A Statistical Analysis of Climate Variability and its Resulting Effects on Avalanche Occurrence in Gothic, Colorado

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Abstract

The global climate is changing on a very broad scale and has been studied extensively. Observed changes include air temperatures, wind patterns, and precipitation rates (IPCC, 2013). These meteorological parameters all drive mountain snowpack structure, and resulting avalanche activity. Linking climate variability and trends to avalanche activity has been minimally studied and the results remain inconclusive. This study uses a 30-year natural avalanche and meteorological dataset from Gothic, Colorado to explore possible trends. A univariate analysis includes linear regression trends and correlations between avalanche and meteorological parameters. Winter seasons were split into two sub-groups to observe trends obscured by the season overall. A significant trend of increasing air temperature was found for both the early and late season. Additionally, an increasing trend in the temperature gradient of the snowpack was found during the early season suggesting decreasing rates of kinetic growth metamorphism. A significant trend of decreasing avalanche occurrence was found during the late season and for the full winter season overall. Temperature and avalanche occurrence results are consistent with other studies found in other areas of the world however these results remain inconclusive due to the complexity of linking avalanche activity to climate fluctuations. Possibilities for future work are outlined as well as suggestions for the snow science field to enhance our ability to draw conclusions from these types of studies.

Introduction

Snow avalanches pose threats to outdoor recreationalists, as well as mountain communities where infrastructure lies within slide paths. Mountain snowpacks are generally comprised of many layers of snow that are defined by the interface between different slabs of snow (Schweizer et al., 2003). Avalanches occur when there is an overlying slab that fails on one of these interfaces. Layers within the snowpack come and go throughout the season due to specific meteorological conditions such as precipitation, wind direction, and wind speed, sensible heat fluxes, and the radiative heating and cooling on the snowpack that are driven by radiation (McClung and Schaerer, 2006). According to the International Panel on Climate Change (2013) global precipitation, wind, and temperature are all changing on a broad scale. Based solely on theory, one could hypothesize that these changes in precipitation, wind, and radiation fluxes may lead to changes in avalanche activity. Climate change and its effects on other cryospheric processes are being widely studied, however the possible effects on snow avalanches are relatively unknown.

This work aims to quantify the relationship between these changing meteorological parameters and any affect they may have on avalanche occurrence or magnitude from Gothic, CO. At this point in time, very few studies have been conducted that analyze a completely natural avalanche dataset and thus, most have not been able to draw concrete conclusions about the possible climatic effects on natural events. In North America, most avalanche datasets come from ski area operators or from highway departments where avalanche control is used. In both (Sinickas et al., 2016; Bellaire et al., 2016), analysis from Western Canada were not able to draw any conclusions due to the possibility of control regimes affecting the snowpack structure and avalanche activity. The snow science field currently lacks many long term natural avalanche datasets, I hope this work serves in part as motivation to maintain or begin the collection of such datasets.

This work will contribute to the field by examining broad scale avalanche patterns from a previously unexplored dataset. Looking to the future, results from this study, and others like it, could give local ski area operators and avalanche forecasters some initial findings to plan for possible changes to their avalanche control regimes. Mountain communities are often bound by road closures from avalanche mitigation which has negative financial implications. Stethem et al. (2003) found that closures on the Trans-Canada Highway could result in downstream economic losses exceeding CAD$100M per year in Canada. The implications of the constantly changing avalanche climate are vast and further study will be needed to better understand it.

1.1 Mountain Snowpacks and Avalanches

Avalanche occurrence and magnitude is directly related to the characteristics of the local snowpack. The structure of a snowpack is determined by a variety of radiative and meteorological forcings (DeWalle and Rango, 2008). It is important to understand the mechanics of avalanches and their contributing factors in order to make sense of their resulting occurrences.

Radiative heating and cooling occurs either when the snowpack is receiving both longwave and shortwave radiation or emitting longwave radiation. These net radiation fluxes can cause sensible heat which is energy exchange when water changes temperature, but does not undergo a phase change. Both the radiation fluxes and sensible heat exchange cause snow metamorphism, which is the physical change of snow crystals due to both heat and pressure (Schweizer et al., 2003). Since the stability of the snow is directly dictated by the types of grains present; these processes are major determining factors in avalanche production.

Orographic uplift is a precipitation mechanism where moist air is forced upwards in the atmosphere due to terrain features, such as mountains; the rising air is then cooled as a result of the adiabatic lapse rates while increasing in altitude. Water vapor will then condense onto some nuclei and upon reaching a specific weight threshold fall due to the forces of gravity. Precipitation varies throughout a region due to local orographic factors which can favor or limit precipitation such as snowfall (Hobbs et al., 1973). Orographic driven precipitation is the primary driver of snowfall amounts in mountainous areas (insert cite). Variability in snowfall can happen on a variety of scales, from an entire region to small variations within a high alpine cirque. Changes in snowfall amounts have drastic effects on the snowpack by affecting the overall load during storm cycles, which then act as a variable in snowpack metamorphism through time. Snow can fall at a variety of different densities depending on the temperature and grain type. The snow water equivalence (SWE) is the measure of the weight in water of a column of snow (DeWalle & Rango, 2008). New snowfall amounts and resulting SWE are the primary drivers of avalanche occurrence (Buser et al., 1985; Birkeland et al., 2001; McCollister, 2004). Using the same data presented in this study, (Chesley-Preston, 2010) found similar results from the Gothic Valley during her analysis of avalanche occurrence and upper level wind patterns.

Wind is a major contributor to the depth of a given column of snow on a slope. Snow is transported and compacted from the wind during deposition and post deposition (McClung and Schaerer, 2006). This will lead to snow depths ranging from a few centimeters to a few meters within a given slope. Although wind is extremely important to avalanche activity, it is excluded from this study due to the lack of data availability. This is discussed in more detail within the limitations section.

