The Climatic Effects of Tree Growth in Colorado: The Influences of Climate Change on the Colorado Rockies' Treeline

Nicki Naylor

Colorado College

Environmental Science Program

Bachelor of Arts Degree in Environmental Science

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Miro Kummel, Professor of Environmental Science

Marc Snyder, Professor of Biology

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Abstract

Throughout the past century, there has been a global shift in climate. Temperatures have been rising, and while precipitation has been fluctuating, it has exhibited not obvious trends. This change in climate has led to global treeline advancement, and has presented ecological, economic, and social implications. Two of the most relevant implications, especially within the context of the western United States, are changing ecosystem dynamics and water yields. Therefore this study aims to explore the effects of climate change at treeline throughout the Colorado Rockies, with the objective to use simple meteorological data to explain and predict radial tree growth. Data was collected at ten individual mountains in five mountain ranges throughout the state. The subsequent dendrochronologies for each mountain were correlated with time, local and regional meteorology, and the other nine sites. The correlation between sites was compared to the distance between sites. Chronologies were also compared to regional wind and storm patterns. Ultimately, no significant climatic trends appeared to influence individual tree growth on a regional scale throughout the Colorado Rockies. In some sites, such as those bordering the western Colorado deserts, increasing precipitation led to increased radial growth. At a small number of sites in the Front Range and the Sawatch Range, increased summer and annual temperatures led to increased radial growth as well. The remaining sites showed no connection between radial tree growth and simple local and regional meteorological data. The dendrochronologies between most mountains were significantly correlated; the correlations ranged from 0.93 to 0.25, with most of the sites correlated at 0.6 and above. Surprisingly, the correlation coefficients between sites did not respond to the distance between mountains in a statistically significant way. Based on an analysis between site correlations, three groups emerged with inter-site correlation at 0.7 and above: west of the Continental Divide, Front Range and Central Rockies, and along the Continental Divide. In general, these groups showed a southwest to northeast orientation. Storm patterns that flow from the southwest to the northeast throughout the state act as the central variable in correlating chronologies between sites. Conclusively this study does not support the hypotheses that claim climate significantly affects radial growth, but instead provides important information that can be used to further understand the implications of climate on treeline dynamics in the Colorado Rockies.

Introduction

Throughout the past century, global temperatures have been rising. In the western part of the United States, temperatures have significantly increased during the past three decades (Williams et al 2010). Thus strong evidence exists supporting the claim that abrupt climate regime-shifts are presently occurring in the Rocky Mountains (Elliott et al 2010)(Grace et al 2002)(Smith et al 2003).

This increase in temperature has been accompanied by a large variability in precipitation. It is predicted that the southwestern United States, from the Rocky Mountains westward, will see progressively more droughts due to the rise in temperatures and decline in precipitation (Williams et al 2010). Regional drought predictions are expected to combine with the microclimates of the Rocky Mountains, and compound the already harsh conditions of treeline. Historically the growing season at alpine treelines has been cold and short, running from mid-June to early September, but the length of the growing season may now be changing due to changing climate.

It has been observed globally that increasing temperatures are causing treeline advancement. Temperature has historically been the dominant driver of global and regional treeline demographics (Elliott 2012). Since the 1950s, there have been abrupt changes in spatiotemporal patterns at treeline, indicating a threshold response due to climate. This has been signified by the recorded correlation between treeline advancement and temperature, which has been higher since 1950 than it was beforehand (Wilmking 2004, Elliott 2012). Temperature appears to determine growth at treeline. Treeline dynamics are believed to be controlled by heat, with temperature considered a limiting factor at large spatial scales (von Bogaert et al 2011, Hofgaard et al 2009, Harsch 2009). Summer temperature increases have been more frequently recorded than winter temperature increases at high elevation sites (Harsch 2009). However, sites that have experienced winter warming have shown a more pronounced likelihood of elevational advancement than those that have warmed during the summer (Harsch 2009). This temperature increase has lead to warmer boundary layers around treeline, where regeneration, and thus treeline advancement occurs. The boundary layer determines the ability of seedling establishment at and above the current treeline (Korner 1998). Temperature, especially within this boundary layer, has a complex relationship with radial growth. While temperature immediately affects the growth rate, there is often an additional lag time due to nonstructural carbohydrate storage. Thus temperature has the ability to influence radial growth for more than one season (Harsch 2009)(Williams et al 2010).

In the past century, temperature has been continually rising, while precipitation has fluctuated but exhibited no obvious trends. Precipitation is coupled to temperature and believed to be influential for treeline dynamics (Miro Kummel: personal communication). Dry winters have been reported to trigger threshold changes in ecological systems when experienced in conjunction with increasing temperatures. Little information exists about the effects of wet winters, and what has been recorded is contentious. Elliott (2012) claims the primary source of precipitation leading to growth at treeline is winter-time storms, while von

Bogaert (2011) claims that winter precipitation is not found to be correlated with tree growth or seedling establishment, especially at the higher latitudes. Consequently the role of precipitation in treeline dynamics is less apparent than the effects of temperature. But it appears that the combination of changes in temperature and precipitation work together to undermine the stability of ecological systems at alpine treelines (Elliott 2012).

As climate has begun to change, it has become apparent that diffuse treelines are the most likely type of treeline to advance and be dependent on changes in temperature, as opposed to abrupt or krummholz treelines. Since there are fewer constraints on diffuse treelines than other types of treeline, they are universally more likely to be in equilibrium with growing season temperatures, thus the most likely to exhibit sensitivity to changes in growing season temperature (Harsch 2009, Harsch et al 2011, Elliott 2011). Additionally, the existence of krummholz and saplings above diffuse treelines often indicates future episodic treeline advancements (Walther 2002, Hofgaard et al 2009).

The consequences of treeline advancement are most importantly focused on ecosystem boundaries and ecosystem dynamics. With advancing treelines, alpine tundra species are being outcompeted. The tundra ecosystem is shrinking, leading to species loss while the subalpine species are advancing. While Engelmann spruce (Picea engelmannii) plays a critical role in forest-tundra ecotones, treeline advancement of the species encourages the intrusion of sub-alpine species. Furthermore, sub-alpine species are invading the forest-tundra ecotones faster than resident species are able to recede upslope (Walther 2002)(Smith et al. 2003).

In addition to ecosystem alterations, treeline advancement has economic and social impacts. Trees in sub-alpine and alpine ecosystems regulate snowmelt, thus water yields. With some studies indicating declining precipitation, the amount of water vapor, soil moisture, and water reserves will also be predicted to decline. The latter predictions, along with the encroaching ecosystem alterations are expected to have serious regional impacts.

This study aimed to discover how climate change influences individual tree growth at treeline throughout Colorado. This study looked at climate change through individual tree ring chronologies at ten mountains in five ranges throughout Colorado. By testing for climatic effects in individual tree cores throughout the Colorado Rockies, local climatic nuances in orography could be compared and applied to more regional climatic trends and variability.

All tree samples were taken at treeline. Treeline, defined as the uppermost limit where individuals have vertical growth over two meters, and is located above timberline – the highest elevation at which trees still maintain stature characteristics of trees found within the contiguous forest – and is believed to record a pure climatic signal (Wilmking 2004, Smith et al 2003, Elliott 2010). Trees at treeline are at their physiological threshold, allowing for subtle variations in climate to produce rapid changes in growth and establishment (Elliott 2012). Climate variations have been recorded at treeline in the past; therefore it was assumed that the impacts of past and present climate variation would be accessible at treeline for this study, and help explain how climate influences individual treelines throughout the state (Grace et al 2002, Weisberg et al 1995, Korner 1998).

I expected that increasing temperatures would cause accelerated annual radial growth, as would precipitation. However, I expected that precipitation would influence annual radial growth much more marginally than temperature. Also, I expected the Continental Divide to act as a climate differential, causing the western portion of Colorado to experience different annual radial tree growth patterns than the eastern portion of the state.

Methods

Study Sites

Throughout Colorado, five mountain ranges were studied; the Front Range, the Mosquito-Ten Mile Range, the Sawatch Range, the Elk Range, and the San Juan Range. The Sangre de Cristo Range was excluded due to the inaccessibility to valid study sites. In each of the five mountain ranges, two study sites were chosen, each on a different mountain. Throughout the state, the study sites were chosen to be on mountains of similar elevation – roughly 14,000 feet – and based on site accessibility. Therefore, the following parameters were defined in order to choose each site: sites in the five named ranges were located on east-facing slopes (with the exception of Pikes Peak that was on a west-facing slope), each sample tree would have a 15 meter radius around it in which no other trees taller than two meters above could grow, and the trees all had to be of similar height and diameter at breast height (DBH). Sites could have been chosen on east or west facing slopes, both of which are defined to be climate neutral. However, due to site accessibility, all sites were on east-facing slopes. From the literature, it became clear that north-facing slopes would retain excessive amounts of water and would be prone to exhibiting cooler temperatures, while the south-facing slopes lose water quickly and would be relatively warm. On both east and west-facing slopes there is no excessive water retention or loss, and the temperatures are indicative of the regional climate.

