THE ROLE OF ELEVATION ON TEMPERATURE TRENDS IN THE WESTERN UNITED STATES:

A COMPARISON OF TWO STATISTICAL METHODS

By

Ruben J Behnke

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Contents

Abstract

Mountainous regions account for 25% of the world’s land surface area (Kapos, et al.), serve as home to 26% of the world’s population (Beniston, 2003), and are very important culturally and socially, and often contain very high biodiversity (Beniston, 2006). These factors make understanding of temperature trends in mountainous regions an important part of climate change research. In this study, the PRISM data set, developed by Dr. Christopher Daly at Oregon State University, is used to study potential variation in running 30 year temperature trends by elevation since 1895 in six mountain chains in the western U.S., including the 1) Cascades, 2) Sierra Nevada, 3) North Rockies, 4) Middle Rockies, 5) Southern Rockies, and 6) Wasatch Range. Similar to studies of other mountainous regions around the world, results indicate that a region-wide temperature trend dependence on elevation is rather difficult to detect, and that results are highly spatially and temporally variable. Finally, interpolation methodology, statistical limitations, and other sources of error are discussed in some detail, as are opportunities for future improvements and additions to this research.

1. Introduction

Mountainous regions account for 25% of the global land surface area (Kapos, et al. 2000), while around 26% of the world's population lives in mountainous regions or within their foothills (Meybeck, et al., 2001). Forty percent of the world's population relies on water sources originating from mountains (Beniston, 2003). Culturally and socially, mountains are very important for many reasons. For several ancestral or native cultures around the world, mountains represent deities or spirits, including Fujiyama in Japan and Kailas in Tibet (Barry, 2008). Modern cultural importance is much more economically oriented, and tourism is the main factor now. But, lifestyle factors, including job and other livelihood issues which result from natural resource availability (such as minerals), are of major importance.

Mountains also often contain very high biodiversity, with a large proportion of plant and animal species, including their associated ecosystems, being unique to a particular mountain or mountain chain (Beniston, 2006). This occurs for two reasons. One is because of the isolation that species which live at high elevations experience. The other is that very rapid gradients in climate on the mountain create a large range of potential habitats. Because of the harsh and spatially limited environment in which these organisms already live, as well as the increased susceptibility of mountains to environmental degradation (especially soil erosion/landslides), mountain environments and ecosystems are particularly fragile (Beniston, 2003; Barry, 2008; Bonan, 2008).

Potential anthropogenic climate change effects in these vulnerable regions add significantly to their vulnerability to environmental degradation. There is much uncertainty about these effects, however. One major uncertainty, and the focus of this paper, is how temperature trends vary by elevation. One reason is that mountain meteorology is very complex and not well measured, and as a result, not well understood – especially on local scales. Barry (2008) summarizes this extreme complexity as being controlled by four main variables: 1) latitude, 2) continentality, 3) altitude, and 4) topography. However, each mountain range or high elevation region has a different combination of these factors, leading several authors (Barry, 2008; Beniston, 2006; Beniston, 2003; Giorgi, 1997) to conclude that the only thing in common among mountain ranges is their complexity.

This presents a problem in mountain research, in general, but it's especially serious for meteorological and/or climatological studies. Barry (2008) lists three obstacles to adequate measurement of mountain weather and climate. The first is that the remoteness of the location leads to neglect since it doesn't affect many people. This same issue means that physical access for installation and maintenance of monitoring equipment is limited. Second, the complexity of mountain terrain means that any one station will only represent a small number of sites or a small portion of the area of the mountain region. Third, making standard weather observations is very difficult in such complex terrain, and across such a large portion of the world, where everything from the culture to political unrest and different scientific goals can make reliable measurements impossible. The combination of these issues means that, in order to get complete measurements of mountain systems around the world, a very large number of stations would need to be set up and maintained.

Because of these issues, there is a lack of observational studies of the variation in climate trends with elevation and across complex terrain. Most studies have focused on European mountain chains with limited work on western North America, where climatic change is strongly impacting ecosystems. Here, terrain-specific interpolated meteorology and a digital elevation model (DEM) are used to make statistical inference on the magnitudes of these trends and the spatial extent and coherence of elevation specific trends in the western United States.

2. Background

2.1 Topoclimate/Microclimate

Although it is beyond the scope of this paper to present a complete, detailed description of the specific factors which contribute to the complexity of mountain meteorology, a brief overview is helpful as part of the motivation for this study. The limitations experienced in observing mountain meteorology have led to the development of several downscaling techniques specifically designed to interpolate observed and/or modeled data to a higher resolution in order to capture the very complex and rapidly changing temperature, precipitation, wind, humidity, radiation, and other meteorological variables which exist in mountainous regions (or ‘complex terrain’). The goal of this downscaling is to capture the ‘topoclimates’ which exist in complex terrain. These very high gradients of climate are a major contributor to the large biodiversity and endemism (species are unique to a particular location) found in mountainous regions. These small scale regions (~100m to 10 km) exist within the larger scale mountain environment and are mostly controlled by different amounts of radiation received because of the greatly varying exposures, facet directions, slope angles, sunlight totals, etc. Further, 'microclimates' (~1cm to 100m) exist within these topoclimates (Barry, 2008). Some examples of these include the surface of leaves, the forest canopy, a clearing, areas near a waterfall or a cave entrance, a small rock outcrop, and different soil layers. These microclimates have the largest gradients, and are often a result of the more intense radiation at high altitudes, which can heat a surface to a temperature much higher than that of the surrounding air (Barry, 2008). As will be discussed in greater detail later, no downscaling technique, in and of itself, can accurately and consistently reproduce these topoclimates or microclimates. Knowledge about the specific geographic and climatic characteristics of the local area is needed. This fact appears to greatly limit the resolution at which downscaling techniques can be used, as well as the spatial extent of very high resolution downscaling projects because the knowledge base needed in such cases is not readily available.

These dramatic differences in surface heating produce very complex wind patterns, which are then modified further by forests, ridges, valleys, clearings, glaciers, urban development, agriculture, and other topological and ecological features. For example, differences in heating between glaciers and surroundings produce 'glacier winds', while sheltered valleys commonly experience cold air pooling at nighttime (Barry, 2008; Lundquist, 2008; Pepin, Daly, and Lundquist – poster). Synoptic conditions, including regional scale wind strength and direction, cloudiness, and precipitation, must favor the development of these cold pools, which are often very shallow and local, and not always recorded by local observation stations. Other winds associated with complex terrain include the Chinook of the Rocky Mountains, the Santa Ana of California, the fohn and bora of the Alps, and the katabatic winds of Greenland and Antarctica. Much more detailed information on topoclimates and microclimates can be found in Barry (2008), Bonan (2008), de Jong (2005), and Whiteman (2000).

2.2 Literature Review

2.2.1 Previous Studies on Climatic Trends in Mountainous Regions

The question of whether or not elevation plays a role in temperature trends is a relatively new one, which is driven largely by the interest in climate change and its potential impacts. Most literature on this topic is less than twenty years old, and the pace of this research seems to be increasing in response to the demand for information on climate change impacts from policymakers, renewable energy companies, etc. Additionally, a significant amount of information on temperature trends in mountainous regions can be retrieved from studies which do not have these trends as their focus. These are not reviewed here, for the most part. There are also a growing number of conferences around the world which focus on mountain ecology and climate change, and a significant portion of this literature review comes from presentations of new, unpublished research given by some of the leaders in mountain meteorology, ecology, and downscaling research.

Just as the topoclimates and microclimates of mountain ranges around the world cannot be generalized, neither can their temperature trends or their variation by elevation. Additionally, Seidel and Free (2003) indicate that temperature trends on diurnal, seasonal, interannual, and multidecadal time scales differ greatly over short distances in complex terrain. They also point out that determining local trends requires local observations, which are not available for many locations around the world. According to Barry (1992), the Alps are, by far, the best studied mountain range in the world. The data used in these studies varies greatly, depending on what is available for a specific location, but includes GHCN (Global Historical Climate Network) and other station networks, radiosonde data, satellite data, dynamically modeled data, and statistically downscaled data.

Pepin and Lundquist (2008) report that study results on whether or not elevational temperature trends are increasing or decreasing do not always agree. Beniston et al. (1997) and Seidel and Free (2003) come to this same conclusion. However, Diaz and Bradley (1997), Liu and Chen (2000) and Beniston and Rebetz (1996) found most high elevation sites to be warming faster than lower elevation sites. Pepin and Lundquist (2008) also list several studies which found no significant relationship between elevation and trend magnitude, including Vuille, et al. (2003), Pepin and Seidel (2005), Liu et al. (2006), and You et al. (2008).

Despite these concerns, Pepin and Lundquist (2008) used GHCN and CRU (Climate Research Unit) station data to construct a table showing, in general, how temperature trends vary by elevation throughout the world (Table 1). Their study indicated that areas near the 0°C isotherm in the extratropics experienced the greatest warming trends due to snow-ice feedback effects. Additionally, stations at mountain summits and other locations where free air drainage/movement (local/regional air flow not impeded by topographic features) was common showed much more consistent trends, and therefore are hypothesized to more accurately represent global changes. An important note Pepin and Lundquist make here is that this consistency is not necessarily due to the notion that mountain locations may be more sensitive to climate change, but that they are less influenced by surface complexities, and may provide a good record of Earth's climate. Figure 2 shows North American temperature trends by elevation, which form a significant negative relationship with elevation.

According to Diaz and Bradley (1997), the greatest warming in high elevations has occurred in Europe and Asia. This same study showed that zonal maximum temperature trends between 30°N and 70°N do not vary linearly with elevation, while minimum temperatures show a somewhat more linear, consistent trend toward greater positive trend magnitudes at higher elevations (Figure 3). Vuille and Bradley (2000) report that trends in the Andes are greatest at low elevations, but that more recent time periods show trends of greater positive magnitude at all elevations.

2.2.2 Global and North American Trends

Globally, temperatures have risen about 0.8°C over the last century (Figure 1, NCDC – 2006), with current warming rates averaging 1.6°C/century. The 2007 IPCC report (AR4 WGII Chapter 4 - Ecosystems, their Properties, Goods and Services - 4.4.7 Mountains) also indicates that both minimum and maximum temperatures are rising, with minimum temperature rising faster (Beniston et al., 1997; Liu and Chen, 2000). Land areas are warming faster than ocean areas and cold season months are warming faster than warm season months. Effects more specific to high elevation regions include the shrinking of glaciers and melting of permafrost, which causes increased ground instability and rock slides (Woodwell, 2004), changes in alpine/Arctic ecosystems, and upward shifts in the ranges of plants and animals in these areas (Beniston, 2000; Theurillat and Guisan, 2001). Please see the above referenced IPCC AR4 WGII Chapter for a complete listing of potential climatic, geological, biographical, and ecological impacts, as well as associated references.

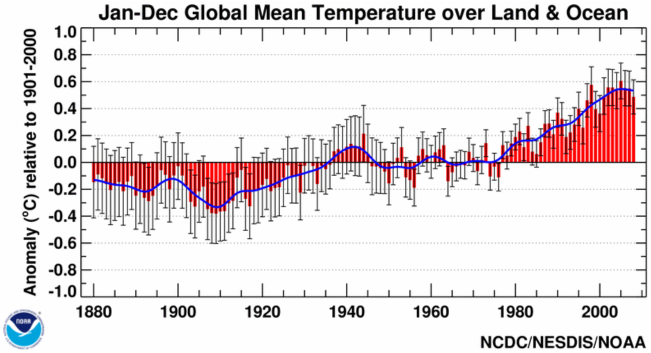


Figure 1. Source(NCDC – 2006). Global temperature anomalies since 1880.

According to the National Oceanic and Atmospheric Administration (NOAA), United States temperatures have risen 0.6°C over the past century. The north central and southwestern U.S. has experienced the greatest warming, while the Southeast U.S. has cooled slightly. The entire western U.S. has experienced some warming, with rates ranging from 0.5°C/century to 1.6°C/century (Figure 2). This fact further emphasizes the importance of studying elevational temperature trends, as the western U.S. is quite mountainous in contrast to the eastern U.S.

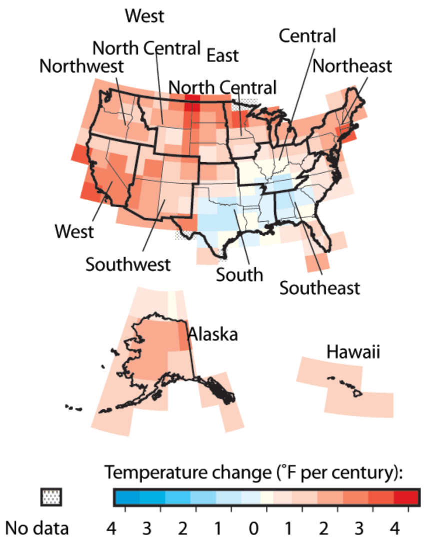


Figure 2. (Source: NOAA – 2008). Mean annual United States temperature trends from 1901 - 2005.

Table 1. (Source: Pepin and Lundquist, 2008). Table showing general temperature trends and their variation by elevation through the world (1948 – 2002). Uncertainty is defined using 95% confidence intervals. Red shading indicates significant warming for the entire continent. Elevation bands were defined by continent by dividing the stations into three equal elevation categories. The North American temperature trend is stronger at lower elevations.

Continent	Number of Sites	Surface Trend (°C/decade)	High Elevation	Middle Elevation	Low Elevation
N. America	552	0.123+/-0.014	0.088+/-0.022	0.122+/-0.020	0.161+/-0.030
S. America	33	0.127+/-.051	0.057+/-0.095	0.149+/-0.072	0.174+/-0.087
Europe	162	.041+/-.040	0.061+/-0.079	-0.008+/-0.072	0.070+/-0.051
Africa	41	0.140+/-0.040	0.168+/-0.074	0.110+/-0.068	0.140+/-0.072
Asia	280	0.151+/-0.027	0.108+/-0.045	0.173+/-0.050	0.172+/-0.043
Australia	14	0.134+/-0.066	0.130+/-0.109	0.193+/-0.138	0.091+/-0.109
Antarctica	2	-0.063+/-0.176	NA	NA	NA

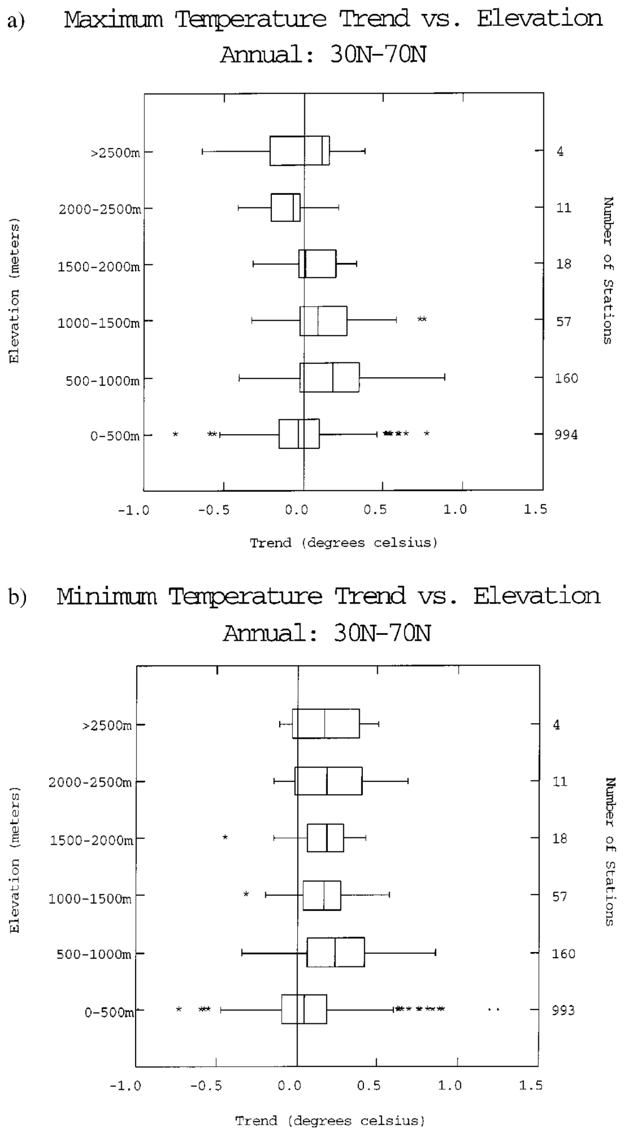


Figure 3. (Source: Diaz and Bradley, 1997). World temperature trends and their variation by elevation from 30°N to 70°N. Maximum temperature trends show no consistent trend by elevation. Minimum temperatures show a somewhat more clear trend toward greater positive trends at higher elevations.

2.3 Free Air versus Surface Meteorology

A significant issue in the study of whether or not temperature trends depend on elevation is that of surface temperature trends versus free air temperature trends (often referred to as trend in lapse rates). Atmospheric surface temperatures are those directly influenced by interaction with the land surface, while free air temperatures are those which experience little or no direct surface influence, although the free tropospheric temperature is still influenced by surface interactions through convective processes (Vimont, 2010, personal communication). Pepin and Losleben (2002) indicate that there can be large differences between the two, since the surface temperature is highly modified by the terrain, while the free air is not. Much of this difference is important on a local scale, and varies with the local terrain and climate (synoptic regimes). For example, Vuille and Bradley (2000) indicate that surface temperature trends in the Andes are rising, but that radiosonde measurements in the region indicate a slight cooling trend in the lower troposphere since 1979. Therefore, surface trends are apparently different from free air temperature trends, in this case. Gaffen et al. (2000) indicates that free air temperature trends are as complex as surface temperature trends. Tropical freezing level heights abruptly increased from 1976 – 1977, then decreased slightly from 1979 – 1997. Mid-tropospheric temperatures cooled slightly from 1979 – 1997, while surface temperatures increased, causing a large increase in lapse rates. Between 1960 and 1997 tropical surface and tropospheric temperatures warmed at about the same rate.

A study of free air versus surface temperature trends in the Colorado Rockies by Pepin and Losleben (2002) indicates that most free air warming in this area has occurred in the late winter and spring, with cooling in autumn. In contrast to the Andes, however, a decrease in surface temperatures at high altitude relative to free-air temperatures has occurred. They present several hypotheses for this, but do not come to a conclusion. This lack of understanding about the changes in lapse rates, and the apparent contrast in surface temperature trends vs. free-air temperature (surface temperatures warming faster than upper air temperatures) trends shows the need for significantly more research in this area (Pepin and Losloben, 2002). Surface trends are the focus of this paper for two reasons: 1) station data is representative of surface temperatures and 2) ecosystem impacts are dependent on surface temperatures.

As already stated, much uncertainty exists, even in the studies performed, because of the scarcity of observational data. The effects of synoptic regime, local terrain, land cover, free air vs. surface temperatures, ENSO (EL Nino Southern Oscillation), feedbacks, etc. on climate trends in mountain regions combine to make prediction of climate change effects very difficult. This has led to using models to predict future climate in these areas. However, the same variables that contribute to the lack of current observations also contribute to the difficulty of modeling climate for these regions. Pepin and Lundquist (2008), however, note that nearly all global climate models produce too strong a warming feedback at high elevations (above the 0°C isotherm), which is likely due to the ice-snow albedo feedback. According to Nogues-Bravo et al. (2007), the IPCC expects mountain ranges to experience 21st century warming rates two to three times higher than those of the 20th century. In accordance with this, isotherms are expected to move upward between 380 and 550 meters in Europe and North America, affecting the range in which plants and animals can survive.

3. OBJECTIVES

3.1 HYPOTHESES

Since the literature shows that North American mountain ranges have not been studied as well as their European counterparts, that existing studies on elevational influences on temperature trends are, for the most part, not regionally or locally specific, and observational networks in mountainous regions are relatively sparse, it is clear we do not understand the influence of elevation on temperature trends or have the high resolution data needed in order to effectively and fully understand topoclimates in complex terrain, or the potential effects of climate change in these regions.

Therefore, my main objective in this study is to study elevational temperature trends in the western United States for specific mountain ranges using a previously validated downscaled, topographically adjusted climate data set, for two periods – 1941 to 1970 and 1971 - 2000. *Are there spatially coherent elevational trends in temperature in mountain regimes and how do they relate to global patterns? Also, are these spatial patterns and general trend patterns consistent globally and across North America or is there significant geographic variability?* Thus, this study has two main hypotheses: 1) trends in mean surface temperature have taken place over the western U.S. since 1941 and these trends are amplified with increased elevation due to a snow-ice albedo feedback and exposure to the free atmosphere, and 2) different mountain chains in the western U.S. experience significantly different trend patterns depending on the primary synoptic regime experienced by each mountain region. Using a high quality interpolated data set, these hypotheses can be tested. Six mountain chains were used in this study, including: 1) Cascades, 2) Sierra Nevada, 3) Northern Rockies, 4) Middle Rockies, 5) Southern Rockies, and 6) the Wasatch Range. Figures 33 and 34 in the appendix show mean seasonal temperatures from 1895 – 2009 for all ecoregions.

3.2 STUDY REGIONS

The geographical outlines for each studied mountainous region are based on Bailey's Level III Ecoregions (Bailey, 1983). Figure 4 shows a map of Bailey's Level III ecoregions, with the six in this study labeled. These ecoregions are used as the basis for this study because these regions are based on precipitation amount and pattern throughout each region, as well as their temperatures and their distribution. Each ecoregion has unique geological, climatic, and ecological characteristics, which are briefly described below (source - EPA's ecoregion website: http://www.epa.gov/wed/pages/ecoregions/level_iii_iv.htm).

The Cascades are composed mostly of volcanoes, both dormant and active. Glaciation has significantly affected the range, and it is characterized by many steep ridges and river valleys in the west, and a high plateau in the east. Ranging up to 14,411 feet in height, it has a moist, temperate climate which supports an extensive and very productive coniferous forest. Subalpine meadows and rocky alpine zones occur at high elevations. It is important to note that the Cascade ecoregion stops in central Washington state, and does not include the North Cascades, which is a distinct and separate ecoregion.

The Sierra Nevada range rises quickly from the dry basin to its east, and slopes gently toward the central California to its west. The east side has been heavily glaciated and alpine conditions exist at its highest elevations. Vegetation includes ponderosa pine and douglas-fir at low west side elevations, pin and Sierra juniper on its east side, to fir and other conifers at higher elevations.

The Northern Rockies is a very rugged, strongly glacier influenced, high marine influenced ecoregion. Although this region is not as high as the Canadian or Southern Rockies, the highest elevations include alpine characteristics and numerous glacial lakes. Douglas and subalpine fir, Englemann spruce, ponderosa pine, western red cedar, western hemlock, and grand fir are common and are indicative of the marine influence.

The Middle Rockies lack the strong maritime influence of the Northern Rockies, and the lack of Pacific tree species is indicative of this. Douglas and subalpine fir, as well as Engelmann spruce are common. Large alpine areas are common, as are partly wooded or shrub and grass covered areas. Intermontane valleys are also grass and/or shrub covered, containing unique flora and fauna.

The Southern Rockies are high, rugged mountains, comprised of land cover/use which follows a pattern of elevational banding. Shrub or grass covers the lowest elevations, while grazing is common at low and middle elevations. Douglas fir, ponderosa pine, aspen, and juniper-oak woodlands are found at low to middle elevations. Coniferous forests cover the middle to high elevations, which also have alpine characteristics.

The Wasatch Range is also a high, steep mountain chain filled with narrow crests, valleys, and some plateaus and open mountaintops. Land cover/use follows an elevational banding pattern similar to that of the Southern Rockies, although aspen, chaparral, juniperpinyon, and scrub oak are found at middle elevations. Summer grazing of livestock is also common.

Table 2 shows the mean, minimum, and maximum elevation for each range. The Southern Rockies has the highest mean elevation (2279 meters), while the Cascades have the lowest (881 meters). All mountain regions have elevation ranges of 2278 meters or greater, with the Sierra Nevada have the greatest (3936 meters). Additionally, the variety of mountainous regions allows me to test the potential influence of synoptic regime on elevational trends.

4. Methodology

4.1 Data Set – PRISM

The main objective of my research is to study temperature trends and their variation with elevation throughout the western U.S. from 1895 to 2009, with a focus on two periods, 1941 – 1970 and 1971 – 2000. As stated earlier, Pepin and Lundquist have performed a similar analysis using GHCN, CRU, and NWS data. However, the number of stations at high elevations in the western U.S. is still less than exists at lower, more populated elevations. To compensate for this, I use the PRISM (Parameter-Regressions on Independent Slopes Model) data set developed by Dr. Christopher Daly at Oregon State University (Daly, et al. 2008). This data set uses an advanced downscaling scheme to interpolate observed maximum and minimum temperature, precipitation, and dew point temperature to a 4 km grid across the conterminous U.S. on a monthly time scale from 1895 to the current month (Note: An 800m dataset is available, but I used the 4 km data set). The PRISM website (http://www.prism.oregonstate.edu/docs/index.phtml) contains many publications, presentations, and posters which describe PRISM's interpolation scheme in detail. These are listed in this paper's reference section. I will summarize the algorithm here.

The PRISM model was developed mainly for interpolating temperature and precipitation in complex terrain. Therefore, elevation is the main variable in the algorithm, which uses several unique methods to accurately model its effect on temperature on a monthly time scale.

The first of these methods is that PRISM uses a knowledge base to "inject knowledge into a climate mapping system" (PRISM overview – presentation, 2008). This knowledge base includes several factors, with the main one being the fact that precipitation increases and temperature decreases with elevation, and that this relationship is often linear. This computer based system automatically makes decisions based on this knowledge base. Other factors in this knowledge base include terrain induced climate transitions (topographic facets and a 'moisture index' or moisture regime – including windward vs leeward sides of a mountain range), coastal effects due to proximity, a two layer atmosphere and a topographic index (allows for temperature inversions), orographic effectiveness of terrain (at lifting the air - based on topographical steepness and orientation, wind direction), and persistence of climate patterns.

The second part of the algorithm, and the mathematical basis of the model, is a moving window regression of climate vs. elevation for each grid cell. The third part of the algorithm is the station weighting used to produce the monthly temperature or precipitation. This weighting is a function of distance from the station, elevation, station clustering (based on physiographic similarity), topographic facet (such as leeward/windward), coastal proximity, vertical layer (inversions), topographic index (to account for things such as cold air pooling), and effective terrain height (orographic profile). For more details on PRISM, please refer to the references listed at the end of this paper, or on the PRISM website.

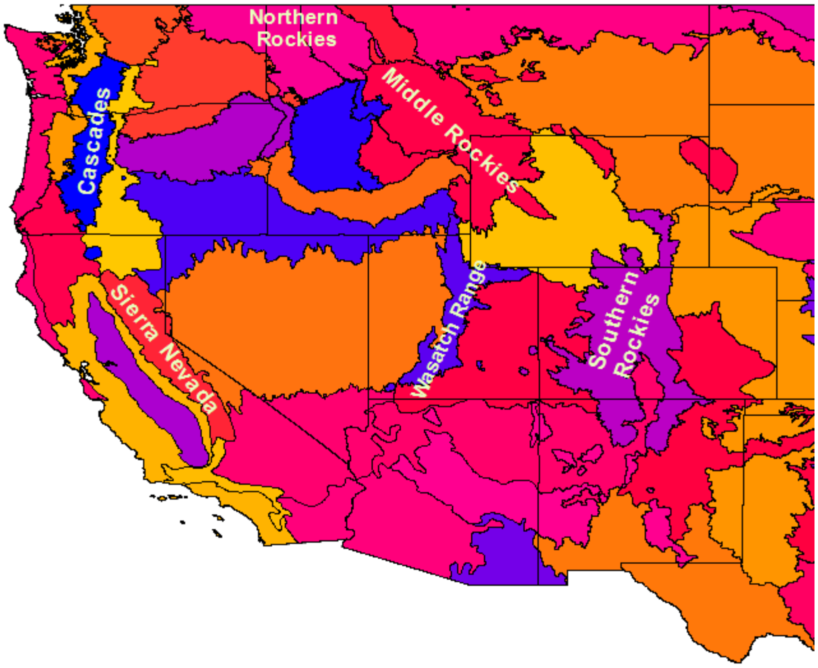


Figure 4. Bailey's Level III Ecoregions. The six ecoregions used in this study are labeled.

4.2 Previous Research

Although it is beyond the scope of this discussion to go into great detail of previous and current attempts to validate PRISM data, the reader should know that some do exist (most of which are not published, at least yet), but they tend to be local, small scale projects that do not represent the fact that PRISM's interpolation represents the average temperature over a 16km^2 area. However, Scully (2010) did a nationwide study similar to that of section 5.3.2, by ecoregion (7474 stations used, plus 712 SNOTEL stations, 1980 - 2003). Although this study's goal was to compare PRISM and Daymet (Thornton et al. 1997), much of the work performed is applicable to this study. I will present here what I feel are the most relevant results.

As discussed previously, higher elevations have many fewer stations than lower elevations. Figure 5 shows the results of an analysis by Scully (2010) which shows this fact. Even though the spatial extent of higher elevations is much less than that of lower elevations, elevations above 1500 meters are significantly underrepresented due to the lack of stations. The opposite is true of lower elevations.

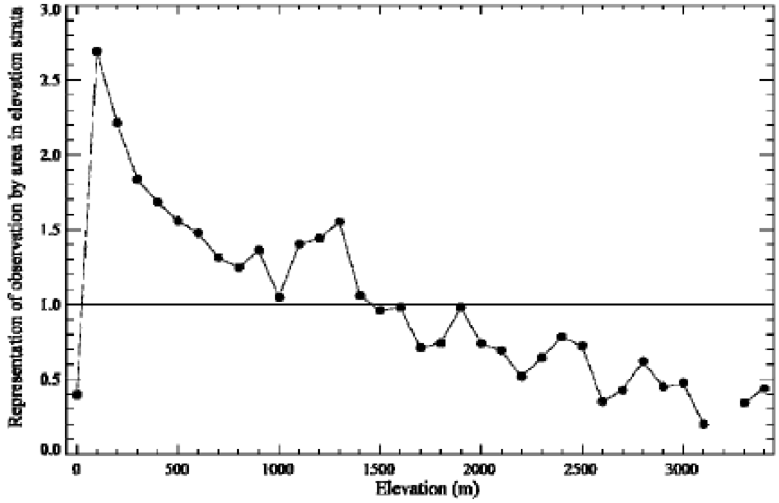


Figure 3. Over- or under-representation of temperature data shown by elevation bin. Horizontal line shows the expected value calculated as the total number of annual Tmin values divided by the number of 1 km pixels in the conterminous United States. Y-axis shows the total number of Tmin values in any 100 m elevation bin divided by the number of pixels in the bin. Values greater than 1 indicate that the elevation bin is overrepresented relative to the overall study area; values less than 1 indicate underrepresentation.

