SPATIAL VARIABILITY IN STEEP COULOIRS: WEAK LAYER VARIATION WITH RESPECT TO WIND DIRECTION

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ABSTRACT: Understanding the spatial variability of the snowpack is critical for avalanche prediction and mitigation. Previous spatial variability research focused primarily on relatively low angle slopes, many of which had fairly uniform characteristics. With snow sports progressing to steeper and more complicated terrain, a need exists to better understand the relationship between this "extreme" terrain and the snowpack variability. This research utilizes nine couloirs from Big Sky, Montana and Teton Pass, Wyoming. We used a probe to measure weak layer heights, slab thicknesses, and snow depths, we cross-verified those measurements with pits, and we georeferenced our sampling points using a sub-meter accuracy GPS. LiDAR data are used to derive terrain parameters, such as slope, aspect, elevation, and curvature in a GIS, and these data are then compared with our snow observations. Our analyses quantify the distribution of snow in the couloirs, and suggest that weak layer thickness normalized by snow depth is significantly correlated with the distance from the windward boundary when all other terrain parameters are accounted for in our sampled population of couloirs. Our results provide insights into the distribution of weak layers and snow depth in steep couloirs, which is a first step in optimizing snow pit locations and explosive placements in this terrain.

1. INTRODUCTION

Avalanches are a dangerous hazard in mountainous areas worldwide. In the United States, avalanches kill more people on an average annual basis than earthquakes, landslides, or other mass movement phenomena (Voight et al., 1990). Last season, avalanches killed 36 people in the United States (avalanche.org, 2010). The best way to mitigate these avalanche deaths is through an increased understanding of avalanches and the snowpack for researchers, professionals, and recreationists alike.

Slab avalanches occur when a more cohesive slab of snow overlies a less cohesive weak layer and the conditions in the snowpack are conducive to weak layer fracture across a slope (Schweizer et al., 2003). Snow accumulates in layers that may or may not be continuous at various scales, from cm to km, and are often difficult to predict. Thus, a crucial element for improving avalanche prediction is understanding the structure and spatial pattern of snow layers as they interact with the terrain. The problem of spatial variability relating to avalanche occurrence has been investigated at various scales, but these studies typically characterize the snowpack on uniform slopes less than 35 degrees. Schweizer et al. (2008) provide a comprehensive review of this previous work. Results vary tremendously due to differences in scale triplets (support size, spacing, and extent of measurements), field methods, analysis methods, and natural variability. The present study is unique in that it looks at spatial patterns of snowpack in couloirs, which are steep, snow-filled gullies bounded on either side by rock walls or trees. The progression of winter sports towards more challenging terrain, coupled with advances in equipment, has increased the number of backcountry skiers, snowboarders, snowmobilers, and climbers who seek out such steep, avalanche-prone terrain.

The distribution of weak layers in couloirs is of particular interest for avalanche prediction and mitigation. While the presence of a weak layer doesn't necessarily indicate unstable conditions, the ability to predict where weak layers are most prevalent is valuable for choosing a location for stability tests, during avalanche mitigation, or during safe route selection. Layer formation results from external and internal processes driven by meteorological conditions during and after deposition. Wind is the most important external driving force in spatial variability in some environments (Sturm and Benson, 2004).

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Thus, we expect topography, which strongly influences wind patterns in couloirs, plays an important role in weak layer location. Hachikubo and Akitaya (1997) demonstrated that the formation of surface hoar, a significant weak layer, is affected by wind. Furthermore, Birkeland et al. (1995) showed that weaknesses in the snowpack form near rocks, and Arons et al. (1998) found that depth hoar, a common weak layer, preferentially grows over rock outcrops. Birkeland (1998) describes the driving processes for near-surface faceting, another common weak layer which is also influenced by topographic parameters such as aspect. With the effect of wind and underlying rocky substrate, the distribution of weak layers in a couloir is likely influenced by the topography.