Although the sites have orographic microclimates, they are also indicative of regional climate. Therefore, on each east-facing slope, a study site was established at treeline. Since treeline at all but one of the sites was diffuse, the samples were collected from an expanse vertical meter range. The one abrupt treeline was on Grays Peak, and due to a rockslide. At treeline throughout Colorado, Engelmann Spruce is the dominant tree species, and therefore was the target species for this study. Within the limits of treeline, there were fourteen trees per site (140 trees total in the study). Each tree had a 15-meter radius in which no other trees higher than two meters were present (Wilmking 2004) and GPS coordinates were taken. One growth core and one age core were taken from each tree. Growth cores (and diameter at breast height measurements) were sampled at breast height, while age cores were sampled as close to the base of the tree as possible. The cores were taken from the north or south sides of the tree in order to reduce the influence of tension wood and compression wood (the curve that occurs at the base of a tree as it grows from a steep slope) (Miro Kummel, Marc Snyder: personal communication). Additionally, once each sample tree was cored, its height was measured based on the principle of similar triangles.

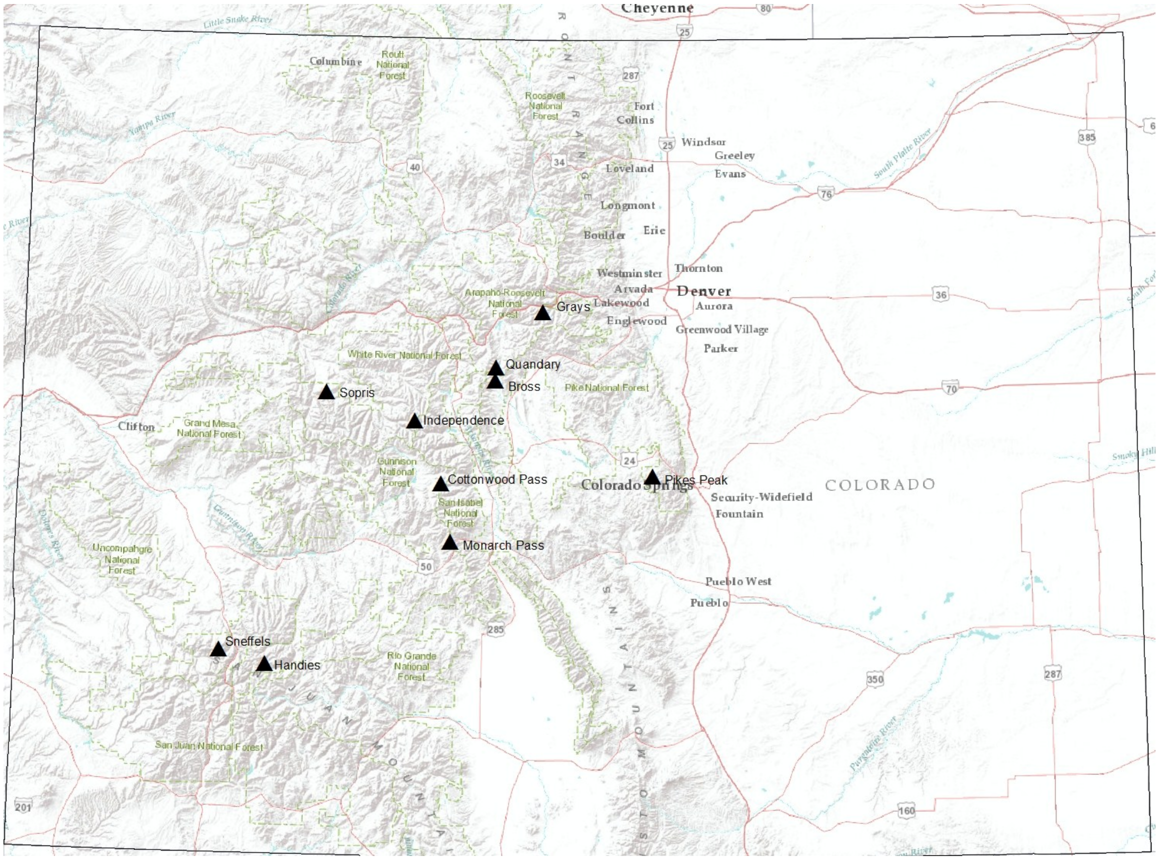


Figure 1. All black triangles represent one of the sites in the study and are labeled.

Description of the Study Sites

Front Range: The two sites in Colorado's Front Range were on Pikes Peak and Gray's Peak. Pikes Peak, located just west of Colorado Springs, is relatively isolated from the rest of the Colorado Rockies and is known for having isolated weather patterns and climatic trends. The data from Pikes Peak were collected through Miro Kummel's previous research on its west-facing slope. Gray's Peak, on the other hand, is deeply embedded in Colorado's Front Range, located off of I-70 outside of Georgetown. The site was also on the west-facing slope, beneath a large rock fall.

The Gray's Peak site was roughly a 0.8-kilometer long, and within a 30.5 vertical meter range at treeline.

Mosquito-Ten Mile Range: The first peak sampled in the Mosquito-Ten Mile Range was Quandary Peak, located on the western side of Highway 9, 16 kilometers south of Breckenridge. The study site was located on the northern side of the trail going up the mountain, in an expanse, wide, east-facing bowl with many terrain micro-features. The horizontal range of the site was about 0.8-kilometer, with a 61-meter vertical range. The second study site in this range was Mount Bross. Coming from Alma, Colorado, CO Road 8 was taken until it intersected with County Road 787. The site was located off County Road 787 on an east-facing bench just north of two mines, with the Quartzville mine just to the north. It was several hundred meters north a historical bristlecone pine forest. All the tree cores from Mount Bross were obtained within a half a kilometer by 46-vertical meter range.

Sawatch Range: Cottonwood Pass is located west of Buena Vista on CO Road 306. The site was on the south side of the road. The site was relatively boggy, in a medium-sized bowl extending for a 0.8-kilometer by 61-vertical meter range. Monarch Pass, the other site in the Sawatch Range, was located just west of the town of Garfield, just to the west of the uppermost Waterdog Lake on an east-facing slope. There were many micro-features that caused the piths of the trees in this site to curve and clump together, consequently making it difficult to find sample trees. All samples for Monarch Pass were taken within a 0.8-kilometer by 61-vertical meter range.

Elk Range: Independence Pass, on Highway 82 just east from Aspen, was sampled at the Upper Lost Man trailhead. The site was located to the west of the trail on an east-facing slope, where two streams ran through the basin. The site was engulfed by dense shrubbery, and all samples were taken within a 0.4-kilometer by 46 vertical meter range. The other site in the Elk Range, Mount Sopris, is on the northern side of the Roaring Fork Valley outside of Basalt. The site was on an east-facing ridge above Thomas Lakes. The site was on the north side of the trail, in a half a kilometer by half a kilometer range.

San Juan Range: Handies Peak, south west of Lake City, CO, is located off CO 30 on the south side of the road. The site, at the base of a wide basin, was on an east-facing slope and a river ran through the southern-most side of the site. The treeline was diffuse, with relatively dense shrubbery. To the south was another basin with significant rock fall, and to the north a grassy slope. Mount Sneffels, the other site in the San Juan Mountains, was located off County Road 361 outside Ouray, CO. This road accessed the Yankee Boy Basin, which is scattered with jeep roads. The site was located above the main parking lot for the trailhead to Mount Sneffels, with a jeep road running through it. The treeline was diffuse, with a stream on the south side of the site. Nearby there were three major mining claims that are no longer operational.

Lab Analysis

After the cores from all of the sites were collected, they were brought into the lab. All 280 cores were mounted, sanded, and measured according to standard dendrochronological techniques (Stokes et al. 1996). Once all the cores had been mounted and labeled, they were sanded with 200, 400, and 600 grit sandpapers. By sanding down to the 600-grit level, the cellular features of the cores were exposed, allowing the radial growth to be measured. Once sanded, the cores were measured on a linear bench. This measurement technique allowed the cores to be measured to the closest 1/1000 millimeter. All measurements (radial growth per year) were recorded onto an Excel spreadsheet where all age and growth cores were condensed into a single sheet per site.

Data Processing

Once all the cores had been measured, the measurements were condensed into a single time series per site. Growth cores were standardized. To standardize, the following procedure was followed. Each site had fourteen trees that had been cored. To standardize a core, the average growth increment for the core was found. Then each ring measurement within that core was divided by the average. Each core had anywhere from 30 to 90 standardized measurements. Once the fourteen cores per site had been standardized, they were organized by year. All the standardized measurements from one year were averaged, and a standard deviation was also determined. This process was done for all cores for all years, until only five cores remained per site per year. Once there were fewer than five measurements for the particular year, no more averages or standard deviations were taken. The compiled annual standardized averages were then used for correlations and comparisons. By standardizing the measurements, the variation throughout the chronology was kept while preventing the larger values from skewing the data (Williams et al 2010). From the standardized growth measurements, graphs were created comparing standardized annual means versus time. This visual representation allowed for a comparison of individual annual radial growth throughout Colorado.

Meteorological Data

Meteorological data were gathered from two organizations: NOAA and USHCN (United State Historical Climatology Network). Weather stations from each organization were found as close as possible to each individual site throughout the state. From the stations, annual temperature and precipitation data were collected, as well as seasonal temperature and precipitation data. Therefore each site had two weather stations to be compared to. From the weather stations, the annual temperature, precipitation and seasonal temperature and precipitation were compiled by averaging seasonal and annual values. Meteorological data, for the most part, dated back as far as the collected chronology, allowing for meaningful correlations between radial growth and meteorology. However, there were cases where data were missing. If multiple years of data were missing, the series was not used. If only one or two values were missing though, the average of the series was taken and used in the place of the missing value.