Snowpacks have inherent characteristics due to their predominant meteorological conditions. Very simply, the stability of a snowpack is primarily driven by the temperature gradients that exist within the snow. Strong temperature gradients drive the growth of faceted snow crystals (kinetic growth metamorphism) which are inherently weak and unstable. Conversely, weak temperature gradients drive the growth of rounded snow crystals (equilibrium growth metamorphism) which are inherently strong and stable (McClung and Schaerer, 2006). Mock and Birkeland, (2000) defined the continental United States into three different snowpack climates. Maritime snowpacks are characterized by high snowfall and warmer temperatures leading to weak temperature gradients, resulting in a more stable snowpack. Continental snowpacks are characterized by low snowfall and cold temperatures leading to strong temperature gradients, resulting in a weaker snowpack. An intermountain snowpack is one that falls in-between continental and maritime and can exhibit both qualities depending on the season. There are many components to snowpack structure and resulting avalanche activity which creates a variety of challenges when linking them to climate fluctuations.

1.2 Previous Studies

A relatively small amount of work has been done linking avalanche activity to our changing climate. The findings remain inconclusive due to the broad and complex nature of avalanche formation. Drawing relationships between climate change and trends in avalanche activity is very challenging for three reasons (Sinickas et al., 2016). First, avalanches are not linked to any one meteorological variable, but rather a complicated network of intermixing variables that create spatially diverse mountain snowpacks. One example of this is when rain on snow events occur, or during warmer months where crusts develop on the surface. Once buried underneath additional layers of snow, these weak layers in the snowpack can cause large and destructive events that can be extremely difficult to forecast (Bellaire et al., 2013). Second, avalanche activity occurs on smaller time scales usually linked to weather systems (2-10 days) than variations in climate which operate on decadal timeframes. (Bellaire et al., 2013). Atmospheric and oceanic oscillations have been shown to have significant effects on precipitation, and thus, avalanche activity. These phases which occur on roughly 1-5 year scale present further challenge by interrupting, masking, or amplifying the baseline climate trends (McClung, 2012; Thumlert et al., 2014). Additionally, patterns in large scale avalanche events are so infrequent that linking them with the complexity of climate variations is extremely difficult (Schneebeli et al., 1997). Finally, like mentioned previously, the avalanche records available are often inconsistent, relatively short, or plagued by human influence via changing avalanche control regimes. Despite these challenges, work has been done analyzing and linking meteorological parameters with avalanche activity throughout the world.

Temperature trends in mountainous areas have been analyzed extensively due to their widespread availability. Bellaire et al. (2016) used a dataset from Rogers Pass in British Columbia. Their study used two meteorological observation sites and over 27,000 avalanche occurrences spanning 34 years. They found trends of increasing air temperature between December and February at both sites throughout the period of study. At similar latitudes and elevations in the Alps, numerous studies have found consistent results of increasing temperatures during winter months (Beniston, 2006; Marty & Meister, 2012; Marty & Blanchet, 2011; Schneebeli et al., 1997).

Similarly, snowfall patterns through time have been studied extensively, mainly in Europe where high quality data is available. Results vary, which affirms the notion that both meteorological and avalanche activity are often very regionally dependent. Schneebeli (1997) found increasing trends in air temperature, however found no trends in snow depth or extreme snowfall events. Far more studies have found significant decreasing trends in either snow cover or snow depth (Bellaire et al., 2016; Beniston, 1997; Marty, 2008; Marty & Blanchet, 2011; Add). Additionally (Marty & Meister, 2012) found no trends in snowfall or snow cover during the winter months. They did however, find significant decreasing trends in snowfall during the springtime, which they attributed to extreme increases in temperatures at their study location in the eastern Swiss Alps at 2690m.

In contrast, studies of avalanches are more limited and none include easily interpretable results. After 50 years of data analysis from the Swiss Alps, no change in avalanche activity was found (Laternser & Schneebeli, 2002; Schneebeli et al., 1997). In contrast, a trend of decreasing avalanche occurrence was found for some sub-areas of a study in Western Canada (Sinickas et al., 2016). Using different locations and datasets, but from the same geographic location (Bellaire et al., 2016) found no significant trends in dry slab avalanche occurrence, however a decreasing trend in moist/wet avalanches was observed between December-May of the study period. Both studies, however, could draw no conclusive results due to the possible biases in the data attributed to avalanche mitigation work. Avalanche control is routine along roadways in mountainous regions and at ski areas, oftentimes closing specific areas and using explosives to intentionally trigger avalanches in order to create safe conditions. Sinickas et al., (2015) suggests that the use of explosives may decrease the frequency of large natural avalanches. Conversely, the same study found no significant difference in the relationship between slide paths controlled using explosives and those with 75% natural avalanche occurrences. Further analysis using other datasets would be extremely useful here support this finding. More conclusive results would allow for additional interpretation of analysis using datasets affected by explosive avalanche control.

In a study that analyzed fluctuations in avalanche paths extent using small diameter trees, (Teich et al., 2012) found evidence to support decreasing avalanche activity. Ekert et al. (2013) found similar results of retreating avalanche runout lengths from the French Alps using a Bayesian hierarchical model, however, researchers did not find significant trends in avalanche occurrence.

Nearly all studies linking avalanche activity to meteorological parameters have found inconclusive results. Additionally, almost all the studies suggest the need for additional analysis. Not only to expand on previous work, but also to examine new datasets. This study does not provide an expanding or altered form of analysis to that of previous studies. It is however, a simple trend analysis using a previously unexplored, long-term avalanche dataset will most certainly add to the increasingly complex task of linking avalanche activity with climate fluctuations.

