SPATIAL, TEMPORAL, AND SPACE-TIME ANALYSIS OF FATAL AVALANCHE ACCIDENTS IN COLORADO AND THE UNITED STATES, 1991 TO 2011

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ABSTRACT: An analysis of fatal avalanche accidents in the state of Colorado (CO) and the United States (US) for 20 winters from 1990-91 to 2010-11, compared temporal trends and clustering in the temporal pattern of accidents. The number of accidents per season in the US has increased through time, and decreased slightly in CO. Variability is high from season to season. Temporal clustering in the US data was much stronger than in CO, and was possibly related to synoptic scale weather patterns. Temporal clusters in CO were possibly related to strong mesoscale storms in seasons with a weak, early season snowpack. Geographic coordinates for accidents in CO allowed an examination of the spatial distribution and clustering of accidents. Spatial clusters were likely related to access to avalanche terrain from ski areas or popular backcountry trailheads. Statistical methods from epidemiology were used to examine space-time clustering. Significant space-time clusters were much fewer than pure spatial clusters, and were highly dependent on the time span of aggregation.

1 INTRODUCTION

The Colorado Avalanche Information Center (CAIC) has long maintained an archive of avalanche accidents in the United States. The archive grew out of data compiled for the early volumes of The Snow Torrents (Gallagher 1967, Williams 1975), and collected by the US Forest Service Westwide Avalanche Network. The archive provided information for subsequent volumes of The Snowy Torrents (Williams and Armstrong 1984, Logan and Atkins 1996) and papers on human factors and decision-making (Atkins 2002, McCammon 2002, among others).

Data was first digitized on punch cards. Initially, data fields were limited to eight characters, resulting in a creative and complex coding schema. The data has gone through many digital formats since. Each curator has added and expanded fields with format changes, additional lines of enquiry, and changes to avalanche data standards. The current database tracks over 160 fields per accident, including geographic coordinates.

Over the last five years, we have been reviewing the Colorado avalanche accident dataset. By backfilling fields and adding missing geographic coordinates, this dataset is now large enough for meaningful spatial analysis. In this paper, we examine spatial patterns in the Colorado accident data and look for temporal trends in the Colorado and United States datasets. Finally, we examine space-time clustering. The results provide insight into temporal relationships between seeming unrelated avalanches accidents in these regions. They may help public safety programs identify periods when avalanche accidents are more likely. The results can also help identify spatial regions with a higher likelihood of human avalanche involvement.

2 DATA AND METHODS

We explored three threads of analysis for this paper. One was purely temporal, comparing the Colorado (CO) accident data to the United States as a whole (US). We examined changes through time aggregated by season, and temporal clustering. The second was purely spatial, examining the CO dataset for spatial patterns. The final thread explored space-time clustering, with methods originally developed for epidemiology.

2.1 Definitions

This analysis considers only avalanche *accidents* that resulted in a fatality. This reduced reporting bias. Non-fatal avalanche incidents are frequently not reported to, or fully documented by, a regional avalanche center. For example, in recent years, the CAIC has only had sufficient time to document fully 25 to 30% of the reported non-fatal incidents.

Avalanche Season begins September 1, and continues through August 31 of the following year (Logan and Atkins 1996). We used the year the

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winter began for the season, so Season 2000 began September 1 2000 and ended August 31 2001.

The *CO dataset* includes all avalanche fatalities that occurred within the state of Colorado, between September 1 1991 and August 31 2011 (Figure 1). We believe the dataset is complete and accounts for all avalanche fatalities. The CO dataset is a subset of the US dataset.

The *US dataset* includes all documented avalanche fatalities that occurred within the United States of America, between September 1 1991 and August 31 2011. There may be a few fatalities not included. In particular, some mountaineering accidents or missing persons may not have been reported as avalanche fatalities.