This paper focuses on how weak layer distribution varies from the windward to the leeward side of a couloir. There are a number of practical applications for this question. For instance, would a snow profile or stability test conducted at the edge of a couloir provide representative information about the conditions in the middle, where one is more exposed to avalanche hazards? Would an explosive charge on the leeward side of a couloir impact the same layers that are found on the windward side to produce effective results?

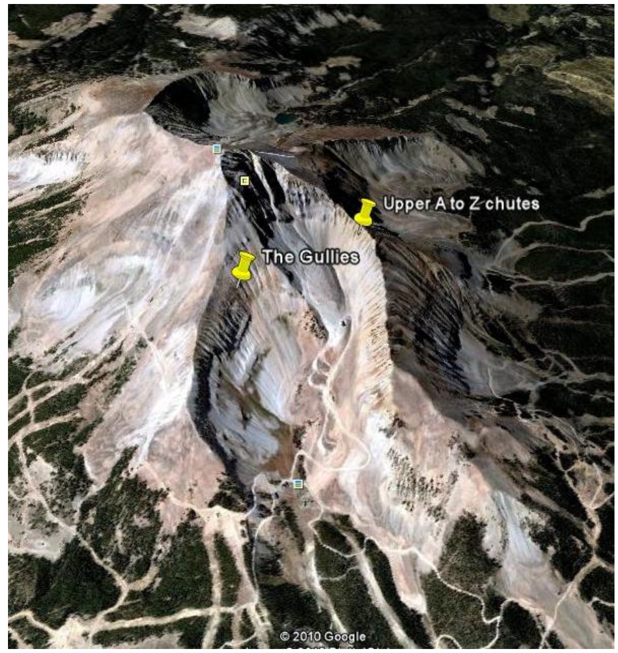

Figure 1: Google Earth image of the Big Sky, MT study site showing the location of the Upper A to Z chutes and the Gullies.

2. METHODS

In this study, we sampled nine couloirs during the winter of 2010. Seven are within the boundary of Big Sky Resort in southwestern Montana and two are located near Teton Pass in northwestern Wyoming. The Montana couloirs are located in a continental snowpack, while the Wyoming location is characterized by more intermountain conditions (Mock and Birkeland, 2000).

At Big Sky Resort, we sampled five couloirs from a south-facing wall (the Upper A to Z chutes) and two from a northeast-facing wall (the Gullies) on Lone Peak (Fig. 1). Prior to sampling, these couloirs were closed to skier traffic or had only recently been opened with minimal skier traffic. Avalanche control work in the Upper A to Z chutes was minimal prior to the sampling, and conditions were more-or-less representative of a backcountry snowpack. Several large ANFO explosives were placed at a location several hundred meters from the sampled areas, but the snowpack layering was well preserved. Previous avalanche control work in the Gullies consisted of hand charges and cornice drops on a face above the couloirs, and avalanche debris undoubtedly affected the snowpack at these sites.

From Teton Pass in Wyoming, we sampled two north-facing couloirs, one from an area called “Unskiable” and one from “The Claw” (Fig. 2). These are in the easily accessible backcountry, but their locations are somewhat obscure so backcountry skier traffic is minimal and layering was fairly well preserved.

To sample each couloir, we manually probed to measure snow depth and depth to each weak layer. Our 70 to 130 measurements per couloir were stratified in an effort to cover the entire width and length of the slope and to maintain relatively equal spacing of several meters between measurement points. Figure 3 shows an example of the sampling scheme, with “zero” points marking the couloir’s edges where the snow depth was zero.

