regression analysis shown in Chapter 4 suggest that both snowfall and MDD trends may affect snow depth trends. Multiple regression analysis was used to isolate the relative importance of each variable. Unfortunately, only a limited number of stations were available and thus the results should be considered with caution. Snowfall explained the dominant portion of the trend in snow depth in four of the five stations. It explained from 77-128% of the variation in snow depth trends among those stations. The explained variance from MDD ranged greatly from 3-61%. Thus, it appears MDD plays an important contributing role in influencing snow depths depending on the location. Hamlet et al. (2005) note that SWE in more continental climates tends to be more sensitive to precipitation trends during the winter than in coastal areas. Further, they add that higher elevation sites such as in the Rockies are relatively insensitive to temperature trends, and downward trends in SWE are primarily due to downward trends in precipitation. Of course, the limited number of stations examined in Hamlet et al. (2005) makes it difficult to assess this observation.

5.4 Pacific Climate Variability and Colorado Snow

Indices of pacific climate were studied to identify whether they explain any of the observed spatial patterns in snow depth, snowfall, or MDD trends. The indices included the Pacific Decadal Oscillation (PDO), the North Pacific Index (NPI), and Southern Oscillation Index (SOI). Each index was correlated with snow depth, snowfall, and MDD time series for stations with statistically significant trends.

There are very clear spatial patterns to the correlations largely partitioned by the Continental Divide. West of the Continental Divide, the PDO Index is negatively correlated with the temporal snow depth trend. Mote (2006) also found the relationship between PDO and 1 April SWE to be negative in the western half of Colorado. Additionally, NPI is positively correlated with the snow depth trend while the SOI does not reveal much of a relationship. The snow depth trend at four stations is negatively correlated with the SOI Index while six stations are positively correlated. The relationships between the climate indices and the snow depth trends are opposite on the other side of the Continental Divide. On the east side, the PDO Index is positively correlated with the snow depth trend while the NPI and the SOI are negatively correlated with the snow depth trend. The SOI index shows a more consistent pattern of correlation values on the eastern side.

Similar patterns emerged for correlations between temporal snowfall trends and the Pacific climate indices. Once again, there are negative correlations with PDO on the western side of the Continental Divide and positive correlations with NPI. The pattern for SOI tends to be positive, but not uniformly so among stations. The signs of the correlations reverse on the eastern side of the state with negative correlations for the PDO and positive correlations for the NPI. The SOI tends to be negative on the eastern side. For MDD, there is no distinct pattern with the PDO or NPI, but there is a uniformly positive correlation with SOI across the region.

The spatial correspondence between the NPI and PDO and snow depth and snowfall trends suggests that Pacific climate variability may explain the trends. The study period covers two phases of the PDO. The first portion occurred during a negative phase (1947-1977) while the second portion occurred during a positive phase (Mantua et al. 1997). Hamlet et al. (2005) examined a similar study period (1947-2003) and concluded that that decadal variability associated with the PDO probably explains the winter precipitation trends, but not the widespread warming. While there were positive correlations with the SOI across the state, it is a higher frequency phenomenon than the PDO or NPI and there has not been a systematic pattern in its sign or strength over time. The monotonic warming trend, therefore, is beyond what can be explained by Pacific climate variability and is consistent with patterns of anthropogenic greenhouse warming (Mote et al. 2005).

5.5 Future Research

Future research will examine in greater detail the physical mechanisms by which variations in Pacific climate affect snow depth, snowfall, melting degree days, and snow days. Because the PDO and NPI mainly influence snowfall, it is hypothesized that a shift in the storm tracks of the Colorado Low may be responsible for variations in snow between the eastern and western parts of the state. In addition, this research methodology, utilizing cooperative observing stations, will be expanded cover the Western United States.

REFERENCES

Auer, I. and Boehm, R., 1994: Combined temperature-precipitation variations in Austria during the instrumental record. *Theor. Appl. Climatol.* **49**, 161–174.

Beniston, M., H. F. Diaz, and R. S. Bradley, 1997: Climatic change at high elevation sites: an overview. *Climatic Change,* **36,** (3-4), 233-251.

Brown, R. D., 2000: Northern hemispheric snow cover variability and change 1915– 97, *J. Climate*, **13**, 2339-2355.