1.3 Gothic

This study uses a data set of natural avalanche occurrence from Gothic, Colorado. The Gothic valley sits roughly 6 miles to the N/NE of the town of Crested Butte. The valley bottom ranges from 2,900 to 3,000 m a.s.l. Major slide paths used in this analysis contain starting elevations between 3,400 and 3,800 m a.s.l. The area is occupied by the Rocky Mountain Biological Laboratory (RMBL) which has allowed scientists a location to study the alpine environment and is primarily used during the summer months for ecological and biological studies. During the season of 1975-1976, Art Mears began collecting avalanche data from the Gothic Valley. The following year billy barr assumed this responsibility and continued to collect avalanche data until the 2005-2006 winter season. The 30-year dataset contains 7,814 individual avalanche occurrences, 99.9% of which are naturally triggered (RMBL data?). billy's commitment to science should be strongly acknowledged because of the expanse of this data, as this may be the only dataset of its kind in the world.

It is worth noting that unlike the Slate River drainage to the west, the Gothic valley is closed to motorized use during the winter months. This has greatly limited the human traffic in the area and allowed for the observation of a pristine alpine environment.

Methods

2.1 Avalanche Data

Avalanche observations were recorded using the standard U.S. Forest Service Avalanche Control and Occurrence observation format (Perla and Martinelli, 1978, p. 225). Avalanche data was provided by billy himself. This study includes the date, size, depth, and sliding interface of each avalanche event. The analysis only includes avalanches that were categorized as either medium, large, or maximum in size relative to their path to limit observation bias of less significant avalanches. These avalanches are defined on the relative scale as >R3, according to the observation format (Perla and Martinelli, 1978, p. 225). The depth of the avalanche crown was estimated in feet using binoculars. It must be acknowledged that this remote observation is prone to many errors. It was still included in this study due to nearly all of the data coming from a single observer. Although the accuracy of the depth observations may not be high they are likely consistent through time which still allows for trend analysis. Sliding interface observations were classified as either having slid on an old snow interface or to the ground in the starting zone of the path. A ratio was then calculated to evaluate the trends through time.

151 named avalanche paths lie in the Gothic Valley are included in billy's data. Many of these paths are located in the far reaches of the valley and cannot be observed each day. In an attempt to limit the bias of the dataset towards more easily visible paths, this study only includes avalanche paths that were always observed, 36 in total. These paths fall into three general areas within the valley and have a variety of solar aspects. It is interesting to note that the 46% of the total avalanche events used in this study occurred on 5 major east facing avalanche paths nearly 800m directly above the Gothic town site.

2.2 Meteorological Data

Meteorological data was provided by RMBL and includes daily temperature minimum and maximums (C), new 24-hour snowfall and SWE totals (cm), as well as snow base depth (cm) measurements. Measurements were taken from the valley floor at the RMBL site 2920 m a.s.l. throughout the entirety of the study period. Temperatures were recorded by automatic telemetry and means were calculated from the daily minimum and maximums. Snow and SWE measurements were taken by hand by billy. Storm boards were measured daily to capture new snowfall and the SWE was calculated using a scale. Both measurements are prone to inherent error.

Mixed precipitation was not considered during the analysis due to limitations in the observations, however, it is inherently captured within the SWE measurements.

Additionally, rain on snow events are not considered in this study due to inconsistencies within the dataset. This is discussed in more depth in the limitations section.

A temperature gradient variable (TG) was created to estimate the average temperature gradient of the snowpack. The snow surface temperature was estimated as the air temperature, and the base of the snowpack was assumed to be 0°C (DeWalle and Rango, 2006). Raleigh et al. (2013) found that air temperature regularly overestimated the snow surface temperature in a variety of climates, including the Swamp Angel Study Plot (SASP) located roughly 85 miles to the southwest of Gothic at a similar elevation (3371 m a.s.l). Due to these limitations and assumptions the TG variable should be thought of as an index of the average temperature gradient on the snowpack rather than a measure itself. TG was calculated using the following formula:

$$Temperature\ Gradient\ per\ day\ = \frac{Average\ Air\ Temperature - 0\,℃}{Average\ Snow\ Depth\ (cm)}$$

2.3 Statistical Analysis

2.3.1 Data Processing

All data processing and analysis was performed in RStudio statistical analysis software. Two avalanche "sub-seasons" were created within each winter year to help extract trends that may be obscured by large interannual variability. The "early" season includes November, December and January while the "late" season includes February, March, and April. November was chosen as the beginning of the "early" season because the dataset includes no class 3 or larger avalanches during any years from the month of October. The goal of this study was to draw trends from a dry snowpack. The snowpack in Colorado during the month of May is either transitioning to isothermal or fully transitioned. The mechanisms behind avalanches in an isothermal snowpack are vastly different and therefore April was chosen as the end of the "late" season.

A variety of different timeframes were tested and splitting the winter season into 2 sub-groups yielded the highest r^2 mean values from linear regression models of temperature, total snowfall, and avalanche occurrence.

2.3.2 Descriptive Statistics

An initial assessment of mean and standard deviation (SD were calculated for all variables through time.

2.3.3 Linear Regression

Simple linear regression was performed to show overall trends of each variable. A function within the "gvlma" package in RStudio allows for a complete testing of assumptions made when running a simple linear regression. This includes skewness, kurtosis, nonlinear link function, and heteroscedasticity. Only variables that met all assumptions were used for linear regression. Plots were generated for all statistically significant variables at a p-value < 0.05.

2.3.4 Correlations

Correlation coefficients were calculated to measure the strength and direction of any possible relationships between avalanche and meteorological parameters. A non-parametric Kendall's tau correlation coefficient was applied here to capture relationships without assumptions of the normality of the data. A pairwise, complete correlation was performed and the correlation coefficients (Kendall's Tau) are defined as weak (<0.3), moderate (0.3-0.6), and strong (>0.6) (Helsel and Hirsch, 1992).