Figure 5. Source: Scully (2010). Representation of elevation bins in the U.S. by number of stations present.

PRISM's mean absolute error for minimum temperature was 0.72°C and 0.74°C for maximum temperature. Mean bias error for minimum and maximum temperatures was -.11°C and -.13°C, respectively. Both variables were underestimated by PRISM in about 63% of the cases. No seasonality in bias or mean absolute error was found.

Figure 6 (taken from Scully, 2010) shows mean absolute error (top) and bias (bottom) for minimum (left) and maximum (right) PRISM interpolated temperature, which is, in large part a function of elevation. Mean absolute error for minimum temperatures increases by about 0.23°C/km, but this error is much smaller for maximum temperature. Temperature bias for minimum temperature averages close to -0.1°C until about 1700 meters, when it jumps to +0.1°C. Bias magnitude increases for maximum temperatures with increasing elevation, beginning at about -.05°C close to sea level and decreasing to about -.275°C by about 1700 meters.

Tmin Tmax

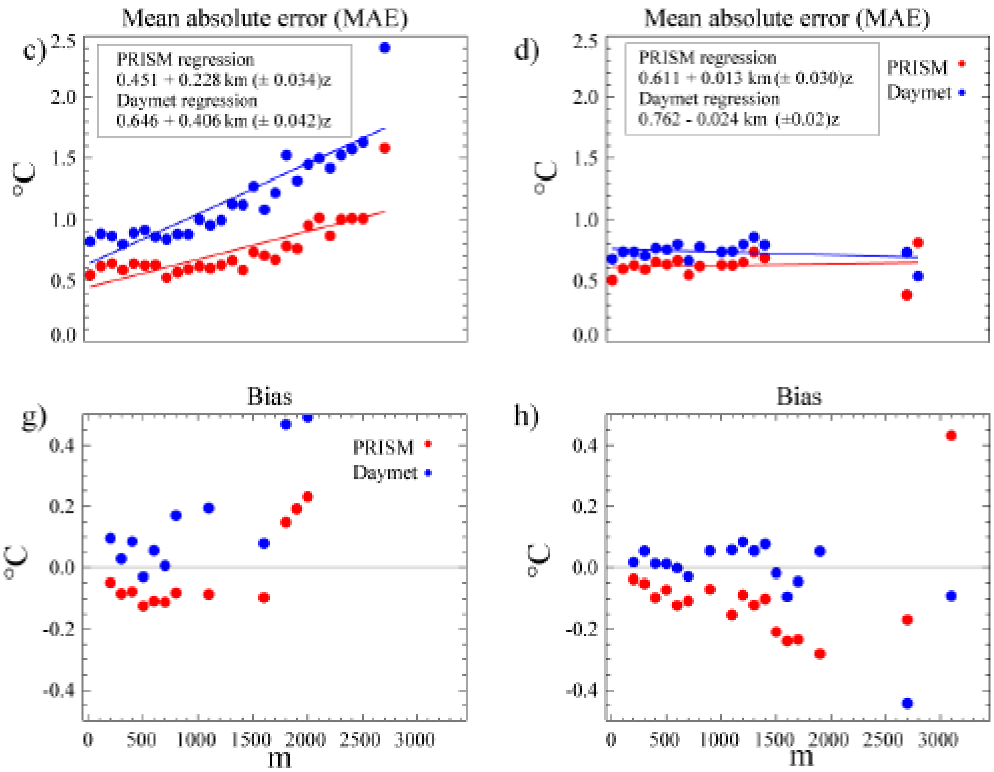


Figure 6. Source: Scully (2010). PRISM mean absolute error and temperature bias for minimum and maximum temperatures. Both error and bias increase at greater elevations, which is expected because fewer stations exist in high elevations, and the more complex topography creates higher temperature gradients in these areas.

4.3 Definition of Mountainous Regions

Although the ecoregions are used as the basis for each of the mountainous areas in this study, I used a buffer of approximately 50km around each ecoregion for the elevational analysis. There are two reasons for this. One, in many cases, Bailey's ecoregions closely follow a particular elevation contour. This means that choosing the exact boundaries of the ecoregion would significantly limit the elevational range of the analysis for each region. Also, the number of stations at high locations is limited, so choosing a larger area allows for the inclusion of more station data. These buffers were created using IDRISI Taiga.

Table 2. Buffered Elevational and Area Statistics.

Region	Mean Elevation (m)	Minimum Elevation (m)	Maximum Elevation (m)	Elevation Range (m)	Std. Dev. (m)	Area (Km^2)
Cascades	881.7	23	3255	3232	517.5	76194.7
Sierra Nevada	1417.3	9	3945	3936	855.3	133754.2
Northern Rockies	1128.2	240	2518	2278	386.7	116043.6
Middle Rockies	1997.2	800	3781	2981	482.6	253857.0
Southern Rockies	2279.9	1283	4005	2722	526.2	313946.3
Wasatch Range	2063.7	889	3711	2822	461.2	125150.4

Figures 7 - 9 show the stations used in the PRISM model, with the PRISM digital elevation model (DEM) overlaid, and the ecoregions and states outlined in black. The areas outlined in white indicate the buffered areas around each ecoregion used in the elevational trend analysis. Table 2 provides detailed information about each buffered area (outlined in white). The distribution of stations the PRISM model uses in its downscaling algorithm for 1941, 1971, and 2000 is shown in these figures (these are the beginning and end years of the periods of study). More stations are available, in general, as time progresses. Additionally, the distribution of these stations is quite good, even across the highest elevations. The one exception to this tends to be the Sierra Nevada, especially across its southern portions. Eastern portions of the Wasatch and southeastern portions of the Middle Rockies also show sparse station locations for 1941 and 1971, with a dramatic increase in station coverage in 2000. Additionally, low elevations at the foothills of the ranges tend to have a concentration of stations (such as the western parts of the Sierra Nevada and Wasatch Range, and the front range of the Southern Rockies.

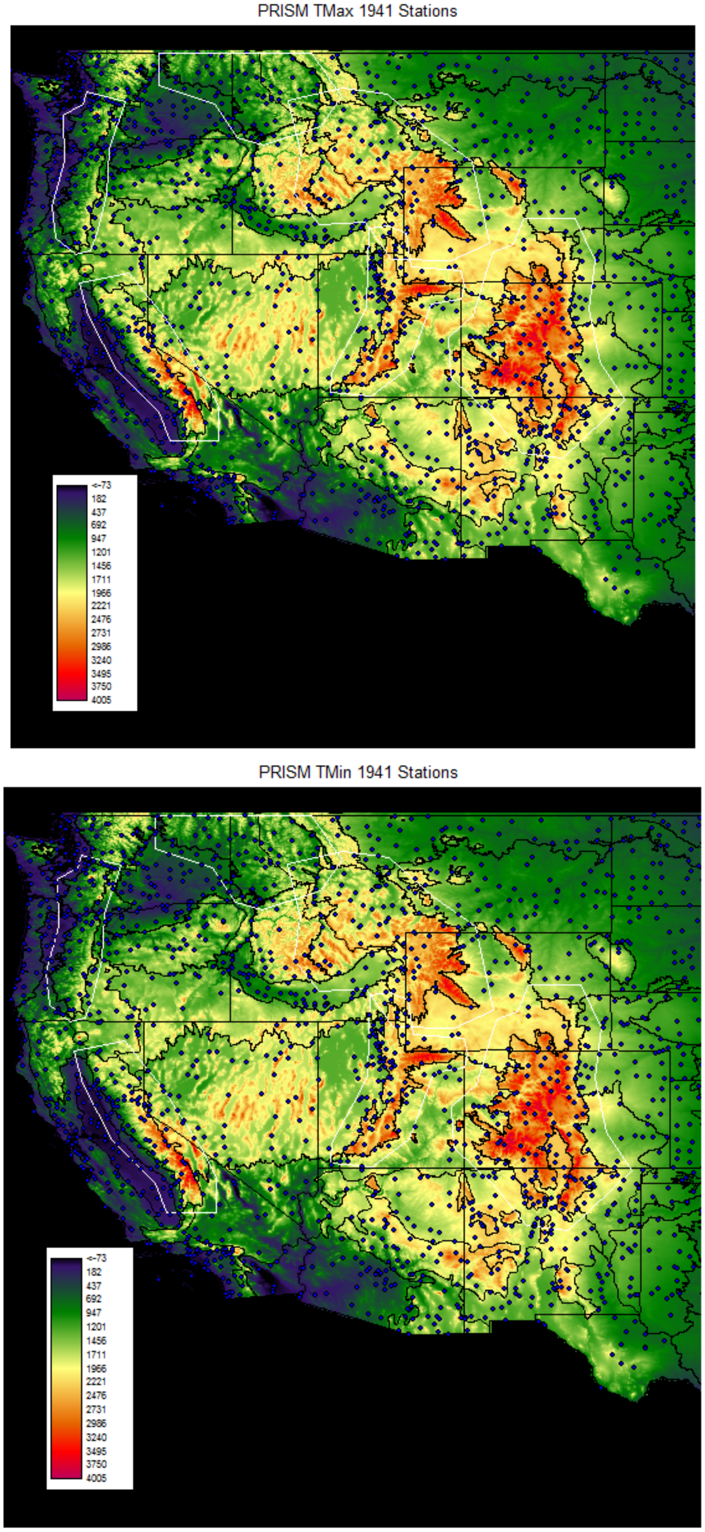
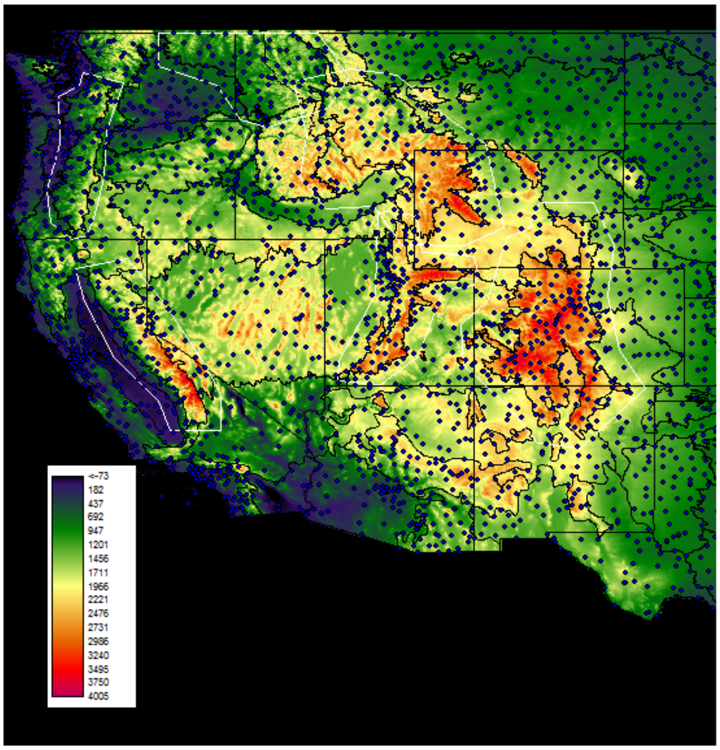


Figure 7. Maps showing PRISM stations used for 1941 maximum temperature (top) and minimum temperature (bottom).

PRISM TMax 1971 Stations



PRISM TMin 1971 Stations

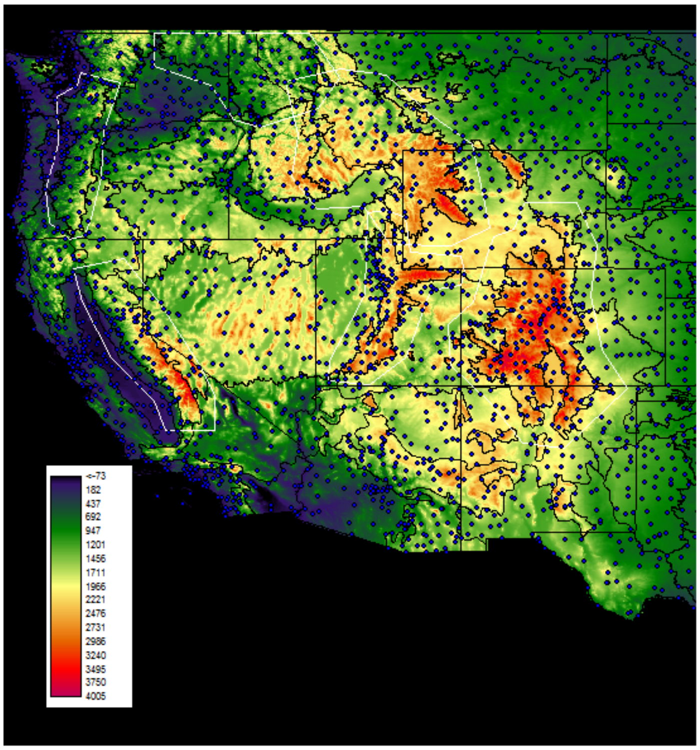
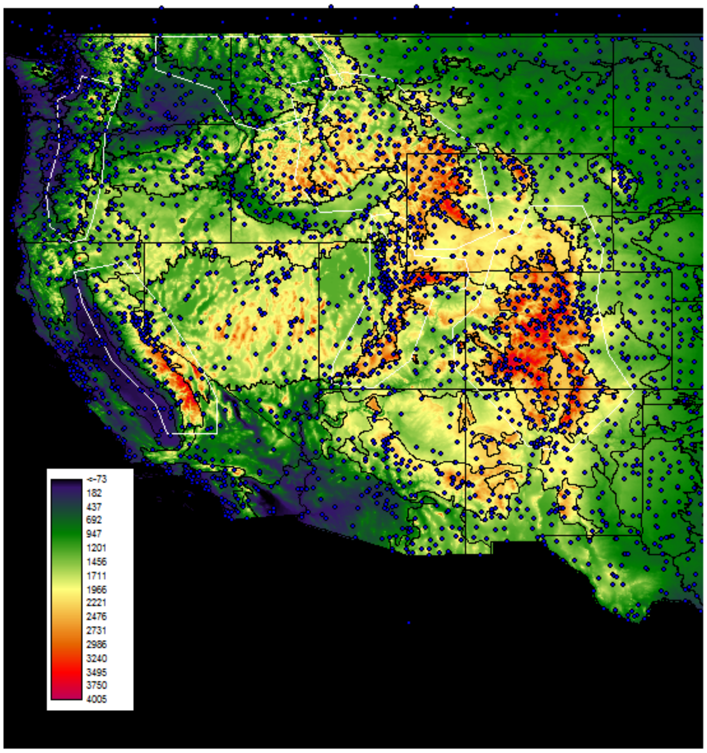


Figure 8. Maps showing PRISM stations used for 1971 maximum temperature (top) and minimum temperature (bottom).


PRISM TMax 2000 Stations

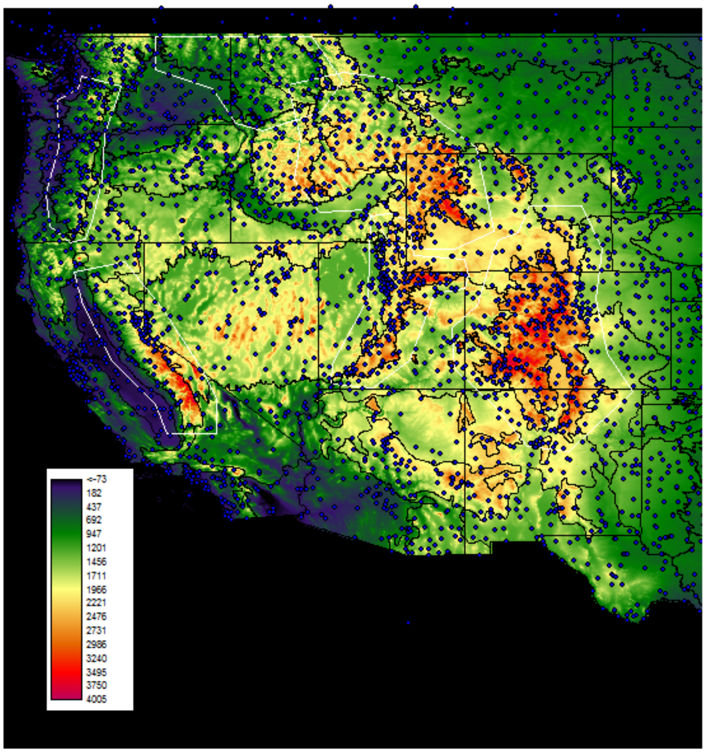

PRISM TMin 2000 Stations

Figure 9. Maps showing PRISM stations used for 2000 maximum temperature (top) and minimum temperature (bottom).

4.4 STATISTICAL METHODS

4.4.1 Least Squares Linear Regression

Two different statistical methods were used in this study. The first was least squares linear regression. This was used for two separate purposes: 1) to determine the general temperature trends (°C/yr) for each buffered ecoregion and to 2) determine the temperature trends with respect to elevation (°C/yr/km) for each buffered ecoregion. Thirty year running means were used for both the mean and elevational temperature trends because thirty years is used to define the climatic normal, and as figure 10 demonstrates, thirty years is the minimum time period for which the trends become relatively smooth (converge to long term trends, which is what I seek to address here).

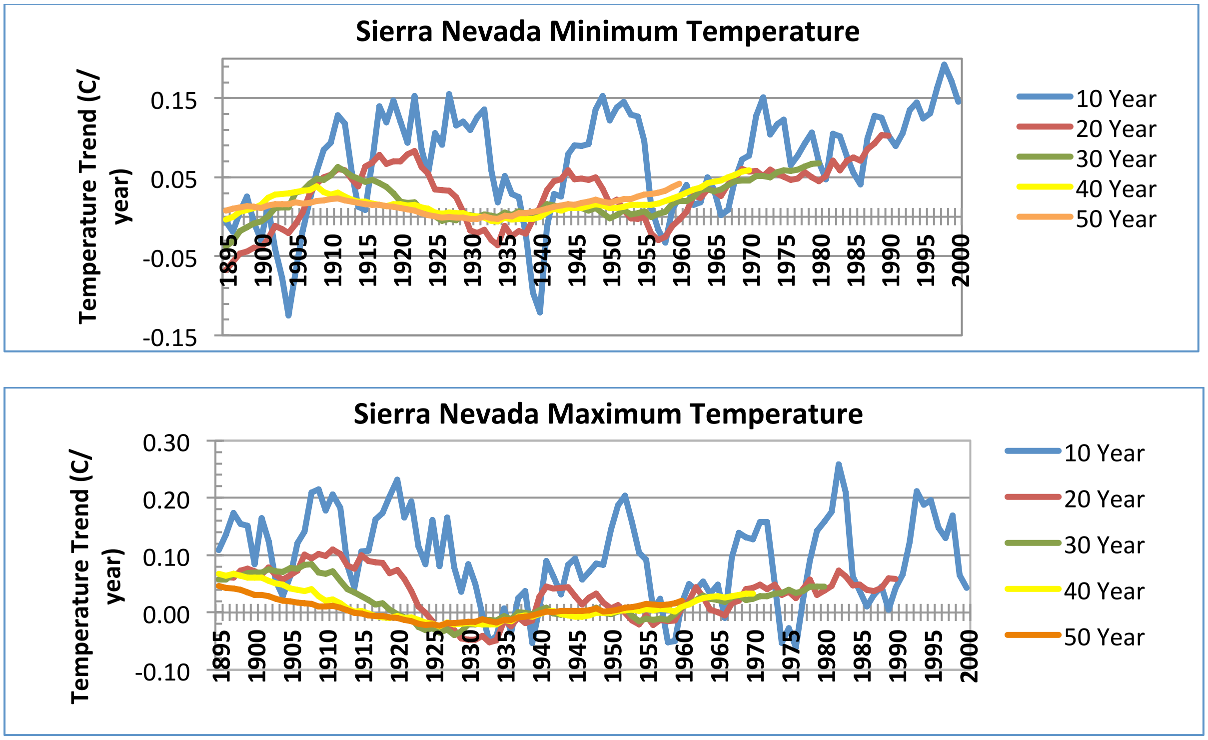


Figure 10. Comparison of 10, 20, 30, 40, and 50 year running mean temperature trends for the Sierra Nevada.

4.4.2 K-Means Cluster Analysis

The second statistical method used was k-means cluster analysis. This method is very useful because it determines how to best group data observations while maintaining consistency in seasonal trends. For this analysis, 30 year running trends for minimum and maximum temperature, precipitation, and dew point for each season and each grid cell, for the entire western U.S., were clustered. Two separate analyses were performed. One analyses used each season separately (4 variables) and the other used the four variables for all seasons (16 variables). Each four variable clustering analysis (one per season) produced different elevation means and different temperature trends for each cluster centroid. The centroid of a cluster represents the multidimensional 'center' for the observations of the variables used in the analysis. Each sixteen variable analysis produced one elevation mean for all seasons (a yearly average) and four different seasonal mean temperatures for each elevation mean (and cluster centroid value). The result was a grouping of the trends into regions for these four variables for each season for both periods, 1941 – 1970 and 1971 – 2000.

There are many variations within the general k-means method, so it is important to discuss the specific steps used for this analysis (Bradley, et al. (1997). First, the observations for minimum and maximum temperature, precipitation, and dew point trends were normalized. As a result, the clustering operates on the variance of the data set. The entire data set is first randomly divided into ten separate groups of equal size (each of which is assumed to be representative of the entire data set). Within each of these ten groups, each observation is assigned to one of k seeds, or randomly placed locations (values of the normalized variables) within the multidimensional space of the analysis. This yields ten different versions for the locations of the k seeds. The version with the lowest Euclidean distance (variance) between seeds and observations is used as the initial step for the next step. This method is used because k-means cluster analysis is very sensitive to the initial seeds used, and this method makes it likely that, if the analyses is repeated, the same answer will emerge.

Next, all observations are assigned to the nearest seed location as determined from the first step, and the total Euclidean distance is calculated. Then, the observations furthest from the centroids are reassigned to the nearest neighbor centroids, the centroid values are recomputed, and the total variance is recalculated. This process continues until the number of observations which are reassigned is less than 0.5% of the total.

The best number of clusters was determined to be fifty, based on the fact that the sum of the squared error (of the Euclidean distance) leveled out at an approximate minimum of fifty clusters in all cases. This method was used because it does not take into account or assume any prior knowledge about the data set before attempting to divide the data into clusters (often referred to as machine learning or a form of data mining). Finally, the mean elevation was calculated for each cluster, based on the location and the elevation the PRISM DEM assigned for each grid cell contained in the cluster.

Although this method was used because it produces robust results, it does not provide any information about which variable is most important. In this study, it only provides information about trend similarity among PRISM grid cells. Dr. Bjorn Brooks of the University of Wisconsin Madison provided sample clustering programs which were adapted for the study during Spring and Fall 2010. Tables 6 – 9 in the appendix provide specific cluster statistics for the period 1971 – 2000 for elevation, as well as minimum and maximum temperature. Figures 33 and 34 are example maps showing the mean spring cluster trends for all 50 clusters for both 1941 – 1970 and 1971 – 2000. Note that the mean cluster value for both variables increases from the early period to the later period. Also, clusters are spatially much more complex in the mountain regions as compared to the plains. In some cases, significant differences occur, including clusters with means trends of opposite signs, in adjacent clusters.

For both periods, clustering for the early period tends to show a clear spatial pattern where clusters with greater positive values are located in mountainous areas. The one exception to this, however, is the Sierra Nevada range, where highly negative mean cluster trends are present for both periods in the northern 2/3 of the range, while positive values occur in the southern 1/3. A visual inspection also seems to indicate that mean cluster trends are more spatially variable in the later period, which may be a reflection of fewer stations in this ecoregion than in other ecoregions.

5. Results

5.1. Mean Seasonal Temperature Trends

As shown in Figure 11, maximum and minimum temperature trends over the western United States for the periods 1941 – 1970 and 1971 – 2000 are highly spatially variable. This variation is largely due to the interaction of the complex terrain with the local synoptic regime, its continentality, and other factors, which are poorly understood. Based solely on temperature trends over these two periods, it is rather difficult to discern terrain influenced trends. Some basic patterns can be seen, however. The Colorado Rockies (Southern Rockies) have generally higher or positive trends during all periods, except for 1941 – 1970 maximum temperature, for which the trends are slightly negative. The central valley of California can be seen as a long oval bordered by generally higher, positive trends to its east, especially for the later period. Later period maximum trends show the Wasatch Range in Utah, while minimum trends for the same period are similar throughout the Cascade Range. The mountain/valley terrain of Nevada can also be seen, especially for 1971- 2000. Otherwise, the trends are generally of greater magnitude for minimum temperatures than for maximum temperatures, which is consistent with global temperature trends. An important note here is that some spatial anomalies in the trends do occur. In particular, an area of highly negative trends is present in the central Sierra Nevada for 1941 – 1970 and in south central Wyoming (not in any ecoregion – but part of this region is included in the buffered Wasatch Range and Southern Rockies regions used in the elevational trend analysis). I did not determine whether these anomalies are due to station data or actual terrain influences, although they appear to be caused by station data because neither anomaly is present for both time periods.

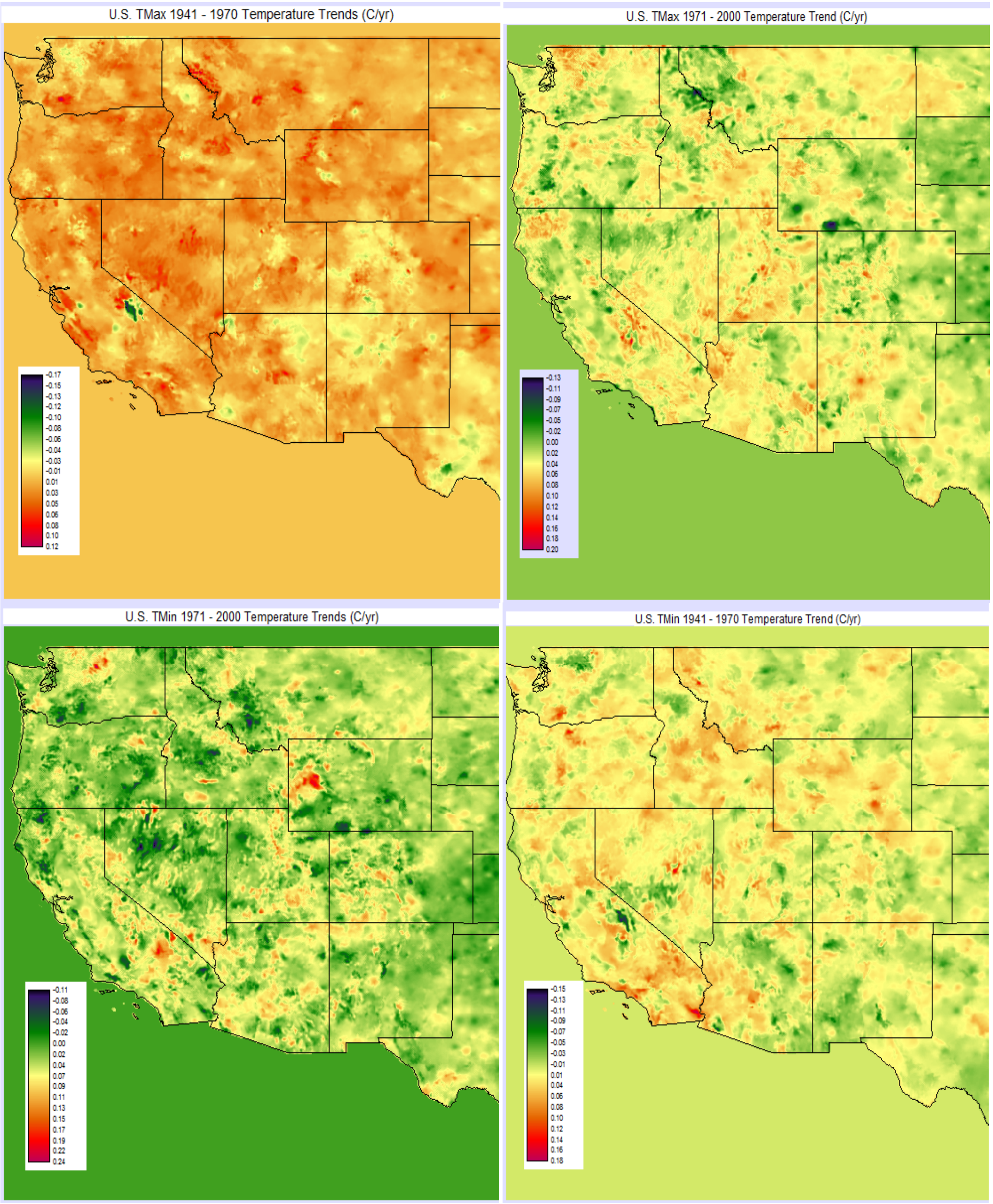
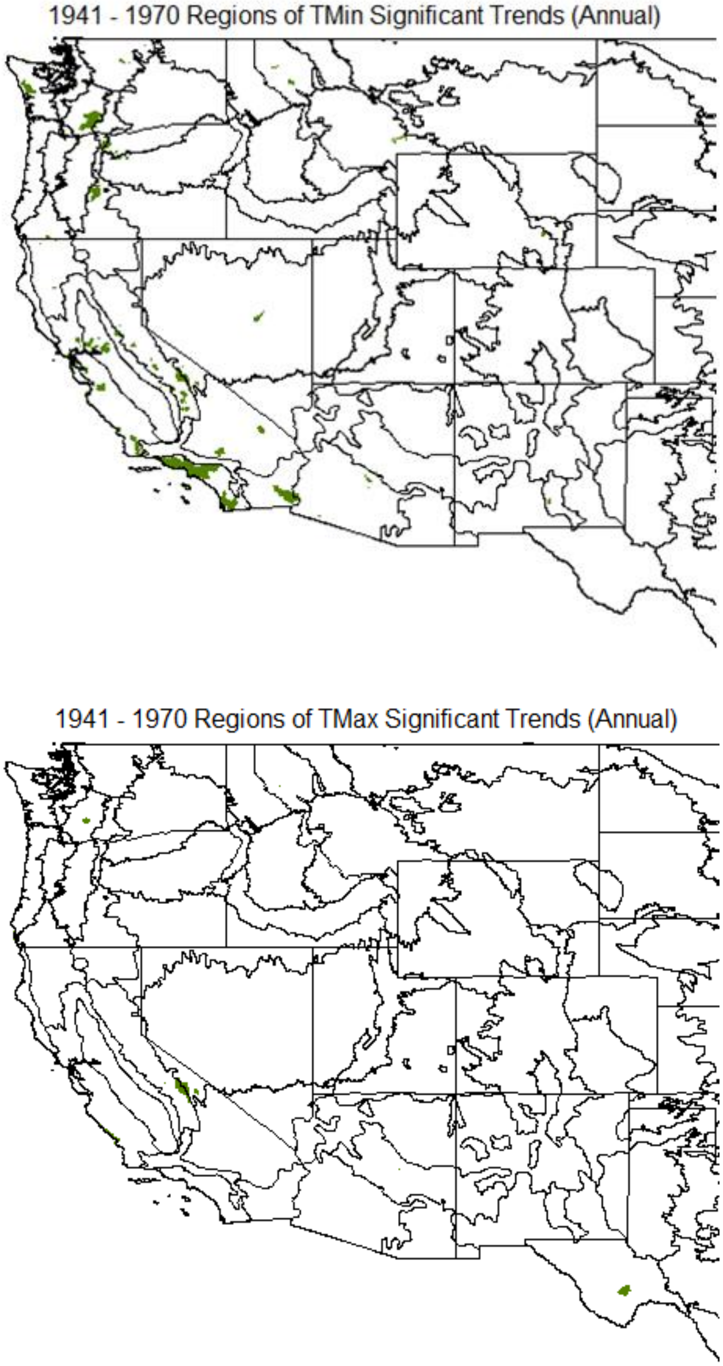


Figure 11. Mean annual temperature trends based on monthly PRISM data (4 km resolution).