Brown, T. B., Barry, R. G., and Doesken, N. J., 1992: An exploratory study of temperature trends for Colorado paired mountain-high plains stations, *Bull. Amer. Meteor. Soc.,* **2**, 181–184.

Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson, 2001: Changes in the onset of spring in the western United States. *Bull. Amer. Meteor. Soc.,* **82,** 399 415.

Clark, M. P., M. C. Serreze, and G. J. McCabe, 2001: The historical effect of El Niño and La Niña events on the seasonal evolution of the montane snowpack in the Columbia and Colorado River basins. *Water Resour. Res.,* **37,** 741–757.

Doesken, N.J. and A. Judson, 1996: *The snow booklet: a guide to the science, climatology, and measurement of snow in the United States*. Colorado State University Department of Atmospheric Science. 86 pp.

Dyer, J.L., and T.L. Mote, 2006: Spatial variability and trends in observed snow depth over North America. *Geophysical Res. Lett.,* **33**, L16503, doi:10.1029/2006GL027258.

Folland, C. K., 2001: Observed climate variability and change. *Climate Change 2001: The ScientificBasis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J. T. Houghton, et al., Eds., Cambridge University Press, 99–181.

Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier, 2005: Effects of temperature and precipitation variability on snowpack trends in the western United States. *J. Climate,* **18,** 4545–4561.

Hidalgo, H.G. and J.A. Dracup, 2003: ENSO and PDO effects on hydroclimatic variation of the Upper Colorado River Basin. *Bull. Amer. Meteor. Soc.*, **4**, 5-23.

Intergovernmental Panel on Climate Change, 2007: *Climate change 2007: Impacts, adaptation and vulnerability. Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report, Summary for Policymakers,* 1-22.

Jackson, D. and K. Dittmer, 2007: Global warming impacts on Pacific Northwest rivers, abrupt climate change, and the fate of Greenland. *Bull. Amer. Meteor. Soc.*, **88**(8), 1174-1176.

Joint Institute for the Study of the Atmosphere and Ocean (JISAO). [Available online: http://jisao.washington.edu/pdo/PDO.latest].

Karl, T. R., Jones, P. D., Knight, R. W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K. P., Lindseay, J., Charlson, R. J., and Peterson, T. C.: 1993: Asymmetric trends of daily maximum and minimum temperature, *Bull. Amer. Meteor. Soc.*,**74**, 1007–1023.

Kiladis, G.N. and H.van Loon, 1988: The Southern Oscillation. Part VII: Meteorological anomalis over the Indian and Pacific sectors associated with the extremes of the oscillation. *Mon. Wea. Rev*., 116, 120-136.

Knowles, N., M.D. Dettinger, and D. R. Cayan, 2006: Trends in snowfall versus rainfall for the western United States. *J. Climate,* **19,** 4545-4554.

Luckman, B. H., 1998: Landscape and climate change in the central Canadian Rockies during the 20th century. *Canadian Geographer,* **42,** 319–336.

Lu, Q., R. Lund, and L. Seymour, 2005: Notes and correspondence: An update of U.S. temperature trends. *J. Climate*, **18**, 4906-4914.

Mantua, M. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.,* **78,** 1069–1079.

McCabe, G. J. and M. P. Clark, 2005: Trends and variability in snowmelt runoff in the western United States. *J. Hydrometeorology,* **6,** 476–482.

Mote, P. W., 2003a: Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophys. Res. Lett.*, **30,** 1601, doi:10.1029/ 2003GL017258.

Mote, P. W., 2003b: Trends in temperature and precipitation in the Pacific Northwest during the twentieth century. *Northwest Sci.,* **77,** 271–282.

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier, 2005: Declining mountain snowpack in western North America. *Bull. Amer. Meteor. Soc.*, January, 39-49.

Mote, P. W., 2006: Climate-driven variability and trends in mountain snowpack in western North America. *J. Climate,* December, **19,** 6209-6220.

National Center for Atmospheric Research (NCAR), The Climate Analysis Section. [Available online: http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html#nam].

National Center for Environmental Predication[Available online: http://www.cpc.ncep.noaa.gov/data/indices/soi].

Regonda, S. K., B. Rajagopalan, M. Clark, and J. Pitlick, 2005: Seasonal cycle shifts in hydroclimatology over the western United States. *J. Climate,* **18,** 372 –384.