Correlations

Initially, the meteorological data was compared to the annual standard growth for each site by bivariate correlations using SPSS. Once all the sites were correlated to annual and seasonal meteorology, the correlation coefficients were mapped in order to spatially determine the effects of both temperature and precipitation in relation to annual standard growth throughout Colorado. Additionally, I tested the relationship between inter-site correlation coefficients and inter-site distance.

Results and Discussion

Initially the radial growth cores were analyzed over time in order to decipher individual growth patterns at each site. Though all the chronologies were initially compared and graphed along their individual time series (ranging from the 1920s-1980s until present), when compared against one another, a consistent trend could be seen: standard annual growth started to increase during the 1970-1980s, and has steadily and persistently increased until the present day (Figure 3). Throughout the last century, temperatures have been observed to increase, most notably since the

1970s. While Colorado's temperature has been increasing over the last century, no obvious trends have been presented in the precipitation data. It has exhibited large fluctuations since the 1900s, but no obvious trends. The radial growth trends mirror the last four decades of temperature meteorology in Colorado in which spring and summer temperatures started to drastically increase (Williams et al. 2010). Most of the trees sampled were relatively young (50 years old or younger), while some trees were a bit older (75-90 years old). The growth rates in the older trees was expected to decline, making those trees less sensitive to climate variations. Remarkably, however, instead of annual growth decreasing as expected, the standard annual growths actually started to increase – often making a U shape – and followed the same trends that were seen in the shorter time series, which were based on younger trees (Grace et al. 2002). Thus, a regional trend of increasing standard annual growth, most likely due to climate change, is presented throughout Colorado in the last four decades.

Seasonally, Colorado's climate has been much more dynamic. As expected, summer temperatures have steeply increased since the 1900s, most drastically since the 1970s. Spring and fall temperatures also show increasing trends. Spring temperatures have rapidly increased since the 1980s. Fall temperatures, while increasing, have been less abrupt. With increasing spring, summer, and fall temperatures, there are large implications for radial growth throughout Colorado. Growing season at treeline has traditionally been limited to the summer months, with some overlap into the spring and fall. However, with spring temperatures increasing, spring is starting earlier. With fall temperatures also increasing, fall is ending later. Thus the growing season for Engelmann spruce at treeline in Colorado is extended annually. Since Colorado's annual and seasonal temperatures started to increase in the 1980s, the observations presented above allow for a conceptual basis that climate – temperature most importantly – has the potential to be connected to radial growth of Engelmann Spruce at treeline.

Correlations between meteorological data and standard annual growth were tested in order to conclude whether increasing temperature trends and fluctuating precipitation patterns had implications on radial growth at each site. There were climatic implications at six sites throughout the state. The six sites that showed significant relation to climate were Mount Sopris, Cottonwood Pass, Monarch Pass, Mount Sneffels, Handies Peak, and Pikes Peak. Sites that were positively impacted by an increase in winter precipitation included Mount Sopris (r^2= 0.16; n=26; p=0.04), Mount Sneffels (r^2= 0.10; n= 23; p=0.0317), and Handies Peak (r^2 = 0.18; n=17; p= 0.0433)(Figure 8). These three sites border the western Colorado deserts, where summer precipitation is not retained as well as winter precipitation. Two other sites were positively correlated with increasing summer and fall temperatures: Cottonwood Pass (summer r^2= 0.2; fall r^2= 0.22) and Pikes Peak (summer r^2= 0.22; fall r^2 = 0.12) (Figure 9). Monarch Pass, alternatively, showed a decreasing annual radial growth with increasing annual precipitation (r^2= 0.12), which may be attributed to the environmental impacts of the nearby quarry. Two major climatic categorizations emerged in Colorado: one based on temperature, the other on winter precipitation. However, these two groupings did not represent a statewide trend.

Geographically, regional annual temperature trends were also explored in hopes to build a greater understanding of the correlations between sites. Thus annual temperature from weather stations connected to each site were gathered and correlated to all the other annual temperature data. This produced correlation coefficients, ranging from 0.1-0.85. When the correlations were looked at geographically, annual temperatures followed a southwest to east-northeast trend throughout Colorado. Similar to growth across the state, annual temperature correlation between sites was not dependent on distance. It can therefore be concluded that temperature is not the driving force behind individual radial growth throughout Colorado's treelines.

Literature previously suggested that temperature acts as the driving variable in treeline advancement globally, as well as within Colorado. An advancing treeline caused by temperature would imply that rising temperature causes more seedling establishment, therefore more individual tree growth (Elliott et al. 2010, von Bogaert et al. 2011). However, as mentioned above, this study did not support the claims reported throughout such literature, nor the hypothesis from the beginning of this paper stating that increasing temperatures cause accelerated radial growth at treeline annually throughout Colorado. While standard annual growth started to drastically increase during the 1980s, at the same time as temperature increases became apparent in Colorado, there were no statewide trends between radial growth and temperature in this study. Instead, regional patterns of radial growth in sampled Engelmann Spruce were connected to storm and wind patterns. This trend, while not explaining site correlations, was a pattern that was not expected.

Two major categorizations of climate emerged throughout Colorado. There were five sites involved, two linked to summer and fall temperatures, and three linked to winter precipitation, all correlated to their respective climatic influences at a 0.7 correlation coefficient or higher. Summer and fall temperatures influenced radial growth at both the Pikes Peak and Cottonwood Pass sites. All correlations were significant (with p-values ≤ 0.001; Figure 9). This association between temperature and radial growth supported this study's hypotheses. The role of precipitation in radial growth throughout Colorado, however, contradicted the hypotheses presented at the beginning of this paper. As seen in three of the study sites, precipitation was a determining factor in radial growth (Figure 8). All of the sites in which precipitation controlled radial growth bordered the Western Colorado deserts. This can be explained by the water retention of drier climates, and the fact that precipitation is less frequent during the growing season in these regions than elsewhere in the state. At one of the sites, Handies Peak, one point existed that indicated much higher winter precipitation than the rest of the annual points on the graph (Figure 8). This point was not an outlier, however, much of the statistical significance for Handies rests on it. Thus two groupings were observed: the western-most sites (Mount Sneffels, Mount Sopris, and Handies Peak) were affected by winter precipitation, and Pikes Peak and Cottonwood Pass were affected by increasing summer and fall temperatures.

Since no statewide climatic trend existed throughout Colorado, it was hypothesized that another factor might correlate the sites regionally. Therefore, a bivariate correlation was run on SPSS comparing site distances and the correlation coefficients of each site in relation to all the others. Through these correlations, the hope was to determine whether distance influenced site correlations so that distance could be linked to climatic variations. It was expected that the closer the sites were – especially if they were located in the same mountain range – the more tightly correlated they would be. Theoretically, this would produce a negative exponential function, asymptoting to zero with increasing distance. However, contrary to what was expected, distance was irrelevant in determining how closely related the standard annual growth of each site was to the others. The graph exhibited a slightly negative linear trend that was not statistically significant (Figure 10). From the graph, it was concluded that distance was irrelevant in determining how tightly correlated the chronologies of each site were, and was exemplified by the fact that several site pairs 50 kilometers apart had lower correlation coefficients than site pairs 200 kilometers apart.

Distance did not play a significant role in the correlation between tree rings at the different sites. Therefore I looked for geographically coherent groups of interconnected sites. Based on the correlation coefficients between sites, three maps were made: one highlighting site pairs with correlation coefficients 0.8 and higher, one with 0.7 and higher, and the last with 0.6 and higher. Eventually, the 0.7-map was chosen to represent which correlations and geographic patterns were important. The 0.8-map did not have enough correlations, while the 0.6-map was too crowded with many correlations for every site. Thus, sites with correlation coefficients of 0.7 or greater were noted and mapped, and ultimately three groups emerged. There were two groups to the west of the Continental Divide, and one to the east (Figure 2). All the sites on the eastern side of the Continental Divide compiled into one group (Pikes Peak, Gray's Peak, Mt. Bross, and Cottonwood Pass). On the west side of the Continental Divide, however, there were two groups. One encompassed the majority of sites on the western side of the divide (Mt. Sneffels, Handies Peak, Mt. Sopris, Independence Pass, Quandary Peak, Mt. Bross, and Cottonwood Pass). The other group was much smaller, including Cottonwood Pass, Monarch Pass, and Handies Peak. Interestingly, the latter group was the only place in the entire study where Monarch Pass was significantly correlated to other sites. Otherwise, Monarch Pass seems to be entirely disconnected from the rest of the Colorado Rockies and any climatic patterns. This geographic trend supported the hypothesis that the Continental Divide acts as a climate barrier, influencing radial growth patterns.