Figures 12 and 13 show where minimum and maximum annual temperature trends for both periods are statistically significant. Here, a statistically significant trend is based on whether or not the slope of the best fit least squares regression line is different from zero (no slope). In this case, the degrees of freedom were based on the number of time series points (30 years of monthly data). Trends for maximum temperature during the early period show virtually no significance across the western U.S., except for a small area on the southeast border of the Sierra Nevada ecoregion. For the later period, the areal spatial extent of significant trends expand slightly, including parts of the Pacific Northwest, California, and a few small portions of the interior western U.S. Minimum temperature trends for the early period are also significant across parts of the Pacific Northwest and California. By far, the largest portion of significant trends are present for later period minimum temperatures. Once again, the Pacific Northwest and California contain most of the significant trends. However, some portions of the Middle and Southern Rockies contain significant trends. Many smaller areas of significant trends are scattered throughout the entire region.

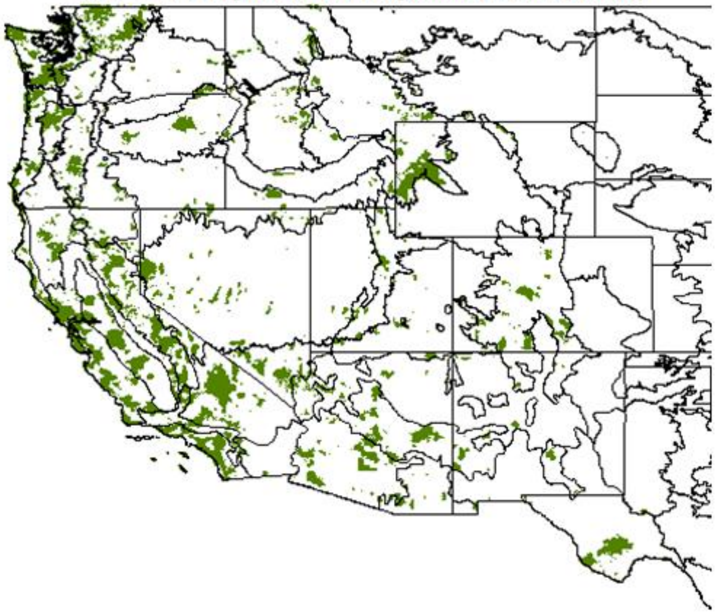


1941 - 1970 Regions of TMin Significant Trends (Annual)

1941 - 1970 Regions of TMax Significant Trends (Annual)

Figure (12). Areas of significant minimum (top) and maximum (bottom) temperature trends for 1941 – 1970. Although the coverage of these areas is greater for minimum temperature, there is relatively very little spatial extent in both cases.

1971 - 2000 Regions of TMin Significant Trends (Annual)



1971 - 2000 Regions of TMax Significant Trends (Annual)

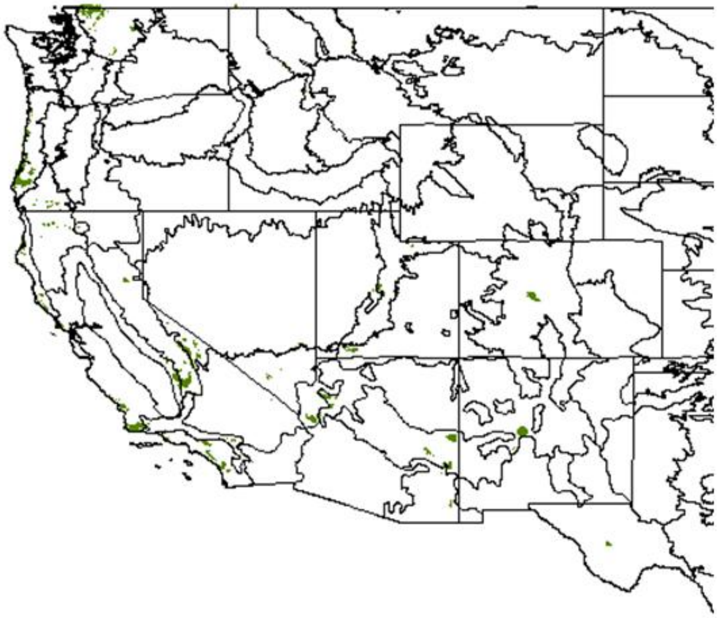


Figure 13. Areas of significant minimum (top) and maximum (bottom) temperature trends for 1971 – 2000. Significant maximum temperature trends now show slightly more coverage than the early period, while minimum temperature trends show much greater extent of significant trends.

The mean seasonal temperature trends for the six mountain ranges in this study share some very general characteristics. Mean seasonal maximum temperature trends are more variable throughout the study period than the minimum trends, which tend to be more consistent and follow a trend closer to zero. Each range shows relatively high trends through the 1920's, after which they level off or decrease to the mid or late 20th century, and then begin a rise. Additionally, seasonal trends for each range tend to share general trends, although some important differences are apparent.

In spite of these similarities, each range has its own unique seasonal temperature trend patterns. As shown in figures 14 – 19, these patterns are quite complex. Interestingly, each season's trends are highly variable, and no single season is more consistent or less variable than another across the different ranges.

The Cascades show peaks for both minimum and maximum trends around 1910, 1945, and 1965, with minimum trends occurring around 1925 and 1955. Spring minimum trends peak close 0.06°C/year around 1965, while the other seasons experience very little or no trend. Trends for the other months then increase, while the spring trend decreases to zero. In contrast to minimum trends, maximum recent trends for the Cascades occur during summer, while the other seasons trends remain near zero. Additionally, the Cascades are currently experiencing the smallest mean seasonal trend magnitudes of any range.

Minimum trends for the Sierra Nevada show a very large range since 1895. Trends rose to between 0.6°C and 1.0°C/year before 1910, and then fell to around -0.06°C/yr by 1927. Since then, all seasons, except winter, have experienced a moderate rate of increase to between 0.04 and 0.06°C/yr. Winter's minimum trend remains near zero. The spring minimum trend has appeared to have leveled off since 1960, while fall's trend has risen sharply since 1957. Maximum trends, on the other hand, peaked for all seasons around 1912, fell to a mean of around zero by 1930 and have risen quickly since 1960. The spring maximum trend has also appeared to have peaked already and is now steady at about 0.05°C/yr.

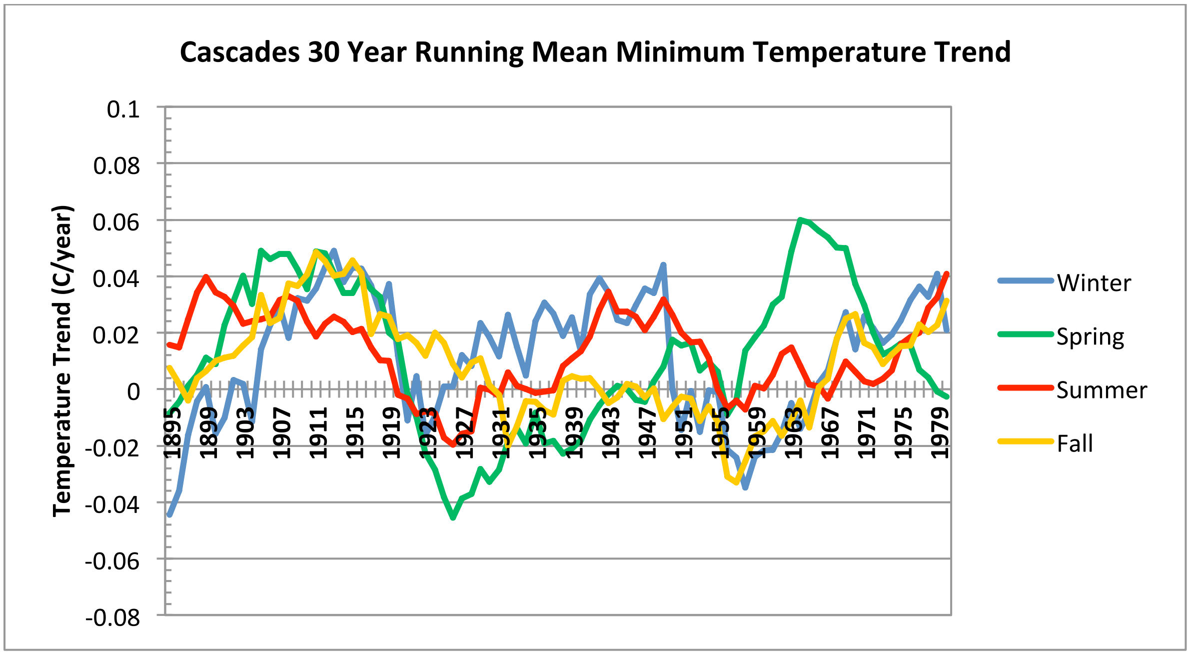
After peaking around 1910, mean maximum temperature trends for the Northern Rockies for spring and summer fell to a minimum around 1937, rose to another peak about 1943, and are currently experiencing a peak. The fall and winter minimum trends for this region have been significantly less variable, although they follow a similar pattern. Winter maximum trends have been the most variable, on the other hand, and have mostly been above zero since 1895. Summer trends have been small, but entirely positive during this period, and fall trends remained close to zero through 1965, and then rose. Spring trends for both variables peaked around 1965 and have since fallen to slightly negative.

In similar fashion to the Northern Rockies, both minimum and maximum trends for spring in the Middle Rockies peaked around 1965, and have since fallen, although they remain above zero in this region. Maximum winter and fall trends are the least variable, while both spring and summer trends experienced a relatively large minimum during the 1920 and 1930's. Except for winter, all maximum trends are still rising. Minimum trends for fall and summer are the least variable and are still rising, while winter trends peaked during the 1930's, fell to slightly negative values around 1960 and then rose very quickly to their current peak.

Both minimum and maximum seasonal trends in the Southern Rockies are quite coherent, with little variation between seasons. Maximum trends show a large peak around 1915, a drop to around zero by 1950 (except fall, which fell to -0.06°C/yr), and then rapidly rise. Spring trends appear to have leveled off recently, while winter trends have dropped very recently. Minimum trends show a small peak around 1915, a long period of trends close to zero from 1920 – 1955, and then a rapid rise of all seasonal trends. Once again, spring trends appear to have leveled off since around 1963.

Maximum trends in the Wasatch Range are very close to the Southern Rockies minimum trends. Spring trends appear to have leveled off in similar fashion, although the other seasons trends continue to rise and have surpassed that of spring. Minimum trends were quite consistent during the earlier part of the 20th century. Maximum trends experienced a larger peak around 1910, fell to near zero by 1920 and stayed there through 1960, after which they rose. Spring shows the highest trend, however, in contrast to the other seasons, which follow each other very closely.

Table 3 summarizes the mean seasonal temperature trends for each ecoregion for 1941 – 1970 and 1971 – 2000. All trends that were found to be significant are positive, which was not expected for the early period, since many locations around the world, including portions of North America, experienced no trend or even slight cooling during this period (**Figure 1**). These results are representative of local rates of change, therefore. All significant trends are for minimum temperatures, except for 1971 – 2000 maximum trends for the Wasatch. The number of significant trends increased nearly threefold over the two periods, as well. Winter, spring, and fall are the most common seasons showing significant trends. A bias toward southern regions having more significant trends is evident, with the Sierra Nevada, Middle Rockies, and Wasatch holding the most significant trends for the later period. Interestingly, these same ranges showed significant summer trends during the early period, but these were not present for the later period. However, the only significant trend for the Southern Rockies for both periods is the summer trend. The Northern Rockies were expected to show more significant trends, especially for the later period, because of their relatively high latitude. However, they are also the lowest in elevation. This is not a tested hypothesis in this paper, but perhaps this moderates their general temperature trends.



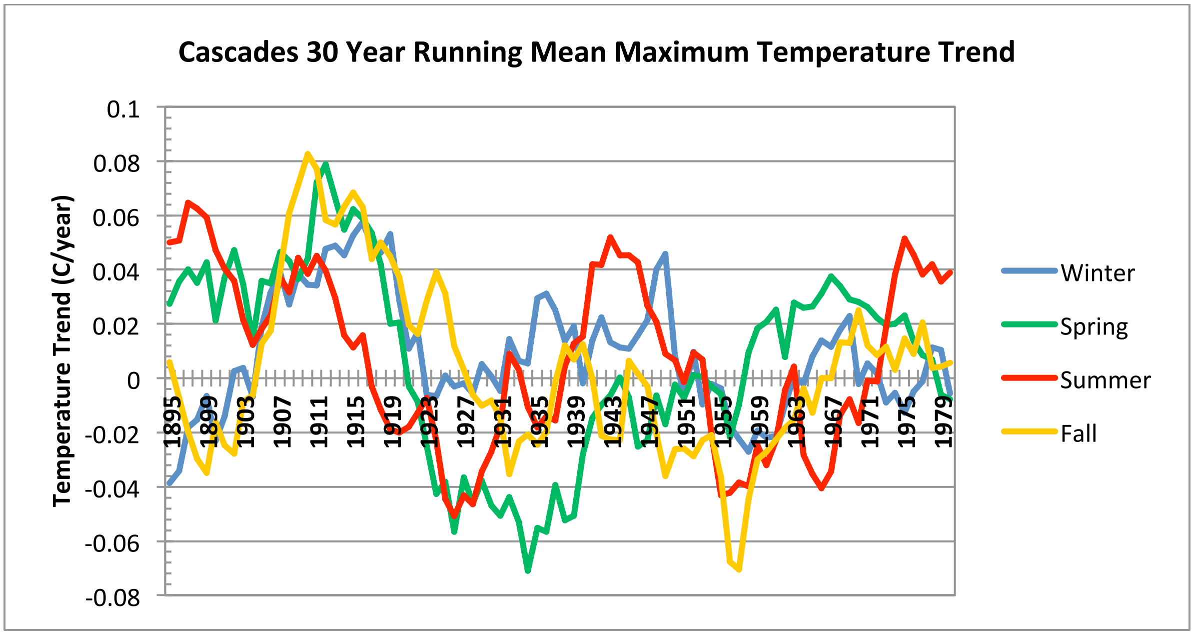
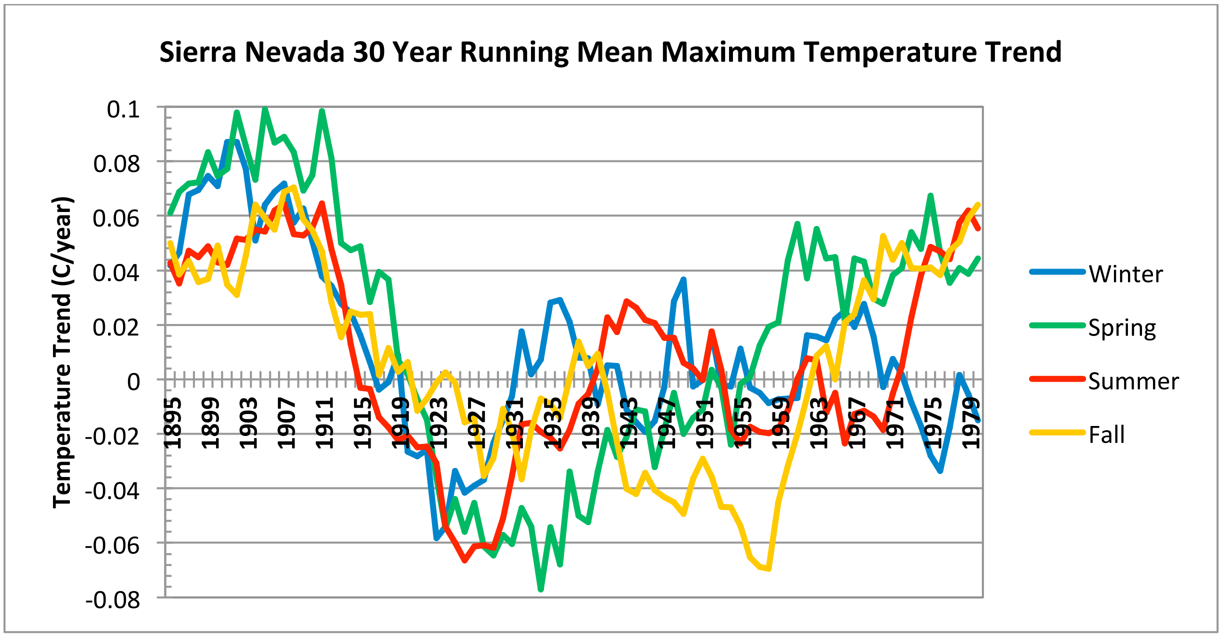


Figure 14. Cascades 30 year running mean minimum (top) and maximum (bottom) temperature trends. In contrast to many locations, trends for maximum temperatures are of greater magnitude than those for minimum temperatures. Patterns over the past century are similar for both, however.



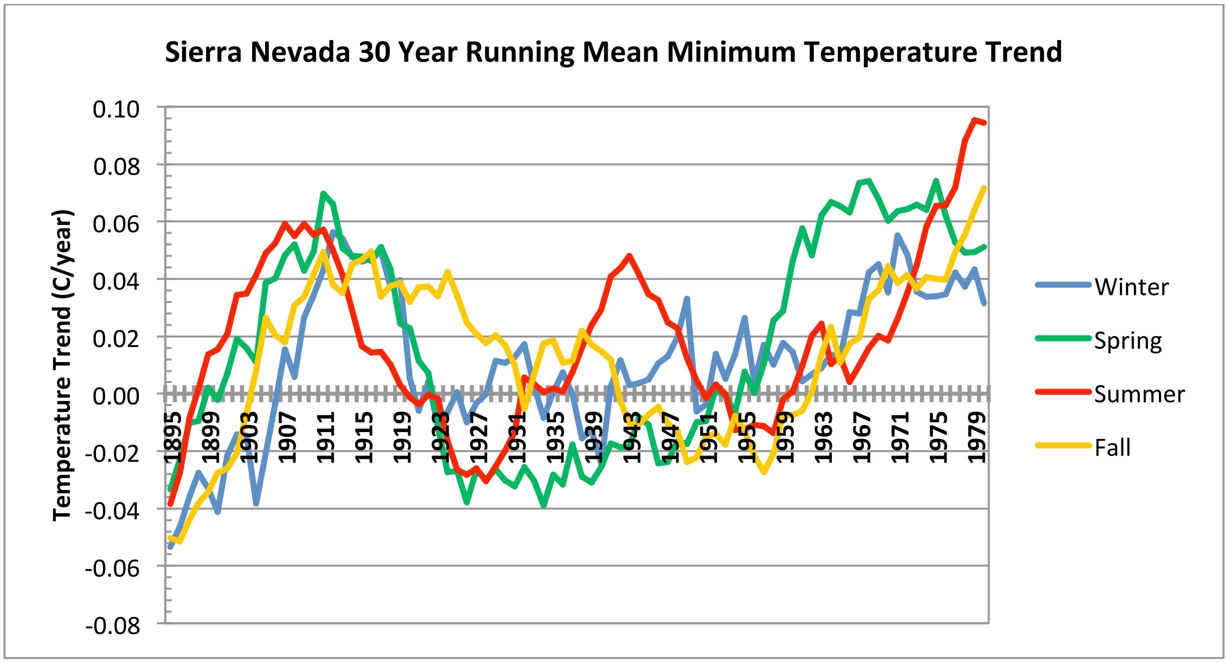
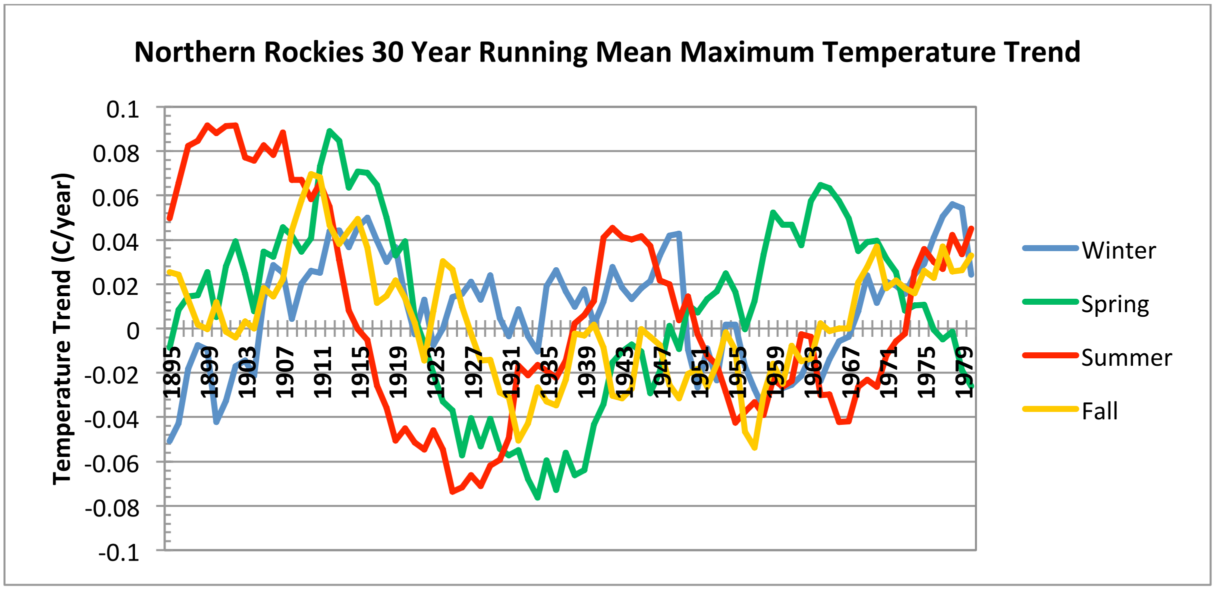


Figure 15. Sierra Nevada 30 year running mean maximum (top) and minimum (bottom) temperature trends. Trends follow similar patterns for both variables since the 1920's, although maximum temperature trends have increased the most in magnitude. Summer minimum temperature trends have risen significantly since 1960, while summer maximum temperature trends have risen sharply since 1970. Spring trends appear to have leveled off since 1960 or so, while winter maximum temperature trends have decreased and winter minimum temperature trends have increased.



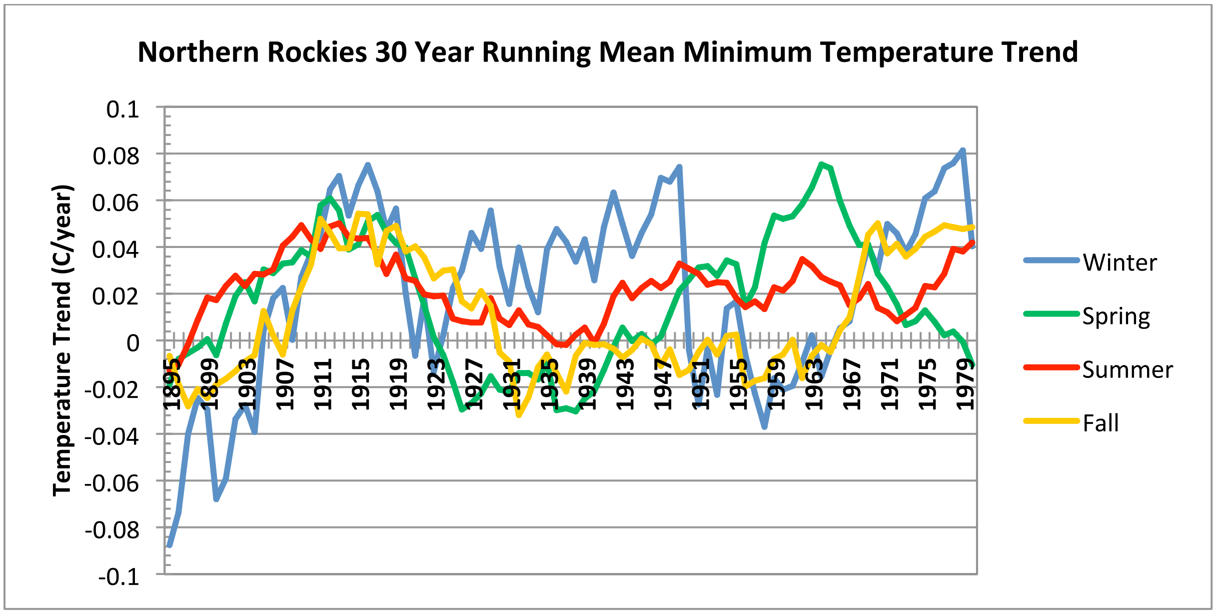


Figure 16. Northern Rockies 30 year running mean maximum (top) and minimum (bottom) temperature trends. For this region, maximum temperature trends have shown greater variability than minimum temperature trends, which have stayed, on average, slightly positive since 1920. Maximum temperature trends showed a decrease from 1940 – about 1960, and then rose. Interestingly, the spring maximum temperature trend was significantly positive, while the other season's trends remain slightly negative during the period 1960 – 1970. Spring minimum temperature trends were also higher than the other season's during this period, but not to the same extent. Winter minimum temperature trends have risen above the others since 1970.

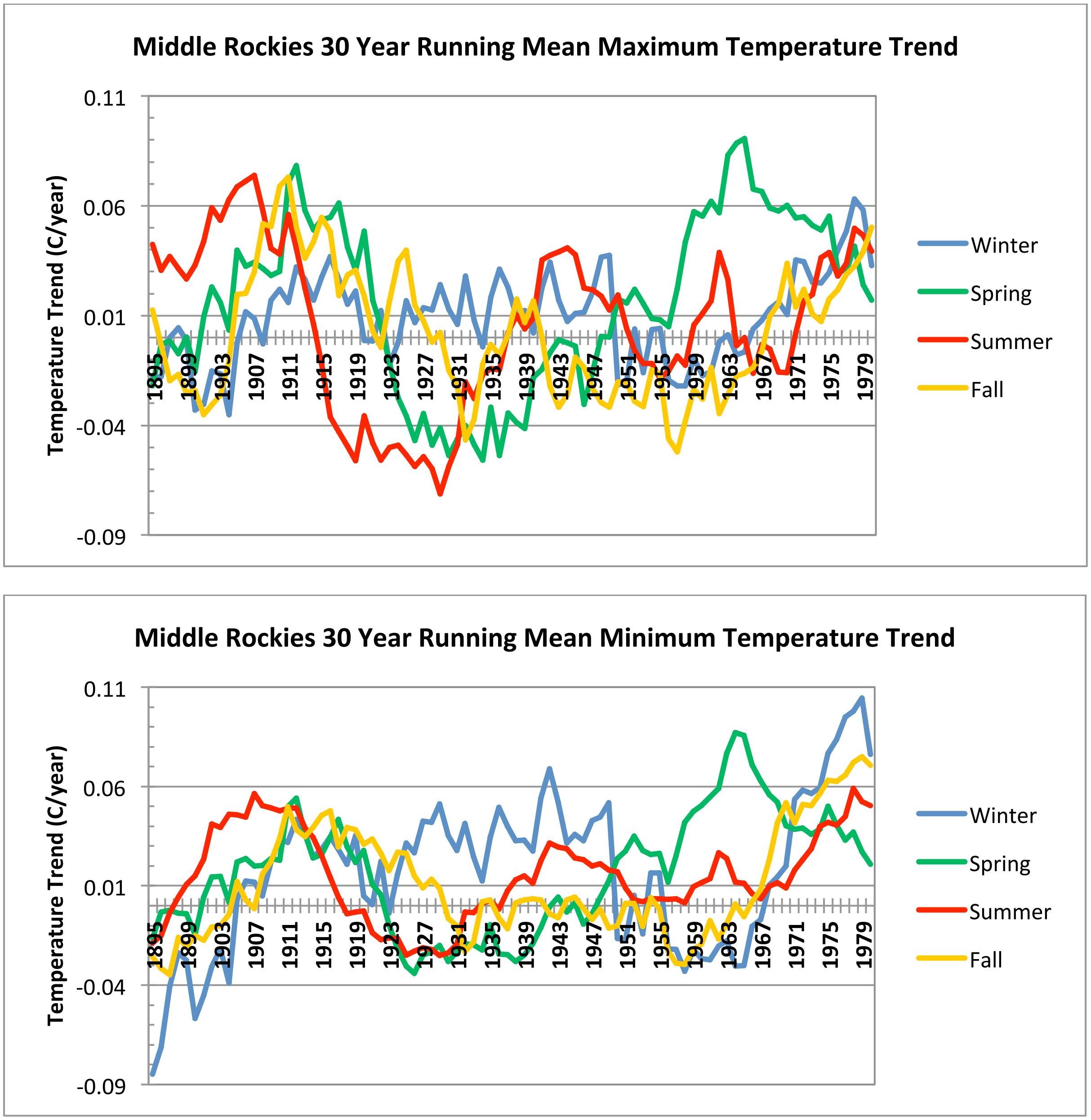


Figure 17. Middle Rockies 30 year running mean maximum (top) and minimum (bottom) temperature trends. Maximum temperature trends have risen since 1930 for all seasons, with spring increasing to values much higher than the other seasons during the period 1955 to 1975, and then dropping below the trend values for the other seasons. Minimum temperature trends are less variable, and have experienced a more consistent rise since 1930, although winter's trend dropped significantly from 1950 – 1968. Since 1970, winter's minimum temperature trend has risen above the others, while spring's minimum temperature trend has also dropped below the others.