Robinson, D. A., 1989: Construction of a United States historical snow database. *Proc. of the 45th Eastern Snow Conferenc*e, 50-59.

Scherrer, S. C., C. Appenzeller, and M. Laternser, 2004: Trends in Swiss alpine snow days — The role of local and large-scale climate variability. *Geophys. Res. Lett.,* **31,** L13215, doi: 10. 1029/2004GL020255.

Scott, D., and D. Kaiser, 2004: Variability and trends in United States snowfall over the last half century. Preprints, *15th Symp. on Global Climate Variations and Change,* Seattle, WA, Amer. Meteor. Soc., CD-ROM, 5.2.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger, 2005: Changes toward earlier streamflow timing across western North America. *J. Climate*, **18,** 1136-1155.

Trenberth, K.E., 1997: The Definition of ENSO. *Bull. Amer. Meteor. Soc.*, 78(12), 2771-2777.

Trenberth, K. E., and J. W. Hurrell, 1994: Decadal atmosphere–ocean variations in the Pacific. *Climate Dyn.,* **9,** 303–319.

U.S. Department of Commerce, 2003: TD-3200 Surface Summary of the Day, National Climatic Data Center, NOAA. [Available online: http://www.ncdc.noaa.gov].

Walker, G. T. ,1924: Correlation in seasonal variations of weather. IX. A further study of world weather. *Memorandum of the Indian Meteorology Department*, *24*, 275–332.

Westerling A. L., H. G. Hidalgo, D. R. Cayan, T. W. Swetnam, Warming and earlier spring increases western U.S. forest wildfire activity. *Science* 313, 940 (2006); published online 6 July 2006 (10.1126/science.1128834).

APPENDIX A

Table A.1: The 120 cooperative observing stations within the Colorado Rocky Mountains with an observation record start year of at least 1950 (United States Department of Commerce 2003).

Station ID	Name	Latitude	Longitude	Elevation (m)	Start Year	Years	Snow Depth Trend (cm yr^{-1})	Snowfall Trend (cm yr^{-1})	MDD Trend (°C yr^{-1})	Snow Day Trend (cm yr^{-1})
5010201	Aguilar 1 SE	37.2	-104.4	1951	1916	84	-1.58	**-3.33**		-1.44
5012505	Alamosa	37.3	-105.5	2297	1904	96				
5013005	Alamosa Bergman Field	37.3	-105.5	2296	1924	76	1.20	-0.89	*1.69*	1.67
5018304	Allenspark 2 NNW	40.1	-105.3	2536	1948	52		0.22	-0.47	
5021402	Altenbern	39.3	-108.2	1731	1948	52	0.90	**-2.31**	*1.94*	0.45
5022802	Ames	37.5	-107.5	2652	1948	52	0.51	0.09	0.04	1.53
5037002	Aspen	39.1	-106.5	2419	1948	52	0.15	-0.03	-0.08	-1.34
5043701	Ayer Ranch	39.0	-104.4	2205	1948	52	2.15	0.26		1.20
5045404	Bailey	39.2	-105.3	2356	1948	52	**3.20**	*1.91*	**-2.47**	**7.20**
5067402	Berthoud Pass	39.5	-105.5	3448	1950	50	1.59	1.09	0.88	1.04
5077605	Blanca	37.3	-105.3	2362	1948	52	-0.31	**2.75**	*1.92*	0.32
5084804	Boulder	40.0	-105.2	1672	1948	52	**2.12**	1.33	-1.43	**2.17**
5090902	Breckenridge	39.3	-106.0	2920	1948	52	-1.45	1.44		0.67
5107101	Buena Vista	38.5	-106.1	2417	1948	52	0.05	-1.17	-1.35	0.13
5117904	Byers 5 ENE	39.4	-104.1	1555	1948	52	-0.07	-0.92	-0.45	-0.05