Results

3.1 Descriptive Statistics

Early Season			Late Season		
Statistic	Mean	St. Dev.	Statistic	Mean	St. Dev.
Tempurature (c)	-8.142	1.747	Tempurature (c)	-4.966	2.024
Total Snowfall (cm)	537.125	169.090	Total Snowfall (cm)	1,016.562	231.085
24hr Snowfall Mean (cm)	4.937	1.895	24hr Snowfall Mean (cm)	5.292	1.574
24hr Snowfall Max (cm)	48.688	16.954	24hr Snowfall Max (cm)	43.750	11.430
24hr SWE Mean (cm)	3.062	1.239	24hr SWE Mean (cm)	3.372	1.076
24hr SWE Max (cm)	32.400	11.446	24hr SWE Max (cm)	31.037	11.362
Basedepth Mean (cm)	71.823	24.224	Basedepth Mean (cm)	139.327	41.854
Basedepth Max (cm)	140.281	50.509	Basedepth Max (cm)	188.531	49.487
Avalanche Occurence (n)	10.724	8.980	Avalanche Occurence (n)	14.032	12.893
Avalanche Size (R-Scale)	3.127	0.171	Avalanche Size (R-Scale)	3.167	0.171
Avalanche Depth (ft)	3.053	0.751	Avalanche Depth (ft)	3.406	0.999

Table 1. Early and Late season summary statistics for all variables.

3.2 Regression

A summary table of all variables and corresponding linear regression statistics for both the early and late season. Plots were generated for all statistically significant trends (p-value<0.05).

3.2.1 Full Year

	Trend	Adj R2	p-value
Temp	0.14	0.27	**7.06E-06**
Total Snowfall	-1.64	-0.01	0.7
24hr NS Mean	-0.02	4.20E-03	0.31
24hr NS Max	0.26	-0.01	0.41
24hr SWE Mean	-7.60E-03	-0.01	0.63
24hr SWE Max	-0.12	-0.005	0.41
Basedepth Mean	-0.32	-0.01	0.62
Basedepth Max	-0.58	-6.20E-03	0.34
Occurrence	-0.57	0.2	**1.70E-04**
Size	0.002	0.007	0.23
Depth	0.009	-0.008	0.47

Table 2. Summary table of linear regression statistics for air temperature (Temp), the total season snowfall (Total Snowfall), mean 24 hour new snowfall (24hr NS Mean), maximum 24 hour new

snowfall (24hr NS Max), mean 24 hour new snow water equivalence (24hr SWE Mean), maximum 24 hour new snow water equivalence (24hr SWE Max), mean seasonal settled snow height (Basedepth Mean), maximum seasonal settled snow height (Basedepth Max) during the full year. Statistics shown are trend analysis for the entire analysis period, the adjusted R^2 value, p- value. Bold designates statistically significant trends (<0.05). Note, temperature gradient (TG) was not included as it did not meet the assumptions for linear regression for the season overall.

3.2.2 Early Season

	Trend	Adj R2	p-value
Temp	0.11	0.38	**0.0001**
Total Snowfall	4.23E-04	-0.03	0.97
24hr NS Mean	-0.01	-0.03	0.63
24hr NS Max	-0.26	-0.01	0.41
24hr SWE Mean	0.005	-0.03	0.82
24hr SWE Max	0.01	-0.03	0.95
Basedepth Mean	0.16	-0.03	0.73
Basedepth Max	-0.22	-0.03	0.82
Occurrence	-0.34	0.08	0.08
Size	0.004	0.02	0.21
Depth	0.006	-0.03	0.68
TG	0.007	0.28	**0.0009**

Table 3. Same format as Table 2. for the early season (nov. – jan.). Temperature gradient (TG) included as it met linear regression assumptions for the season.

3.2.3 Late Season

	Trend	Adj R2	p-value
Temp	0.16	0.56	**5.94E-07**
Total Snowfall	-5.64E-03	-0.01	0.44
24hr NS Mean	-0.03	1.10E-03	0.33
24hr NS Max	-0.26	0.01	0.23
24hr SWE Mean	-9.90E-03	-0.03	0.64
24hr SWE Max	-0.26	0.02	0.23
Basedepth Mean	-0.8	6.60E-04	0.32
Basedepth Max	-0.94	4.90E-04	0.33
Occurrence	-0.77	0.29	**8.60E-04**
Size	0.001	-0.02	0.65
Depth	0.01	-0.02	0.58
TG	0.001	0.45	**1.39E-05**
SI	0.0002	-0.03	0.94

Table 4. Same format as Table 2. for the late season (feb. – apr.). Temperature gradient (TG) and sliding interface ratio (SI) included as it met linear regression assumptions for the season.

3.3 Air Temperature Plot

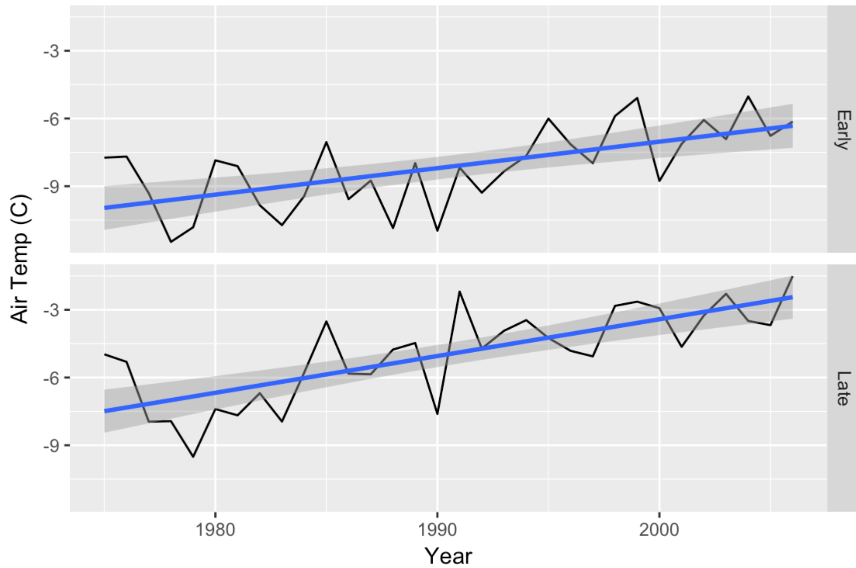

Figure 1. Plot showing early and late season monthly mean air temperature through time and resulting linear regression model.