The groups on the west side of the Continental Divide, as presented above, demonstrated an interesting regional trend: the two groups followed a southwest to northeast directional trend throughout Colorado (Figure 2). Interestingly, the storm patterns in Colorado follow the same southwest to northeast pattern. The storm patterns thus likely help determine how tightly correlated standard annual growth is between sites on the western side of the Continental Divide. Based on personal communication with David Battisti (University of Washington) and my visual analysis of a time-lapse video of infrared satellite images of water vapor, storms were seen to enter Colorado from the southwest part of the state, exiting on the northeast side of the Colorado Rockies. These storms originate in the tropics, flowing west, and as these storms drift north they catch the Westerlies that flow throughout North America (UWMadison 2008)(David Battisti: personal communication). While some storm patterns enter Colorado directly from the west, the majority of storm patterns originate in the tropics and enter from the southwest. Within Colorado, storms flow southwest to northeast along the San Juan Range. When storms hit the Sawatch Range, they start to trend directly north. The storm patterns, driven by wind, continue north along the western side of the Sawatch Range, until they reach the junction of the Sawatch, Elk, and Mosquito-Ten Mile Ranges. Then storms trend northeast along the Mosquito-Ten Mile and Front ranges until they leave Colorado (Rasmussen 2011, Figure 11). This southwest to northeast storm pattern supports the claim that the storm system throughout Colorado strongly influences why sites on the western side of the Continental Divide are so closely interconnected (with the exception of Monarch Pass). So while the storm patterns do not cause sites to be tightly correlated to one another, they do help create a connection between sites. This connection is one that needs to be explored further in future research.

The driving idea behind this study was to discover whether or not simple meteorological data could help explain and consequently predict radial growth at treeline throughout the Colorado Rockies. Because radial growth did not regionally respond to temperature, it was concluded that Engelmann spruce were sensitive to more complex variables than can be reflected in simple meteorological data. There are a number of possible variables (not taken into account in this study) that may impact radial growth. First, as previously mentioned, the growing season at Colorado's treelines is lengthening: spring is starting earlier and fall is ending later.

Not only is the growing-season lengthening, but it is also becoming less climatically harsh (Smith et al. 2003). Hence, while temperatures are increasing, especially during the growing season months, it is plausible that radial growth is more responsive to the number of days the trees have to grow than the temperature during those days.

Another possible factor influencing radial growth may be the amount of light available to the trees at treeline. This possibility would be compounded by Elliott's claim that climate change in the Colorado Rockies will most likely be mediated by slope aspect (Elliott et al. 2010). Just as temperature and precipitation effects are more severe on north and south-facing slopes, the available light on those aspects may similarly influence radial growth (with north-facing trees growing less due to less sunlight, and the reverse for south-facing trees). In addition, nutrient storage in trees, while not likely to dominantly control radial growth, is likely to marginally influence annual radial growth, especially in trees at treeline. With the latter explanation, it would be necessary to consider lag times in trees, as well as soil and air climates, and how the two influence nutrient cycling.

It is also possible that radial growth is reacting to soil climates in addition to air climate. The two – air and soil climates – are coupled complexly, depending on variables such as boundary layer thickness and soil moisture, in addition to simple meteorological data (Miro Kummel: personal communication). It has been recorded that many variables involved in treeline dynamics (such as regeneration and treeline advancement) are correlated to soil moisture (Weisberg 1995). This coupling would fortify the hypothesis that radial growth is dependent on both soil and air climatology. Furthermore, soil climate has been determined as a dominant factor in growth (or growth inhibition if soil temperatures are low) and nutrient uptake. Cold soils, due to extended snow cover at high altitude forests have been documented to constrain tree growth activities (Smith et al 2003, Korner 1998). Therefore, since meteorological stations measure air temperature and precipitation that is not perfectly reflected in the growing environments of species such as Engelmann Spruce, growth may be constrained by soil climate in addition to meteorology.

Throughout the study, climate influenced radial growth in unexpected ways. Annual temperature was tightly correlated between sites in a linear southwest to east-northeast trend, which allowed me to hypothesize that temperature was the dominant variable influencing radial growth. Instead, annual temperature had negligible regional impacts. Temperature did, however, positively impact growth for Pikes Peak and Cottonwood Pass during the summer and fall seasons, supporting the hypothesis that Pikes Peak would be relatively representative of the eastern Colorado Rockies. Despite evidence of local trends spurred by temperature, no universal temperature trends emerged throughout Colorado. Precipitation, alternatively, had statewide trends. Winter precipitation strongly impacted radial growth in sites bordering the western Colorado deserts. Overall, climate was not a principle variable driving patterns of radial growth. Storm patterns, however, helped connect the patterns in site correlations, but was not a causality, so needs to be explored further.

Conclusion

Throughout this study the following question was posed: is simple meteorological data sufficient to explain and predict tree growth at treeline throughout Colorado? The hypotheses stated in the beginning of the paper predicted that yes, meteorology could explain radial tree growth. It has been shown globally that temperature significantly helps define treeline dynamics, while the impact of precipitation is rather ambiguous. Colorado's treeline is changing due to longer growing seasons and a more favorable, warmer climate. It was hypothesized that as temperature increased throughout the state, radial growth would simultaneously increase as well. Precipitation was expected to positively influence radial growth, but to a lesser extent than temperature. Additionally, the Continental Divide was expected to serve as a climate barrier, leading to more growth on its western side, where weather patterns enter the state. Pikes Peak was expected to be relatively indicative of climatic patterns in the eastern part of the state.

The study did not deliver the expected results. Temperature was not as influential on individual radial tree growth as expected. Instead, winter precipitation strongly impacted radial growth, in sites bordering the western Colorado deserts. Pikes Peak, as expected, was marginally indicative of the climatic effects in the eastern Colorado Rockies. Pikes Peak, Mount Bross, Grays Peak and Cottonwood Pass served as the only sites with radial growth governed by temperature. Pikes Peak and Cottonwood Pass experienced increased radial growth with increased summer and fall temperatures. Ultimately Colorado was not regionally affected by climate (as defined by temperature and precipitation), but rather by wind and storm patterns flowing throughout the state.

The geographical arrangement of the groups with interrelated correlation coefficients higher than 0.7 confirmed the hypothesis that the Continental Divide acts as a climate barrier. The two groups of tightly correlated sites on the western side of the state ran in a southwest to northeast direction (the same directionality of storms), while the eastern portion of the state showed no directional trend. Thus distance between sites was not important, but rather the placement of sites along the storm track was. Monarch Pass was seemingly disconnected from the majority of the Colorado Rockies, which hypothetically can be explained by a split in the storm track with part of the storm flowing just to the west of the site, and the rest of the storm to the south of the site, towards Pikes Peak.

Ultimately simple meteorology (i.e. temperature and precipitation) was inadequate for explaining, and therefore predicting, individual radial growth in trees at treeline throughout Colorado. It was concluded that radial growth is sensitive to more complex factors, with the most important hypothesized variable being the coupling between meteorology and soil climate. In addition to the latter coupling, nutrient and carbon cycling as well as the influence of light and slope aspect can be further depicted and analyzed to better understand radial growth dynamics at Colorado's treeline. Thus while temperature is indeed important in treeline dynamics globally as well as within Colorado, it is only one variable to take into consideration. A more holistic approach must be taken in order to further understand the biological, ecological, social and economic implications of treeline advancement and accelerated individual tree growth.

Appendix A

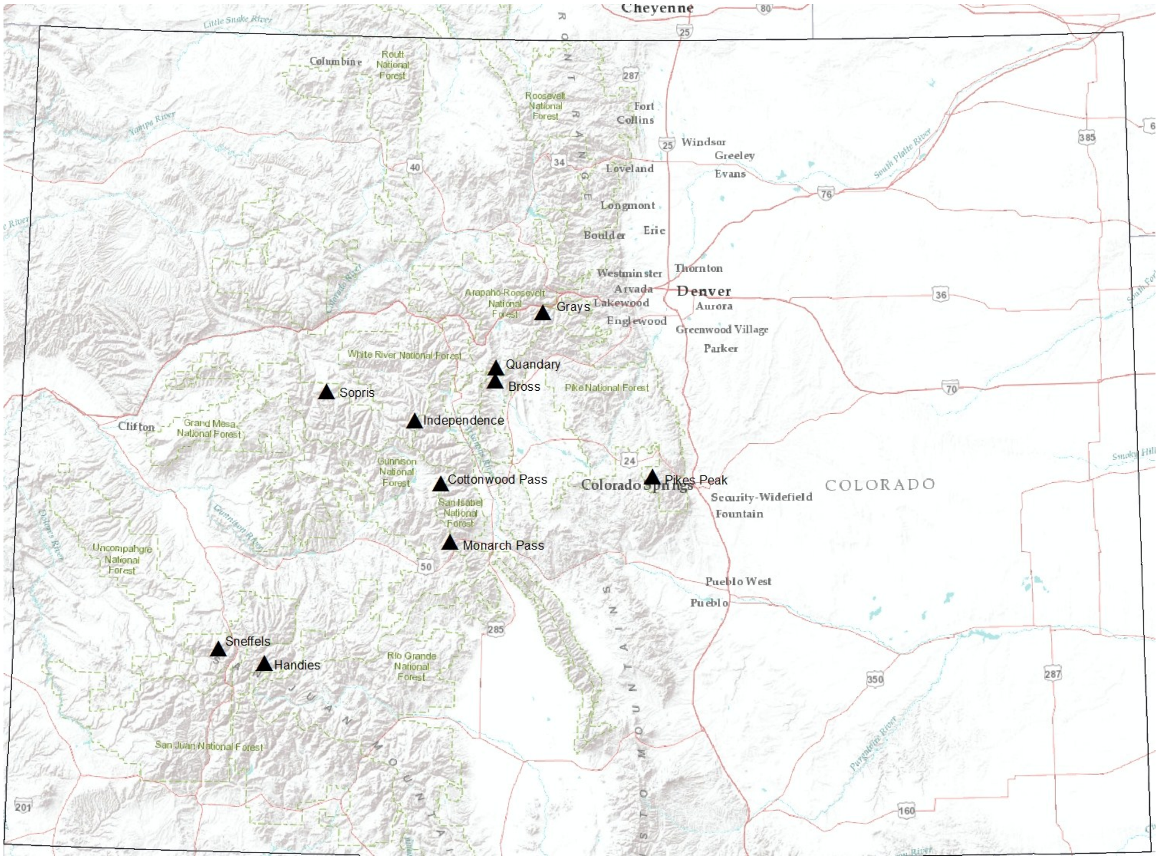


Figure 1. Map of the ten sites in five mountain ranges throughout Colorado.