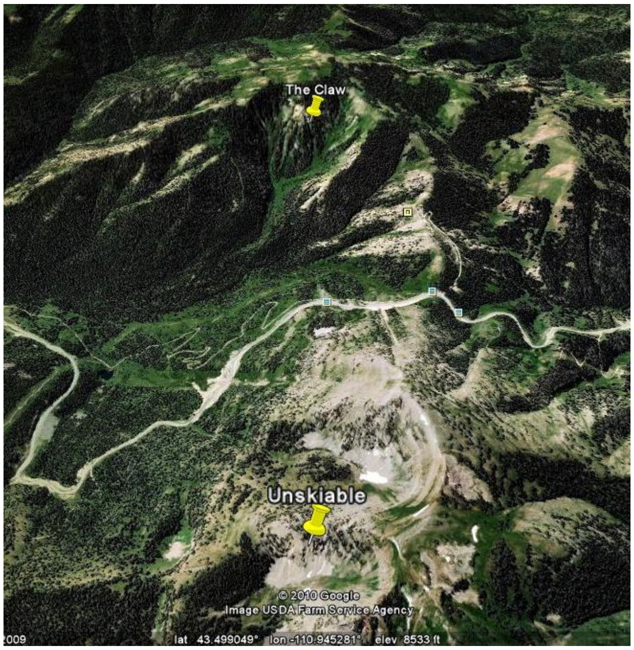

Figure 2: Google Earth image of the Teton Pass, WY study sites showing the location of the Claw and Unskiable

We defined weak layers as obvious soft or hollow layers in the snowpack observed using an avalanche probe. User uncertainty exists with this method, but the benefits of probing are quick data collection allowing a larger sample size and the ability to conduct research in steep terrain without burdensome equipment. In each couloir, we dug at least one snow profile for cross-verification of probing results, and in many cases probing results could be verified with hand pits to increase certainty, although this was not always practical in deeper or firmer snowpacks. While it is probable our techniques overlooked some thin or difficult to identify weak layers, the same researcher conducted all of the sampling to ensure consistency in measuring weak layer thickness.

We utilized a Trimble GeoXH 2008 handheld GPS to georeference sampling locations. Post-processing of coordinates with differential corrections allowed for sub-meter horizontal accuracy, typically ranging from 30cm to 80cm (root mean square values). At times, poor satellite strength reduced the accuracy of the GPS locations to several meters.

We imported the georeferenced sampling locations into a GIS for analysis. Light detection and ranging (LiDAR) data provide a one meter resolution digital elevation map (DEM) of the study locations. We derived the following terrain variables from the DEM for each sample: solar radiation, elevation, slope angle, profile curvature, plan curvature, and aspect. Radiation and elevation values are normalized for each couloir to allow comparison between couloirs. We converted continuous values for profile and plan curvature into categorical values of either convex or concave, and redefined aspect values into 8 compass directions, with the average value for each couloir being assigned to each sample within that couloir.

Although we made a number of snowpack observations, we defined the response variable for this work as the cumulative weak layer thicknesses normalized by the total snow depth; that is, the percentage of the snowpack composed of weak snow. Using R software, we utilized sequential variable selection techniques for our analyses (The R Foundation for Statistical Computing, 2009). The first step of the analysis is to determine a multiple linear regression model which best describes the response variable from the terrain parameters described above and in Table 1. To do this, we compared the model outputs from forward selection, backward elimination, and forward-backward stepwise regression. We deemed the forward-backward

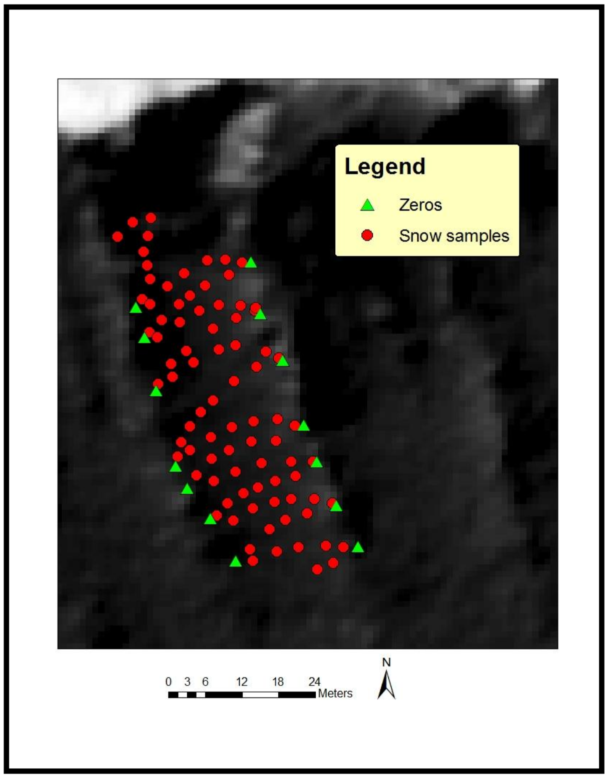

Figure 3: Example of sampling scheme showing snow observations and couloir boundary locations (denoted by the zero points).