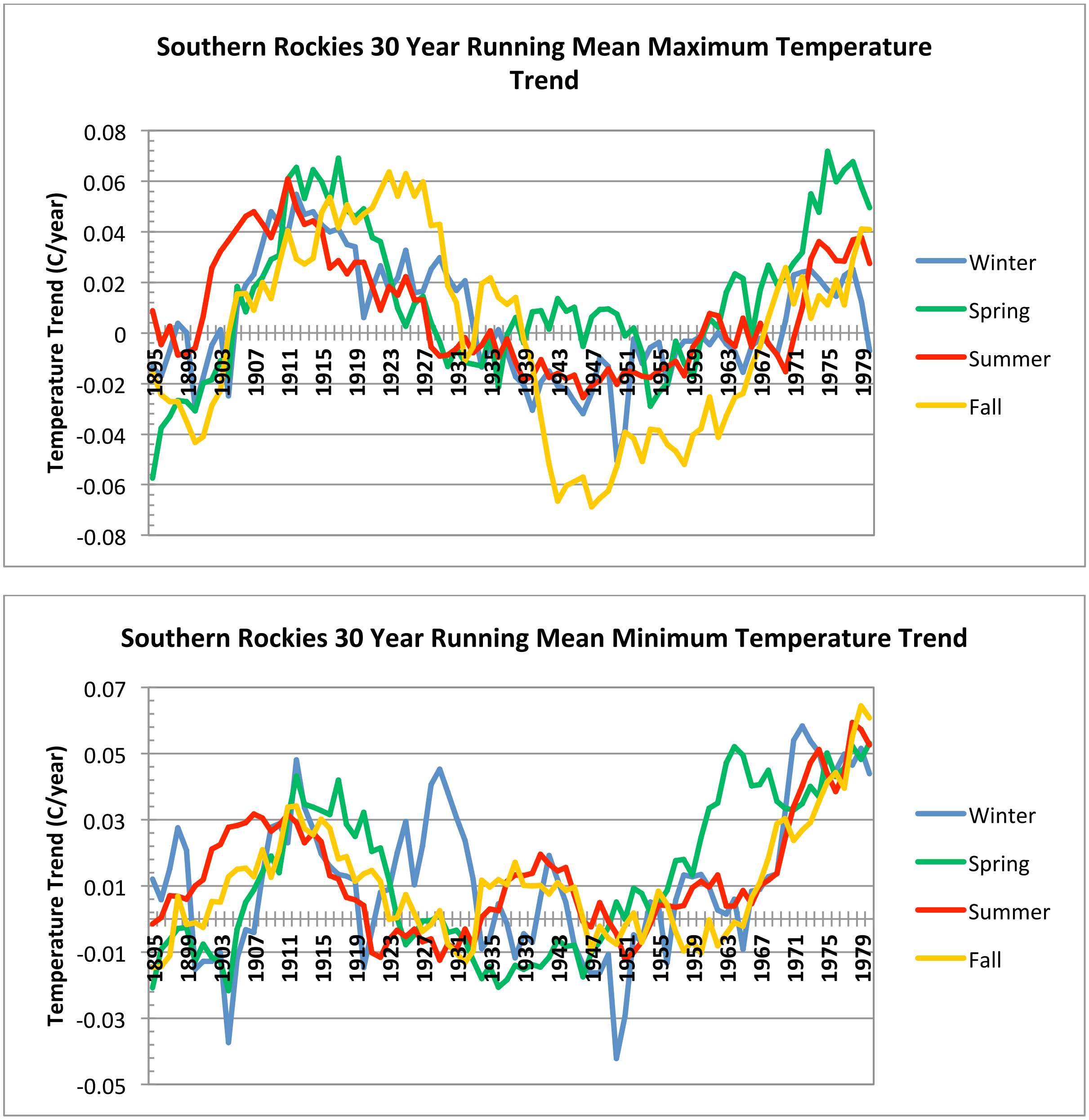
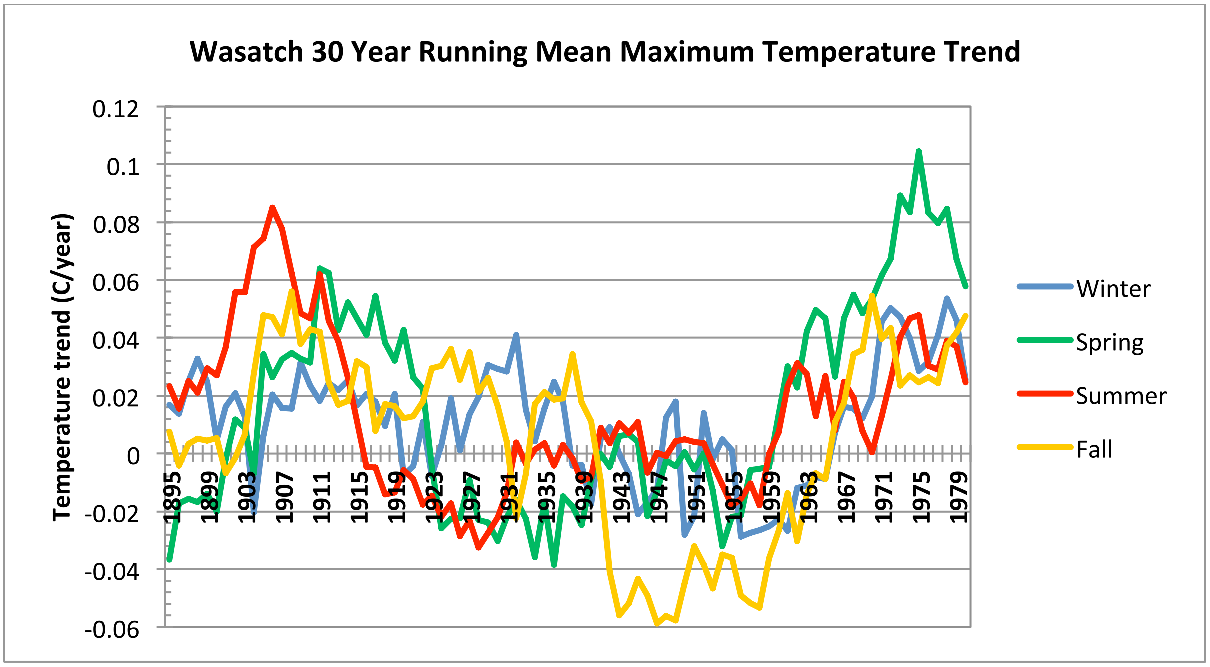


Figure 18. Southern Rockies 30 year running mean maximum (top) and minimum (bottom) temperature trends. Minimum temperature trends show dramatic swings over the past century, from being significantly positive in the 1910's to significantly negative during the 1940's and 1950's, and have appeared to reach a maximum about 1975 – 1980 and are beginning to decrease. Maximum temperature trends follow a similar pattern, but have less magnitude. Similar to the Northern and Southern Rockies, spring minimum temperature trends were above the other season's trends. Since 1970, all season's maximum temperature trends are quite similar.



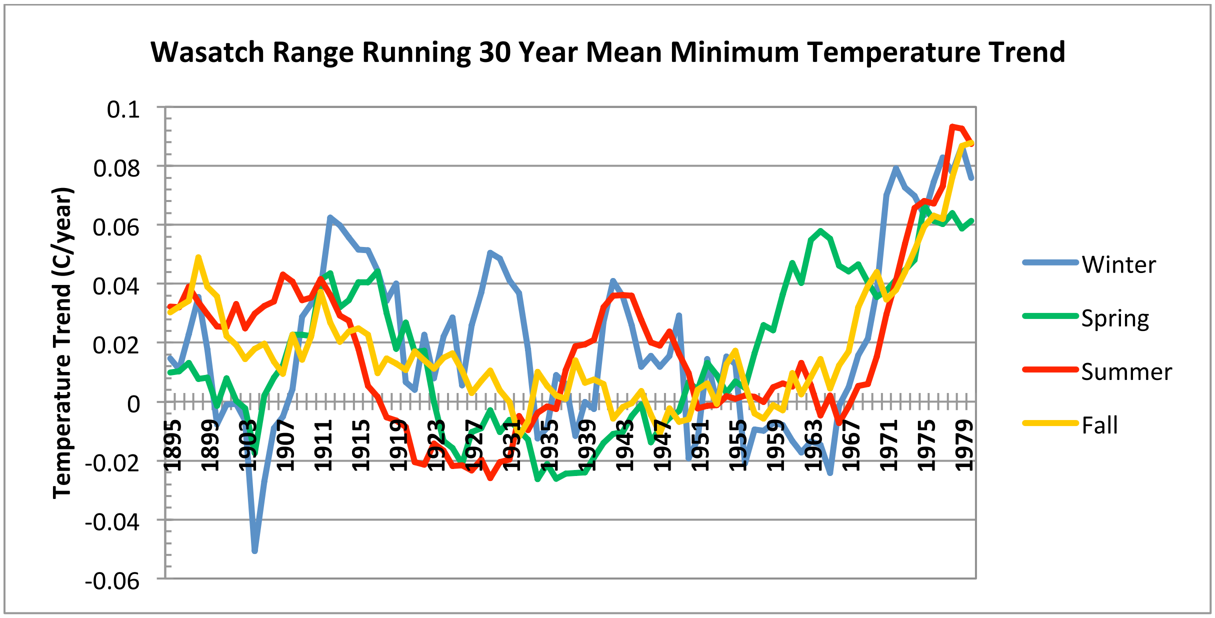


Figure 19. Wasatch Range 30 year running mean maximum (top) and minimum (bottom) temperature trends. Maximum temperature trends during the mid 20th century are close to zero, and then experience a significant rise after 1960. Spring experiences the greatest rise in trends. Minimum temperature trends are not quite as consistently close to zero, especially summer trends, but they are also quite small during the mid 20th century. As with maximum temperature trends, a large rise has occurred since 1965 or so, with each season experiencing very similar trends during this period.

Table 3. Table showing time period, season, and location of significant trends in mean ecoregion temperature. All significant trends are positive. As expected, the period 1971 – 2000 shows a large increase in the number of significant trends. All significant trends are for minimum temperature, except for the 1971 – 2000 spring Wasatch Range maximum temperature trend.

			1941 - 1970	1971 - 2000				1941 - 1970	1971 - 2000
Cascades	Winter	Tmax			**Sierra Nevada**	Winter	Tmax		
		Tmin					Tmin		+
	Spring	Tmax				Spring	Tmax		
		Tmin					Tmin		+
	Summer	Tmax				Summer	Tmax		
		Tmin					Tmin	+	
	Fall	Tmax				Fall	Tmax		
		Tmin					Tmin		+
Northern Rockies	Winter	Tmax			**Middle Rockies**	Winter	Tmax		
		Tmin					Tmin		
	Spring	Tmax				Spring	Tmax		
		Tmin					Tmin		+
	Summer	Tmax				Summer	Tmax		
		Tmin					Tmin	+	
	Fall	Tmax				Fall	Tmax		
		Tmin		+			Tmin		+
Southern Rockies	Winter	Tmax			**Wasatch Range**	Winter	Tmax		
		Tmin					Tmin		+
	Spring	Tmax				Spring	Tmax		+
		Tmin					Tmin		+
	Summer	Tmax				Summer	Tmax		
		Tmin	+	+			Tmin	+	
	Fall	Tmax				Fall	Tmax		
		Tmin					Tmin		+

5.2 Elevational Temperature Trends

5.2.1 Cluster Results

This section describes two analyses that were used to determine if seasonal temperature trends for both minimum and maximum temperatures vary by elevation. The first analysis used was k-means clustering for these variables for two periods, 1941 – 1970 and 1971 – 2000. Figures 20 – 21 show the results of four variable clustering (of each season's trends for minimum and maximum temperature, mean dewpoint, and precipitation). Figures 22 – 23 show the results of sixteen variable clustering (of all four season's trends for the above variables), which was performed in order to test the hypothesis that seasonal elevational temperature trends are stronger than yearly trends. Table 4 shows the values and significance levels of these elevational temperature trends. These clustering analyses were performed for the entire western U.S. west of 105°W longitude. An important note here is that the mean centroid trends (y-axis) and elevational trends in table 4 are about one order of magnitude less that of the individual grid cell trends. This occurs because each centroid is the mean value of each cluster's observational values.

As figure 21 shows, this analysis indicates that a positive relationship exists between elevation and both winter minimum and maximum temperature trends for the period 1941 -1970. This means that temperature trends increased with increasing altitude over the western U.S., on average. Table 4 indicates that both of these elevational trends are significant. Spring, on the other hand, experienced significant negative elevational trends over the same time period, but this was due to a strongly negative trend for a cluster located at about 3000 meters (a statistical outlier). Maximum and minimum trends are opposite for summer and fall. Summer maximum trends are slightly negative, while minimum trends are moderately positive. For autumn, however, the opposite is true, with maximum trends being positive and minimum trends being negative. Neither summer or fall trends are significant.

Four variable clustering analysis for the period 1971 – 2000 shows that winter and spring trends have changed sign for both maximum and minimum temperatures, although winter’s minimum trend is nearly constant with elevation (figure 21). Maximum winter trends are now significantly negative, and both spring trends are significantly positive. Summer maximum trends are now positive, but minimum trends are nearly flat. Autumn minimum elevational temperature trends are now significantly positive, in contrast to a negative trend in 1941 – 1970.

Sixteen variable clustering for 1941 – 1970 produced similar results to that of the seasonal clustering, where winter trends show a positive relationship with elevation and spring trends show a negative relationship (figure 22). The main difference for winter and spring is that the relationships are not as strong, but minimum trends for these seasons were still significant for this analysis. Both autumn trends are slightly negative, but very similar. Summer trends were mixed, with slightly positive minimum trends and somewhat negative maximum trends.

Figure 23 shows significantly positive elevational temperature trends for spring for 1971 – 2000. Both winter trends are slightly negative, both in direct contrast to the 1941 – 1970. Summer trends are nearly flat for this period, while both a significantly positive autumn minimum trend exists alongside a nearly flat maximum trend.

As expected, the four variable clustering produced more significant results than the sixteen variable (yearly) analysis. This is likely because the yearly analysis operates on trends averaged over seasonal trends, which are of opposite sign and different magnitudes. However, the differences between them are important. Seasonal clustering for 1941 – 1970 showed both winter and spring maximum trends to be significant (positive and negative, respectively), and seasonal clustering for 1971 – 2000 showed winter maximum trends to be significant, whereas the yearly clustering did not. This indicates that seasonal trends can be different than or larger than yearly trends. Also, the yearly analysis indicates the same seasons and time periods as being significant as the seasonal analysis does.

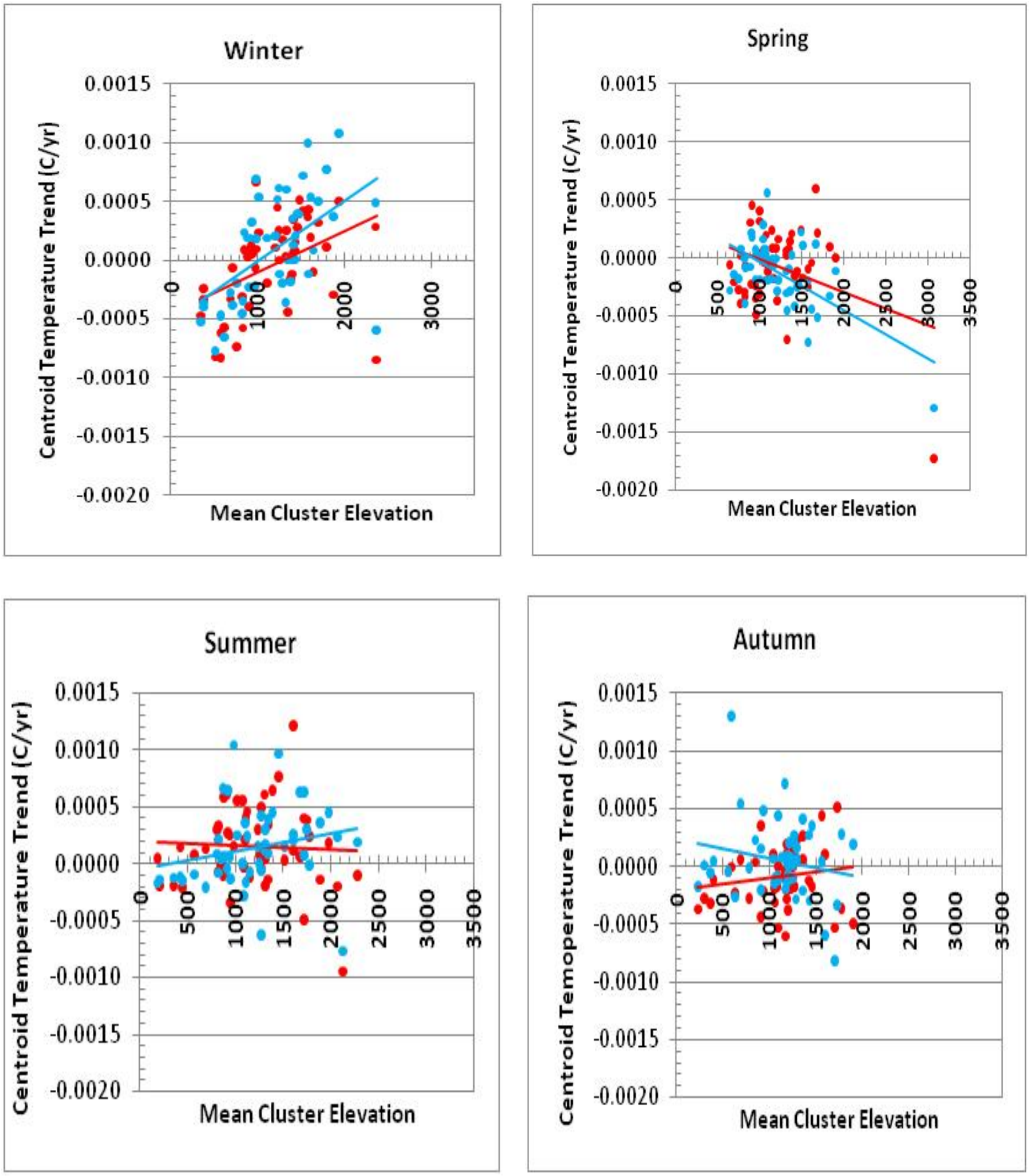


Figure 20. 1941 – 1970 Seasonal Elevational Trend Graphs based on four variable clustering. Red = TMax. Blue = TMin. Winter elevational clustering trends show that both maximum and minimum trends for the entire western U.S. increased with increased elevation, while spring shows the opposite, with elevational temperature trends decreasing with increased elevation. Maximum temperature shows no trend for summer, but minimum temperature shows an increase. Autumn trends are mixed, with minimum trends showing a negative relationship with elevation, and maximum trends showing a positive relationship.

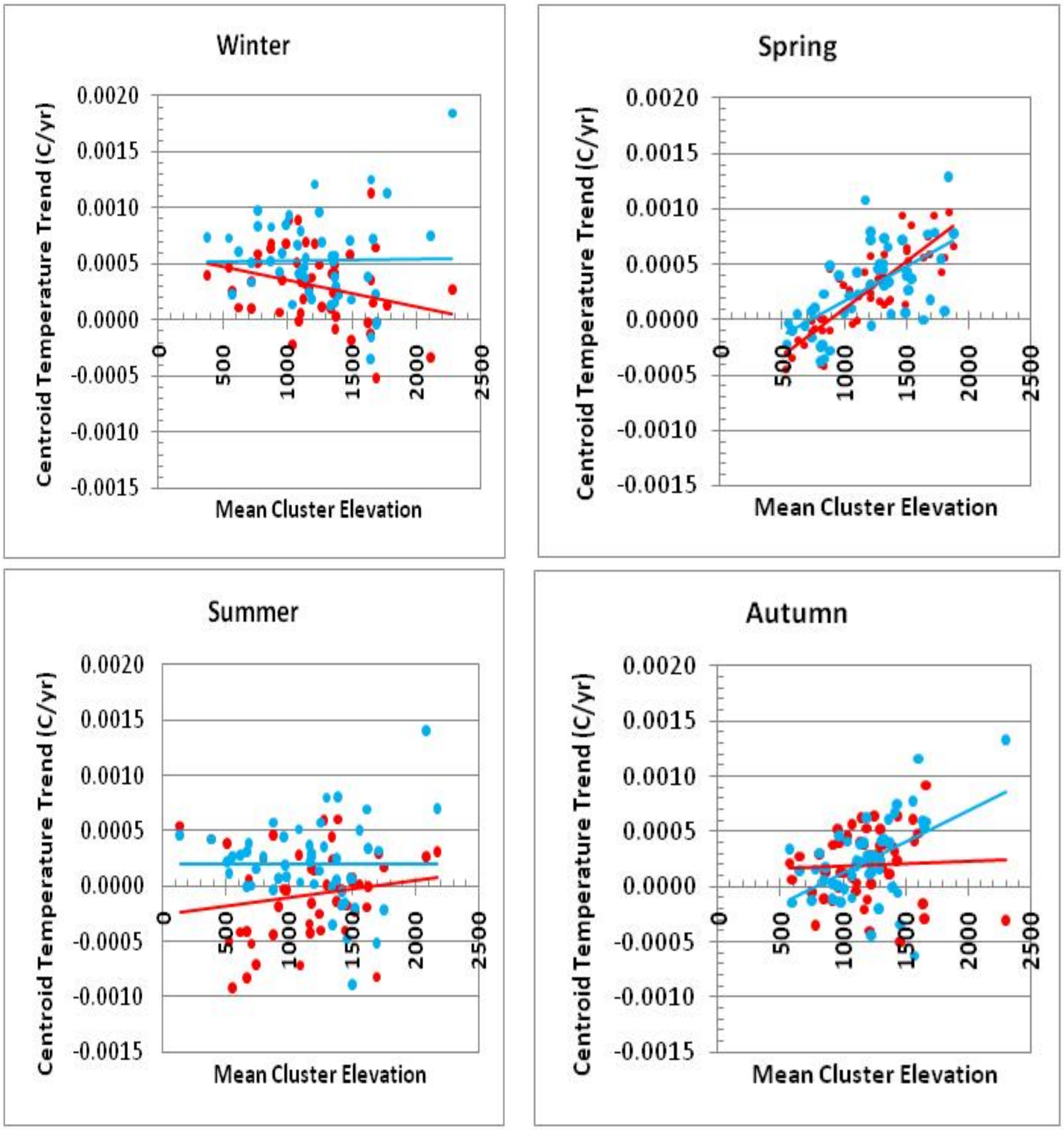


Figure 21. 1971 – 2000 Seasonal Elevational Trend Graphs based on four variable clustering. Red = TMax. Blue = TMin Winter elevational clustering trends indicate that minimum trends are steady, while maximum trends are decreasing. This is the opposite of 1941 – 1970 results. Spring trends for both variables are the opposite of those for 1941 – 1970, with both variables showing a positive relationship with increasing elevation. The same is true for summer, where maximum trends are increasing and minimum trends are steady. For autumn, maximum trends are steady, while minimum trends are increasing.

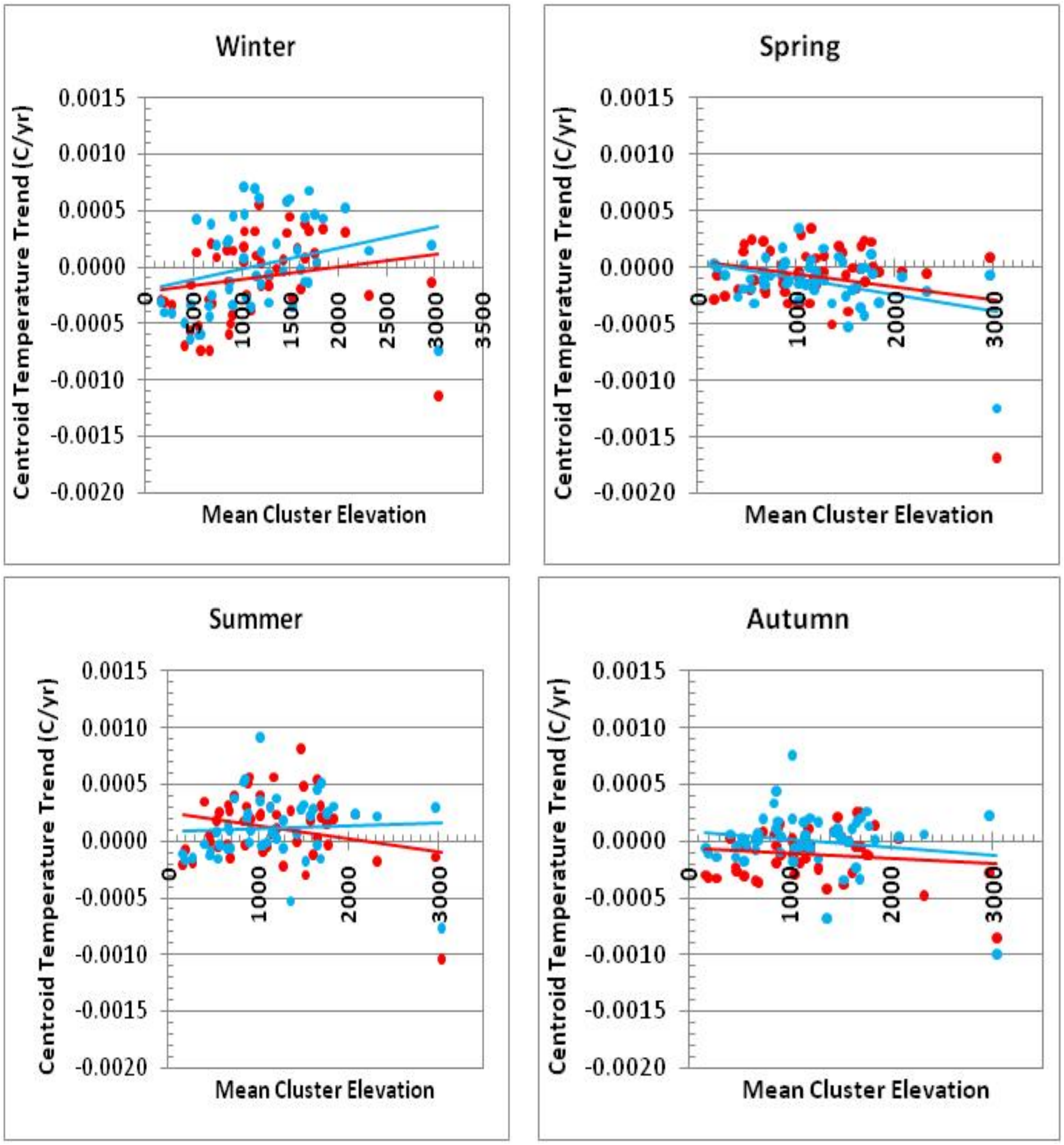


Figure 22. 1941 –1970 Seasonal Elevational Trend based on 16 variable clustering. Red = TMax. Blue = TMin. Both maximum and minimum trends show a positive relationship with height for winter, and both variables show a negative relationship for spring. In contrast to the four variable clustering, summer minimum trends are close to zero, while maximum trends are negative. Both variables show slight negative relationships with elevation.

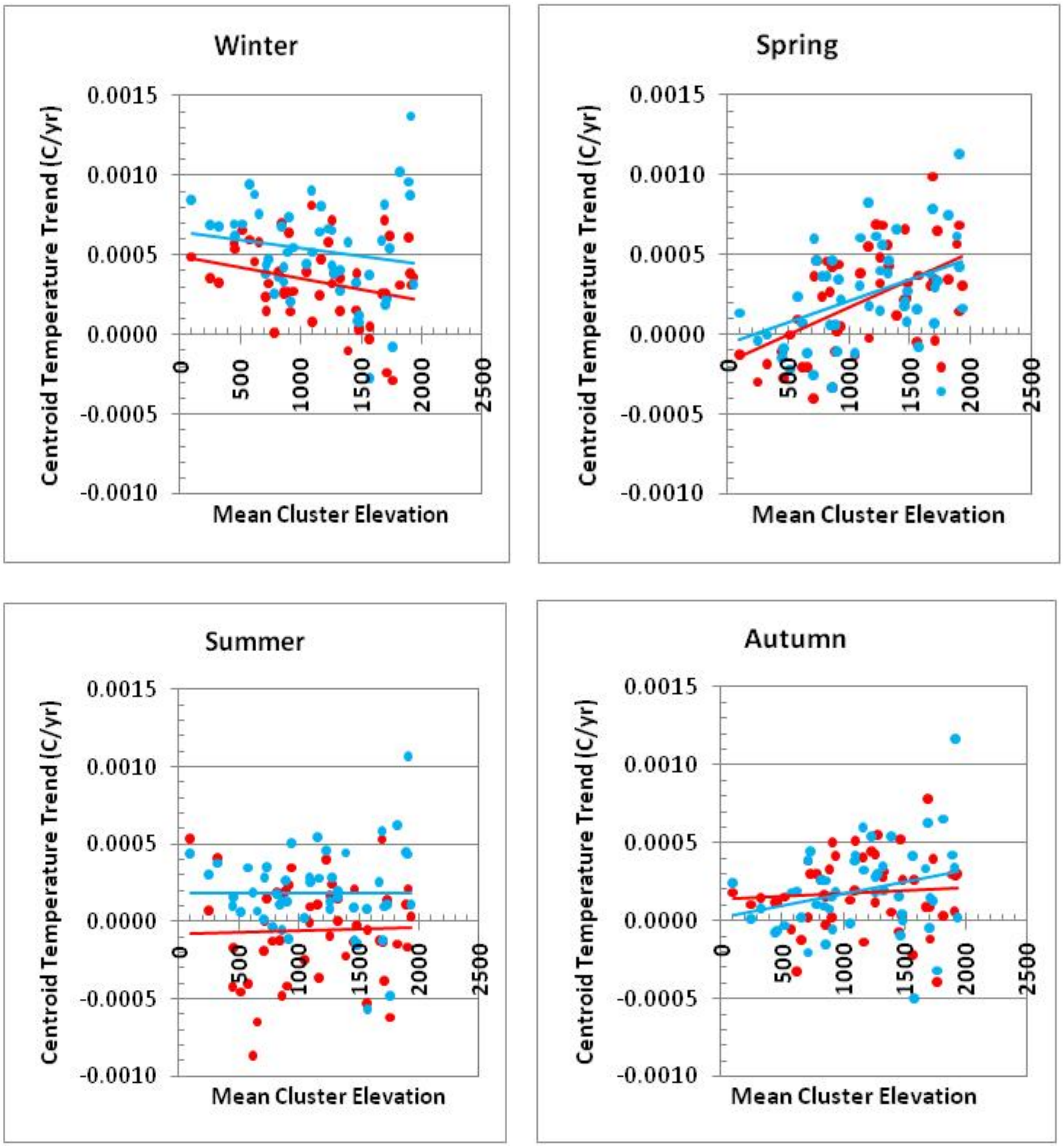


Figure 23. 1971 – 2000 Seasonal Elevational Trend based on 16 variable clustering. Red = TMax. Blue = TMin. For this period, winter elevation trends are opposite those of 1941 – 1970, for both winter and spring minimum and maximum temperature trends. This agrees with the four variable clustering results, except that the sixteen variable clustering produces a negative winter minimum trend, rather than no trend. For summer, this analysis produced very small negative trends at all elevations for maximum trends, and small positive trends at all elevations for minimum temperatures. This is in contrast to the four variable analysis, which produced a maximum trend with a positive relationship to elevation. Results for autumn are very similar to the four variable analysis, with a flat maximum temperature trend and an increasing minimum trend.