3.4 Avalanche Occurrence Plot

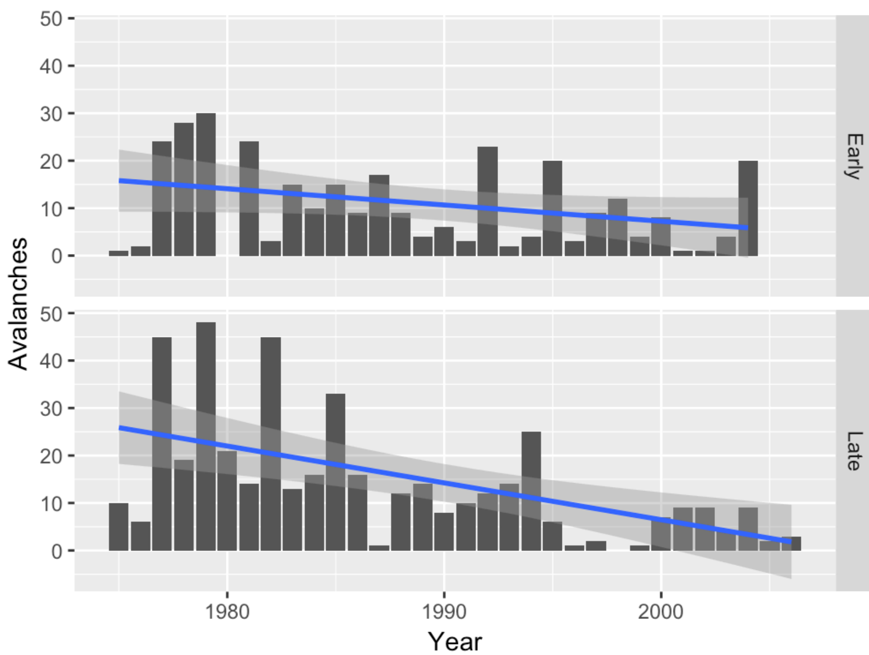

Figure 2. Plot showing avalanche occurrence through time. Note: gaps in the data reflect periods where no avalanches were observed that met the thresholds for this analysis.

3.5 Snow Temperature Gradient Plot

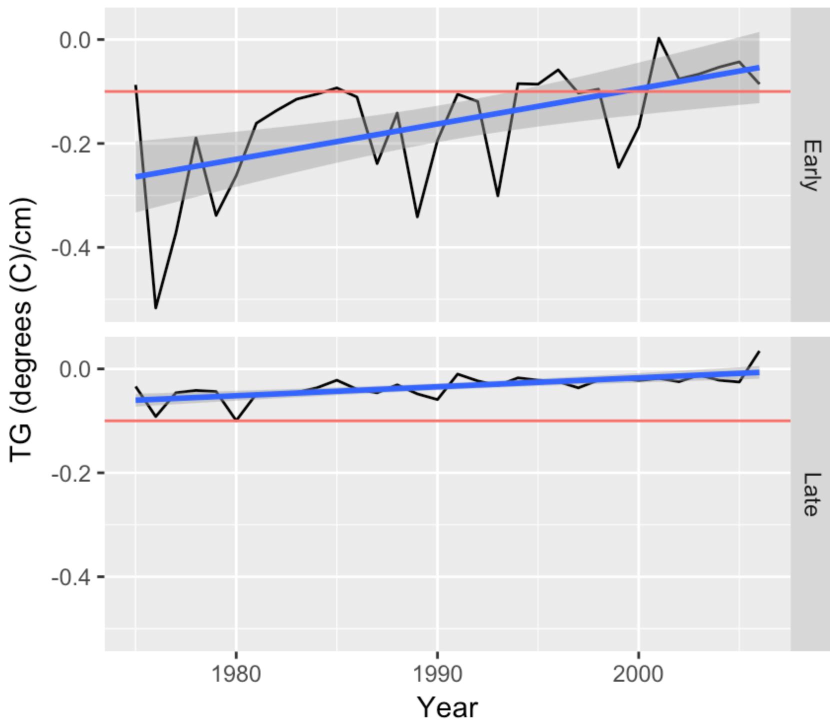

Figure 3. Plot showing snow temperature gradient through time. Red line indicates the threshold for kinetic (below the line) and equilibrium (above the line) growth metamorphism.

3.6 Correlations

Two correlation matrices including select variables are shown below. Variables that did not meet data normality assumptions were not included. Additionally, maximum 24-hour snowfall and SWE were excluded for simplicity and readability as their values were similar to mean 24-hour snowfall and SWE.