Station ID	Name	Latitude	Longitude	Elevation (m)	Start Year	Years	Snow Depth Trend (cm yr^{-1})	Snowfall Trend (cm yr^{-1})	MDD Trend ($^{o}\text{C yr}^{-1}$)	Snow Day Trend (cm yr^{-1})
5129401	Canon City	38.3	-105.1	1625	1948	52	1.52	0.85	-1.65	**2.58**
5144002	Cedaredge	38.5	-107.6	1903	1948	52	1.24	*1.77*	0.01	0.47
5145805	Center 4 SSW	37.4	-106.1	2339	1948	52	0.05	0.44	1.51	-0.13
5152804	Cheesman	39.1	-105.2	2097	1948	52	-0.10	0.18	**-3.54**	0.03
5166001	Climax	39.2	-106.1	3450	1949	51	-0.33	-1.42	1.19	0.39
5171302	Cochetopa Creek	38.3	-106.5	2438	1948	52	-1.02	-0.74	**4.85**	*-2.29*
5174102	Collbran	39.2	-107.6	1823	1948	52	-1.52	-0.98	-0.84	-1.18
5177202	Colorado Nat'l Monument	39.1	-108.4	1762	1948	52	-1.67	**-3.23**	0.95	-0.94
5177801	Colorado Springs	38.5	-104.4	1872	1924	76	1.65	0.92	0.96	1.20
5188602	Cortez	37.2	-108.4	1875	1931	69	-1.12	**-3.44**	-0.65	-1.40
5192802	Craig	40.3	-107.3	1914	1948	52	-1.02	-0.13	-0.05	-1.45
5195902	Crested Butte	38.5	-106.6	2701	1909	91	-1.55	-1.02	-0.42	1.43
5218405	Del Norte 2 E	37.4	-106.2	2399	1948	52	-0.19	0.24	0.60	1.08
5219202	Delta	38.5	-108.0	1503	1910	90	-1.49	**-4.60**	**2.82**	-1.67
5222004	Denver Stapleton Int'l AP	39.5	-104.5	1611	1948	52	0.27	-1.34	1.36	0.55
5222504	Denver WSO City	39.5	-104.6	1623	1948	52	0.03	-0.75	-0.17	0.63
5228102	Dillon 1 E	39.4	-106.0	2763	1909	91	-1.37	**-4.68**	1.14	-0.22
5232602	Dolores	37.3	-108.3	2115	1948	52	**-2.57**	0.60		-0.96
5243202	Durango	37.2	-107.5	2010	1913	87	0.81	1.00	-0.61	0.25
5245402	Eagle County AP	39.4	-106.6	1980	1948	52	*-1.90*	-1.46	**3.17**	**-2.33**
5275904	Estes Park	40.2	-105.3	2294	1948	52		-0.80	-1.05	
5300504	Fort Collins	40.4	-105.1	1525	1949	51	0.84	1.63	1.52	0.78
5301602	Fort Lewis	37.1	-108.0	2317	1940	60	0.22	1.01		0.13
5302704	Fort Lupton 2 SE	40.0	-104.5	1531	1948	52	-1.54	-1.46		-1.14

Station ID	Name	Latitude	Longitude	Elevation (m)	Start Year	Years	Snow Depth Trend (cm yr^{-1})	Snowfall Trend (cm yr^{-1})	MDD Trend (°C yr^{-1})	Snow Day Trend (cm yr^{-1})
5306301	Fountain	38.4	-104.4	1695	1948	52	-0.52	0.43		-1.03
5307901	Fowler 1 SE	38.1	-104.0	1320	1948	52	1.16	-1.30		1.36
5311302	Fraser	39.6	-105.5	2610	1909	91	-0.35	-1.53	-0.59	0.13
5314602	Fruita 1 W	39.1	-108.5	1366	1948	52	0.30	**-3.19**	*1.98*	0.00
5322201	Gardner	37.5	-105.1	2123	1948	52	0.55	0.97		0.41
5324602	Gateway 1 SE	38.4	-108.6	1387	1948	52	*-1.72*	**-2.70**	**2.63**	**-2.37**
5326104	Georgetown	39.4	-105.4	2597	1948	52	**2.81**	**2.12**	0.59	**2.84**
5335902	Glenwood Spgs #2	39.3	-107.2	1753	1948	52	1.03	-1.39	**2.33**	1.18
5348802	Grand Junction Walker Field	39.1	-108.3	1475	1900	100	-0.71	**-3.82**	1.05	-0.75
5349602	Grand Lake 1 NW	40.2	-105.5	2658	1948	52	-1.00	-0.44	**5.83**	1.53
5350002	Grand Lake 6 SSW	40.1	-105.5	2526	1948	52	0.82	-0.80	*2.00*	-1.04
5354105	Great Sand Dunes N M	37.4	-105.3	2475	1950	50	**2.31**	**3.14**	1.48	**2.62**
5354604	Greeley	40.3	-104.4	1418	1948	52		*-1.88*	-0.55	
5359202	Green Mt Dam	39.5	-106.2	2359	1948	52	*-1.98*	**-2.72**	-1.48	-1.36
5364304	Grover 10 W	40.5	-104.3	1549	1948	52	-0.61	-1.39	*1.81*	1.02
5365601	Guffey 10 SE	38.4	-105.2	2499	1950	50	0.39	0.78		0.98
5366202	Gunnison 3 SW	38.3	-106.6	2329	1928	72	0.19	**-2.49**	1.12	0.82
5373802	Hamilton	40.2	-107.4	1899	1948	52	**-3.56**	**-6.26**		**-13.91**
5385004	Hawthorn	39.6	-105.2	1806	1948	52	-0.12	-0.16		-0.07
5386702	Hayden	40.3	-107.2	1963	1948	52	0.43	0.11	**3.22**	0.36
5395105	Hermit 7 ESE	37.5	-107.1	2743	1948	52		-0.42	**2.52**	
5423404	Idaho Springs	39.5	-105.3	2306	1948	52	1.79	**2.24**	0.52	**3.02**
5425002	Ignacio 1 N	37.1	-107.4	1969	1948	52		**-2.76**	1.17	
5445204	Kassler	39.3	-105.1	1677	1948	52	1.13	-0.80	**-2.47**	1.00