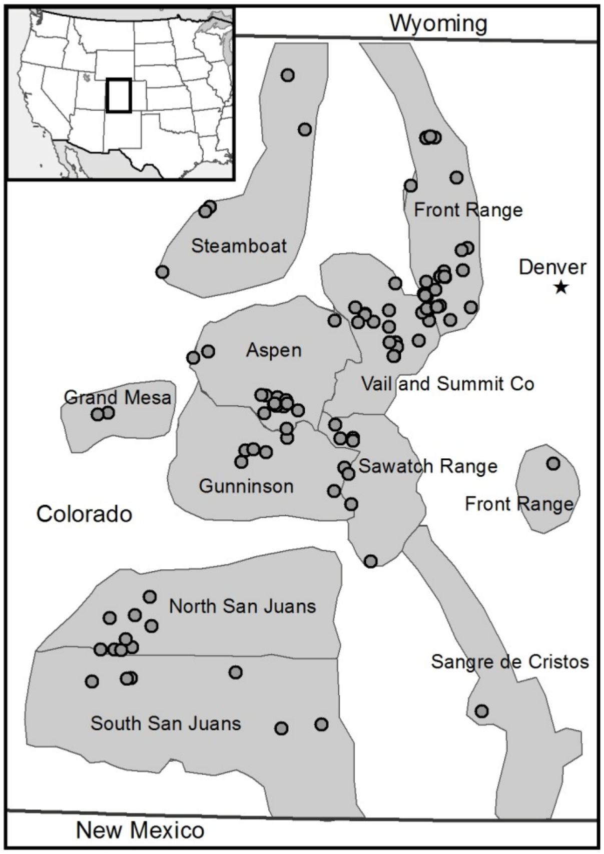

Figure 1. Map of the CO dataset. Each circle represents one accident. Gray polygons delineate current CAIC forecast zones.

2.2 Reviewing the datasets and assigning coordinates to accidents

A single reviewer, the first author of this paper, checked the accidents in the CO dataset against original investigation reports and files in the Accident Archives. The reviewer corrected minor errors, added additional data, and updated User Group to the most recent category. The reviewer crosschecked the US dataset against records maintained by the American Avalanche Association (AAA; 2012). The AAA records only cover the study period from season 1998 on.

The reviewer assigned geographic coordinates and one of three quality rating to each accident in the CO dataset:

1. Coordinates measured in the field by Global Positioning Systems (GPS), or derived from topographic maps by the accident investigators. When possible, we used the victim's burial location.
2. Coordinates assigned by the dataset reviewer, derived from the investigation report. The reviewer used a combination of topographic maps and imagery from Google Earth to match the accident investigators' maps, photographs, and notes. When possible, we used the victim's burial location.
3. Coordinates assigned by the dataset reviewer based on sparse or limited information in the investigation reports. In some instances, accident investigators were unable to reach the site, relied on witness or rescuer accounts, or were unable to gather detailed information. The reviewer assigned coordinates based on best professional judgment, using landmarks like peaks or passes. These coordinates may be several kilometers from the accident location, with no way to quantify the error.

The coordinates allowed us to analyze the CO accidents spatially and temporally as point processes. The uncertainty associated with the Quality 3 coordinates limited the scale of analysis, but was negligible compared to the area of the forecast zones. We address some issues related to uncertainty in the qualitative assessment of clustering.

2.3 Descriptive Statistics and Temporal Trends

Considered seasonally, both the CO and US datasets exhibited distributions similar to normality (Shapiro-Wilk normality; see Table 1). That allowed us to use parametric descriptive statistics, linear regression, and ANOVA. We modeled change through time with linear models.

2.4 G Function

The *G* function examines the cumulative frequence distribution of nearest-neighbors (O'Sullivan and Unwin 2003). It provides an indication of spacing and clustering between points. *G* increases rapidly when events are clustered closely in time, and increases more slowly when events are spaced further apart. The general *G* funtction is:

$$G(d) = \frac{\text{no.}[d_{min}(s_i) < d]}{n} \quad (1)$$

Where G at time *d* is the fraction of all nearest neighbor distances less than *d*, $d_{min}(s_i)$ is the nearest neighbor time for event s_i, and *n* the number of events. The *G* function can be simplified to one dimension to indicate clustering in a time series or along a transect (O'Sullivan and Unwin 2003). A nearest-neighbor time is used instead of distance. When plotted, rapid increases in *G* indicate clustering at those distance.