Table 1: Terrain parameters used in the sequential variable selection.

Variable	***Type***	***Example***
Relative Elevation	Continuous	0.788
Relative Radiation	Continuous	0.361
Slope Angle	Continuous	52.3
Profile Curvature	Categorical	Concave
Plan Curvature	Categorical	Convex
Aspect Group	Categorical	NE

stepwise regression model the most suitable because it produced the lowest Akaike Information Criterion (AIC) value, which is a tool for comparing models (Akaike, 1974). Although the final regression model did not include all of the original terrain parameters, it took all of them into account because the technique gives each variable a chance to be in the model. Based on graphical assessment, we concluded that the assumptions of linearity, equal variance, and normality were met, but the data lacked spatial independence.

The next step of the analysis adjusts for spatial correlation between sampling points. To account for the lack of independence between observations, we constructed an empirical semivariogram and updated the multiple linear regression model using a spherical correlation model. In this step, we give sampling points weights based on their spatial proximity; points close together have less importance in determining the fit of the model.

To this point, our analysis gives us a model that accounts for solar radiation, elevation, slope angle, aspect, and plan and profile curvature, and is adjusted for spatial correlation. Now we can focus on the question: When all other terrain parameters are accounted for, does proximity to the edge of the couloir or proximity to the windward side of the couloir have a significant effect on the relative amount of weak snow in the snowpack?

To address this question, we created two additional variables: proximity to the edge of the couloir and proximity to the windward side of the couloir. We digitized couloir boundaries by hand in GIS based on points defined in the field, and supplemented this process with hillshade maps and orthophotographs. The windward side of each couloir is defined as the side nearest to the dominant wind direction during the winter of 2010. Weather stations at the summit of Lone Peak at Big Sky and the summit of Rendezvous Peak at Jackson Hole Mountain Resort recorded wind data. These wind stations are relatively unobstructed by terrain and are less than 15 km from the sampling sites, providing a good estimate of the dominant wind direction at each location. In the GIS, we calculated proximity to the nearest edge and proximity to the windward edge for each sampling point. Figure 4 shows an example of the proximity to the windward edge as determined in the GIS. Finally, we added each of these continuous variables separately to the previous model and tested for their significance.

3. RESULTS

Our analysis first described the response variable in terms of the terrain variables listed in Table 1. The forward-backward stepwise multiple regression model producing the lowest AIC was:

$$PercentageWL \sim 0.221 - 0.378\,E - 0.214\,NE + 0.071\,profile + 0.008\,slope + 0.110\,S$$

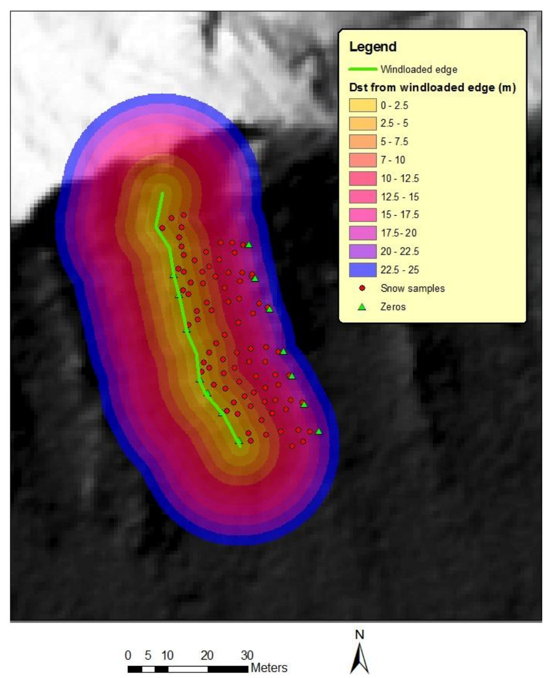

Figure 4: Example of proximity to windward edge calculation performed in GIS.