3.6.1 Early Season

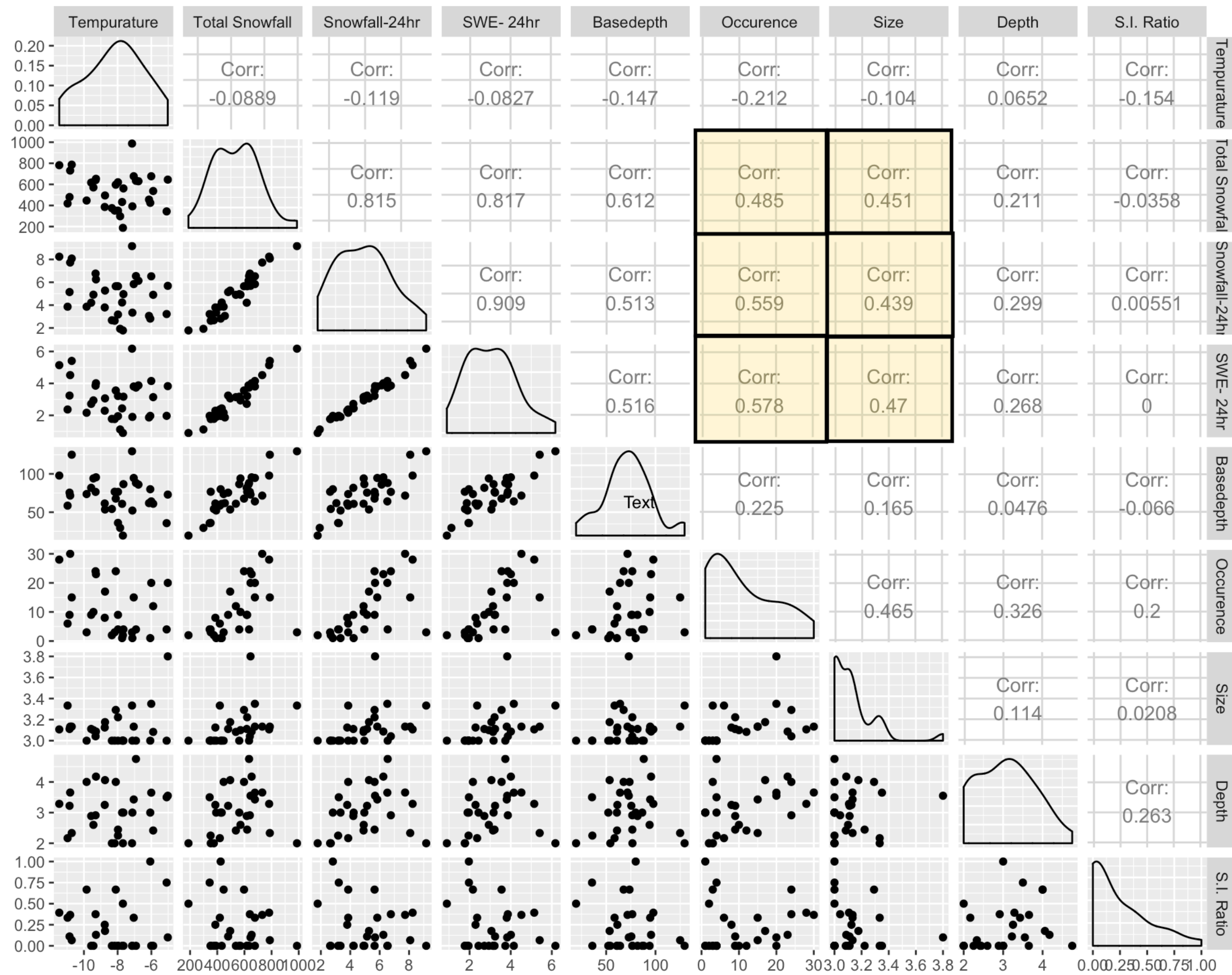

Figure 4. A complex correlation matrix plot for the early season of Temperature, Total Season Snowfall, Mean 24-hour Snowfall, Mean 24-hour SWE, Mean Basedepth, Avalanche Occurrence, Avalanche Size, Avalanche Depth, and the Sliding Interface Ratio. Depicted correlation coefficients are Kendall's tau. Moderate and strong correlation coefficients between avalanche and meteorological parameters are shown in yellow.