Table 4. Table showing results of regression analysis (cluster centroid vs elevation – C/yr versus km), including slope of cluster centroids with respect to elevation, squared correlation, and significance values. In general, four variable clustering produced more significant results than sixteen variable clustering because much less averaging of trend data was involved (seasonal versus yearly). Despite this, results are similar. Specifically, there are only three significant values the four variable clustering produced which the sixteen variable clustering did not. These include winter TMax 1941 – 1970, spring TMax 1941 – 1970, and winter TMax 1971 – 2000. Otherwise, four variable clustering showed greater significance levels than did sixteen variable clustering, but this does not change analysis results.

1941 - 1970 (4 variable clustering)				
		Slope (°C/yr/km)	R^2	P-value
Winter	Tmax	0.000355	0.198	0.00147
	Tmin	0.000517	0.297	0.000043
Spring	Tmax	-0.000248	0.110	0.01875
	Tmin	-0.000418	0.356	0.000005
Summer	Tmax	-0.000035	0.002	0.7452
	Tmin	0.000161	0.053	0.106648
Fall	Tmax	0.000111	0.027	0.2514
	Tmin	-0.000170	0.035	0.1822

1971 - 2000 (4 variable clustering)				
		Slope (°C/yr/km)	R^2	P-value
Winter	Tmax	-2.38E-04	0.08168	0.0443
	Tmin	1.42E-05	0.00021	0.9208
Spring	Tmax	8.50E-04	0.7147	1.14E-14
	Tmin	6.17E-04	0.3752	2.27E-06
Summer	Tmax	1.56E-04	0.0307	0.2236
	Tmin	1.06E-09	1.49E-06	0.9933
Fall	Tmax	4.29E-05	0.001925	0.7623
	Tmin	5.65E-04	0.2376	0.00033

1941 - 1970 (16 variable clustering)				
		Slope (°C/yr/km)	R^2	P-value
Winter	Tmax	1.13E-04	0.038	0.176
	Tmin	0.000185	0.082	0.043500
Spring	Tmax	-0.000113	0.055	0.10204
	Tmin	-0.000148	0.162	0.003800
Summer	Tmax	-0.000117	0.060	0.086
	Tmin	0.000000	0.003	0.699
Fall	Tmax	0.000046	0.019	0.3456
	Tmin	-0.000071	0.029	0.2353

1971 - 2000 (16 variable clustering)				
		Slope (°C/yr/km)	R^2	P-value
Winter	Tmax	-1.39E-04	0.0751	0.0542
	Tmin	-1.01E-04	0.026	0.263
Spring	Tmax	3.44E-04	0.2684	1.16E-04
	Tmin	2.69E-04	0.1692	3.01E-03
Summer	Tmax	2.17E-05	0.001206	0.8108
	Tmin	-6.23E-10	1.25E-06	0.9938
Fall	Tmax	3.59E-05	0.00567	0.6032
	Tmin	1.51E-04	0.06978	0.0638

5.2.2 Linear Regression

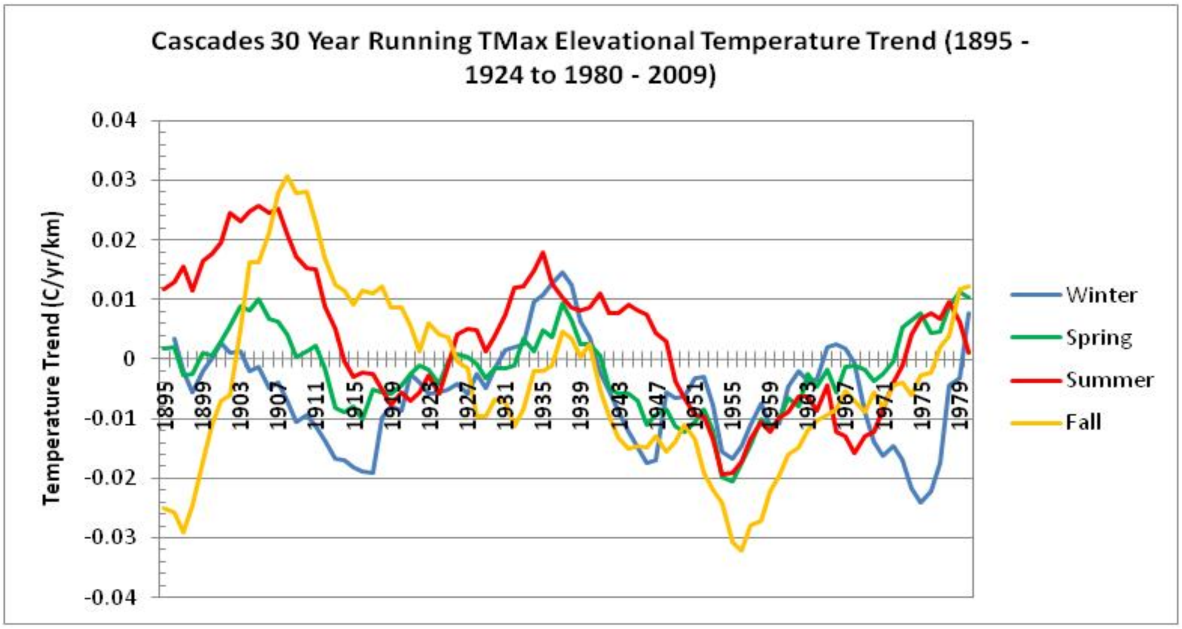
In addition to k-means clustering, linear regression for the mean minimum and maximum temperatures for each *buffered* ecoregion against elevation was performed in order to produce 30 year running means of seasonal elevational temperature trends (figures 24 - 29). These analyses were done in order to provide more regionally specific elevational temperature trends, in contrast to the clustering which was done for the entire western United States. In general, elevational temperature trends are of lower magnitude than mean temperature trends, but they follow a similar pattern through time. This means that when mean temperature trends are positive, higher elevations show greater or more positive temperature trends than do lower elevations. There are some general additional significant differences for all ranges, however. The most noticeable is that spring's elevational trend does not tend to peak around 1965 and then level off, as it does for many of the mountain ranges mean trends. It continues to rise, in most cases. Seasonal elevational trends tend to be much more consistent with each other as well, and variability through time is less than mean trends.

Both minimum and maximum elevational trends in the Cascades closely follow the pattern of the mean trends. Magnitudes are generally about ½ to 1/3 their value, however. All seasonal trends for both variables are currently rising. Maximum elevational trends have experienced a sharp rise since 1975.

Seasonal elevational trends in the Sierra Nevada range also closely follow the pattern of their mean trends, although their magnitudes are only about ¼ that of the mean trends. Here, maximum trends are more variable than minimum trends. Winter maximum trends have shown the greatest increase, while summer's maximum trends have leveled off since 1960. All seasonal minimum trends have experienced a moderate rise since 1950, and are very similar in magnitude. No seasonal trend shows a recent, noticeable difference from the others.

Through 1950, maximum elevational trends for the Northern Rockies are relatively small, but they do not follow their respect mean temperature trend patterns very closely. All seasons experience a large decrease to relatively large negative elevational trends (~ 0.04°C/yr/km) by 1967, which is starkly different from all other regions. Recently, winter and fall trends have increased somewhat, but spring and summer trends remain negative. In contrast, minimum elevational trends are very steady through 1950 as well, but they only decrease slightly through 1968 and then rise sharply.

The Middle and Southern Rockies, as well as the Wasatch, follow the relatively steady trend pattern of the Northern Rockies through about 1955. Maximum winter elevational trends for the Southern Rockies and the Wasatch are the most variable in comparison to the other seasons, have the largest magnitudes, and are of opposite sign during the 1920's and again during the 1950's. Additionally, these variables do not indicate a recent increase in elevational trends, as minimum elevational trends for these ranges and both maximum and minimum elevational trends in the Middle Rockies show. Recent trends for spring are greatest for the Middle Rockies for both variables, while recent trends for the Wasatch in fall also show a large increase. The mean seasonal trend patterns and elevational trends for these three ranges do not follow each other as closely as the Cascades, Sierra Nevada, and Northern Rockies. As Barry (2008) discusses, this may be due to their greater continentality.



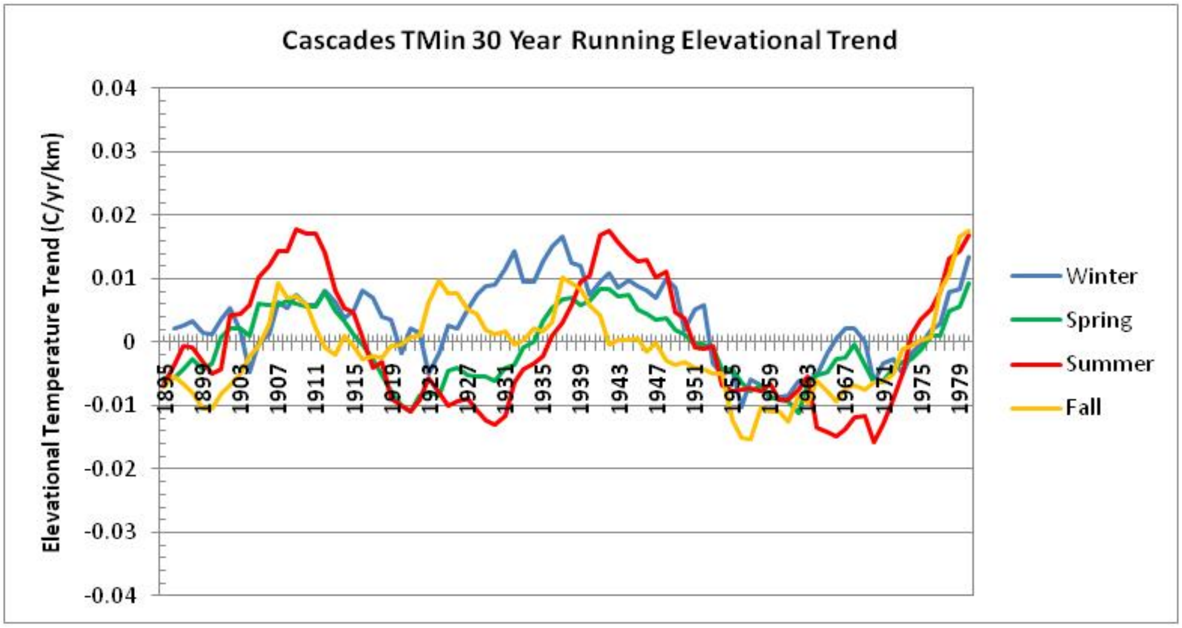
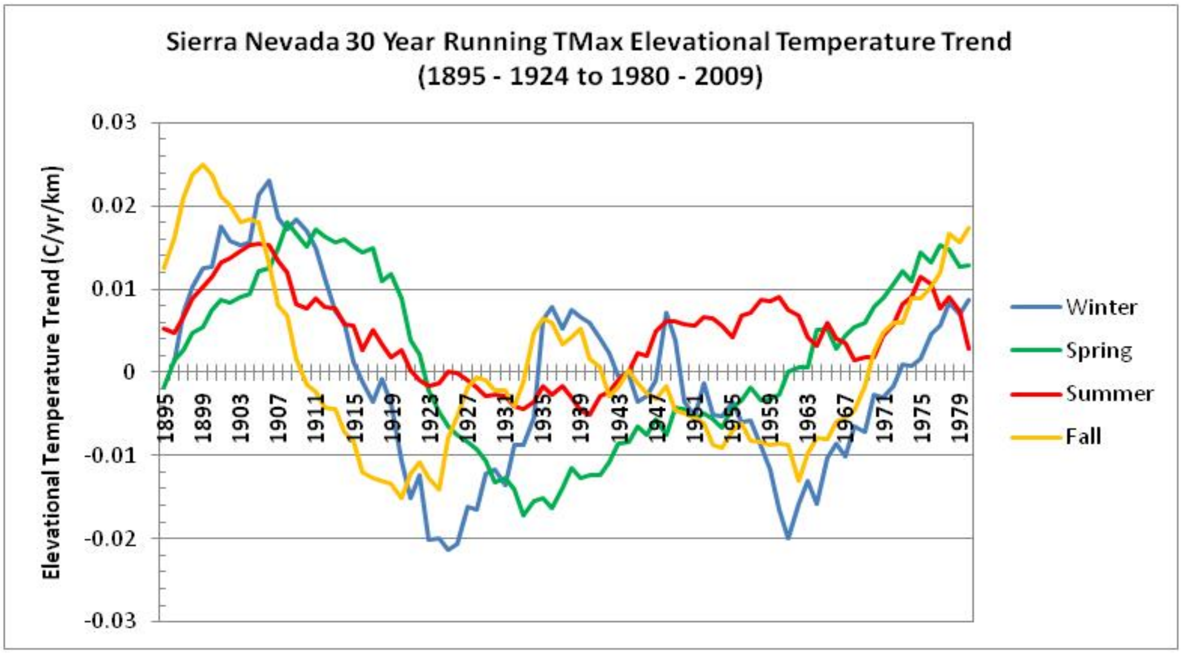


Figure 24. Cascades 30 year running mean elevational maximum (top) and minimum (bottom) temperature trend. Maximum elevation temperature trends show a decrease in magnitude and value over the 20th century for all seasons except for winter. All seasons show a similar pattern, except for winter, which experienced a large dip around 1975 and then a sharp increase. Minimum trends do not show a general trend over the past century, but instead follow a cyclical pattern centered around the zero trend line. Summer's trend is the greatest in magnitude, and has risen sharply since 1970, along with the trends for the other seasons.



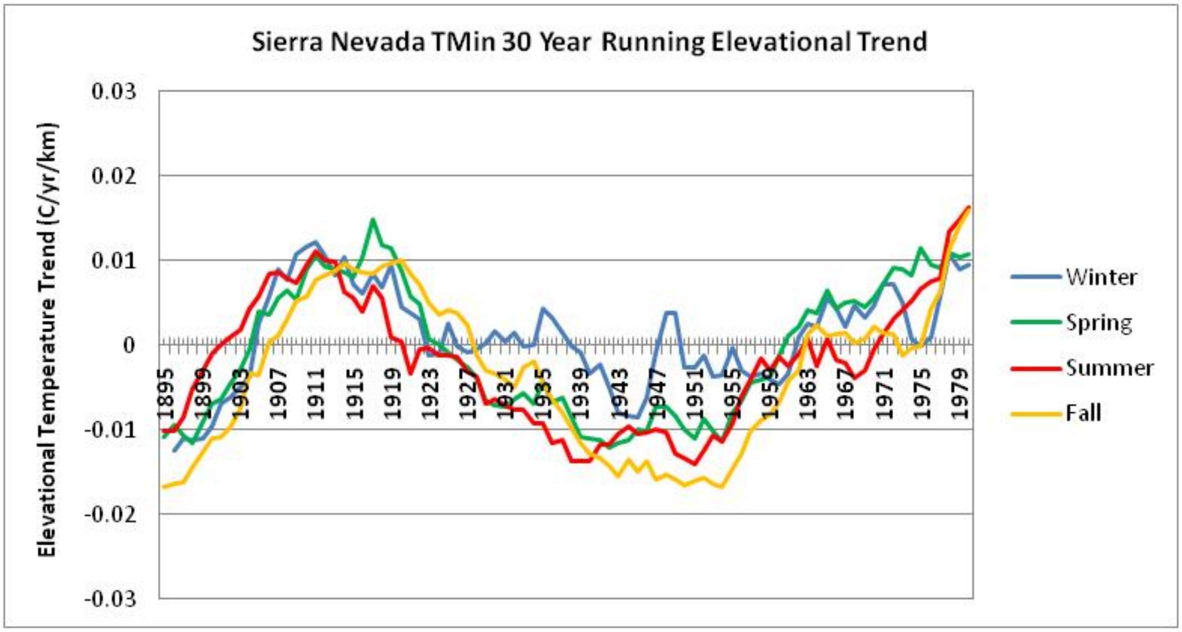
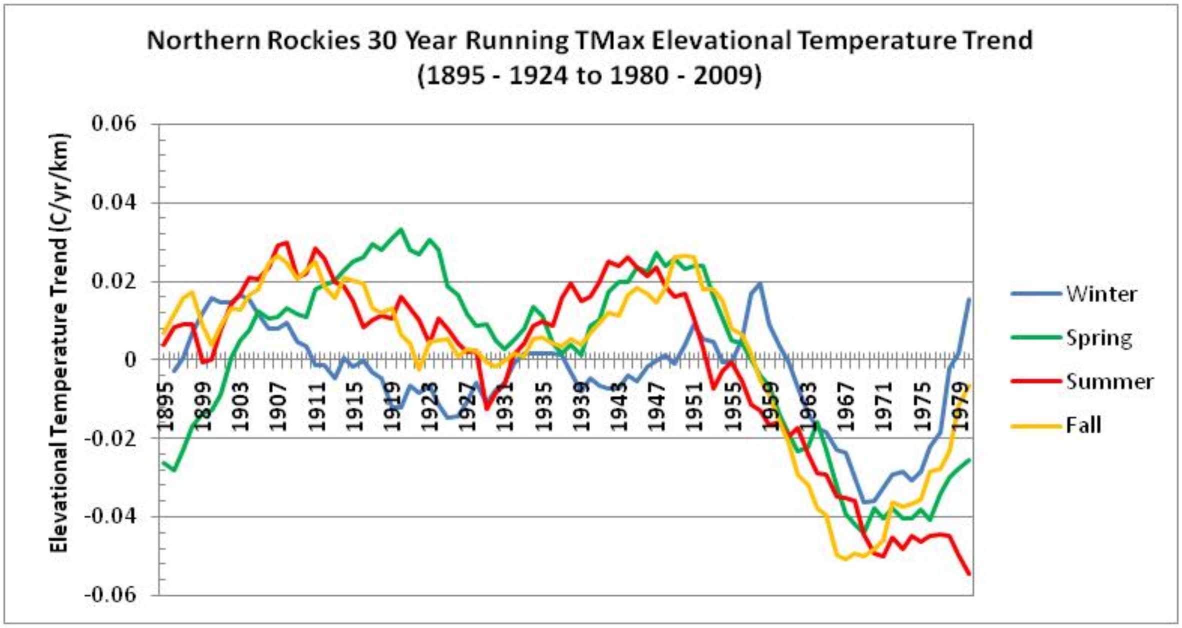


Figure 25. Sierra Nevada 30 year running mean elevational maximum (top) and minimum (bottom) temperature trends. Maximum trends show a small dip from 1925 – 1960, after which all seasons show positive elevational temperature trends. Elevational minimum temperature trends are less variable and also lower in magnitude than maximum trends, but show a similar dip during the 20th century, with a longer positive trend in elevational temperature trends, beginning in 1955.



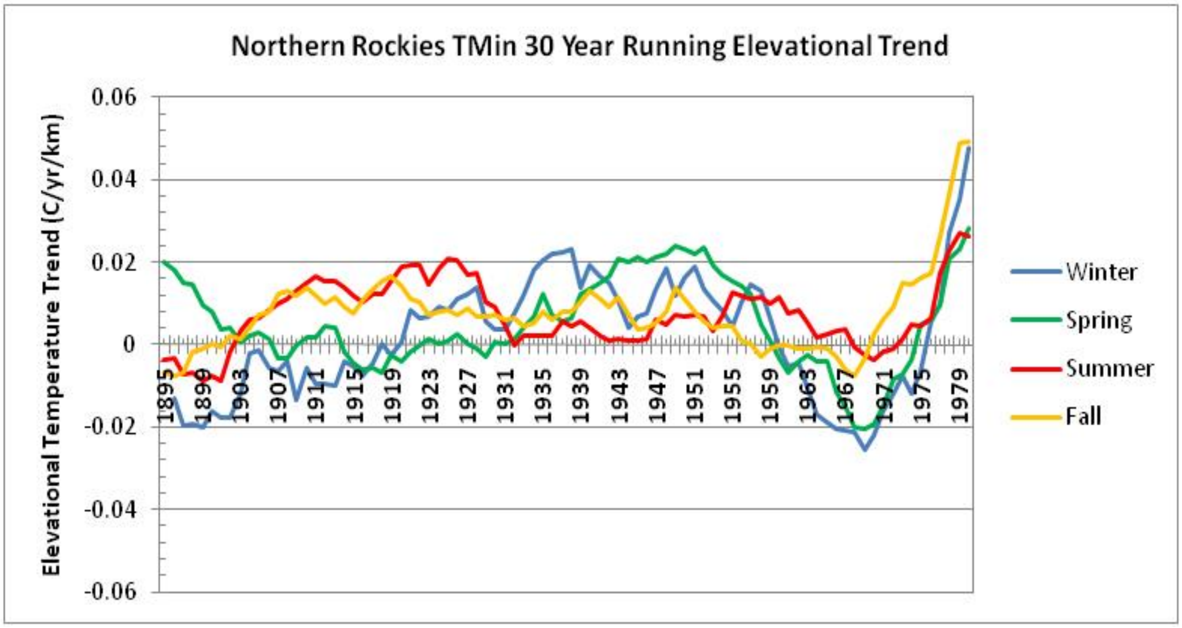
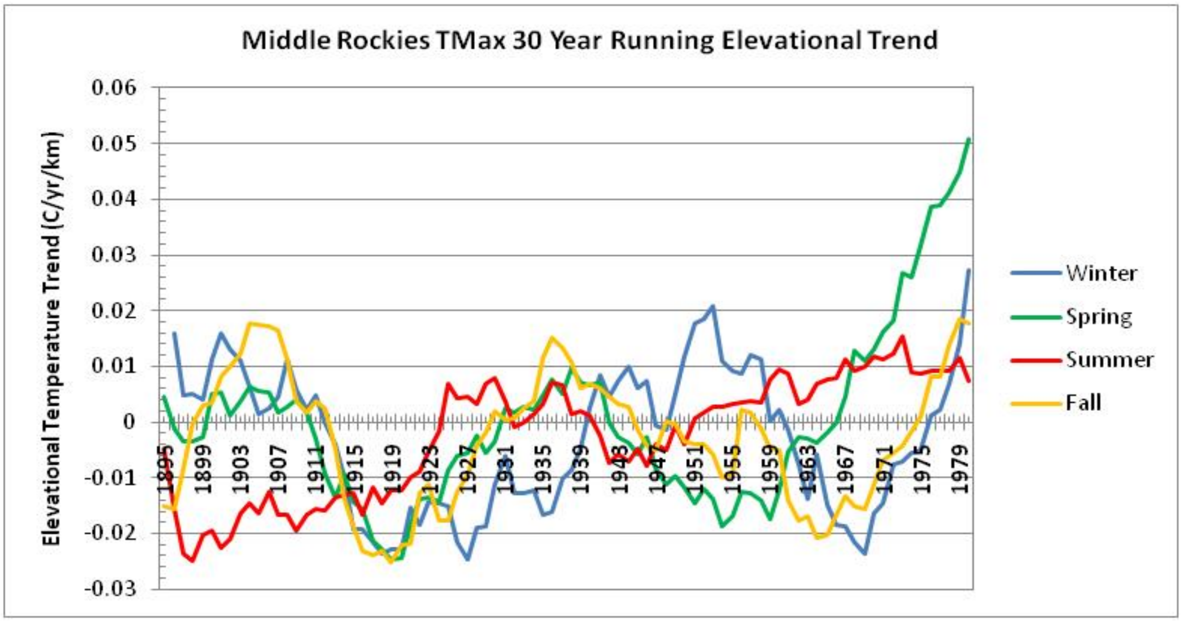


Figure 26. Northern Rockies 30 year running mean elevational maximum (top) and minimum (bottom) temperature trends. Maximum trends show slightly positive values for all seasons except winter through 1955, after which all seasons experience a large decrease toward negative elevational temperature trends. Summer trends continue to decrease, while the other seasons appear to be showing a positive trend once again. Minimum trends are less variable than maximum trends, and more closely follow the zero trend line through 1970. Since then, however, all seasons have shown a steep increase.



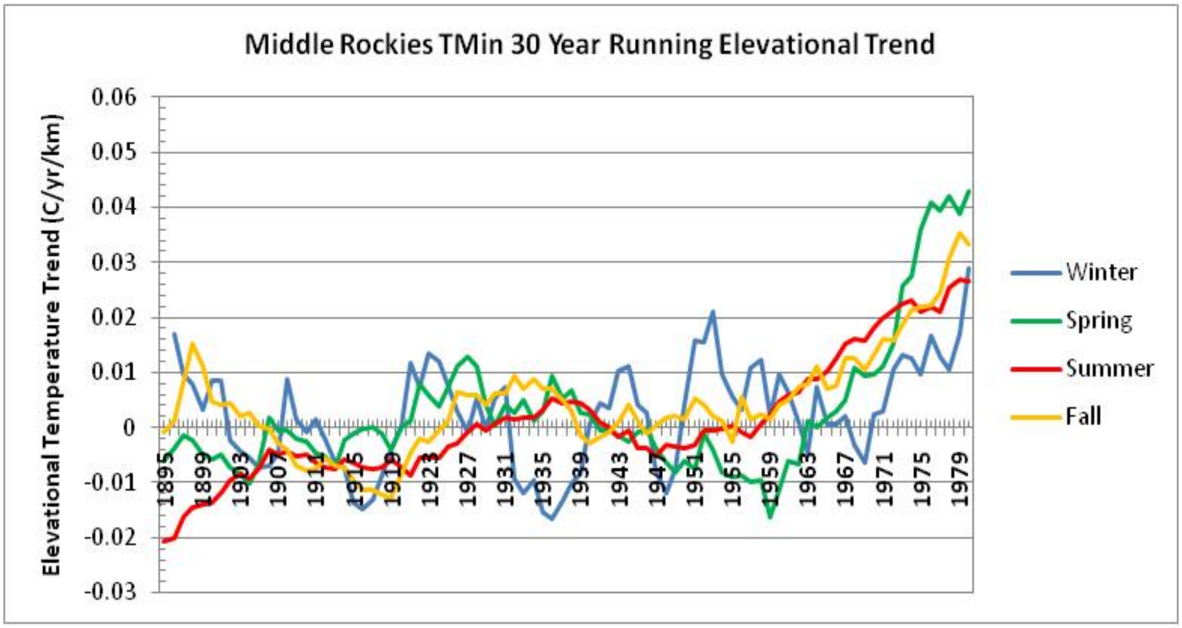
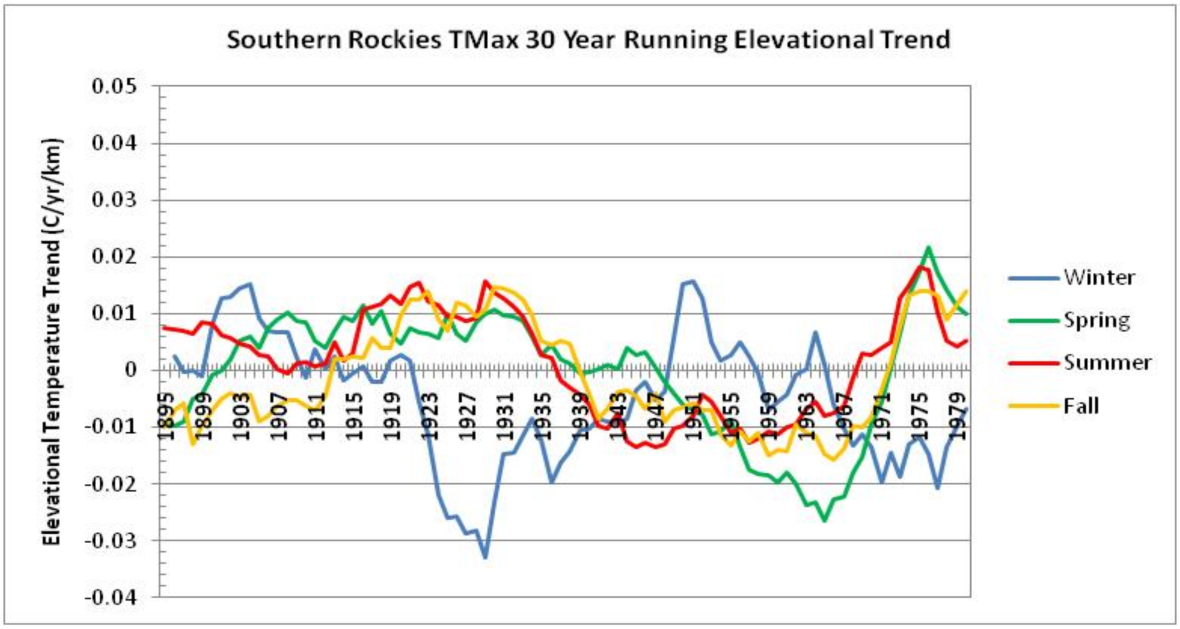


Figure 27. Middle Rockies 30 year running mean elevational maximum (top) and minimum (bottom) temperature trends. Once again, maximum temperature trends are more variable, although summer trends follow a slow positive trend throughout the majority of the time series. Both variables center around the zero trend line for most of the century, but after 1970 (minimum) and 1980 (maximum) all seasons show positive trends. Spring shows the greatest recent trends for both variables.