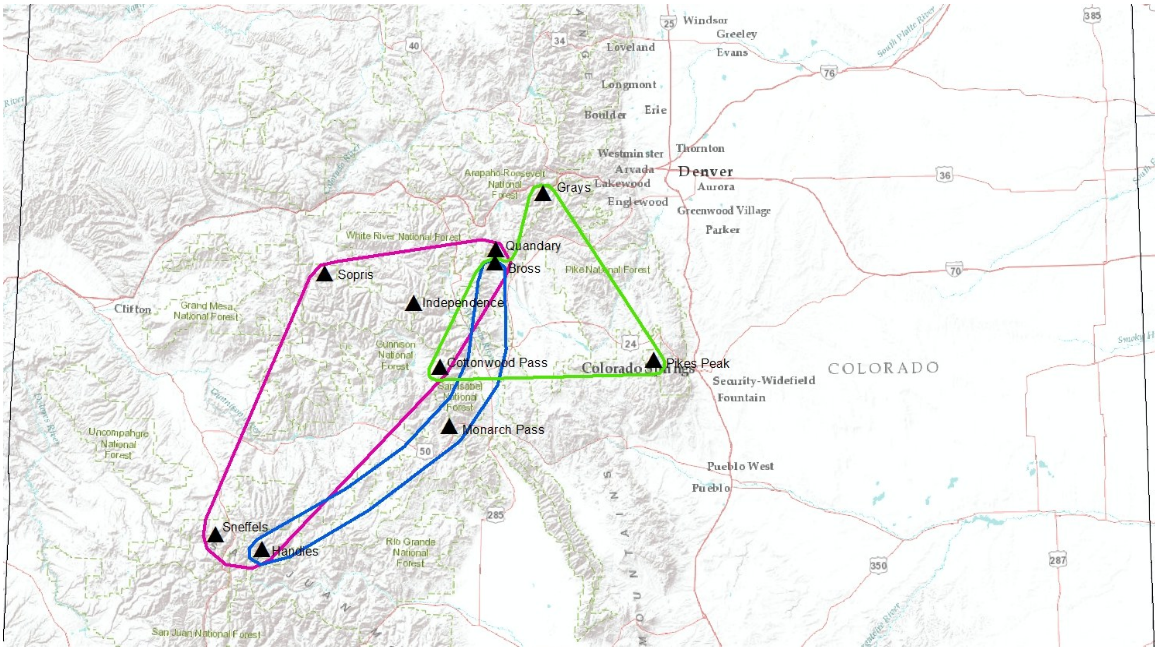


Figure 2. Map of the groupings created by the correlation coefficients between sites. The two groupings to the west of the Continental Divide are displayed in pink and

blue. Both follow the same southwest to northeast pattern as storm flows throughout the state. The grouping in green encompasses all the sites on the Continental Divide and to the west of the divide.

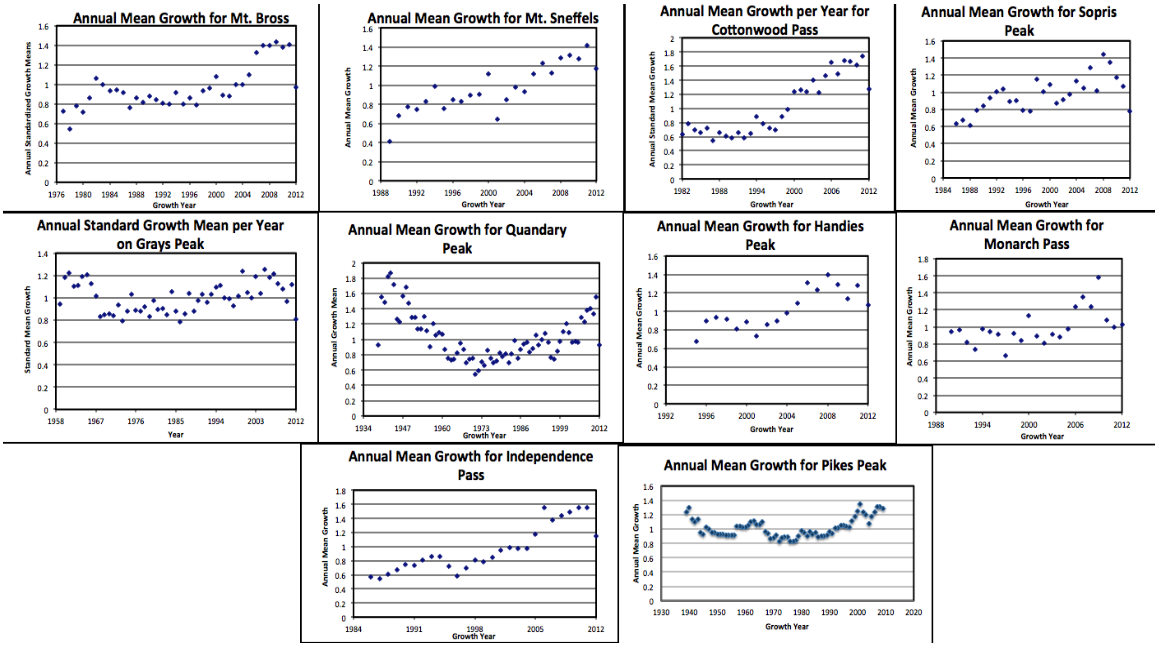


Figure 3. Standardized Series. This compilation of graphs is of all the chronologies, each on its own time scale. The growth year is on the x-axis, and the standard annual growth on the y-axis (no units). Through comparison an upward trend can be seen since the 1970s/1980s.

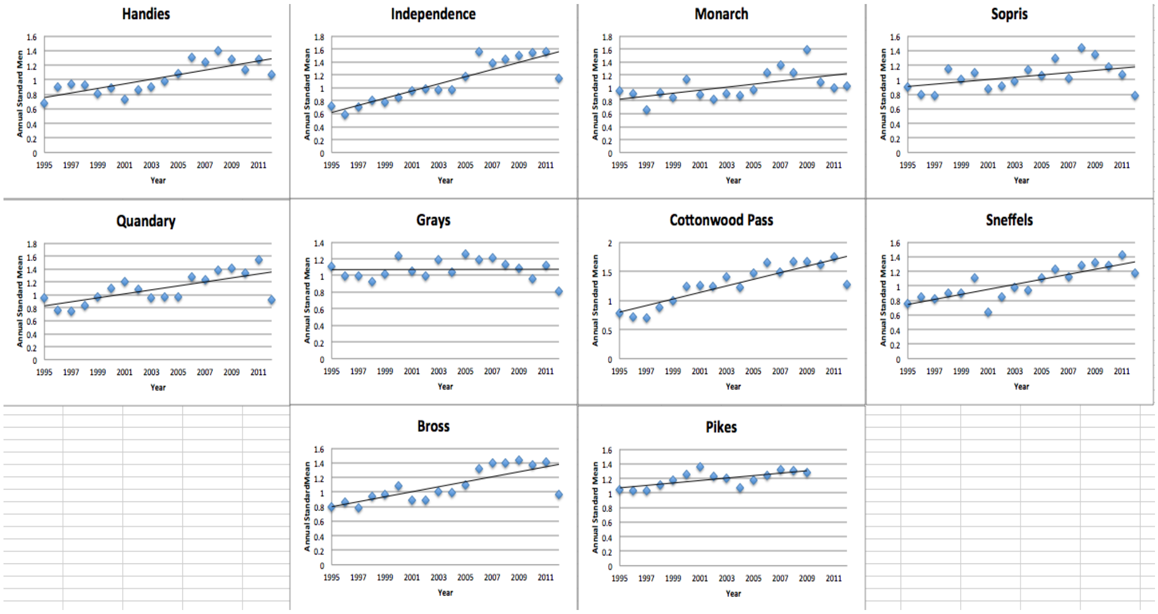


Figure 4. Standardized Series since 1995. This compilation of chronologies is gathered from the same data as in figure 3, but all chronologies are on the same time

scale (1995-present). A universal upward trend can be seen: all sites show increases in standard growth with each consecutive year.