3.4.2 Late Season

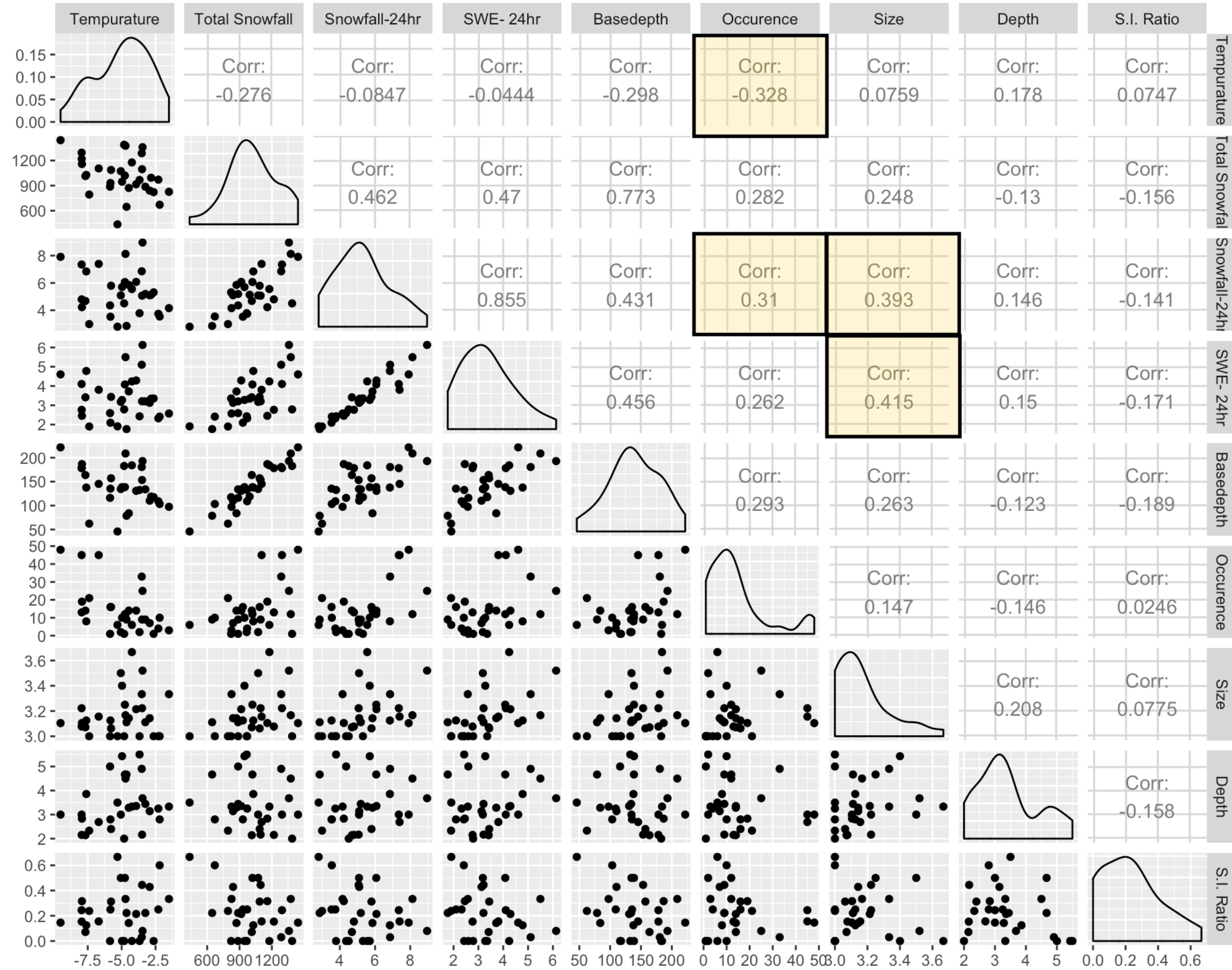

Figure 5. A complex correlation matrix plot for the late season of Temperature, Total Season Snowfall, Mean 24-hour Snowfall, Mean 24-hour SWE, Mean Basedepth, Avalanche Occurrence, Avalanche Size, Avalanche Depth, and the Sliding Interface Ratio. Depicted correlation coefficients are Kendall's tau. Moderate and strong correlation coefficients between avalanche and meteorological parameters are shown in yellow.

Discussion

Significant trends found for air temperature in both the early and late seasons is consistent with global climate change. Additionally, (McGuire et al. 2012) found similar increasing temperature trends from the Front Range of Colorado which lies roughly 100 miles to the northeast of Gothic. In Gothic, the trend is most severe in the late season where it is increasing at a rate of 0.16 °C per year (Figure 5). Though a substantial trend is also found for the entire year (0.14 °C)(Figure 3). Interestingly, this does not seem to have a meaningful effect on either the mean or maximum new 24-hour snow totals. Bellaire et al. (2015) found a similar increasing temperature trends, but only during the months of December-February. In their study at Rogers Pass, British Columbia mean snow totals also decreased throughout the entire year at the lower elevation plot (1315 m). It is possible that the temperatures in the Gothic area have remained cold enough to inhibit any substantial changes on snow precipitation as a result of increasing temperatures. Mean monthly temperatures from both seasons were not measured to rise above -2°C which is a possible reason why no trends were detected in snowfall. At 3000 m a.s.l, Gothic is situated at a high elevation and rarely sees above freezing temperatures during the winter months. Based on the simple linear regression model, at the current rate of warming, mean wintertime (nov.-apr.) temperatures in Gothic during the winter season will be reach 0°C by the year 2039.

No other significant trends were found for any of the other meteorological variables. It is worth noting that the total snowfall on a yearly time frame was close to meeting the significance threshold (p-value < 0.05) with a p-value of 0.07 on a trend of -1.64cm/year (Figure 3). It is possible that additional years of data could increase the significance. This would likely have drastic implications for snowfall. A more in depth analysis of solid/wet precipitation ratio could be explored to associate warming temperatures with less snowfall. Further study would be needed to draw conclusions about the effect that could have on avalanche activity.

Three avalanche variables were examined in this study including occurrence, size, and depth. No significant trends were found for either the size or depths of recorded avalanches. Occurrence, however, exhibits a very significant decreasing trend in the late season and throughout the year overall with P-values of 8.60E-04 and 1.70E-04 respectively (Figure 3,5). These decreasing trends of -0.57 for the season overall and -0.77 for the late season indicate that medium to large avalanches are happening less frequently in Gothic from 1976 to 2006 (Figure 3,5,9). Although the avalanche occurrence trend was also found to be decreasing (-0.34) in the early season, it did not meet the threshold for significance with a P-value of 0.08.

Moderate to weak correlations were found between a variety of avalanche and meteorological variables. In the early season, correlation coefficients ranged from 0.44 to 0.47 for relationships between avalanche size and total snowfall, 24-hour snowfall, and 24-hour SWE. Similarly, correlation coefficients ranged from 0.49 - 0.58 for relationships between avalanche occurrence and Total Snowfall, 24-hour Snowfall, and 24-hour SWE. Slightly fewer moderate relationships were found during the late season. Correlation coefficients of 0.39 and 0.41 were found between avalanche size and 24-hour snowfall and 24-hour SWE respectively. A moderate relationship was found for avalanche occurrence and 24-hour snowfall (0.31). Additionally, a moderate negative relationship was found between avalanche occurrence and air temperature (-0.32).

These results are generally consistent with the study from Roger's Pass that used similar methods (Bellaire et al., 2016). The relationships between avalanche and meteorological parameters are generally stronger during the early season. Bellaire et al. (2016) also found more moderate relationships between dry snow avalanche occurrences and snowfall parameters in their "early" season than from the "mid" or "late" seasons. One theory is that during this time the snowpack is much shallower, and thus weaker, where increases in loading on the snowpack may amplify avalanche activity. Incorporating snow profiles from the study areas would aid in supporting this theory however this would assume that the snow pack is relatively spatially homogenous, which is rarely the case. Landry et al. (2004) showed that we cannot assume snow structure or stability is homogenous throughout uniform slopes.