2.5 Ripley's K

We used Ripley's K function to summarize the spatial point patterns over a range of distances (O'Sullivan and Unwin 2003). In practice, it overlays a circle of radius *d* over a point, and counts other points within the circle. It provides a metric of a pattern's clustering or dispersion, compared to a complete spatially random pattern. Monte-Carlo simulations are used to develop a confidence envelope for a spatially random pattern. We used the implementation of Ripley's K in ArcGIS (ESRI 2012), with boundary corrections applied (SIMULATE_OUTER_ BOUNDARY_VALUES).

2.6 Distance to Roads

We used the minimum straight-line distance to a maintained winter road as a metric of distance into the backcountry. We chose roads maintained in most weather conditions by the state or county, and incorporated them into the GIS as line features (Scott and Greene 2010). We calculated the minimum distance to a road for each accident in Colorado.

2.7 Space-time scan statistic

To detect space-time clusters in the Colorado data, we used SaTScan v9.1.1 and its space-time permutation scan statistic (Kulldorff et al. 2005; Kulldorff et al. 2009). This statistic overlays space-time cylinders of varying size over the study area where the spatial extent of the cluster is determined by the cylinder radius and the duration by the cylinder height. For each cylinder, the observed number of avalanche fatalities is compared to the expected number if all events were independent of each other. The model adjusts for purely spatial or purely temporal clustering.

Statistical significance for each cluster is assessed using a Monte-Carlo simulation where fatality events are randomly placed in the space-time field and number of events within the cylinder counted to generate a simulated distribution. The spatial cluster detection employs a similar technique without the additional height/time parameter.

We ran two parameterizations of the space-time permutation. One aggregated over 5 year periods, similar to the ANOVA analysis in section 3.1. The second aggregated over 1 year, similar to the seasonal analysis in section 3.1. In both cases, the specified geographic area was the maximum extent of the dataset; maximum spatial window was 50% of the study area; and maximum temporal window 50% of study period.

3 RESULTS AND DISCUSSION

3.1 Comparative analysis of US and CO

Table 1 summarizes the seasonal distribution of fatalities in both the CO and US dataset. There were 118 fatalities in 108 separate accidents in CO, and 543 fatalities in 452 accidents in the US. Fatalities occurred in 16 states, with two thirds of the accidents in four states. Only Colorado and Utah had fatalities in every season of the study period.

The number of fatalities varied greatly from season to season. The CO data show a slight decrease in seasonal fatalities through time, while the US data shows a slight increase (Figure 2). Neither linear trend is statistically significant ($p>0.1$), and R^2 values are very low. Removing the 1993 season as an outlier is not sufficient to make

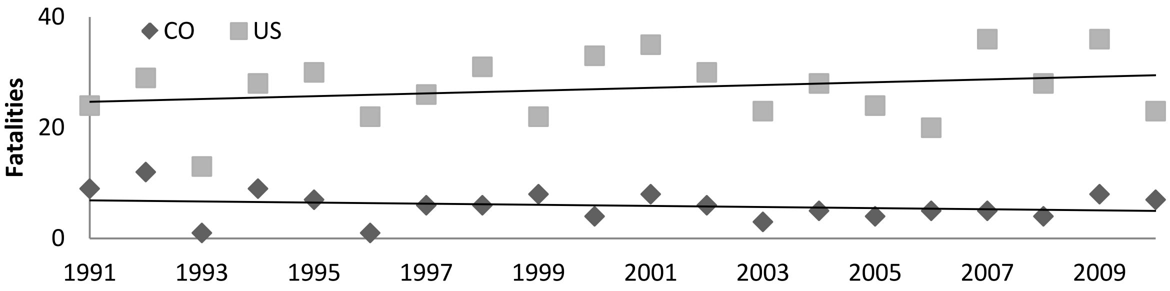

Figure 2. Fatalities by season, for both CO and US data. Trend lines were fit for illustrative purposes, but are not statistically significant.

the trends statistically significant. Higher order trends do not improve the fit or significance.