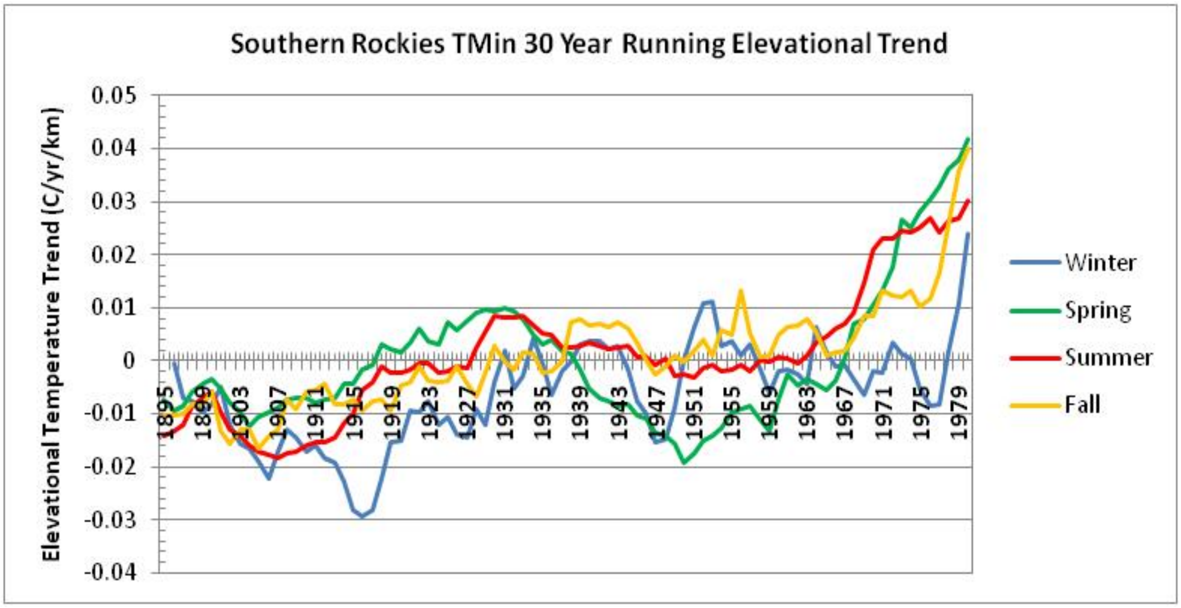
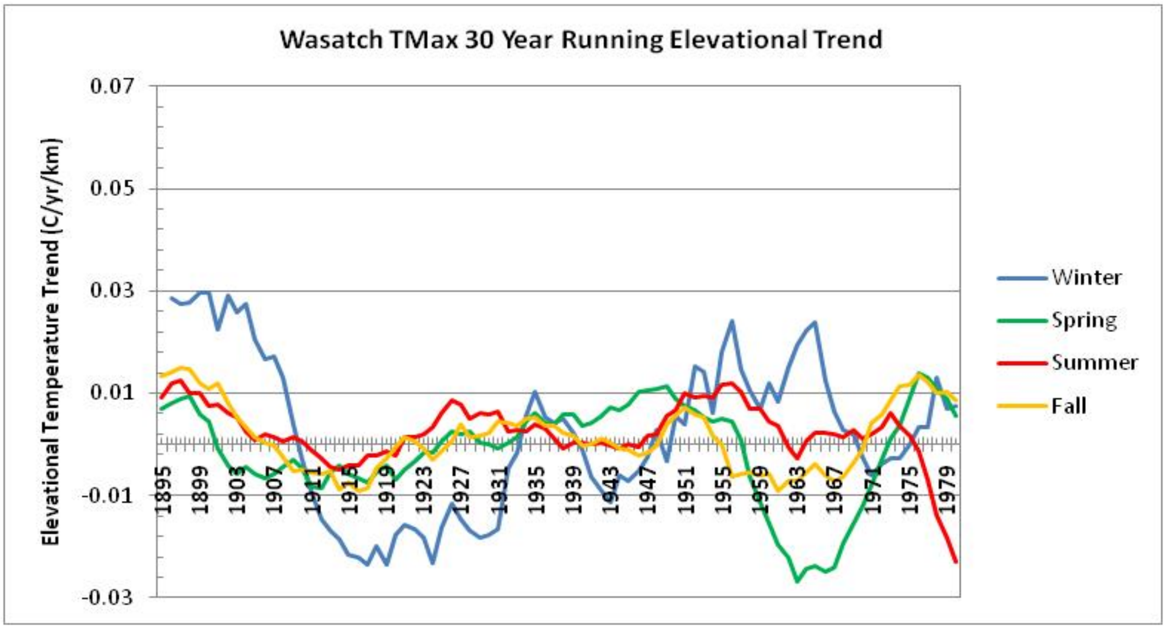


Figure 28. Southern Rockies 30 year running mean elevational maximum (top) and minimum (bottom) temperature trends. Maximum trends are the most variable, especially winter, which shows a pronounced cyclical pattern relative to the other seasons. Winter trends also remain negative, while trends for the other seasons have risen above zero since 1970. Minimum trends are less variable, and show a more consistent rise from somewhat negative values in 1910 to about zero in 1960. After this, all seasons experienced a large positive trend, except winter, which remained close to zero until 1977, and then rose sharply.



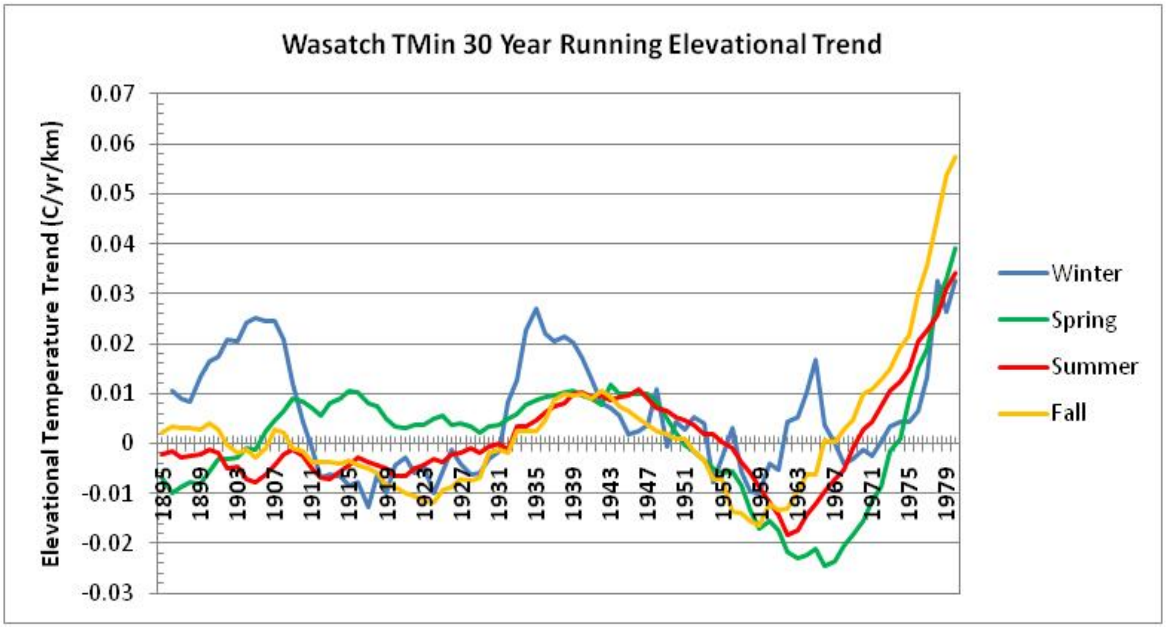


Figure 29. Wasatch Range 30 year running mean elevational maximum (top) and minimum (bottom) temperature trends. Both variables show that winter trends are more variable than other seasons. For this ecoregion, maximum summer trends show a recent sharp decline, while recent minimum trends show a recent sharp increase. Maximum trends for the other seasons are quite small, but positive. Minimum trends are approximately three times as large, and interestingly, fall shows the greatest increase. Also, summer trends follow the other seasons trends for the minimum temperature trends.

6. Discussion

6.1 Mean and Elevational Temperature Trends

The lack of meteorological observations in complex terrain has led to the development of interpolation techniques designed to estimate meteorological conditions in the large areas between the stations which do exist in these regions. However, the climate, ecology, and geology of complex terrain has been hypothesized to be more sensitive to climate change than that of more homogenous, lower elevation regions (Barry, 2008; Beniston, 2003; Pape, et al. 2009). Therefore, it is important to study the relative impacts of climate change on regions of higher elevation compared to those for lower elevation regions.

The purpose of this study was to use a high quality, elevation adjusted data set (PRISM) to determine if temperature trends varied by elevation over the past century for six mountain ranges in the western United States. In particular, two time periods (1941 – 1970 and 1971 – 2000) were analyzed in more detail because global and North American trends exhibited a steady or slightly decreasing trend during the early period and increasing trends during the later period (NCDC – 2006, Figure 1).

As hypothesized, all six mountain regions experienced changes in their respective mean seasonal temperature trends over the past century. All regions also experienced the same general trend patterns through this time period, beginning with a peak in trends during the 1910's, followed by a minimum or leveling off by the 1930's. By the 1960's, both minimum and maximum trends experienced an increase, although for the Cascades and

Northern Rockies, trends stayed relatively steady. Although not shown, an analysis using the PRISM data set showed the recent positive temperature trends in the western U.S. began earlier than those from the Great Plains eastward. Maximum trends tended to show more variability than minimum trends over all periods. All significant trends were positive, with the number of significant trends nearly tripling for the period 1971 – 2000. During this same period, 10 of 11 significant trends occurred for minimum temperature.

Spring temperature trends show a significant increase beginning about 1960. While the other seasons also show a trend increase at about this time, they rise more slowly and are generally still rising. Spring trends generally peaked in the mid 1960's and have since decreased. The exception to this is that of maximum Wasatch and Southern Rockies spring trends, which are stronger, but are temporally more consistent with that of the other seasons. The rapid rise in spring temperatures is consistent with several other studies, including Clow (2010), McCabe and Wolock (2009), and Mote (2005), which indicate that earlier snowmelt and warmer temperatures are contributing to less spring snowpack at high elevations in western North America.

The second hypothesis this study sought to answer was whether or not temperature trends varied by elevation and mountain range in the western United States. Two analyses were performed this portion of the research. The first method used was cluster analysis, where seasonal minimum and maximum temperature, precipitation, and dew point trends were clustered using an advanced k-means algorithm. This analysis showed that both minimum and maximum elevational temperature trends were significant for winter and spring 1941 – 1970. The trends were positive for winter, but negative for spring. For 1971 – 2000, spring elevation trends were still significant, but now they were positive. Only the trend for maximum temperature was now significant, but it too had changed sign, to negative. No summer trends were significant. Minimum fall trends for 1971 – 2000 were significantly positive. An important note here is that spring 1941 – 1970 trends are likely significant due to the highly negative trend for the cluster at 3000 meters. Additionally, yearly averages of these variables, based on seasonal averages, were clustered. This analysis produced similar, although less significant results. These generally agree with those found in table 4, showing that yearly results are smaller and are not as significant. Overall, this analysis indicates that spring temperatures are currently warming faster at higher elevations than at low elevations.

The second method used to analyze elevational temperature trends was a running 30 year mean for a buffered area around each ecoregion. Here, maximum temperature trends are more variable, although the magnitude for minimum and maximum trends is about 1/3 to ½ that of the mean trends. Temperature trends by elevation generally follow a pattern similar to that of their respective mean ecoregion trends (for example, positive mean temperature trends tend to occur if temperature trends increase with elevation, and vice versa). The Northern Rockies maximum trend shows a large decrease around 1960, while the minimum trend shows a large increase from about 1970. The Cascades and Sierra Nevada show a smaller average elevational trend magnitude than the other ranges. Minimum trends experience a larger recent increase than that of maximum trends.

Seasonal differences are small. Spring trends are much higher than those of the other seasons for the Middle Rockies, however. This analysis also indicates that, with the exception of the maximum trends for the Northern Rockies and possibly Wasatch Range, higher elevations are warming faster than lower elevations. Virtually no temporal difference is apparent among seasonal trends for any ecoregion.

Results from this analysis agree with those of Pepin and Lundquist (2008), in the sense that temperature trends in mountainous regions are not necessarily easily distinguishable from those elsewhere. However, very generally, both my analyses do indicate that higher elevations are experiencing greater warming rates (there is also a large amount of spatial variation, which makes this an inconclusive result for the entire western U.S.). This is in contrast to the findings of Pepin and Lunquist (2008), who base their results on GHCN data. A few possible reasons may exist for this discrepancy. One is the different sources of data used. The other is the difference in time periods analyzed. Pepin and Lundquist use the period 1948 – 2002 to determine trends, while I essentially break this period into two separate analyses, each of which produces different results for winter and spring elevational trends. Pepin and Lundquist do not do a seasonal analysis; nor do they analyze by ecoregion or mountain range. Additionally, my research seems to indicate the greatest trends occur further south and for inland mountainous terrain, which is in general contrast to the results of Pepin and Lundquist. Once again, however, the differences in time periods may be a significant factor. This may be a valuable area for future research.

There is significant uncertainty in these results, both spatially and temporally, however, due to the lack of stations in these areas. Despite this, overall results from this study appear to be in line with other research, indicating that spring is warming faster than other seasons, and recent temperature trends are greater at higher elevations. These results, including the lack of detailed findings (spatial differences and their causes, for example), highlight the need for more data collection and continued development and evaluation of interpolated meteorological data sets. Future sections of this paper discuss sources of error and suggest future work that may contribute to knowledge about what drives temperature trends in western North America.

6.2 Potential Role of Large Scale/ Synoptic Regimes

As discussed earlier, mountain meteorology is relatively poorly observed, and as a result, not well understood, especially at a small scale. Therefore, causes for varying temperature trends with changing elevation are somewhat difficult to discern. Scully (2010) indicates that actual temperatures in mountainous areas are controlled much more strongly by local terrain and other factors, rather than large scale pattern changes, such as ENSO. This is consistent with observations, which indicate that terrain factors such as aspect and slope orientation, and local meteorological factors, such as cold air pooling produce the greatest variations in temperature in these areas.

Table 3 indicates that, in general, mean temperature trends are less significant the lower in elevation the mountain range is, as well as the more maritime influence it has (Cascades and Northern Rockies). The combination of high elevation and strong continentality seems to indicate a better likelihood of higher mean temperature trends (Sierra Nevada, Middle Rockies, and Wasatch Range). Surprisingly, the only significant mean seasonal trends for the Southern Rockies are for summer minimum temperatures. This pattern is not explained by greater elevation or continentality. The fact that spring temperatures show the greatest changes may be explained by earlier snowmelt and decreasing snowfall (Clow, 2010). Although this particular study was focused on the Colorado Rockies, similar spring temperature patterns exist in other ranges, perhaps indicating this is also the case in these areas.

Elevational temperature trends do not appear to follow this same pattern related to maritime influence and continentality, in general. Table 5 shows these for 1971 - 2000. For example, nearly all minimum temperature elevational trends are significant for the Southern Rockies, except for winter and spring, which were the only significant mean trends. The Cascades (mostly maximum trends) and Northern Rockies (mostly minimum trends) each show several significant seasonal trends. Rangwala (2008) suggests that increasing humidity at higher locations may explain why certain high altitude regions (Tibetan Plateau, in particular) are warming during the winter. Whether or not this is due to synoptic regime changes is unclear. He also indicates that the snow-albedo feedback is a more important factor for warming during the spring and summer months for the Tibetan Plateau, which also appears to be valid for the Colorado Rockies.

6.3 Sources of Error

As discussed previously, a potentially large source of error is the interpolation algorithm used by PRISM. However, PRISM data was used because it is specifically adjusted for elevation, and many studies have concluded that it is the most accurate interpolated data set (see Reference section). Station data are too sparse at high elevations to determine elevational temperature trends. As pointed out by Dan Vimont (2010, personal communication) the linear interpolation used by PRISM may lead to the station trends being interpolated to different elevations, so that the interpolated trends are artificially similar to those of the nearby stations used. Although PRISM takes into account inversions, the analysis of station trends used in PRISM and trends of grid cells based on those stations would be a good verification step.

The clustering algorithm was designed to minimize potential error in determining which grid cells were most similar, but this may also be a source of error. There are many clustering algorithms available, and it may be worthwhile to try other algorithms. Error in the linear regression analyses can stem from the fact that there are many more stations at lower elevations than at high elevations. This doesn't necessarily change the trends, though. A potential problem is that the number of stations used in the PRISM interpolation changes with time, potentially influencing the trends. No studies have been done, to the best of my knowledge, which quantifies the potential impact of this fact. Trend analysis could be done using only the stations at the beginning of the period, either 1941 or 1971 to avoid this issue. I am only able to speculate on this issue, however, since the number of stations increases with time, and a steady or cooling trend was experienced through 1970 followed by a warming trend through 2000, it may be reasonable to expect that these respective trends were ‘enhanced’ by the greater number of stations as time progressed. Additionally, the changing number of stations affects the effective sample sizes of each cluster (the number of actual stations that occur within the cluster). In turn, this means that each cluster should not necessarily be equally weighted in the regression analysis (Dan Vimont, 2010, personal communication). Additional error due to estimation occurs because the mean cluster elevation is then regressed against mean cluster temperature trend, and then a trend line is fit (another estimation). Performing this analysis while taking into account these effects may produce more robust results.

As discussed earlier, each PRISM grid cell represents the average temperature over a 16km^2 area, making comparison with independent observational data very difficult. To compensate for this, Wang, et al. (2006) developed a PRISM based interpolation tool (Climate WNA) which estimates point based temperatures. This technique is shown to provide better estimates than grid based interpolation.

Although not discussed in detail in this paper, temperature patterns that appear to be inhomogenous (such as jumps in the data) appear in a select few time periods in some ecoregions. No further analysis was performed on these cases, but it makes sense that this result is based on station data, not on the PRISM algorithm.

6.3.1 Niwot Ridge Comparison

As discussed earlier, the analyses presented in this study depend on the accuracy of PRISM data, mainly the interpolation algorithm. The validation of PRISM temperature data is a necessary step, however, it is also quite difficult. One reason is because there are few independent, reliable station records available against which to compare PRISM data. Another, more serious issue is that PRISM grid cells represent the average monthly temperature across a 4km by 4km area. Wang (et al, 2006) indicates that this presents a potentially significant problem, as the elevation in some cells varies by as much as 1200 meters. This means that comparing single station data to that of a PRISM grid cell can be of limited value. Nevertheless, I compared the Niwot Ridge, CO station data to that of PRISM.

Figure 30 (top) shows that a comparison of actual minimum temperatures shows good agreement, while actual maximum temperatures are significantly different. I did not determine a reason as to why PRISM's maximum temperatures so much higher than the station's. Figure 30 (middle and bottom) shows that general seasonal minimum temperature patterns between PRISM and Niwot Ridge experience generally good agreement. Maximum temperature patterns do not agree as well, which is in agreement with the graph of actual temperatures (top). Although the series are too short to determine trends, no large differences in trends are apparent.

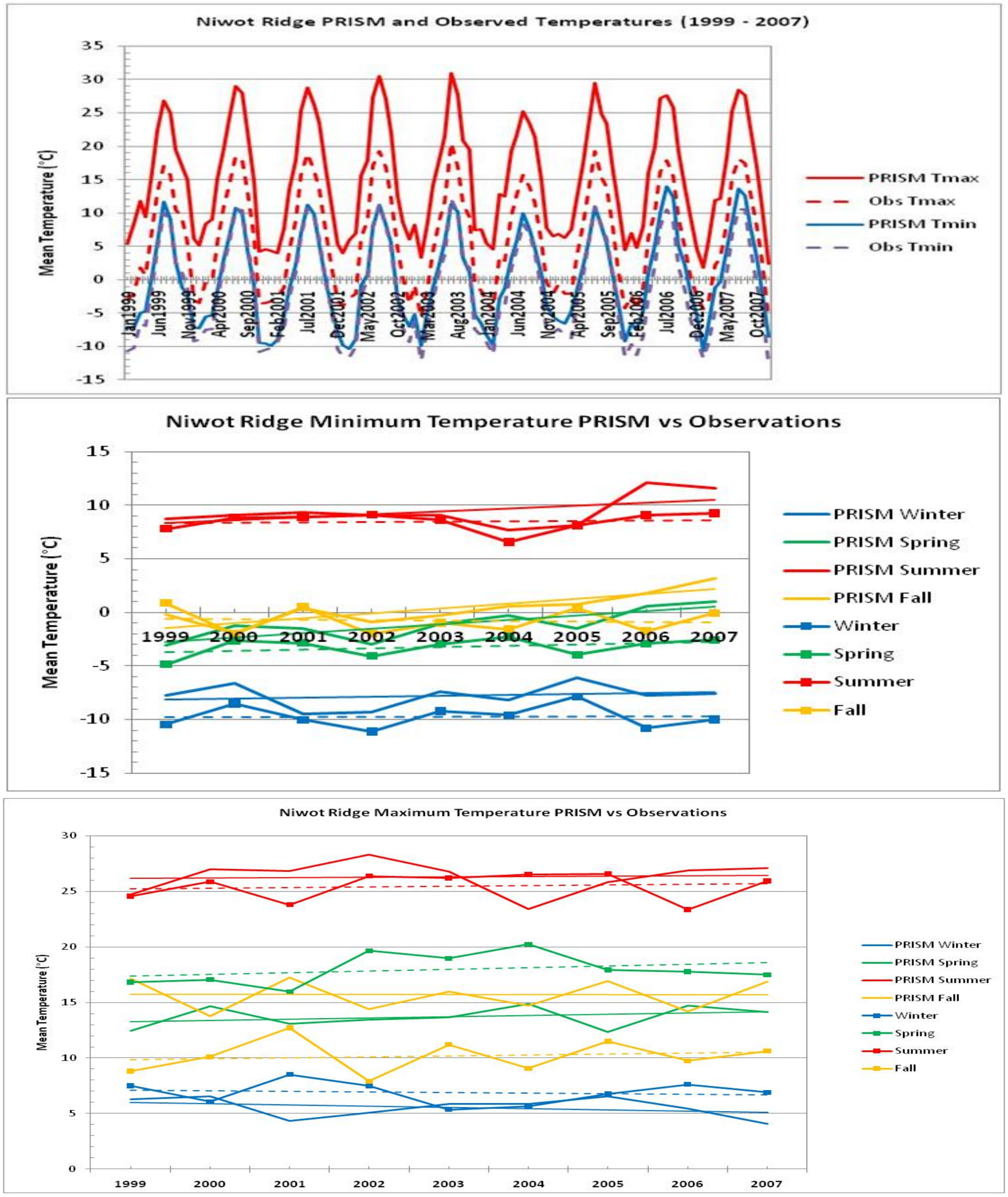


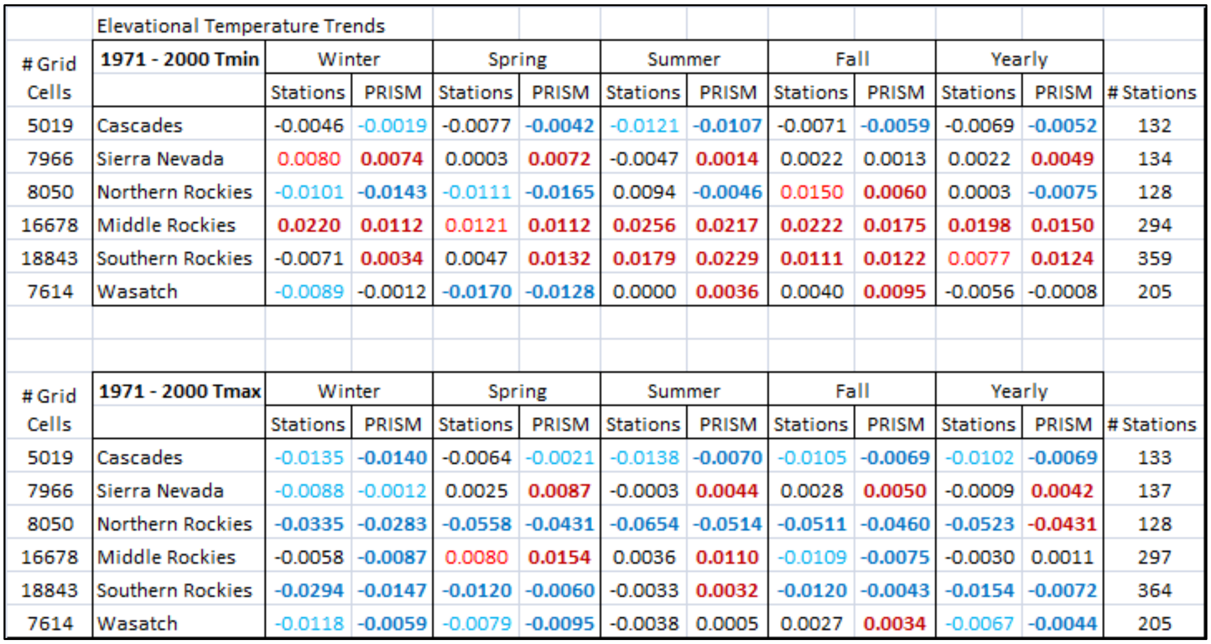
Figure 30. Top – Actual monthly PRISM temperatures vs. mean monthly Niwot Ridge temperatures. Minimum temperatures agree much better than maximum. **Middle** – Seasonal minimum temperature comparison. **Bottom** – Seasonal maximum temperature comparison. The seasonal series are not long enough to compare trends, but a comparison of general seasonal temperature patterns shows generally good agreement, especially for minimum temperatures.

6.3.2 Station Grid Cell Comparison

To determine whether or not general PRISM trends are reliable, an analysis comparing the elevational trends of all station locations within each buffered ecoregion against the elevational trends generated by the interpolated PRISM data was performed. Table 5 shows the results of this analysis. With few exceptions, the interpolated PRISM data are very highly significant due to the large number of grid cells. In virtually every case, the sign and magnitude of station grid cell elevational trends is comparable to that of the interpolated data. Their significance tends to be less, however. Interpolated elevational trends do not show a positive or negative bias with respect to that of station grid cells, nor do their magnitudes show a positive or negative magnitude bias. Yearly elevational trends tend to be less significant than seasonal trends, mainly for station locations. In agreement with previous results, winter and spring trends are the most significant.

One additional aspect of the interpolated PRISM elevational trends is that they exhibit a cyclical pattern over time, as figures 24 -29 show. This provides an argument against the hypothesis that PRISM methodology produces either a positive or negative bias in sign or magnitude in trends, since otherwise would expect the same direction in trends for all regions for both time periods. This is not proof, however.

Table 5. Comparison of elevational temperature trend results based on locations (grid cells) of stations used in PRISM and the entire interpolated data from each buffered ecoregion. Bold red and blue indicate highly significant trends (p-value < 0.001), while regular red and blue indicate significant trends (.001 < p < .05). Regular black font indicates no significant trend.



Elevational Temperature Trends

# Grid Cells	**1971 - 2000 Tmin**	Winter		Spring		Summer		Fall		Yearly		
		Stations	PRISM	Stations	PRISM	Stations	PRISM	Stations	PRISM	Stations	PRISM	# Stations
5019	Cascades	-0.0046	-0.0019	-0.0077	**-0.0042**	-0.0121	**-0.0107**	-0.0071	**-0.0059**	-0.0069	**-0.0052**	132
7966	Sierra Nevada	0.0080	**0.0074**	0.0003	**0.0072**	-0.0047	**0.0014**	0.0022	0.0013	0.0022	**0.0049**	134
8050	Northern Rockies	-0.0101	**-0.0143**	-0.0111	**-0.0165**	0.0094	**-0.0046**	0.0150	**0.0060**	0.0003	**-0.0075**	128
16678	Middle Rockies	**0.0220**	**0.0112**	0.0121	**0.0112**	**0.0256**	**0.0217**	**0.0222**	**0.0175**	**0.0198**	**0.0150**	294
18843	Southern Rockies	-0.0071	**0.0034**	0.0047	**0.0132**	**0.0179**	**0.0229**	**0.0111**	**0.0122**	0.0077	**0.0124**	359
7614	Wasatch	-0.0089	-0.0012	**-0.0170**	**-0.0128**	0.0000	**0.0036**	0.0040	**0.0095**	-0.0056	-0.0008	205

# Grid Cells	**1971 - 2000 Tmax**	Winter		Spring		Summer		Fall		Yearly		
		Stations	PRISM	Stations	PRISM	Stations	PRISM	Stations	PRISM	Stations	PRISM	# Stations
5019	Cascades	-0.0135	**-0.0140**	-0.0064	-0.0021	-0.0138	**-0.0070**	-0.0105	**-0.0069**	-0.0102	**-0.0069**	133
7966	Sierra Nevada	-0.0088	-0.0012	0.0025	**0.0087**	-0.0003	**0.0044**	0.0028	**0.0050**	-0.0009	**0.0042**	137
8050	Northern Rockies	**-0.0335**	**-0.0283**	**-0.0558**	**-0.0431**	**-0.0654**	**-0.0514**	**-0.0511**	**-0.0460**	**-0.0523**	**-0.0431**	128
16678	Middle Rockies	-0.0058	**-0.0087**	0.0080	**0.0154**	0.0036	**0.0110**	-0.0109	**-0.0075**	-0.0030	0.0011	297
18843	Southern Rockies	**-0.0294**	**-0.0147**	**-0.0120**	**-0.0060**	-0.0033	**0.0032**	**-0.0120**	**-0.0043**	**-0.0154**	**-0.0072**	364
7614	Wasatch	-0.0118	**-0.0059**	-0.0079	**-0.0095**	-0.0038	0.0005	0.0027	**0.0034**	-0.0067	**-0.0044**	205

7. Conclusion

The uniqueness and fragility of ecosystems at high elevations and complex terrain requires that we understand the potential impacts of climate change in these regions. The lack of observations in these locations has facilitated the development of algorithms which interpolate meteorological variables in these regions to a high resolution. The development of these downscaling techniques for mountain regions is an active area of research, as is the placement of very high resolution sensor networks. Research on elevational temperature trends in the western U.S, and around the world, is a relatively new field of study, and one that requires much more research and observations to understand.