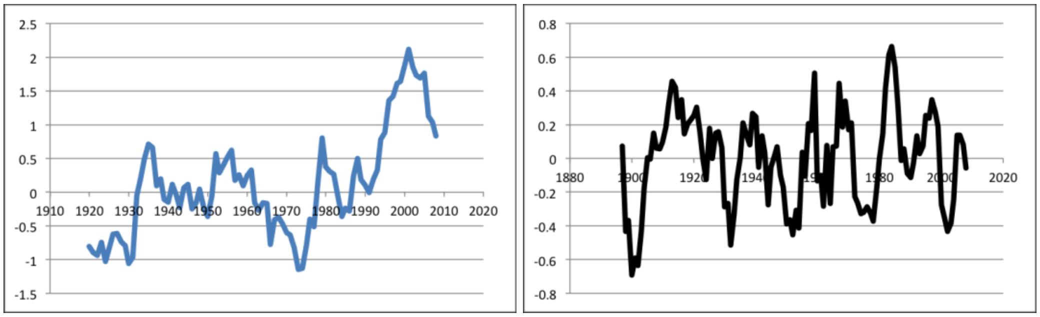


Figure 5. Colorado's Annual Temperature and Precipitation. The temperature graph in blue on the left, and precipitation is in black on the right. Both graphs show climate since 1900. The x-axis is the year, with the y-axis being the anomoly measurement (in degrees Centigrade). Temperature starts to increase just after 1970, while precipitation shows no trend.

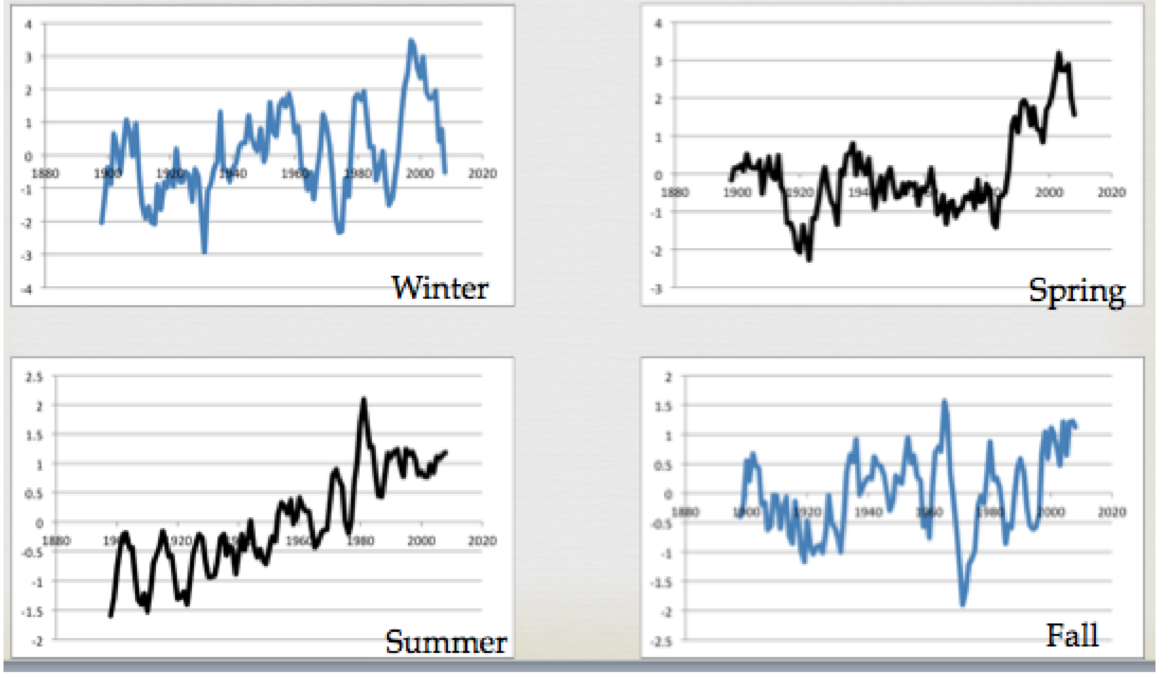


Figure 6. Seasonal Temperature in Colorado. The x-axis on each graph is the year, and the y-axis is the anomaly in degrees Fahrenheit. Summer and spring show obvious increasing trends.

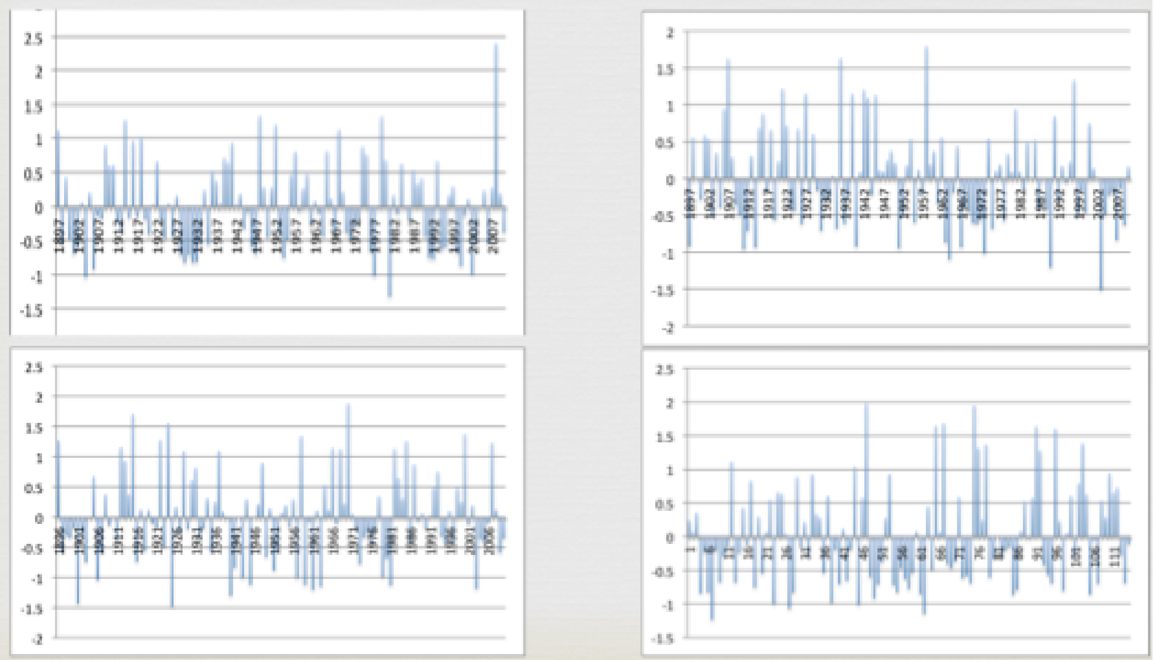
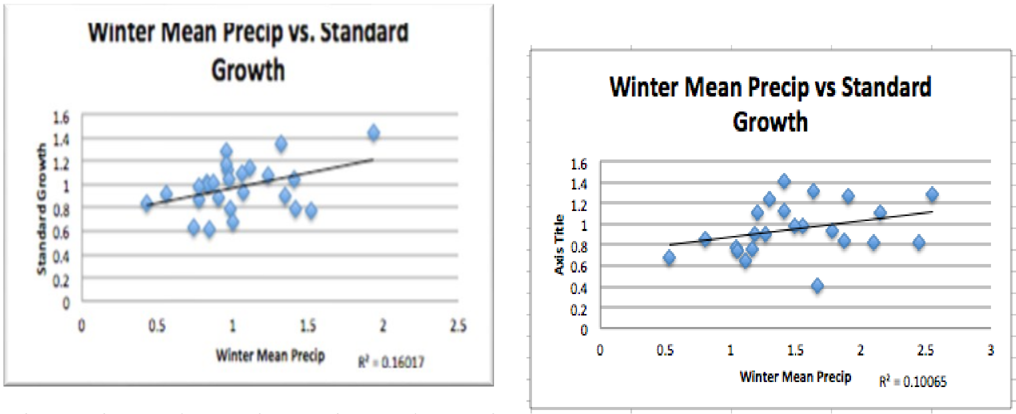


Figure 7. Seasonal Precipitation in Colorado. Winter is in the upper left, spring upper right, summer lower left, and fall lower right. Year is on the x-axis and anomaly (in inches) is on the y-axis.



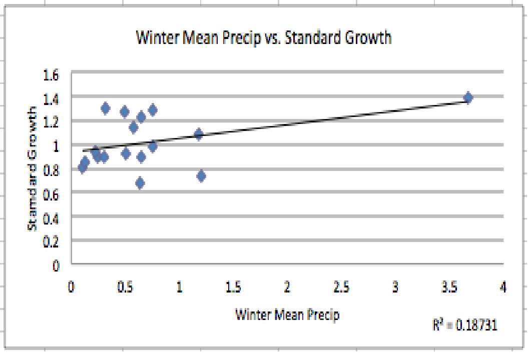


Figure 8. Winter Precipitation Influences. Above are the three sites influenced by winter precipitation, with Mt. Sopris on the upper left, Mt. Sneffels on the upper right, and Handies Peak on the lower left. The x-axis has the mean winter precipitation, with the standard annual growth on the y-axis.