We compared five-season blocks (1991-1995, 1996-2000, 2001-2005, 2006-2010). Previous researchers described trends in seasonal avalanche fatalities with five-year running averages (Logan and Atkins 1996). We chose five-year blocks to follow that practice. The blocks were sufficiently large to reduce the seasonal variability, while still allowing us to detect temporal change. The five-year fatality average in CO decreased from 7.6 to 5.8, and increased in US from 24.8 to 28.6. Single factor ANOVA failed to find differences in the five year means (p>0.1). Again, apparent trends in the data are not statistically significant.

		CO	US
	Total Fatalities	118	543
	Total Accidents	108	452
Seasonal	Minimum	1	13
	1st Quartile	4	23
	Median	6	28
	Mean	5.9	27.1
	3rd Quartile	7.5	30.5
	Maximum	12	36
	Shapiro-Wilk normality (W)	0.96	0.95
	p(W)	0.75	0.57

Table 1. Summary statistics for the CO and US datasets

3.2 Fatalities by Activity

Investigators assign avalanche victims to one of 20 user groups, developed from Logan and Atkins (1996). Some categories do conflate activity, location, and assumed intention. The latest iteration of the CAIC database better separates the categories, but the historical US data has not been migrated to the new format.

In the US, Snowmobilers are the largest single user group, accounting for 195 (36%) of the total fatalities during the study period. The Snowmobiler user group shows a strong increasing trend in fatalities through time, as Snowmobilers make up an increasing portion of the annual fatalities (R^2 0.19, p=0.055).

A more accurate comparison may be between Snowmobilers, as motorized backcountry recreation, and non-motorized backcountry recreation (NMBC) that includes Climber, Hiker, Snowshoer, Ski Tour, Ski Out of Bounds, Snowboard Tour, and Snowboard out of bounds groups. NMBC accounted for 54% of US fatalities, compared to Snowmobiler at 36%. There is no significant trend in NMBC fatalities through time. The final 10% of fatalities included Inbounds skier and snowboarders (3%), Residents (3%), Workers (3%), and miscellaneous forms of recreation (1%).

In CO, Backcountry Ski Tourers account for 32 (27%) of the avalanche fatalities. Snowmobilers are the next largest group, with 21 (18%) of the fatalities. NMBC in CO accounted for 72% of fatalities. There were no significant trends through time for either NMBC or Snowmobilers in CO.

3.3 Temporal Clustering

The two datasets showed marked differences in the cumulative frequence distribution of nearest-neighbor times (Figure 3). Clustering is weak and bimodal in the CO data. The first cluster is at two days or less, with 11% of the nearest neghtbor days. The second cluster is 5 to 7 days, with 20% of the nearest-neighbor days. The US data indicates very strong clustering at 1 to 4 days apart,with 69% of nearest neighbor days 4 days or less. Temporal clustering in the US data was much stronger than in CO. The plot (Figure 3) is truncated at 90 days. Longer intervals show seasonal effects, which overwhelm the short-term clustering.

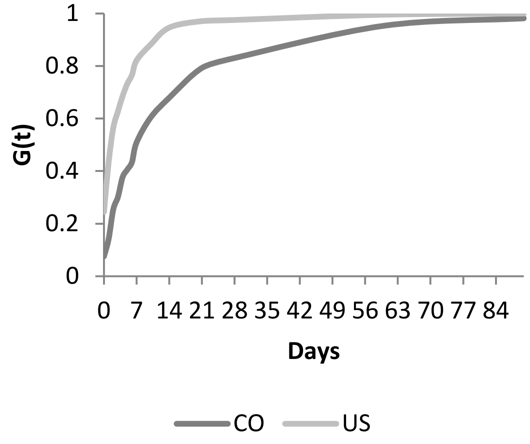

Figure 3. Plot of G(t), in days, for CO and US datasets.

3.4 Qualitative assessment of temporal clusters

The temporal clustering of fatalities is tighter over the United States than it is in Colorado. This is in part due to the greater number of accidents, but also due to synoptic weather patterns that link avalanche fatalities over large regions of the United States. A storm creates dangerous conditions over many mountain ranges as it passes over the western US. A recent example was in 2010, with a fatality in Montana March 31, Wyoming April 2, and Utah April 4 (Colorado Avalanche Information Center 2012a).