Next, we accounted for the spatial correlation of our response variable. Our variable had spatial structure that was best described with a spherical semivariogram model (Fig. 5). The range for our data was 13.3 meters, with a nugget of .44. Given the spatial autocorrelation we adjusted our regression model by weighting points based on their proximity to each other. This resulted in a model which has the smallest variance among all unbiased terrain parameter inputs and a lower AIC value than the previous model:

$$\mathit{PercentageWL} \sim 0.253 - 0.244\,E - 0.180\,NE + 0.053\,\mathit{profile} + 0.008\,\mathit{slope} + 0.067\,S$$

The model has a residual standard error of 0.295 and an approximate r^2 value of 0.24. The model is highly significant ($p < 0.0001$).

With this model in hand we could assess the contribution and significance of the location of points within the couloirs. First, we added the proximity to the edge of the couloir variable to the above model. The coefficient for this variable was -0.003, but a t-test of significance for this variable as an addition to the model resulted in a two-sided p-value of 0.59. Thus, this variable did not help to explain the percentage of the snowpack consisting of weak layers.

In order to refine our analysis further, we added the proximity to the windward edge of the couloir as a variable to the same model. This variable had an estimated coefficient of -0.012, but more importantly the t-test of significance for this additional term was highly significant, with a two-sided p-value of 0.0003.

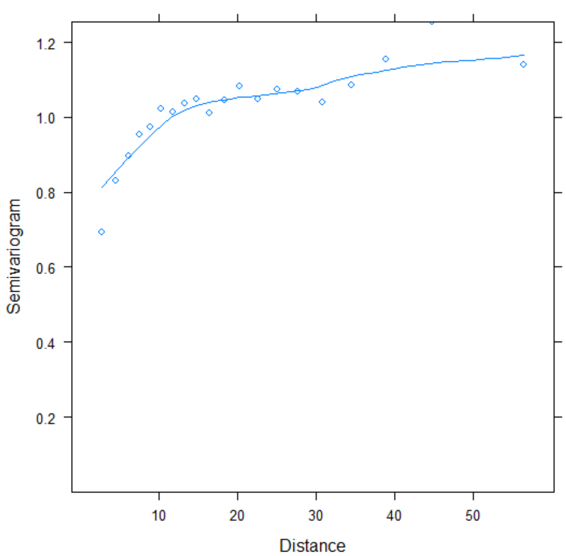

Figure 5: Semivariogram of the data from our study, which we fit with a spherical correlation model.

4. DISCUSSION

The results from the stepwise multiple regression model demonstrate the difficulty in correlating snowpack properties in steep couloirs based simply on terrain parameters. The model considered relative elevation, relative solar radiation, slope angle, aspect, and curvature, but only accounted for 24% of the variance of our snowpack observations. Obviously, there are other variables that affect weak layer formation which the model didn't consider, such as wind dynamics and snow metamorphism which act independently from the terrain or at a scale smaller than the scale of this study. In spite of the relatively low amount of variability explained by the model, it is encouraging that our model is statistically significant given that our measurements are in such a highly variable environment.

After accounting for the effects of the terrain parameters discussed above, the proximity to couloir edge and to windward edge produced interesting results. The addition of the proximity to couloir edge was insignificant (p-value of 0.59). On the other hand, the proximity to the windward edge was a significant additional variable to the model (p-value of 0.0003). These results remind us that each side of the couloir is not the same. If they were, the proximity to couloir's edge variable would be as significant as the proximity to the windward edge. Thus, our results suggest that it definitely matters what side of the couloir you are on, and that local knowledge about wind patterns in a given area can be critically important.