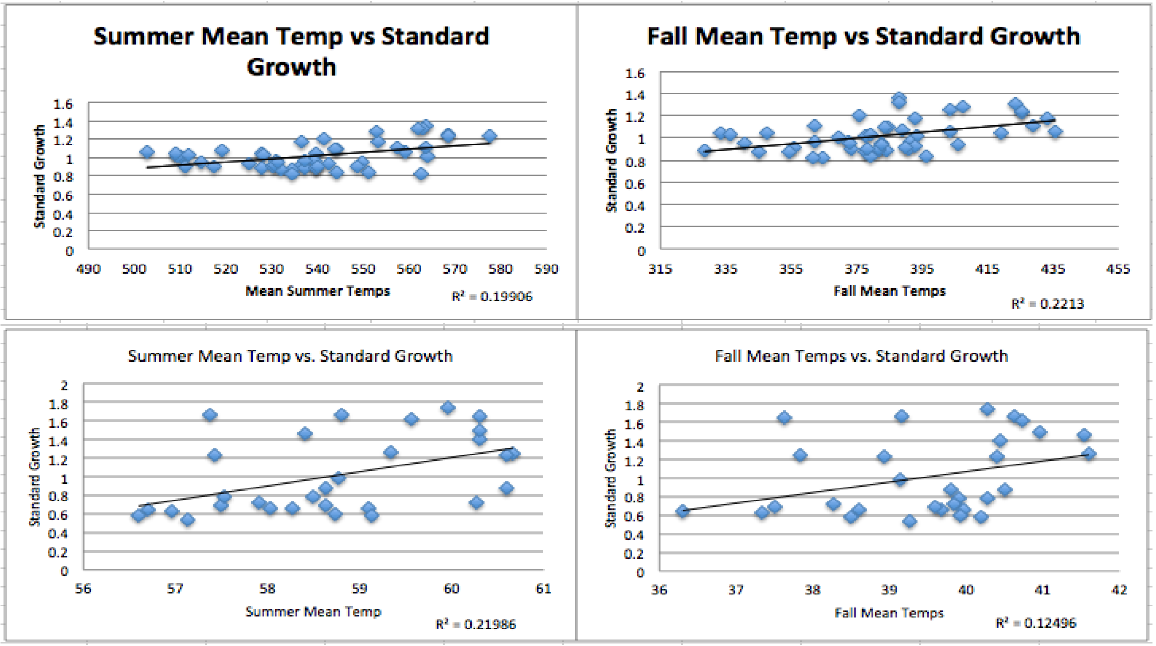


Figure 9. Temperature influences. Summer and fall temperature correlations for Pikes Peak (top) and Cottonwood Pass (bottom).

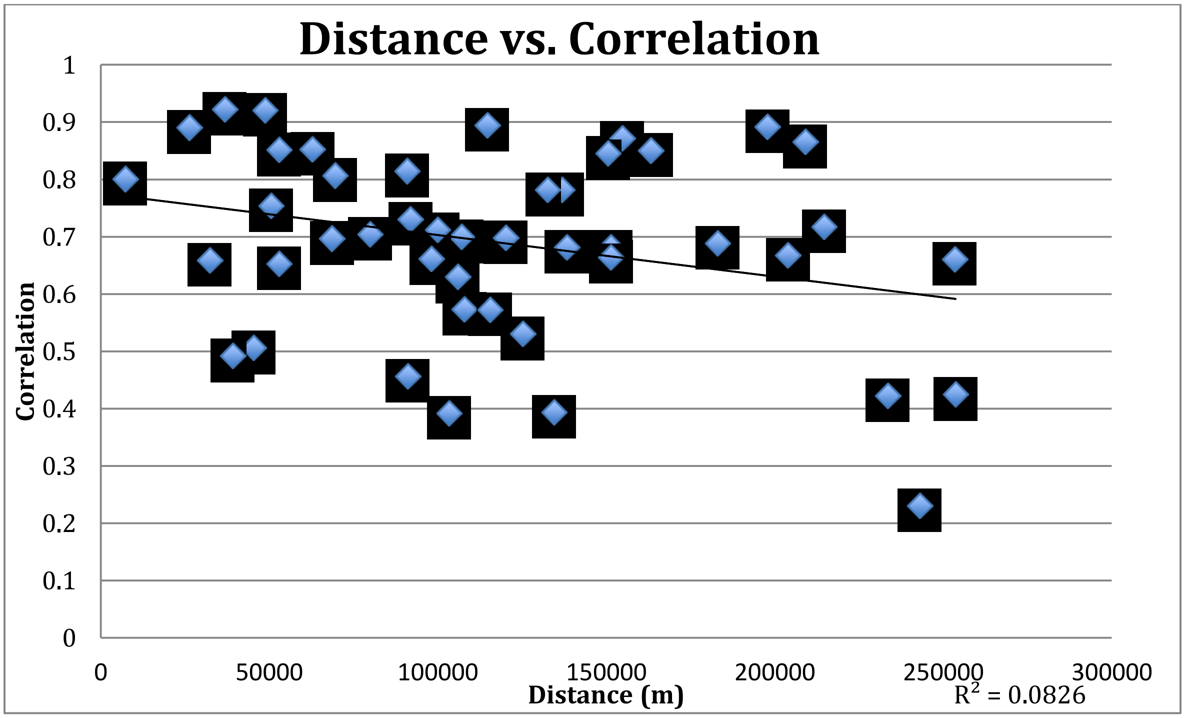


Figure 10. Distance vs. Correlation Coefficient. Distance not a driving factor in how closely correlated chronologies were throughout Colorado.

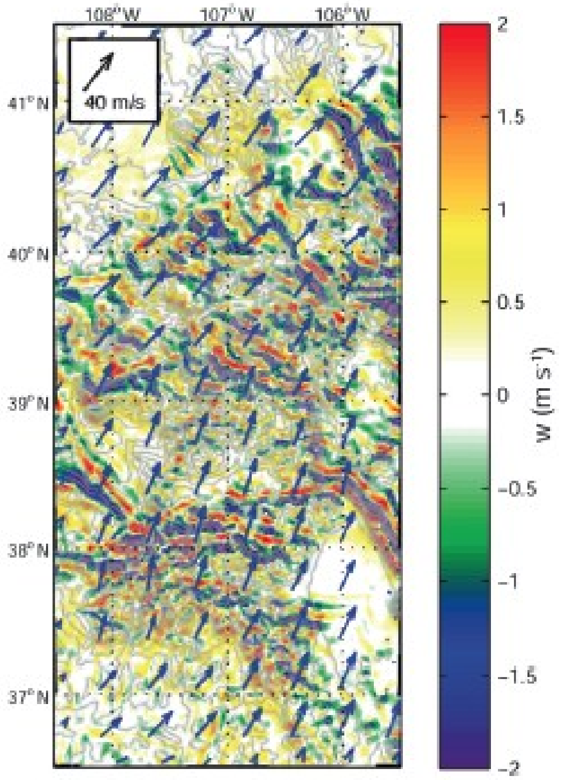


Figure 11. Wind flow patterns throughout Colorado. (Rasmussen 2011).

Bibliography

Cook, E.R., & Kairiukstis, L.A. (1990) *Methods of Dendrochronology: Applications in the Environmental Sciences*. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Elliott, G.P. (2012) Extrinsic Regime Shifts Drive Abrupt Changes in Regeneration Dynamics at Upper Treeline in the Rocky Mountains, USA. *Ecology*, **93**, 1614-1625.

Elliott, G.P. (2011) Influences of 20th Century Warming at the Upper Tree Line Contingent on Local-Scale Interactions: Evidence from a Latitudinal Gradient in the Rocky Mountains. *Global Ecology and Biogeography*, **20**, 46-57.

Elliott, G.P., & Kipfmueller, K.F. (2010) Multi-Scale Influences of Slope Aspect and Spatial Pattern on Ecotonal Dynamics at Upper Treeline in the Southern Rocky Mountains, USA. *Arctic, Antarctic, and Alpine Research*, **42**, 45-56.

Grace, J., Berninger, F., & Nagy, L. (2002) Impacts of Climate Change on Tree Line. *Annals of Botany*, **90**, 537-544.

Harsch, M.A., & Bader, M.Y. (2011) Treeline Form – A Potential Key to Understanding Treeline Dynamics. *Global Ecology and Biogeography*, **20**, 582-596.

Harsch, M.A., Hulme, P.E., McGlone, M.S., & Duncan, R.P. (2009) Are Treelines Advancing? A Global Meta-Analysis of Treeline Response to Climate Warming. *Ecology Letters*, **12**, 1040-1049.

Hofgaard, A., Linda, D., & Hakan, H. (2009) Tree Recruitment Above the Treeline and Potential for Climate-Driven Treeline Change. *Journal of Vegetation Science*, **20**, 1133-1144.

Humphries, H.C., Bourgeron, P.S., & Mujica-Crapanzano, L.R. (2008) Tree Spatial Patterns and Environmental Relationships in the Forest-Alpine Tundra Ecotone at Niwot Ridge, CO, USA, *Ecological Research*. **23**, 589-605.

Korner, C. (1998) A Re-Assessment of High Elevation Treeline Positions and Their Explanation. *Oecologia*. **115**: 445-459.

Rasmussen, R., Liu, C., Ikeda, K., Gochis, D., Yates, D., Chen, F., Tewari, M., Barlage, M., Dudhia, J., Yu, W., & Miller, K. (2011) High-Resolution Coupled Climate Runoff Simulations of Seasonal Snowfall over Colorado: A Process Study of Current and Warmer Climate. *American Meteorological Society*, **24**, 3015-3048.

Smith, W.K., Germino, M.J., Hancock, T.E., & Johnson, D.M. (2003) Another Perspective on Altitudinal Limits of Alpine Timberlines. *Tree Physiology,* **23**, 1101-1112.