Past patterns in mean seasonal temperature trends, as well as seasonal elevational temperature trends, suggest that the current dramatic rises will not continue. Specific causes behind this rise are not well understood. However, if anthropogenic climate change is the driving factor, then these patterns can be expected to continue. If this occurs, then ecological systems in these locations will be affected.

The uncertainty in these trends is the motivation behind nearly all potential future work in this research. Data analysis of higher resolution models and high density station networks will be important. This data is expected to be included in the development of new interpolated data sets, including TopoMet (Joel Oyler, personal communication, NTSG, 2010), as well as updated PRISM and Daymet data sets (personal communication, Peter Thornton). Analysis of the PRISM 800 meter data may provide better estimates of independent station comparison. Additionally, clustering only temperature trends by individual ecoregions over all 30 year time periods since 1941 may provide better insights into elevational trends. Part of this may include dividing the ecoregions into smaller parts (such as splitting the Sierra Nevada into north/south divisions). Region specific snow cover/temperature trend analyses may provide insight into the effects of the snow-ice albedo feedback process. Empirical orthogonal function analysis and/or principal component analysis may be able to show similar spatial and temporal patterns among mountain areas. Finally, comparison of PRISM grid cell values to Climate WNA point estimates would likely be a valuable study.

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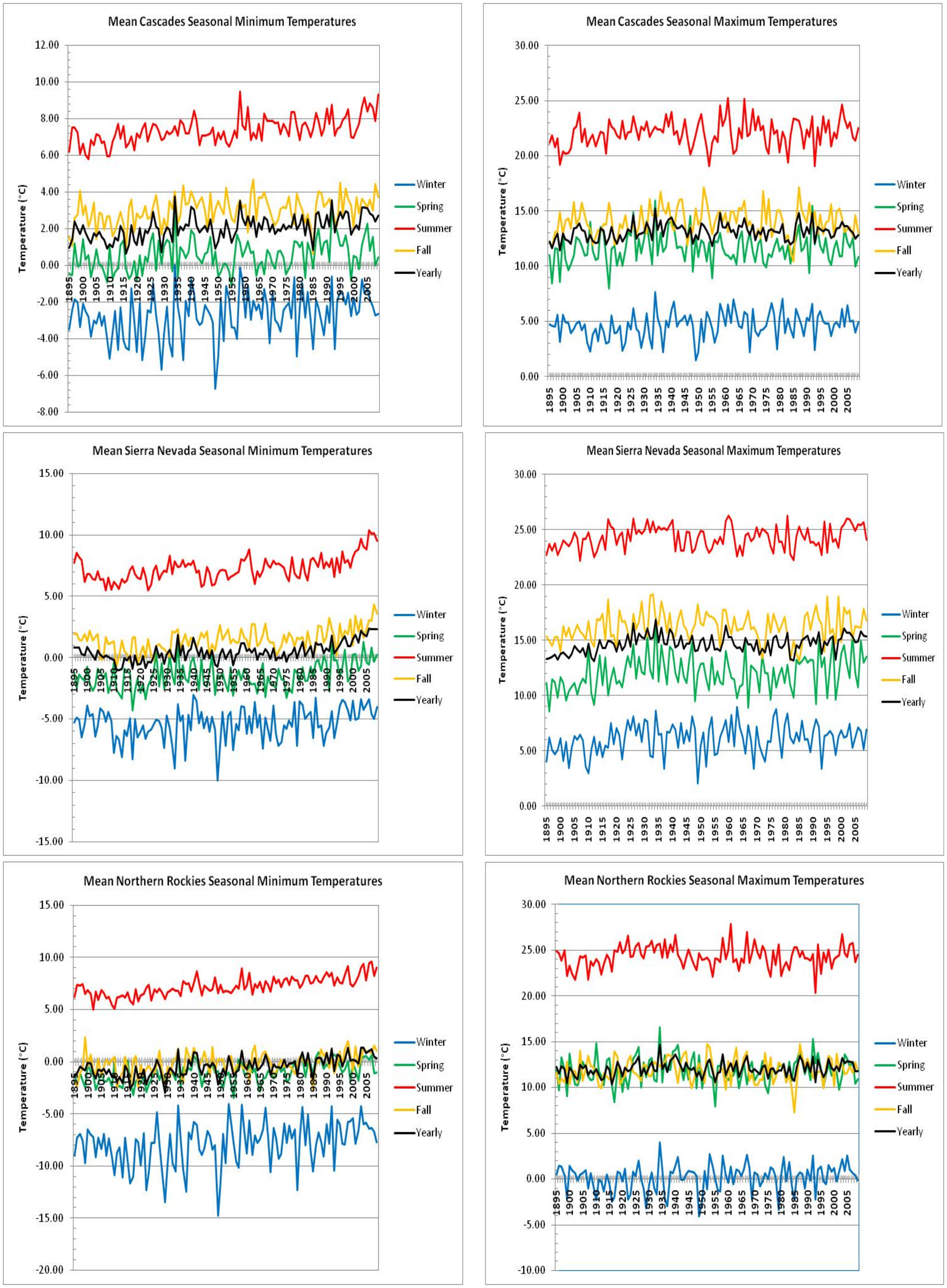
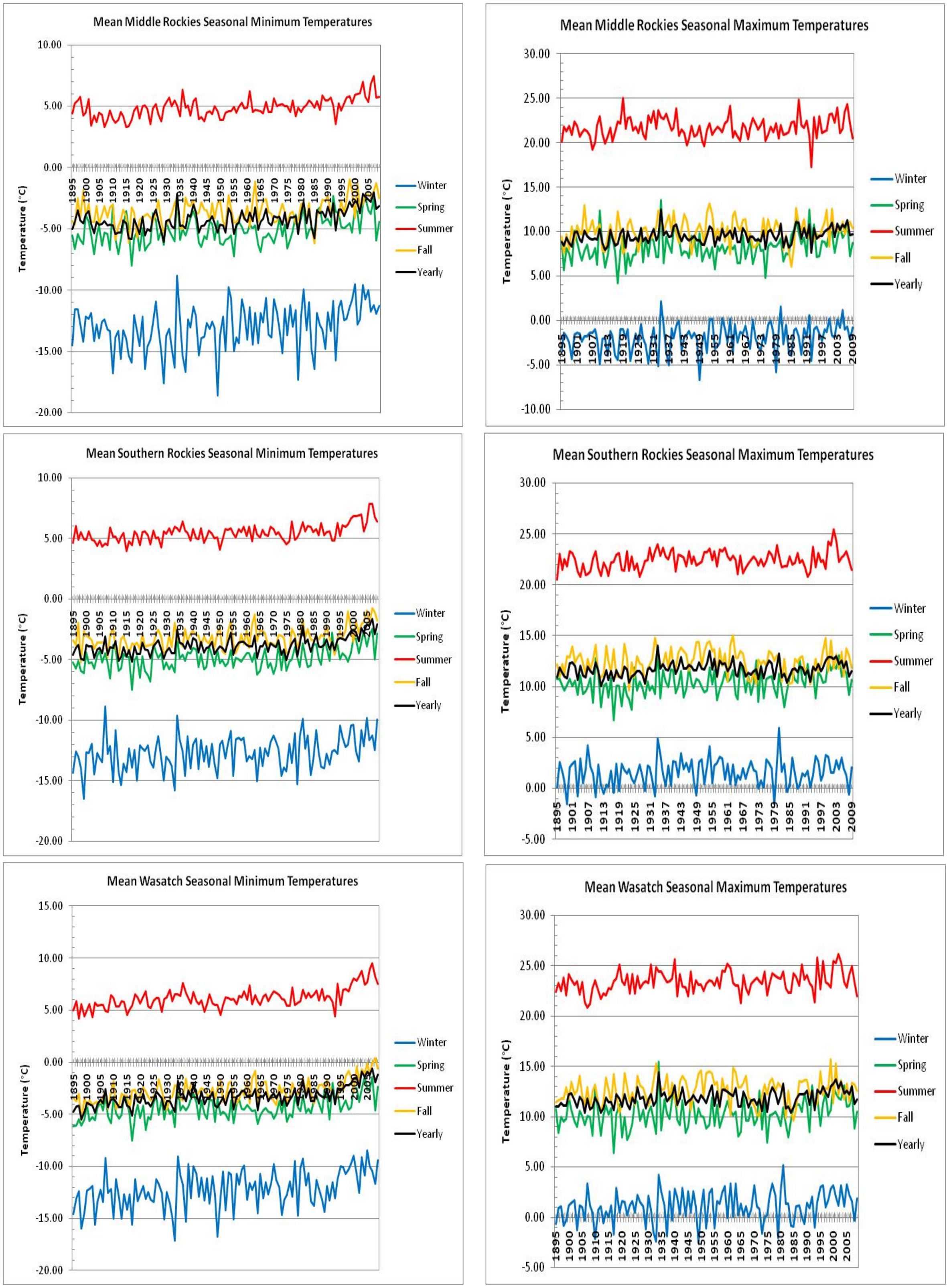


Figure 31. Mean Cascades, Sierra Nevada, and Northern Rockies seasonal temperatures.



Mean Middle Rockies Seasonal Minimum Temperatures

Mean Middle Rockies Seasonal Maximum Temperatures

Mean Southern Rockies Seasonal Minimum Temperatures

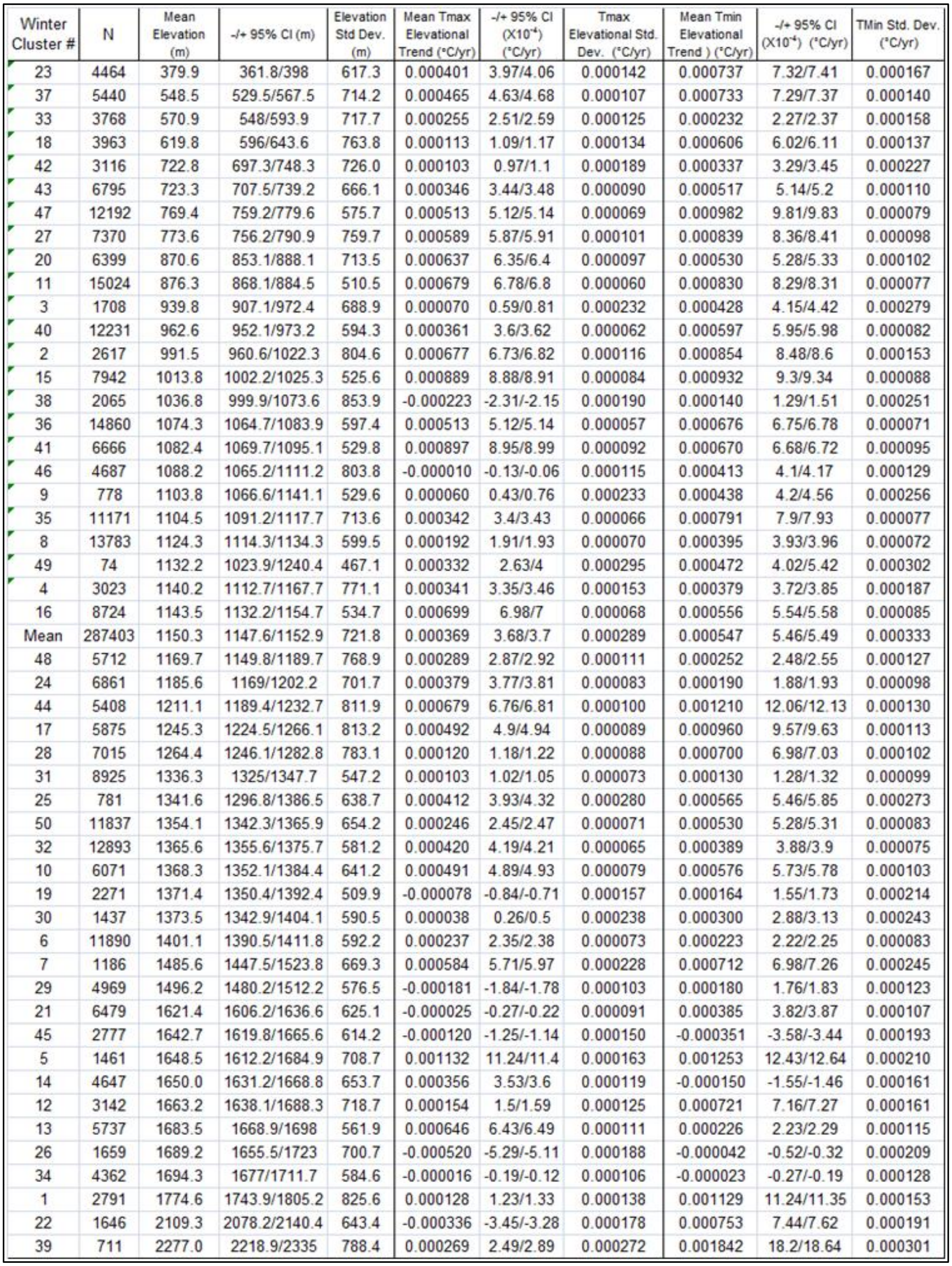
Mean Southern Rockies Seasonal Maximum Temperatures

Mean Wasatch Seasonal Minimum Temperatures

Mean Wasatch Seasonal Maximum Temperatures

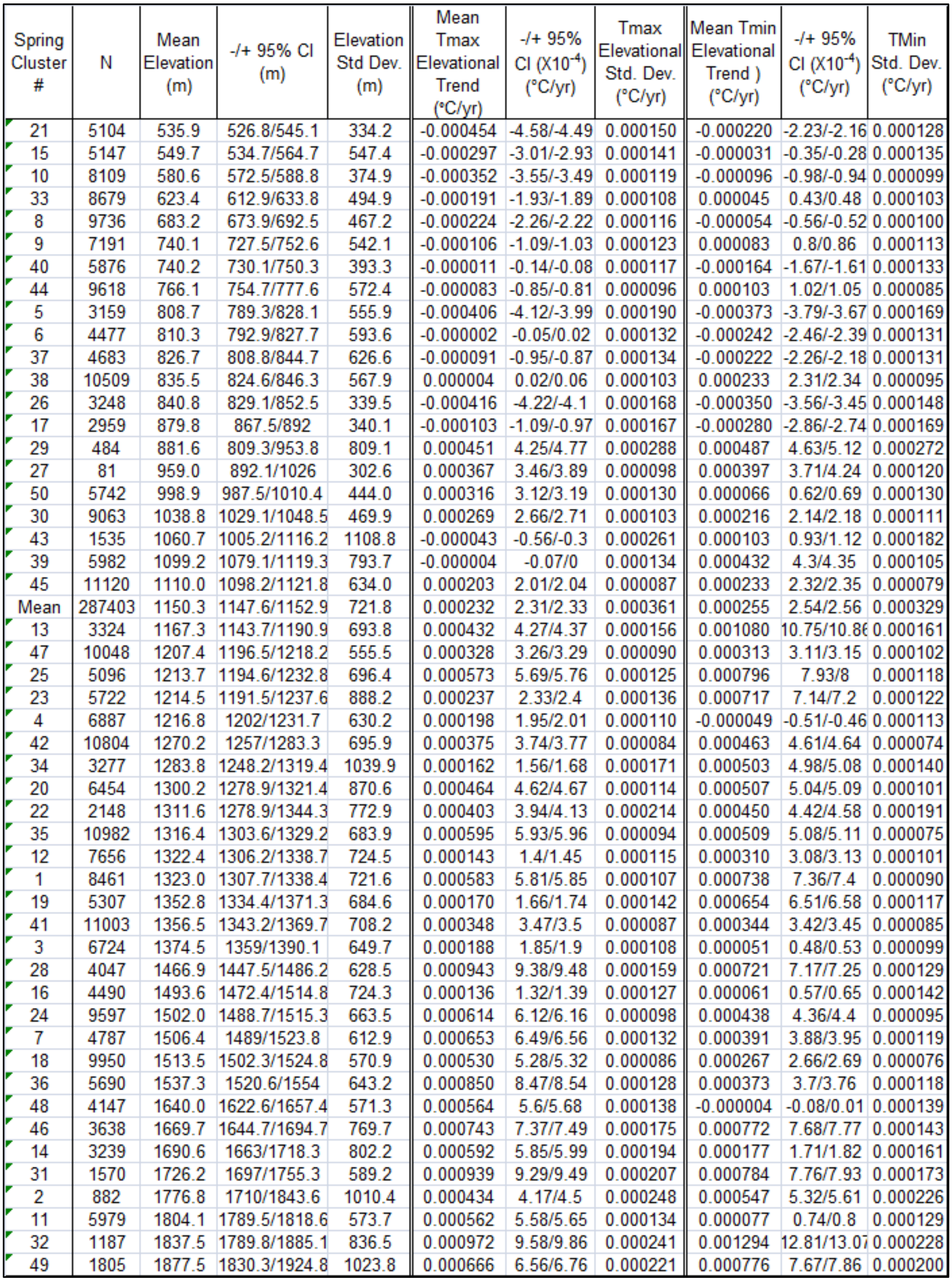
Figure 32. Mean Middle Rockies, Southern Rockies, and Wasatch Seasonal Temperatures.

Table 6. 1971 – 2000 winter cluster elevation and temperature trend statistics.



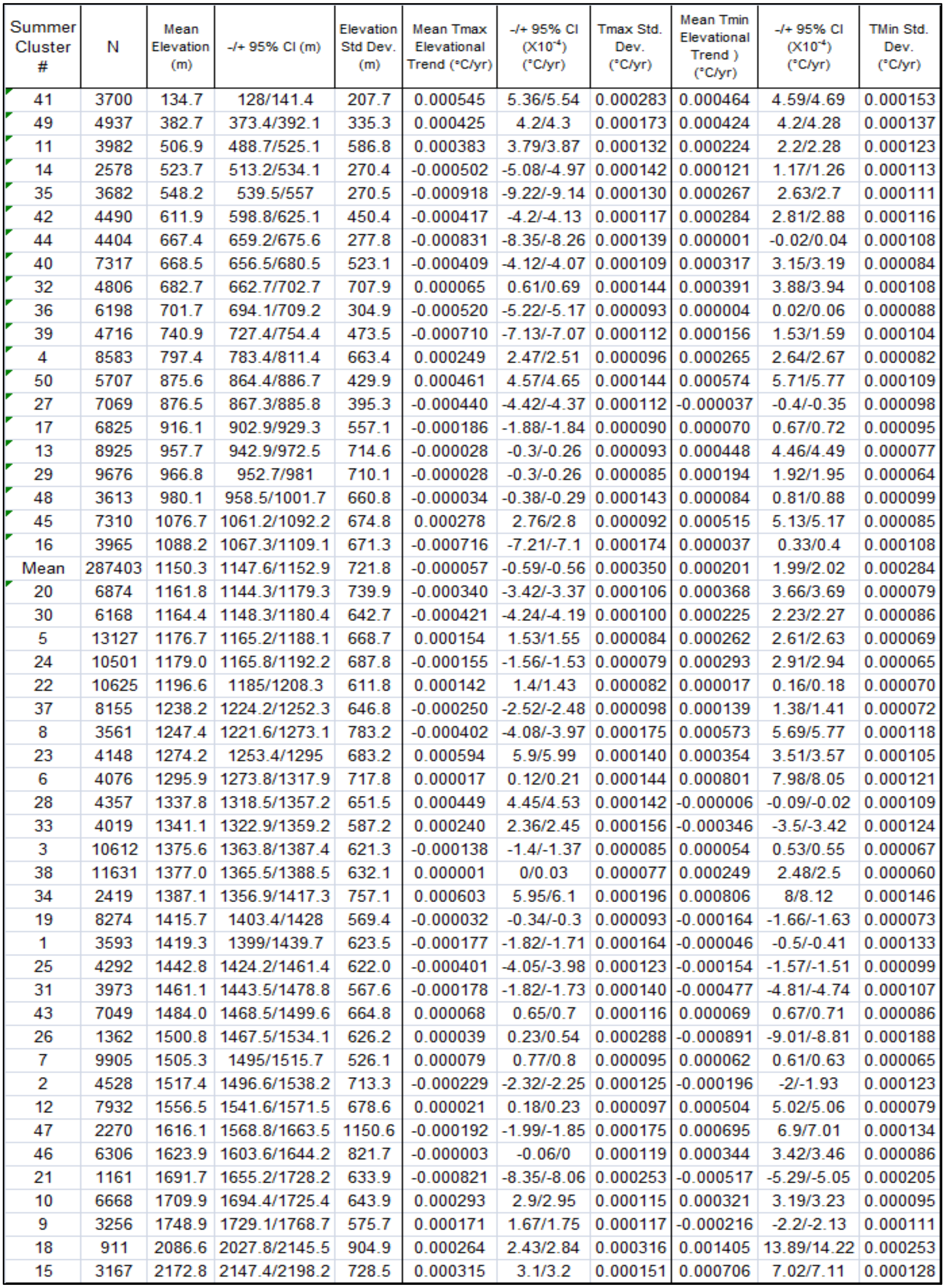
Winter Cluster #	N	Mean Elevation (m)	-/+ 95% CI (m)	Elevation Std Dev. (m)	Mean Tmax Elevational Trend (°C/yr)	-/+ 95% CI $(X10^{-4})$ (°C/yr)	Tmax Elevational Std. Dev. (°C/yr)	Mean Tmin Elevational Trend) (°C/yr)	-/+ 95% CI $(X10^{-4})$ (°C/yr)	TMin Std. Dev. (°C/yr)
23	4464	379.9	361.8/398	617.3	0.000401	3.97/4.06	0.000142	0.000737	7.32/7.41	0.000167
37	5440	548.5	529.5/567.5	714.2	0.000465	4.63/4.68	0.000107	0.000733	7.29/7.37	0.000140
33	3768	570.9	548/593.9	717.7	0.000255	2.51/2.59	0.000125	0.000232	2.27/2.37	0.000158
18	3963	619.8	596/643.6	763.8	0.000113	1.09/1.17	0.000134	0.000606	6.02/6.11	0.000137
42	3116	722.8	697.3/748.3	726.0	0.000103	0.97/1.1	0.000189	0.000337	3.29/3.45	0.000227
43	6795	723.3	707.5/739.2	666.1	0.000346	3.44/3.48	0.000090	0.000517	5.14/5.2	0.000110
47	12192	769.4	759.2/779.6	575.7	0.000513	5.12/5.14	0.000069	0.000982	9.81/9.83	0.000079
27	7370	773.6	756.2/790.9	759.7	0.000589	5.87/5.91	0.000101	0.000839	8.36/8.41	0.000098
20	6399	870.6	853.1/888.1	713.5	0.000637	6.35/6.4	0.000097	0.000530	5.28/5.33	0.000102
11	15024	876.3	868.1/884.5	510.5	0.000679	6.78/6.8	0.000060	0.000830	8.29/8.31	0.000077
3	1708	939.8	907.1/972.4	688.9	0.000070	0.59/0.81	0.000232	0.000428	4.15/4.42	0.000279
40	12231	962.6	952.1/973.2	594.3	0.000361	3.6/3.62	0.000062	0.000597	5.95/5.98	0.000082
2	2617	991.5	960.6/1022.3	804.6	0.000677	6.73/6.82	0.000116	0.000854	8.48/8.6	0.000153
15	7942	1013.8	1002.2/1025.3	525.6	0.000889	8.88/8.91	0.000084	0.000932	9.3/9.34	0.000088
38	2065	1036.8	999.9/1073.6	853.9	-0.000223	-2.31/-2.15	0.000190	0.000140	1.29/1.51	0.000251
36	14860	1074.3	1064.7/1083.9	597.4	0.000513	5.12/5.14	0.000057	0.000676	6.75/6.78	0.000071
41	6666	1082.4	1069.7/1095.1	529.8	0.000897	8.95/8.99	0.000092	0.000670	6.68/6.72	0.000095
46	4687	1088.2	1065.2/1111.2	803.8	-0.000010	-0.13/-0.06	0.000115	0.000413	4.1/4.17	0.000129
9	778	1103.8	1066.6/1141.1	529.6	0.000060	0.43/0.76	0.000233	0.000438	4.2/4.56	0.000256
35	11171	1104.5	1091.2/1117.7	713.6	0.000342	3.4/3.43	0.000066	0.000791	7.9/7.93	0.000077
8	13783	1124.3	1114.3/1134.3	599.5	0.000192	1.91/1.93	0.000070	0.000395	3.93/3.96	0.000072
49	74	1132.2	1023.9/1240.4	467.1	0.000332	2.63/4	0.000295	0.000472	4.02/5.42	0.000302
4	3023	1140.2	1112.7/1167.7	771.1	0.000341	3.35/3.46	0.000153	0.000379	3.72/3.85	0.000187
16	8724	1143.5	1132.2/1154.7	534.7	0.000699	6.98/7	0.000068	0.000556	5.54/5.58	0.000085
Mean	287403	1150.3	1147.6/1152.9	721.8	0.000369	3.68/3.7	0.000289	0.000547	5.46/5.49	0.000333
48	5712	1169.7	1149.8/1189.7	768.9	0.000289	2.87/2.92	0.000111	0.000252	2.48/2.55	0.000127
24	6861	1185.6	1169/1202.2	701.7	0.000379	3.77/3.81	0.000083	0.000190	1.88/1.93	0.000098
44	5408	1211.1	1189.4/1232.7	811.9	0.000679	6.76/6.81	0.000100	0.001210	12.06/12.13	0.000130
17	5875	1245.3	1224.5/1266.1	813.2	0.000492	4.9/4.94	0.000089	0.000960	9.57/9.63	0.000113
28	7015	1264.4	1246.1/1282.8	783.1	0.000120	1.18/1.22	0.000088	0.000700	6.98/7.03	0.000102
31	8925	1336.3	1325/1347.7	547.2	0.000103	1.02/1.05	0.000073	0.000130	1.28/1.32	0.000099
25	781	1341.6	1296.8/1386.5	638.7	0.000412	3.93/4.32	0.000280	0.000565	5.46/5.85	0.000273
50	11837	1354.1	1342.3/1365.9	654.2	0.000246	2.45/2.47	0.000071	0.000530	5.28/5.31	0.000083
32	12893	1365.6	1355.6/1375.7	581.2	0.000420	4.19/4.21	0.000065	0.000389	3.88/3.9	0.000075
10	6071	1368.3	1352.1/1384.4	641.2	0.000491	4.89/4.93	0.000079	0.000576	5.73/5.78	0.000103
19	2271	1371.4	1350.4/1392.4	509.9	-0.000078	-0.84/-0.71	0.000157	0.000164	1.55/1.73	0.000214
30	1437	1373.5	1342.9/1404.1	590.5	0.000038	0.26/0.5	0.000238	0.000300	2.88/3.13	0.000243
6	11890	1401.1	1390.5/1411.8	592.2	0.000237	2.35/2.38	0.000073	0.000223	2.22/2.25	0.000083
7	1186	1485.6	1447.5/1523.8	669.3	0.000584	5.71/5.97	0.000228	0.000712	6.98/7.26	0.000245
29	4969	1496.2	1480.2/1512.2	576.5	-0.000181	-1.84/-1.78	0.000103	0.000180	1.76/1.83	0.000123
21	6479	1621.4	1606.2/1636.6	625.1	-0.000025	-0.27/-0.22	0.000091	0.000385	3.82/3.87	0.000107
45	2777	1642.7	1619.8/1665.6	614.2	-0.000120	-1.25/-1.14	0.000150	-0.000351	-3.58/-3.44	0.000193
5	1461	1648.5	1612.2/1684.9	708.7	0.001132	11.24/11.4	0.000163	0.001253	12.43/12.64	0.000210
14	4647	1650.0	1631.2/1668.8	653.7	0.000356	3.53/3.6	0.000119	-0.000150	-1.55/-1.46	0.000161
12	3142	1663.2	1638.1/1688.3	718.7	0.000154	1.5/1.59	0.000125	0.000721	7.16/7.27	0.000161
13	5737	1683.5	1668.9/1698	561.9	0.000646	6.43/6.49	0.000111	0.000226	2.23/2.29	0.000115
26	1659	1689.2	1655.5/1723	700.7	-0.000520	-5.29/-5.11	0.000188	-0.000042	-0.52/-0.32	0.000209
34	4362	1694.3	1677/1711.7	584.6	-0.000016	-0.19/-0.12	0.000106	-0.000023	-0.27/-0.19	0.000128
1	2791	1774.6	1743.9/1805.2	825.6	0.000128	1.23/1.33	0.000138	0.001129	11.24/11.35	0.000153
22	1646	2109.3	2078.2/2140.4	643.4	-0.000336	-3.45/-3.28	0.000178	0.000753	7.44/7.62	0.000191
39	711	2277.0	2218.9/2335	788.4	0.000269	2.49/2.89	0.000272	0.001842	18.2/18.64	0.000301

Table 7. 1971 – 2000 spring cluster elevation and temperature trend statistics.