Station ID	Name	Latitude	Longitude	Elevation (m)	Start Year	Years	Snow Depth Trend (cm yr^{-1})	Snowfall Trend (cm yr^{-1})	MDD Trend (°C yr^{-1})	Snow Day Trend (cm yr^{-1})
5466402	Kremmling	40.0	-106.2	2253	1948	52	-0.62	-0.06	-0.48	0.41
5473402	Lake City	38.0	-107.2	2643	1948	52	-0.91	-1.06		**-2.96**
5488401	Leadville	39.1	-106.2	3030	1948	52	0.21	0.09	-0.49	-0.19
5504802	Little Hills	40.0	-108.1	1872	1948	52	0.09	0.95	-0.88	0.65
5511604	Longmont 2 ESE	40.1	-105.0	1509	1948	52	-0.41	*-1.87*	0.90	-1.02
5532205	Manassa	37.1	-105.6	2344	1948	52	-0.92	**2.25**	1.58	-1.13
5532702	Mancos	37.2	-108.2	2128	1948	52	*-1.97*	-0.40	1.37	-0.32
5540802	Marvine	40.0	-107.3	2239	1948	52	1.51	0.25	0.52	0.85
5548402	Meeker 3 W	40.0	-107.6	1884	1948	52	-0.80	**-2.55**	**2.56**	0.30
5553102	Mesa Verde NP	37.1	-108.3	2169	1948	52	-0.88	-0.81	*-1.85*	0.16
5570605	Monte Vista 2 W	37.4	-106.1	2332	1948	52	0.57	**2.61**	1.01	*1.71*
5571702	Montrose 1	38.3	-107.5	1764	1948	52		**-3.90**		
5572202	Montrose No 2	38.3	-107.5	1763	1948	52	-1.41	-1.14		-1.30
5597002	Northdale	37.5	-109.0	2036	1948	52	*-2.69*	0.48		-2.34
5599001	North Lake	37.1	-105.0	2684	1948	52	0.95	*2.02*		0.21
5601202	Norwood	38.1	-108.2	2140	1948	52	-0.60	0.35		-0.43
5620302	Ouray	38.0	-107.4	2390	1948	52	*-1.68*	-1.64		0.71
5625802	Pagosa Springs	37.2	-107.0	2210	1948	52	-0.41	-0.65		0.91
5626602	Palisade	39.1	-108.2	1466	1948	52	-1.55	-1.31		-1.15
5627102	Palisade Lakes 6 SSE	37.3	-107.1	2467	1948	52	-0.51	-0.08		0.53
5631502	Paradox 1 E	38.2	-108.6	1610	1948	52	*1.87*	-0.13		1.72
5632604	Parker 6 E	39.3	-104.4	1923	1948	52	0.62	*-1.76*		-0.35
5641001	Penrose 3 NNW	38.3	-105.0	1650	1948	52	-1.52	-0.63		-1.73
5651302	Pitkin	38.4	-106.3	2804	1948	52	-0.55	-0.72		-0.05