This theory can be expanded to the trends found in temperature, TG, and avalanche occurrence. Like mentioned previously, temperature gradients within snowpacks are driven by the height of the snow and its temperature. Snowpack depths are not changing significantly in Gothic, although temperature is increasing. In theory, this is weakening the predominant temperature gradient of the snow in this area which would result in less faceting of snow crystals, and presumably a more stable snowpack. This trend is seen during the early season in Gothic where the average temperature gradient of the snow is increasing by 0.006 °C per year with a p-value of 0.00096. This would suggest that less kinetic growth metamorphism is taking place in Gothic each early season which in theory is creating a more stable snowpack. Persistent deep slab avalanches are common in continental snowpacks where faceted crystals grow regularly in the early season, creating a basal weak layer for the rest of the year. With less faceted crystals growing in the early season one could expect to see less persistent deep slab avalanches throughout the year in Gothic, however this isn't the case. No significant trend was found in the sliding interface ratio, size, or depth of avalanches.

One assumption made in this theory is that there is only one temperature gradient within a snowpack, which is not the case. Many different temperature gradients can exist throughout a snowpack (McClung and Schaerer, 2016). Crystals in one section of a snowpack may be undergoing rounding while others, either above or below, may be faceting. This further complicates the phenomenon and affirms the reality that attributing broad and general meteorological trends to avalanche activity is very difficult.

4.1 Limitations

Avalanches are complex, and their antecedent conditions vary greatly. This study used a broad and simplified approach to draw some general trends from a long-term dataset. The limitations in this type of analysis are vast and should be considered prior to drawing any conclusions.

The primary drawback to the Gothic avalanche dataset was that no wind data was recorded from the RMBL site. Wind is a primary driver of avalanche formation (McClung and Schaerer, 2006) and should be applied as a variable to accurately capture trends in avalanche activity. The closest SNOTEL site is located at the top Schofield Pass at the head of the valley. The station at Schofield Pass records wind direction and speed, however, didn't begin collecting data until 1984, ten years after avalanche observations began in Gothic. Incorporating wind to the later 2/3rds of the analysis could prove to be useful.

Another limitation is both avalanche and meteorological parameters are highly variable throughout the collection period. This seasonal variability can mask trends that appear at smaller time scales. Castebrunet et al. (2012) used a stepwise regression analysis to reduce the effect of the high seasonal variability that is common in these relatively short datasets of 30-50 years. Their study masked these outlier years in order to smooth and more accurately capture the possible trends in avalanche activity and meteorological parameters that may be affected by smaller variations in climate (3-10 years). Similar approaches were used in Marty (2008) and (Durand et al., 2009) which suggests applying that technique here could be worthwhile. Another example of mid range (2-15 years) timescale analysis is found in (Thumlert et al., 2014) where trends avalanche activity were closely related to large scale ocean and atmospheric oscillations.

The temperature gradient variable was created under some broad assumptions. The air temperature does not always accurately reflect the temperature of the snow surface. Additionally, the base of the snowpack is not always 0°C, although this is generally more reliable. These estimates were a function of the limited data available.

Nearly all limitations presented here would benefit from more data collection and homogenization, as well as digitization of that data. Additionally, snow profiles would aid in the accuracy of some inferences made when analyzing these types of trends. For example, speculation that warmer temperatures in recent years have lowered avalanche occurrence rates in Gothic due to smaller temperature gradients within the snowpack. The ability to cross reference this inference with real data from a snow profile would greatly increase confidence in the theory. Recent efforts such as the ability for public observers to submit in depth snow profiles to local avalanche centers could contribute to this, however, the uncertainty of and variability of skillsets between observers would be a limitation. Organizations like Avanet also provide platforms to share this data where users can create a profile where they outline their skills or credentials to make qualified observations. This setup would be advantageous for researchers because observations could be hand-picked based on their presumed accuracies. This is a highly dynamic area of snow science, and hopefully will evolve into something beneficial for avalanche and climate researchers.

Conclusion

Mountain climates are changing rapidly and the effects are being studied and quantified in a variety of fields but is limited in snow science. This study used simple linear regression and correlations to draw trends and infer relationships between avalanche activity and meteorological parameters from a long-term dataset of natural avalanches in the Gothic Valley, Colorado. Increasing trends were found in winter temperatures, and snowpack temperature gradients while a decreasing trend was found in avalanche occurrence. Relationships between avalanche and meteorological parameters were found at a variety of scales. Initial results suggest that the snowpack during the early season may be experiencing less kinetic growth metamorphism, presumably resulting in a more stable snowpack throughout the year. The possible effect this could be having on avalanche activity remains inconclusive. Only seven out of a possible thirty four trends were significant indicating a more in depth analysis could be explored to allow for more concrete conclusions to be made about the changing avalanche occurrence in Gothic. Snow and avalanche research is a very dynamic field and any additional work will continue to enhance our understand of its elaborate nature. This paper has provided a review of previous findings linking avalanche activity to climate fluctuations and offered some additional initials findings from a previously unexplored natural avalanche dataset.

5.1 Further Work

The options for further analysis using this dataset are vast. More robust statistical methods could be applied to these seasonal trends. A multivariate regression analysis using avalanche occurrence, air temperature, and snow/SWE parameters could provide insight as to whether the decreasing trend in occurrence is being driven by both meteorological parameters or individually. Seasonal trends could also be explored using different time intervals to understand the antecedent conditions that lead to the possible trend in occurrence.

A more focused analysis of individual avalanche events could reveal additional relationships between climate fluctuations and avalanche activity. By defining large scale avalanche events one could then look for trends in their antecedent conditions. If trends exist in large avalanche events, relationships may exist between them and their preceding meteorological conditions.

Another Westwide Avalanche Network site (Yule Creek) is located directly to the north of the Gothic Valley. A Hierarchical Bayesian Model could be used to statistically combine the Gothic and Yule Creek datasets based on their geographic proximity modeled after (Sinickas et al., 2016). Like most areas of snow and avalanche study, there are seemingly endless possibilities for continued research.

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This thesis is dedicated to those who lost their lives to avalanches in the backcountry of Colorado. "That is the problem with snow science... it is only true science on the macro scale, in theory, and in the lab. On the side of the mountain it is as much witchcraft as true science." - A wise backcountry skier

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