Spring Cluster #	N	Mean Elevation (m)	-/+ 95% CI (m)	Elevation Std Dev. (m)	Mean Tmax Elevational Trend (°C/yr)	-/+ 95% CI (X10^{-4}) (°C/yr)	Tmax Elevational Std. Dev. (°C/yr)	Mean Tmin Elevational Trend) (°C/yr)	-/+ 95% CI (X10^{-4}) (°C/yr)	TMin Std. Dev. (°C/yr)
21	5104	535.9	526.8/545.1	334.2	-0.000454	-4.58/-4.49	0.000150	-0.000220	-2.23/-2.16	0.000128
15	5147	549.7	534.7/564.7	547.4	-0.000297	-3.01/-2.93	0.000141	-0.000031	-0.35/-0.28	0.000135
10	8109	580.6	572.5/588.8	374.9	-0.000352	-3.55/-3.49	0.000119	-0.000096	-0.98/-0.94	0.000099
33	8679	623.4	612.9/633.8	494.9	-0.000191	-1.93/-1.89	0.000108	0.000045	0.43/0.48	0.000103
8	9736	683.2	673.9/692.5	467.2	-0.000224	-2.26/-2.22	0.000116	-0.000054	-0.56/-0.52	0.000100
9	7191	740.1	727.5/752.6	542.1	-0.000106	-1.09/-1.03	0.000123	0.000083	0.8/0.86	0.000113
40	5876	740.2	730.1/750.3	393.3	-0.000011	-0.14/-0.08	0.000117	-0.000164	-1.67/-1.61	0.000133
44	9618	766.1	754.7/777.6	572.4	-0.000083	-0.85/-0.81	0.000096	0.000103	1.02/1.05	0.000085
5	3159	808.7	789.3/828.1	555.9	-0.000406	-4.12/-3.99	0.000190	-0.000373	-3.79/-3.67	0.000169
6	4477	810.3	792.9/827.7	593.6	-0.000002	-0.05/0.02	0.000132	-0.000242	-2.46/-2.39	0.000131
37	4683	826.7	808.8/844.7	626.6	-0.000091	-0.95/-0.87	0.000134	-0.000222	-2.26/-2.18	0.000131
38	10509	835.5	824.6/846.3	567.9	0.000004	0.02/0.06	0.000103	0.000233	2.31/2.34	0.000095
26	3248	840.8	829.1/852.5	339.5	-0.000416	-4.22/-4.1	0.000168	-0.000350	-3.56/-3.45	0.000148
17	2959	879.8	867.5/892	340.1	-0.000103	-1.09/-0.97	0.000167	-0.000280	-2.86/-2.74	0.000169
29	484	881.6	809.3/953.8	809.1	0.000451	4.25/4.77	0.000288	0.000487	4.63/5.12	0.000272
27	81	959.0	892.1/1026	302.6	0.000367	3.46/3.89	0.000098	0.000397	3.71/4.24	0.000120
50	5742	998.9	987.5/1010.4	444.0	0.000316	3.12/3.19	0.000130	0.000066	0.62/0.69	0.000130
30	9063	1038.8	1029.1/1048.5	469.9	0.000269	2.66/2.71	0.000103	0.000216	2.14/2.18	0.000111
43	1535	1060.7	1005.2/1116.2	1108.8	-0.000043	-0.56/-0.3	0.000261	0.000103	0.93/1.12	0.000182
39	5982	1099.2	1079.1/1119.3	793.7	-0.000004	-0.07/0	0.000134	0.000432	4.3/4.35	0.000105
45	11120	1110.0	1098.2/1121.8	634.0	0.000203	2.01/2.04	0.000087	0.000233	2.32/2.35	0.000079
Mean	287403	1150.3	1147.6/1152.9	721.8	0.000232	2.31/2.33	0.000361	0.000255	2.54/2.56	0.000329
13	3324	1167.3	1143.7/1190.9	693.8	0.000432	4.27/4.37	0.000156	0.001080	10.75/10.86	0.000161
47	10048	1207.4	1196.5/1218.2	555.5	0.000328	3.26/3.29	0.000090	0.000313	3.11/3.15	0.000102
25	5096	1213.7	1194.6/1232.8	696.4	0.000573	5.69/5.76	0.000125	0.000796	7.93/8	0.000118
23	5722	1214.5	1191.5/1237.6	888.2	0.000237	2.33/2.4	0.000136	0.000717	7.14/7.2	0.000122
4	6887	1216.8	1202/1231.7	630.2	0.000198	1.95/2.01	0.000110	-0.000049	-0.51/-0.46	0.000113
42	10804	1270.2	1257/1283.3	695.9	0.000375	3.74/3.77	0.000084	0.000463	4.61/4.64	0.000074
34	3277	1283.8	1248.2/1319.4	1039.9	0.000162	1.56/1.68	0.000171	0.000503	4.98/5.08	0.000140
20	6454	1300.2	1278.9/1321.4	870.6	0.000464	4.62/4.67	0.000114	0.000507	5.04/5.09	0.000101
22	2148	1311.6	1278.9/1344.3	772.9	0.000403	3.94/4.13	0.000214	0.000450	4.42/4.58	0.000191
35	10982	1316.4	1303.6/1329.2	683.9	0.000595	5.93/5.96	0.000094	0.000509	5.08/5.11	0.000075
12	7656	1322.4	1306.2/1338.7	724.5	0.000143	1.4/1.45	0.000115	0.000310	3.08/3.13	0.000101
1	8461	1323.0	1307.7/1338.4	721.6	0.000583	5.81/5.85	0.000107	0.000738	7.36/7.4	0.000090
19	5307	1352.8	1334.4/1371.3	684.6	0.000170	1.66/1.74	0.000142	0.000654	6.51/6.58	0.000117
41	11003	1356.5	1343.2/1369.7	708.2	0.000348	3.47/3.5	0.000087	0.000344	3.42/3.45	0.000085
3	6724	1374.5	1359/1390.1	649.7	0.000188	1.85/1.9	0.000108	0.000051	0.48/0.53	0.000099
28	4047	1466.9	1447.5/1486.2	628.5	0.000943	9.38/9.48	0.000159	0.000721	7.17/7.25	0.000129
16	4490	1493.6	1472.4/1514.8	724.3	0.000136	1.32/1.39	0.000127	0.000061	0.57/0.65	0.000142
24	9597	1502.0	1488.7/1515.3	663.5	0.000614	6.12/6.16	0.000098	0.000438	4.36/4.4	0.000095
7	4787	1506.4	1489/1523.8	612.9	0.000653	6.49/6.56	0.000132	0.000391	3.88/3.95	0.000119
18	9950	1513.5	1502.3/1524.8	570.9	0.000530	5.28/5.32	0.000086	0.000267	2.66/2.69	0.000076
36	5690	1537.3	1520.6/1554	643.2	0.000850	8.47/8.54	0.000128	0.000373	3.7/3.76	0.000118
48	4147	1640.0	1622.6/1657.4	571.3	0.000564	5.6/5.68	0.000138	-0.000004	-0.08/0.01	0.000139
46	3638	1669.7	1644.7/1694.7	769.7	0.000743	7.37/7.49	0.000175	0.000772	7.68/7.77	0.000143
14	3239	1690.6	1663/1718.3	802.2	0.000592	5.85/5.99	0.000194	0.000177	1.71/1.82	0.000161
31	1570	1726.2	1697/1755.3	589.2	0.000939	9.29/9.49	0.000207	0.000784	7.76/7.93	0.000173
2	882	1776.8	1710/1843.6	1010.4	0.000434	4.17/4.5	0.000248	0.000547	5.32/5.61	0.000226
11	5979	1804.1	1789.5/1818.6	573.7	0.000562	5.58/5.65	0.000134	0.000077	0.74/0.8	0.000129
32	1187	1837.5	1789.8/1885.1	836.5	0.000972	9.58/9.86	0.000241	0.001294	12.81/13.07	0.000228
49	1805	1877.5	1830.3/1924.8	1023.8	0.000666	6.56/6.76	0.000221	0.000776	7.67/7.86	0.000200

Table 8. 1971 – 2000 summer cluster elevation and temperature trend statistics.



Summer Cluster #	N	Mean Elevation (m)	-/+ 95% CI (m)	Elevation Std Dev. (m)	Mean Tmax Elevational Trend (°C/yr)	-/+ 95% CI (X10^{-4}) (°C/yr)	Tmax Std. Dev. (°C/yr)	Mean Tmin Elevational Trend) (°C/yr)	-/+ 95% CI (X10^{-4}) (°C/yr)	TMin Std. Dev. (°C/yr)
41	3700	134.7	128/141.4	207.7	0.000545	5.36/5.54	0.000283	0.000464	4.59/4.69	0.000153
49	4937	382.7	373.4/392.1	335.3	0.000425	4.2/4.3	0.000173	0.000424	4.2/4.28	0.000137
11	3982	506.9	488.7/525.1	586.8	0.000383	3.79/3.87	0.000132	0.000224	2.2/2.28	0.000123
14	2578	523.7	513.2/534.1	270.4	-0.000502	-5.08/-4.97	0.000142	0.000121	1.17/1.26	0.000113
35	3682	548.2	539.5/557	270.5	-0.000918	-9.22/-9.14	0.000130	0.000267	2.63/2.7	0.000111
42	4490	611.9	598.8/625.1	450.4	-0.000417	-4.2/-4.13	0.000117	0.000284	2.81/2.88	0.000116
44	4404	667.4	659.2/675.6	277.8	-0.000831	-8.35/-8.26	0.000139	0.000001	-0.02/0.04	0.000108
40	7317	668.5	656.5/680.5	523.1	-0.000409	-4.12/-4.07	0.000109	0.000317	3.15/3.19	0.000084
32	4806	682.7	662.7/702.7	707.9	0.000065	0.61/0.69	0.000144	0.000391	3.88/3.94	0.000108
36	6198	701.7	694.1/709.2	304.9	-0.000520	-5.22/-5.17	0.000093	0.000004	0.02/0.06	0.000088
39	4716	740.9	727.4/754.4	473.5	-0.000710	-7.13/-7.07	0.000112	0.000156	1.53/1.59	0.000104
4	8583	797.4	783.4/811.4	663.4	0.000249	2.47/2.51	0.000096	0.000265	2.64/2.67	0.000082
50	5707	875.6	864.4/886.7	429.9	0.000461	4.57/4.65	0.000144	0.000574	5.71/5.77	0.000109
27	7069	876.5	867.3/885.8	395.3	-0.000440	-4.42/-4.37	0.000112	-0.000037	-0.4/-0.35	0.000098
17	6825	916.1	902.9/929.3	557.1	-0.000186	-1.88/-1.84	0.000090	0.000070	0.67/0.72	0.000095
13	8925	957.7	942.9/972.5	714.6	-0.000028	-0.3/-0.26	0.000093	0.000448	4.46/4.49	0.000077
29	9676	966.8	952.7/981	710.1	-0.000028	-0.3/-0.26	0.000085	0.000194	1.92/1.95	0.000064
48	3613	980.1	958.5/1001.7	660.8	-0.000034	-0.38/-0.29	0.000143	0.000084	0.81/0.88	0.000099
45	7310	1076.7	1061.2/1092.2	674.8	0.000278	2.76/2.8	0.000092	0.000515	5.13/5.17	0.000085
16	3965	1088.2	1067.3/1109.1	671.3	-0.000716	-7.21/-7.1	0.000174	0.000037	0.33/0.4	0.000108
Mean	287403	1150.3	1147.6/1152.9	721.8	-0.000057	-0.59/-0.56	0.000350	0.000201	1.99/2.02	0.000284
20	6874	1161.8	1144.3/1179.3	739.9	-0.000340	-3.42/-3.37	0.000106	0.000368	3.66/3.69	0.000079
30	6168	1164.4	1148.3/1180.4	642.7	-0.000421	-4.24/-4.19	0.000100	0.000225	2.23/2.27	0.000086
5	13127	1176.7	1165.2/1188.1	668.7	0.000154	1.53/1.55	0.000084	0.000262	2.61/2.63	0.000069
24	10501	1179.0	1165.8/1192.2	687.8	-0.000155	-1.56/-1.53	0.000079	0.000293	2.91/2.94	0.000065
22	10625	1196.6	1185/1208.3	611.8	0.000142	1.4/1.43	0.000082	0.000017	0.16/0.18	0.000070
37	8155	1238.2	1224.2/1252.3	646.8	-0.000250	-2.52/-2.48	0.000098	0.000139	1.38/1.41	0.000072
8	3561	1247.4	1221.6/1273.1	783.2	-0.000402	-4.08/-3.97	0.000175	0.000573	5.69/5.77	0.000118
23	4148	1274.2	1253.4/1295	683.2	0.000594	5.9/5.99	0.000140	0.000354	3.51/3.57	0.000105
6	4076	1295.9	1273.8/1317.9	717.8	0.000017	0.12/0.21	0.000144	0.000801	7.98/8.05	0.000121
28	4357	1337.8	1318.5/1357.2	651.5	0.000449	4.45/4.53	0.000142	-0.000006	-0.09/-0.02	0.000109
33	4019	1341.1	1322.9/1359.2	587.2	0.000240	2.36/2.45	0.000156	-0.000346	-3.5/-3.42	0.000124
3	10612	1375.6	1363.8/1387.4	621.3	-0.000138	-1.4/-1.37	0.000085	0.000054	0.53/0.55	0.000067
38	11631	1377.0	1365.5/1388.5	632.1	0.000001	0/0.03	0.000077	0.000249	2.48/2.5	0.000060
34	2419	1387.1	1356.9/1417.3	757.1	0.000603	5.95/6.1	0.000196	0.000806	8/8.12	0.000146
19	8274	1415.7	1403.4/1428	569.4	-0.000032	-0.34/-0.3	0.000093	-0.000164	-1.66/-1.63	0.000073
1	3593	1419.3	1399/1439.7	623.5	-0.000177	-1.82/-1.71	0.000164	-0.000046	-0.5/-0.41	0.000133
25	4292	1442.8	1424.2/1461.4	622.0	-0.000401	-4.05/-3.98	0.000123	-0.000154	-1.57/-1.51	0.000099
31	3973	1461.1	1443.5/1478.8	567.6	-0.000178	-1.82/-1.73	0.000140	-0.000477	-4.81/-4.74	0.000107
43	7049	1484.0	1468.5/1499.6	664.8	0.000068	0.65/0.7	0.000116	0.000069	0.67/0.71	0.000086
26	1362	1500.8	1467.5/1534.1	626.2	0.000039	0.23/0.54	0.000288	-0.000891	-9.01/-8.81	0.000188
7	9905	1505.3	1495/1515.7	526.1	0.000079	0.77/0.8	0.000095	0.000062	0.61/0.63	0.000065
2	4528	1517.4	1496.6/1538.2	713.3	-0.000229	-2.32/-2.25	0.000125	-0.000196	-2/-1.93	0.000123
12	7932	1556.5	1541.6/1571.5	678.6	0.000021	0.18/0.23	0.000097	0.000504	5.02/5.06	0.000079
47	2270	1616.1	1568.8/1663.5	1150.6	-0.000192	-1.99/-1.85	0.000175	0.000695	6.9/7.01	0.000134
46	6306	1623.9	1603.6/1644.2	821.7	-0.000003	-0.06/0	0.000119	0.000344	3.42/3.46	0.000086
21	1161	1691.7	1655.2/1728.2	633.9	-0.000821	-8.35/-8.06	0.000253	-0.000517	-5.29/-5.05	0.000205
10	6668	1709.9	1694.4/1725.4	643.9	0.000293	2.9/2.95	0.000115	0.000321	3.19/3.23	0.000095
9	3256	1748.9	1729.1/1768.7	575.7	0.000171	1.67/1.75	0.000117	-0.000216	-2.2/-2.13	0.000111
18	911	2086.6	2027.8/2145.5	904.9	0.000264	2.43/2.84	0.000316	0.001405	13.89/14.22	0.000253
15	3167	2172.8	2147.4/2198.2	728.5	0.000315	3.1/3.2	0.000151	0.000706	7.02/7.11	0.000128

Table 9. 1971 – 2000 **f**all cluster elevation and temperature trend statistics.

Fall Cluster #	N	Mean Elevation (m)	-/+ 95% CI (m)	Elevation Std Dev. (m)	Mean Tmax Elevational Trend (°C/yr)	-/+ 95% CI $(X10^{-4})$ (°C/yr)	Tmax Std. Dev. (°C/yr)	Mean Tmin Elevational Trend (°C/yr)	-/+ 95% CI $(X10^{-4})$ (°C/yr)	Tmin Std. Dev. (°C/yr)
6	2052	573.7	543.7/603.7	692.8	0.000214	2.06/2.21	0.000180	0.000345	3.37/3.54	0.000192
28	5077	596.3	582.1/610.6	518.1	0.000064	0.61/0.67	0.000114	-0.000147	-1.5/-1.44	0.000126
24	6420	654.7	642.3/667.2	509.5	0.000272	2.69/2.75	0.000118	0.000147	1.44/1.5	0.000130
39	5026	747.0	728.5/765.5	668.3	-0.000044	-0.47/-0.41	0.000099	-0.000120	-1.23/-1.17	0.000113
47	4410	780.7	764.9/796.5	535.5	-0.000349	-3.52/-3.45	0.000119	0.000153	1.49/1.56	0.000121
37	2850	812.1	784.1/840.1	763.0	0.000295	2.89/3	0.000146	0.000304	2.99/3.1	0.000153
25	10770	850.6	838.8/862.3	623.2	-0.000113	-1.14/-1.11	0.000068	0.000058	0.56/0.59	0.000075
33	7005	859.1	840.6/877.5	788.3	0.000133	1.31/1.35	0.000091	0.000175	1.72/1.77	0.000100
20	7944	914.1	899.4/928.8	668.6	-0.000126	-1.28/-1.24	0.000092	-0.000106	-1.08/-1.04	0.000089
50	7026	920.9	907.9/933.9	556.1	0.000378	3.76/3.8	0.000094	0.000023	0.21/0.26	0.000108
45	1446	957.6	932.6/982.6	484.5	0.000521	5.09/5.34	0.000242	0.000009	-0.06/0.23	0.000284
26	673	962.0	923.2/1000.7	512.5	-0.000009	-0.27/0.08	0.000229	-0.000129	-1.48/-1.09	0.000259
10	1190	966.9	934.5/999.4	570.9	0.000404	3.92/4.16	0.000211	0.000465	4.54/4.77	0.000201
11	8648	978.3	963.1/993.4	718.1	0.000137	1.35/1.39	0.000089	-0.000142	-1.44/-1.41	0.000088
46	11546	1012.9	1000.5/1025.2	678.4	0.000124	1.22/1.25	0.000071	-0.000022	-0.23/-0.2	0.000076
8	380	1035.3	992.3/1078.3	426.3	0.000464	4.4/4.89	0.000246	0.000410	3.88/4.32	0.000215
19	12485	1071.4	1059.3/1083.5	688.7	0.000080	0.79/0.81	0.000060	0.000104	1.03/1.06	0.000070
34	490	1072.1	1034.7/1109.4	420.8	0.000564	5.42/5.86	0.000247	-0.000102	-1.32/-0.72	0.000335
16	7805	1101.8	1085.3/1118.2	739.6	-0.000043	-0.45/-0.41	0.000089	0.000189	1.87/1.91	0.000086
7	9810	1109.3	1095.5/1123.1	697.9	0.000034	0.32/0.35	0.000081	0.000238	2.37/2.4	0.000084
48	6847	1140.1	1122.3/1157.9	751.6	0.000410	4.08/4.12	0.000095	0.000387	3.85/3.89	0.000101
2	4043	1146.5	1128.8/1164.2	574.2	0.000626	6.22/6.3	0.000126	0.000224	2.19/2.29	0.000161
Mean	287403	1150.3	1147.6/1152.9	721.8	0.000198	1.97/1.98	0.000268	0.000191	1.9/1.92	0.000282
9	5139	1167.4	1148.8/1186.1	683.4	-0.000208	-2.11/-2.05	0.000103	0.000395	3.92/3.99	0.000124
3	11119	1170.7	1157.8/1183.6	694.3	0.000381	3.8/3.82	0.000068	0.000399	3.97/4	0.000074
4	6737	1185.0	1167.9/1202.1	715.9	0.000528	5.26/5.31	0.000092	0.000626	6.23/6.28	0.000105
18	7971	1193.3	1177.7/1208.9	710.4	-0.000114	-1.16/-1.13	0.000073	0.000288	2.86/2.9	0.000080
27	3594	1208.2	1180.3/1236.1	853.2	-0.000400	-4.04/-3.96	0.000124	0.000118	1.15/1.22	0.000118
5	13306	1217.3	1205.6/1229	690.8	0.000229	2.28/2.3	0.000064	0.000198	1.97/1.99	0.000065
1	3487	1222.3	1199.7/1245	682.3	0.000031	0.28/0.35	0.000110	-0.000434	-4.38/-4.29	0.000138
38	9293	1223.8	1208/1239.7	778.1	0.000289	2.88/2.91	0.000080	0.000132	1.3/1.33	0.000085
44	6606	1251.3	1236.4/1266.3	619.4	0.000643	6.41/6.45	0.000089	0.000278	2.76/2.8	0.000101
15	7810	1281.4	1267/1295.7	647.1	0.000300	2.98/3.02	0.000090	-0.000202	-2.04/-2	0.000093
13	12181	1289.1	1277.9/1300.3	630.0	0.000376	3.75/3.78	0.000072	0.000161	1.6/1.62	0.000079
23	8961	1299.7	1285.7/1313.8	678.6	0.000523	5.22/5.25	0.000092	0.000233	2.31/2.35	0.000083
36	9967	1307.8	1295/1320.5	647.7	0.000168	1.66/1.69	0.000077	0.000418	4.16/4.2	0.000086
29	4969	1322.5	1298/1346.9	878.8	0.000384	3.81/3.87	0.000101	0.000441	4.38/4.44	0.000106
40	3801	1364.4	1341.6/1387.2	716.5	0.000113	1.1/1.17	0.000113	0.000611	6.07/6.16	0.000142
21	10629	1371.1	1357.9/1384.4	697.8	0.000113	1.12/1.15	0.000073	0.000397	3.96/3.99	0.000086
22	11974	1397.4	1386.4/1408.5	617.6	0.000365	3.64/3.66	0.000071	0.000001	-0.01/0.02	0.000076
49	2107	1412.9	1377.7/1448.1	824.7	0.000320	3.13/3.28	0.000178	0.000676	6.69/6.83	0.000171
41	5490	1432.1	1410.7/1453.6	811.1	0.000239	2.36/2.42	0.000107	0.000743	7.4/7.46	0.000116
43	4726	1435.0	1418.2/1451.7	588.1	0.000642	6.38/6.45	0.000113	-0.000057	-0.6/-0.54	0.000114
32	1219	1452.3	1405/1499.7	842.6	-0.000502	-5.14/-4.9	0.000212	-0.000342	-3.51/-3.33	0.000160
14	1194	1559.2	1513.6/1604.7	802.8	0.000611	5.99/6.23	0.000212	0.000777	7.64/7.91	0.000237
42	2165	1571.4	1546/1596.8	602.6	0.000418	4.11/4.25	0.000161	-0.000624	-6.33/-6.15	0.000219
31	1665	1597.4	1560.8/1633.9	761.2	0.000487	4.77/4.96	0.000189	0.001158	11.47/11.69	0.000224
35	3605	1639.2	1615.6/1662.8	722.1	-0.000154	-1.59/-1.5	0.000138	0.000598	5.93/6.02	0.000132
12	1283	1647.4	1622.9/1671.8	446.6	-0.000284	-2.98/-2.71	0.000244	0.000542	5.31/5.52	0.000189
17	1884	1663.6	1629.3/1698	760.7	0.000921	9.13/9.29	0.000176	0.000587	5.78/5.95	0.000190
30	578	2298.0	2231/2365	820.2	-0.000302	-3.26/-2.79	0.000286	0.001331	13.07/13.55	0.000293

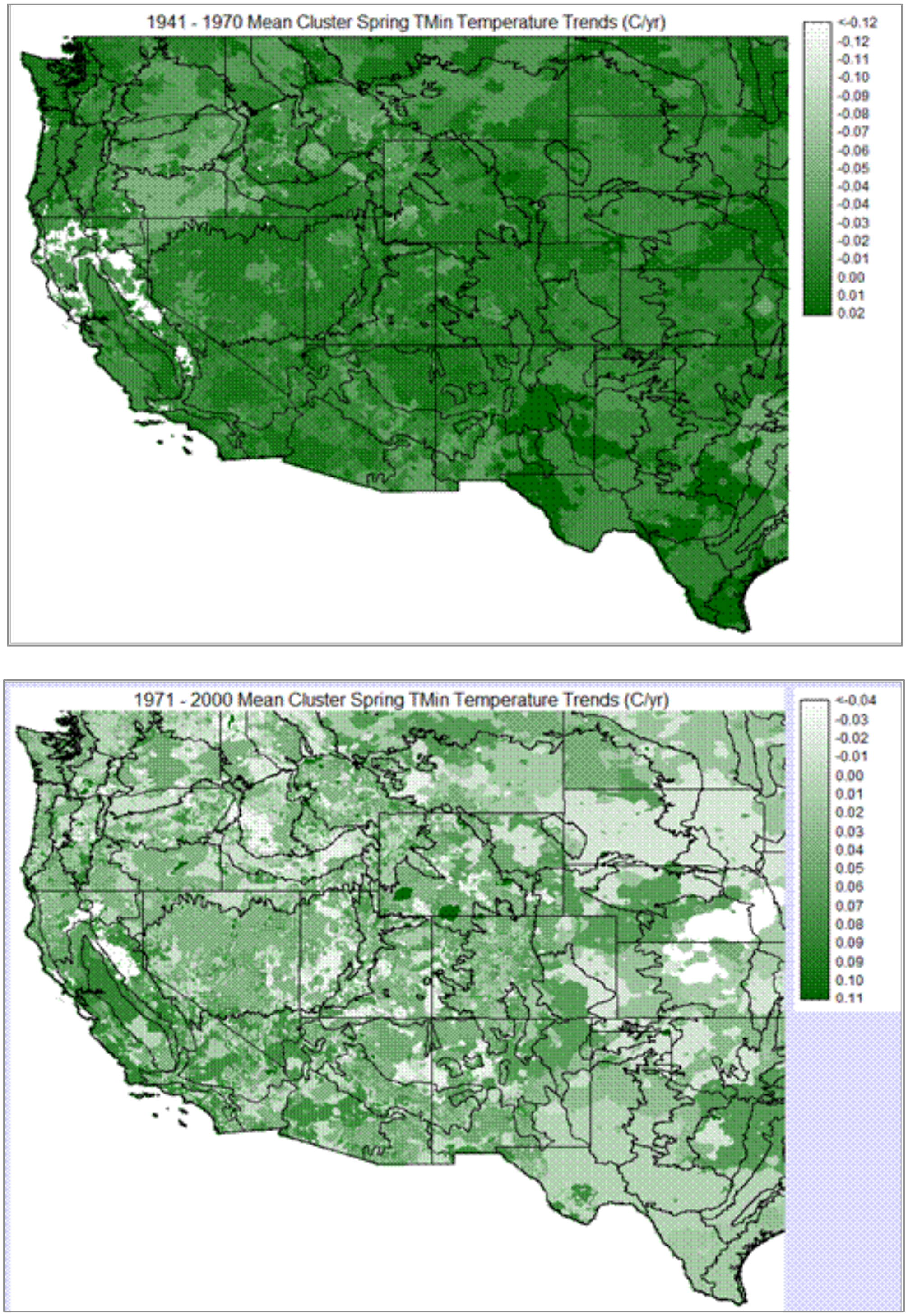


Figure 33. Mean spring cluster minimum temperature trends for 1941 – 1970 and 1971 – 2000.

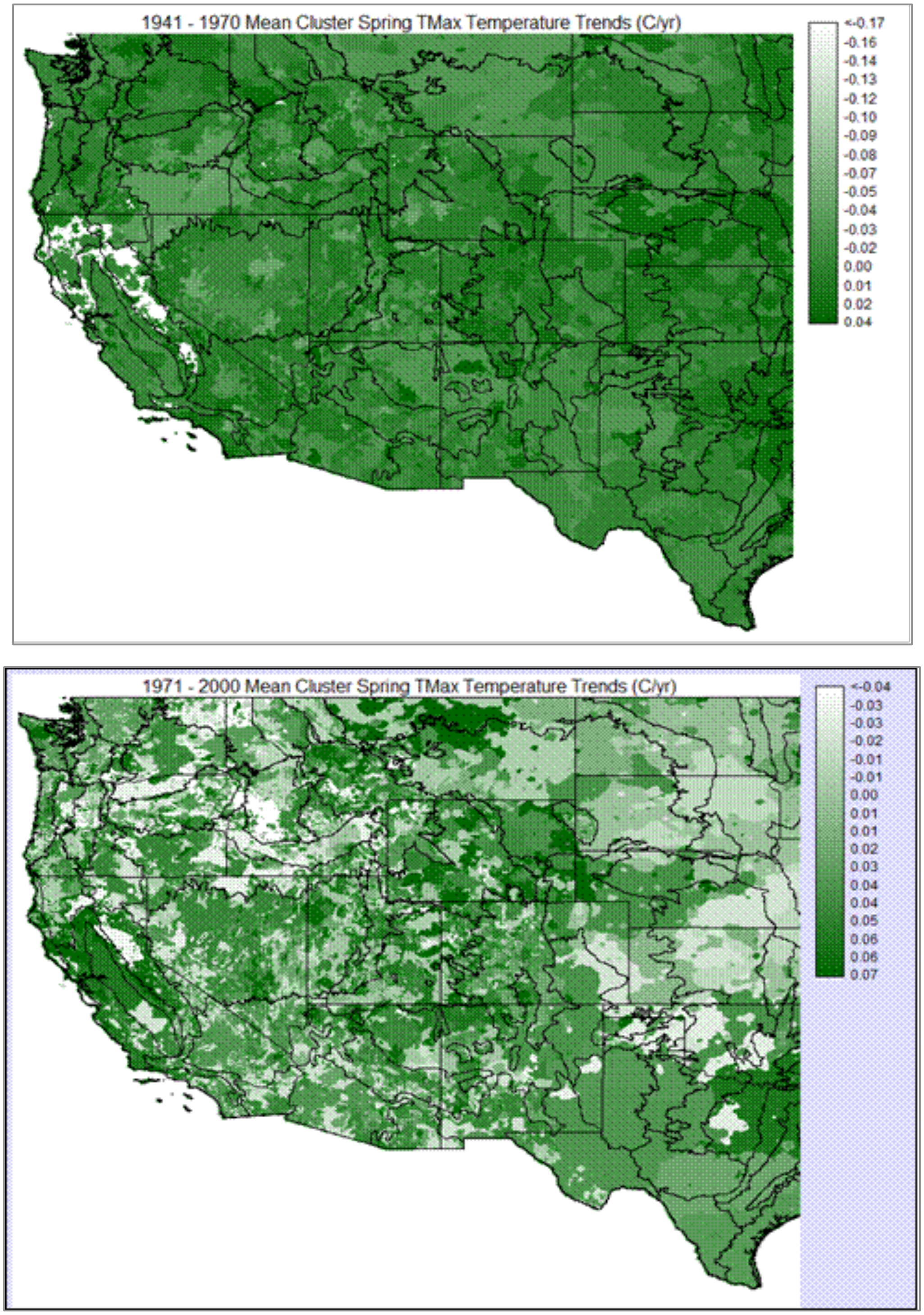


Figure 34. Mean spring cluster maximum temperature trends for 1941 – 1970 and 1971 – 2000.