Station ID	Name	Latitude	Longitude	Elevation (m)	Start Year	Years	Snow Depth Trend (cm yr^{-1})	Snowfall Trend (cm yr^{-1})	MDD Trend (ºC yr^{-1})	Snow Day Trend (cm yr^{-1})
5652402	Placerville	37.6	-108.0	2301	1948	52	-1.16	0.97		-0.03
5674301	Pueblo City Reservoir	38.2	-104.4	1430	1948	52	-0.25	0.23		-0.41
5679702	Pyramid	40.1	-107.1	2441	1948	52		*-1.95*		
5683202	Rangely 1 E	40.1	-108.5	1612	1950	50	0.70	0.07		0.34
5692504	Red Feather Lakes 2 SE	40.5	-105.3	2489	1948	52	1.65	-0.46		1.50
5701702	Rico	37.4	-108.0	2682	1948	52	0.77	0.75		-1.32
5703102	Rifle	39.3	-107.5	1622	1910	90	0.10	-1.27		-0.02
5728701	Rush 1 N	38.5	-104.1	1832	1949	51	0.26	0.57		-0.10
5731501	Rye	37.6	-104.6	2088	1948	52	1.88	*-1.81*		1.72
5733705	Saguache	38.1	-106.1	2345	1948	52	-0.87	-1.42		-1.15
5737001	Salida	38.3	-106.0	2182	1948	52	-0.52	-0.65		-0.21
5761802	Shoshone	39.3	-107.1	1808	1948	52	**-2.85**	**-4.06**		**-2.59**
5765602	Silverton	37.5	-107.4	2840	1913	87	0.56	0.51		1.34
5784804	Spicer	40.3	-106.3	2541	1948	52	-0.50	-0.86		-0.31
5793602	Steamboat Springs	40.3	-106.5	2023	1915	85	-0.58	-0.34		-0.44
5806401	Sugarloaf Reservoir	39.2	-106.2	2968	1948	52	-0.99	-1.28		-0.82
5815402	Tacoma	37.3	-107.5	2225	1949	51	0.70	**2.11**		0.01
5818402	Taylor Park	38.5	-106.4	2806	1948	52	-0.91	**-2.09**		0.74
5820402	Telluride 4 WNW	37.6	-107.5	2643	1911	89	0.20	1.11		0.93
5842901	Trinidad	37.1	-104.3	1838	1948	52	0.50	0.68		0.37
5843401	Trinidad Las Animas County	37.2	-104.2	1751	1924	76	0.60	0.77		**2.47**
5850101	Twin Lakes Res	39.1	-106.2	2803	1949	51	-0.19	-0.29		0.13
5858202	Vallecito Dam	37.2	-107.4	2332	1948	52		**-2.07**		
5874205	Wagon Wheel Gap 3 N	37.5	-106.5	2593	1948	52		-0.54		

Station ID	Name	Latitude	Longitude	Elevation (m)	Start Year	Years	Snow Depth Trend (cm yr^{-1})	Snowfall Trend (cm yr^{-1})	MDD Trend (°C yr^{-1})	Snow Day Trend (cm yr^{-1})
5875604	Walden	40.4	-106.2	2475	1948	52	-1.34	**2.09**		-1.19
5878101	Walsenburg	37.4	-104.5	1875	1948	52	*1.73*	**5.22**		*2.08*
5883904	Waterdale	40.3	-105.1	1594	1948	52	*-1.84*	0.14		**-2.29**
5893101	Westcliffe	38.1	-105.3	2396	1948	52	1.11	*1.94*		1.61
5898601	Wetmore 2 S	38.1	-105.1	2007	1948	52		0.36		
5914704	Windsor	40.3	-104.5	1457	1948	52	1.08	**3.12**		*2.28*
5917502	Winter Park	39.5	-105.5	2761	1948	52	*1.85*	**-2.28**		**2.03**
5918302	Wolf Creek Pass 4 W	37.3	-106.5	2876	1948	52	-0.09	**-2.21**		-0.88
5926502	Yampa	40.1	-106.6	2405	1948	52	-0.81	0.94		-1.08