Stokes, M.A., & Smiley, T.L. (1996) *An Introduction to Tree-Ring Dating.* University of Arizona Press, Tucson, AZ.

University of Wisconsin, Madison (2008) http://www.youtube.com/watch?v=ifP7unhBta0

Van Bogaert, R., Haneca, K., Hoogesteger, J., Jonasson, C., de Dapper, M., & Callaghan, T.V. (2011) A Century of Treeline Changes in sub-Arctic Sweden Shows Local and Regional Variability and Only a Minor Influences of 20th Century Climate Warming. *Journal of Biogeography*, **38**, 907-921.

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O., & Bairlein, F. (2002) Ecological Responses to Recent Climate Change. *Nature*, **46**, 389-395.

Weisberg, P.J., & Baker, W.L. (1995) Spatial Variation in Tree Regeneration in the Forest-Tudnra Ecotone, Rocky Mountain National Park, Colorado. *Canadian Journal of Forest Research*, **25**, 1326-1339.

Williams, A.P., Michaelsen, J., Leavitt, S.W., & Still, C.J. (2010) Using Tree Rings to Predict the Response of Tree Growth to Climate Change in the Continental United States during the Twenty-First Century. *Earth Interactions*, **14**, 1-20.

Wilmking, M., Juday, G.P., Barber, V.A., & Zald, H.J. (2004) Recent Climate Warming Forces Contrasting Growth Responses of White Spruce at Treeline in Alaska Through Temperature Thresholds. *Global Change Biology*, **10**, 1724-1736.

Appendix B: The Art of Data Collection

Many people, upon first thought, imagine data collection to be easy, maybe even relaxing. Unfortunately, that is not the case. In fact, many things go wrong: cars don't have enough clearance, slipping into streams, roads not existing where they should, etc. This made data collection an interesting two months, especially since I was collecting the data alone. I had gone up to Pikes Peak treeline with a group of researchers involved with Miro Kummel's project the day before I embarked on my own adventure. It seemed relatively straightforward (with the exception of hitting the pith the first time); drive to the trailhead, park, hike to treeline, core 14 trees, and come down. Simple right? No.

I drove from Colorado Springs toward Grays Peak the day after my introduction on Pikes Peak. I had not been away from Colorado Springs for more than 5 hours when I encountered my first problem. I was two miles from the Gray's Peak trailhead on the access road. It was a dirt road and had been smooth for quite a few miles. Two miles from the trailhead, however, the road became a rough, wild sea of two-foot deep potholes. These deep potholes lasted only for 100 yards, but there was no way to maneuver a vehicle through them without having to dip through at least ten of them. It isn't a problem for four-wheel drive cars with quite a bit of clearance. My car, though, is a low-lying Subaru, with equal clearance to a racecar. It was dark by the time I reached the potholes and a Jeep was trailing me. Being stubborn, I told myself I could weasel my little car through. Ten yards in, however, I realized how delusional that idea had been, and in fact, I was going to have to reverse down the section I had just come up, forcing the Jeep behind me to do the same. Thankfully for me, the driver of the Jeep was kind enough to direct me down the potholes, since I could not see any of them through the rear view mirror. Once I was out of the potholes, I had to turn around on this very narrow single lane road. One side of the road delved down into a ravine, and thinking about making a 40-point turn on the edge of it made my stomach turn. Again, the man in the Jeep directed me. Talk about a lot of trust to put into a person who you don't know! After ten minutes of jerking back and forth, I was able to drive down the road until I found a place to set up my tent.

I set up my tent in a dense patch of woods, and all night was convinced that I was slowly sliding down into the ravine. At four in the morning a steady roar of large vehicles commenced. I put a jacket over my head telling myself people could not possibly be driving up to climb this 14er this early in the morning. My alarm was set for 6:00 am. I told myself the roar of oversized vehicles and chatter of enthusiastic hikers would stop. After an hour and a half, however, I realized it was only going to get worse with time. People were already pointing at my tent, making snide comments about my campsite choice. I decided it was time to get moving. I packed up, grabbed an apple, and started walking up the two miles to the trailhead. Immediately a family asked me why I was hiking with straws and large metal rods in my backpack. So I got to explain (for the first of many times) my project. As it turned out, both of the parents had graduated from CC, and were thrilled to see a student out doing research! We swapped stories until the trailhead where they continued up the trail and I bushwhacked to treeline. The coring, of course, went seamlessly. I even got a ride down to my car by an old couple, which saved me from getting soaked by the ensuing thunderstorm. The next few days at the site went relatively smoothly, and then I was ready to move to the next site.

Quandary Peak gave me no problems, but Mount Bross, the third site I visited, was not an easy site to find initially. I arrived at the site a few days early to meet up with some family members and hike the quartet: Mount Democrat, Mount Lincoln, Mount Bross, and Mount Cameron. The day after the hike I drove just outside of Alma to find the road that would take me up to my site, near the Quartzville mine. However, the road that I was supposed to take did not exist. I drove in circles for a half hour, until a group of fishermen flagged me down and asked me where I was trying to go. I told them and they directed me to go back towards Kite Lake, where I come from. Then there would be a county road branching right, and I was to take that. I followed their directions, and came to a place, again, where my car did not sufficient clearance to continue. I parked and started walking up toward the Bristlecone Pine forest. On my walk up, the man who owns the summit of Mount Bross drove past. I had met him the night before at Kite Lake, where he had said that hiking was simply too strenuous, and he preferred to drive to the top of mountains. He stopped to chat, declaring how sorry he was for not having room in his ATV, because he would have given me a ride up to the top of Mount Bross, then back down to my site (the top of Mount Bross is private property). I told him it was fine, I actually enjoy walking, and he continued on his way (with 5 additional ATVs in tow). Once at my site I realized I had forgotten the straws needed to store the cores in. Thankfully, a lone jeep came rambling down the road. He offered me a ride, which I accepted, and once I had the straws, he said that he needed to do his Good Samaritan deed, so would drive me back up to my site. That was much to my benefit, for after an hour of coring, a thunderstorm commenced. I tried to hide in patches of trees, not wanting to retreat if it would pass soon. Once my raincoat was soaked through, I decided to walk the mile or two back to the car. Of course, once I got back to the car it was only ten of fifteen minutes until the weather cleared. Then I was able to go finish coring.

Sites from then on out were fairly straightforward for a while. There was the occasional walking up the wrong trailhead for an hour before realizing there was another trailhead with the same name at the top of Independence Pass, and several bear encounters on Mount Sopris. My encounters with bears thankfully, were not aggressive, although I did take out my pruning saw and WD40 on those occasions, in hopes that lubing up the bears eyes' and throwing sharp objects would provide me with enough time to run away. Realistically not a great plan, but thankfully I never had to test my defenses. The next large obstacle occurred at Mount Huron. The trailhead going up the east-facing slope of the peak was a rarely used trail, and the access road was that for Mount Missouri. This access road, again, was one my little car could not drive up. I realized this when a 2-foot deep river appeared in the middle of the access road. I parked and waded across, soaking my shoes and pants in the process, and walked the four miles up to where the trailhead for Mount Huron was supposed to be (it should be noted that no car, trucks or ATVs realistically could never have driven this road, due to 3 or 4 three-foot tall rocks in the middle of the road). I could not find the trail anywhere. Eventually I found myself at a lake, above where the trailhead was supposed to be, where a trail went up a peak to the east.

After wandering up the trail for fifteen minutes I realized it was the trail for Mount Missouri. So I headed down and began to bushwhack around the south end of the lake. I unknowingly had chosen to go through the delta of the lake, where there was dense shrubbery everywhere and streams every 20 feet or so. I was soaked up to my belly button by the time I made it to the other side of the lake. Still, I decided to try and get to treeline. After 20 minutes of crawling up the side of this mountain covered in wet moss and rotting logs, I looked to my right and was sure I had seen the impossible: there were ragged clothes, a compass, and other remains of another hiker who had passed along this same untraveled area quite some time before me. I knew this was a sign that I needed to get out of this place as fast as possible. If I was to get hurt there I had no cell service, was in the dense forest, and was not on a trail. Overall, it was not a wise place to be alone. So I scrambled down as fast as I could without slipping, re-waded across the delta of the lake, and arrive at the road scared, soaked, and white as a ghost. I walked down the road, still looking for the supposed trail up the east face of Mount Huron, hoping for some miracle so I could get my tree cores. However, I soon found myself back at the deep river I had crossed at 6AM that same morning. Another group of hikers had just waded the river, so I asked them if I could look at their map to see if it showed something different than my own. Unfortunately it did not. Once I had sandals and dry clothes on, I decided that I never wanted to try and repeat what had I had just experienced, and struggled to convince myself that it would be wisest to find a new site. After talking with Miro Kummel, and describing how shaken I was about the experience, he told me not to worry, I would find a new site; there would be many options.

The experience finding the person's ragged belongings made me much more cautious in the rest of the data collection. I experienced no other large obstructions, only slipping in streams and hiding from thunderstorms. The people I met along the way were very supportive and interested in the research, and provided good company. Hopping into many alpine lakes and climbing more fourteeners, including Mount Huron, celebrated the end of my data collection. Redemption never felt so sweet (even if I hiked up the other side, on the standard trail).