In Colorado, the bimodal temporal clustering suggests two mechanisms. The cluster at two days corresponds with a single avalanche cycle. Qualitatively, those cycles are often large storms in seasons with a weak early season snowpack. A dramatic example was January 22 2012. There were three fatal accidents within an 18-hour period in northern Colorado (Colorado Avalanche Information Center 2012b). The five to seven-day cluster suggests separate avalanche cycles that correspond with the periodicity of storms. A recent example was accidents in East Vail Chutes on January 4 and January 8 2008 (Colorado Avalanche Information Center 2012b). These also illustrate a tight spatial cluster.

3.5 Spatial Analysis of CO data

Fatalities occurred in 22 counties in CO. Pitkin (22), Summit (17), Clear Creek (12), and Eagle (9) counties account for 50% of the fatalities. The CAIC currently forecasts for 10 zones in the Colorado Mountains. At least one fatality has occurred in each zone, with the most fatalities in the Front Range, Vail and Summit, and Aspen zones (Figure 1). Not surprisingly, the fatality density is highest in areas with good road access and numerous ski areas that provide convenient out-of-bounds access.

The cumulative frequency distribution of nearest-neighbor distances indicates clustering at distances less than 15 km (Figure 4). One third of the accident locations are within 2.5 km of each other. The long tail indicates a few accidents are widely dispersed. The two accidents with the largest nearest-neighbor distances are in the southeast sections of the CAIC forecast zones (see Figure 1).

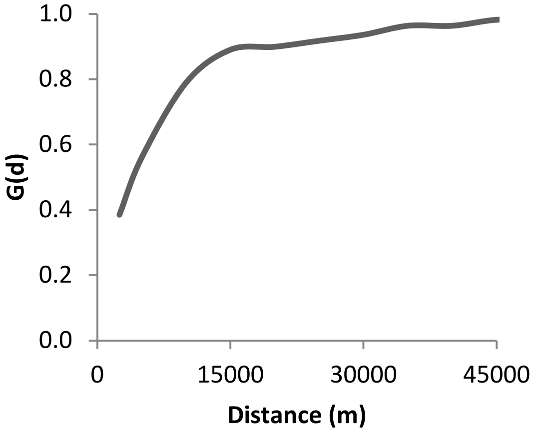

Figure 4. Plot of G(d), in meters, for CO accidents.

Ripley's *K* shows statistically significant ($p<0.01$) clustering of fatalities at all distances, compared to a spatially random process (Figure 5). The observed *K* is much larger than the expect *K* from the spatially random Monte Carlo simulations.

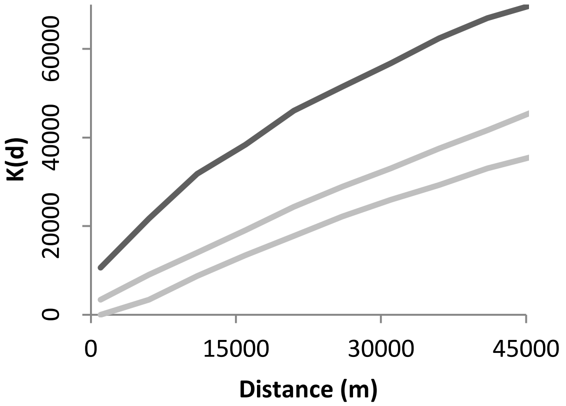

Figure 5. Ripley's K for accident locations in CO. The dark gray line is the observed K, while light gray lines show the upper and lower confidence envelope for a simulated, spatially random process.

3.6 <u>Qualitative assessment of spatial clusters</u>

Only two of the clusters we identified included a single avalanche path with multiple accidents. One path was near the Lindley backcountry hut, and both victims were caught in the low-angled run out by avalanches that initiated above them. The other path was in the East Vail Chutes, backcountry terrain accessed from Vail Ski Resort. Both victims were caught while descending the avalanche path.