The negative coefficient for the proximity to the windward edge suggests that for this set of sampled couloirs, the percentage of snowpack composed of weak layers decreased as distance from the windward side of the couloir increased. At first this result seems counterintuitive. Windward edges are typically windloaded with greater volumes of snow, and thus their deeper snowpack would inhibit weak layer formation compared with the leeward side of the couloir. However, the winter of 2010 was unusual in our study area. We received early season snow, strong winds, and low temperatures that led to conditions of prolonged instability and large avalanches (see Chabot et al., 2010). These conditions likely loaded windward sides of couloirs with snow and possibly stripped the lee sides before extremely cold weather that led to widespread depth hoar formation. As a result, the windward sides started the season with a thick weak layer while that layer may not have formed on the other side of the couloirs. Other factors may also have contributed to our observations. For example, the leeward sides of the couloirs likely gained strength due to more exposure to wind, while the windward sides were sheltered, thus preserving weak layers. Because the study sites were not randomly sampled, the results of this study only apply to the couloirs which were studied. Furthermore, these data were all collected during the 2010 winter season, and it is dangerous to apply inferences made in this season to all other seasons. Therefore, extrapolating our results from these couloirs to other couloirs or to other winters is speculative. For an observational study such as this, results would be more meaningful if they were from a larger sample covering a wider geographic range with different snow conditions.

A number of potential sources of error exist in our methodology. Data collection relied on manual probing to ascertain the presence and height of weak layers. Some weak layers were obvious, such as those beneath a stout crust, and some could be easily verified by quickly digging a hand pit for visual and hand inspection. However, there was a fair amount of uncertainty in identifying weak layers, especially for north-facing couloirs where crusts weren't present. One solution to this uncertainty would be using more sensitive technology, such as a SnowMicroPenetrometer (SMP). However, operating an SMP in such terrain would be challenging and the large differences in snow depth would also create potential problems and slow down data collection. Another technique would be to dig profiles and trenches to decrease uncertainty. However, this would be slower and would therefore limit the amount of data and the spatial extent of our data collection.

Another potential source of error is GPS accuracy. The post-processed differential corrections estimate a root mean square value for accuracy, which averaged less than a meter. This estimation is based on the strength of signal qualities and locations of the satellites. However, this estimation doesn't consider error introduced through multipath signals (reflections from trees, landscape, or people) and electromagnetic interference (from electronic devices such as avalanche beacons). We believe these errors are relatively minor since visual inspection of sampling locations revealed no noticeable errors; all "zero" points were positioned correctly relative to the other sample locations.

Skier tracks and avalanche debris probably affected results. Due to dangerous avalanche conditions in the backcountry during the winter of 2010, most of the sampling days were confined to inbounds terrain for safety measures. As discussed in the methods, these locations saw very little skier traffic, but a number of them were subject to avalanche debris which could change the structure and layering of the snowpack.

5. CONCLUSION

From a group of nine couloirs in Montana and Wyoming, we modeled the percentage of snowpack composed of weak layers using terrain parameters derived from a one meter DEM. Relative solar radiation, relative elevation, slope angle, aspect, and curvature accounted for 24% of the variability observed in the snowpack observations. Proximity to the windward side of the couloir is a significant variable when added to the model, and the percentage of the snowpack composed of weak layers decreases away from the windward side.

Ron Perla's famous saying that "The only rule of thumb in avalanche work is that there are no rules of thumb" is probably applicable to this study. In the couloirs sampled in this study, a snowpit dug near the windward side of a couloir would improve the chances of identifying dangerous layers, but different terrain in different snow climates will undoubtedly have different snowpacks. Our data also show the wide variability in such terrain. Therefore, assessing the usefulness of a snowpit or explosive placement on the windward versus leeward side of a couloir still needs to be considered on a case by case basis.

There is great potential for further research in this area. A larger sample of couloirs with varying aspects, sizes, and snowpacks would increase the value and significance of the results. Potential exists for predictive modeling, in which weak zones could be located based on terrain parameters and high resolution DEM's. Refined methodologies, such as using a SMP, would decrease uncertainties in the data collection. Some of these ideas will be built in to our 2010-11 field season.

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