Tight spatial clusters occurred in avalanche paths along larger terrain features like ridgelines or drainages and accessed from similar locations. We listed the following clusters in order of increasing minimum nearest neighbor distance:

- 5 fatalities in East Vail Chutes
- 2 fatalities on opposite sides of a ridge accessed from the Berthoud Pass road
- 3 fatalities on the same face of Diamond Peak, accessed from the Cameron Pass road
- 2 fatalities in terrain accessed from Aspen Ski Area
- 6 fatalities in the backcountry adjacent to Arapahoe Basin Ski Area
- 2 fatalities on Quandary Peak south of Breckenridge
- 3 fatalities in the backcountry terrain along a ridge accessed from Aspen Highlands Ski Area

The next tightest clusters are larger in diameter. Access points are common or similar, but the avalanche paths spread over larger terrain features. Examples include Berthoud Pass, with four fatalities in three adjacent drainages, or Dry Gulch with three fatalities spread along a 2 km section of valley.

3.7 <u>Distance to Roads</u>

Figure 6 shows the minimum distance to maintained roads for accidents in each of the 10 CAIC forecast zones. There was a highly significant difference ($p<0.001$) in variance between the zones. The distance to roads showed few patterns when split out by user group. There was no significant difference ($p=0.15$) in variance among the NMBC user groups or Snowmobilers.

The differences between zones likely reflect zone shape and access more than differences in user groups. The Front Range and Vail Summit zones are relatively linear, with major roads running through the zones that limit the distance from roads that recreators can achieve. The Sawatch zone is relatively linear, too, but has few maintained roads bisecting the zone. The Aspen and Gunnison zones are more round than linear, and have few maintained roads that bisect the zone.

3.8 <u>Space-Time Clustering</u>

Aggregating over five years, SaTScan detected one significant cluster ($p<0.1$). The cluster was from 2006-2010, centered in southern portion of the study zone, contained six fatalities, and included at least one fatality for four of the five seasons. It included several very-dispersed accidents.

Aggregating over 1 year, SaTScan detected one significant cluster ($p<0.1$). This cluster was centered in the North San Juan zone, where there were three fatal accidents between February 1992 and June 1992. The proportion of fatalities was much higher within the cluster than other areas of the state. No other season produced such strong space-time clustering.

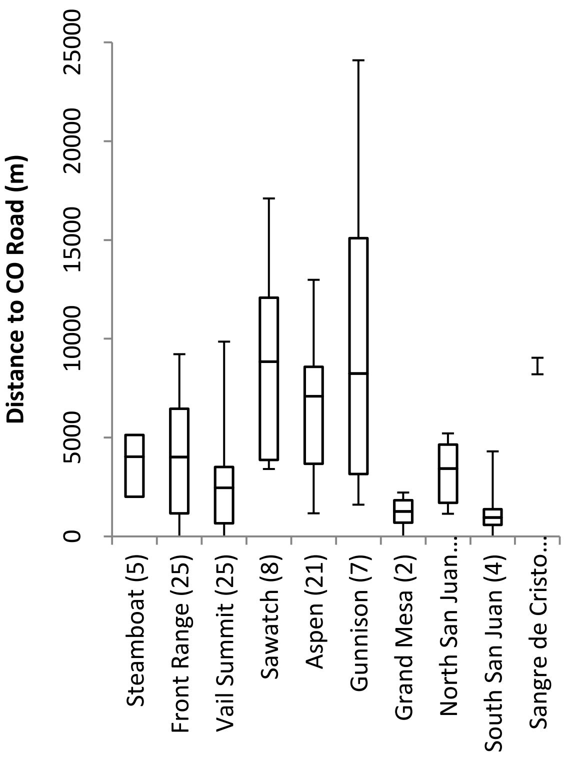

Figure 6. Box plots for minimum distance to road by CAIC forecast zone. Number of accidents is listed in parentheses after the zone name. Whiskers extend to the minimum and maximum values, boxes extend from the first to third quartile, with the mean marked by a line.

4 CONCLUSIONS

Seasonal avalanche fatalities in the United States have increased over the past 20 years. Seasonal avalanche fatalities have decreased slightly in CO over the past 20 years. In both cases, the change is slow, and subject to large seasonal variability.

When we decomposed the US seasonal fatalities into user groups, only Snowmobilers show a statistically significant increase in fatalities through time. As a user group, the number of snowmobilers has increased dramatically over the study period. Machines have become increasingly powerful, and riders more skillful (Chabot 2002). These changes may account for some or most of the increasing trend. Other user groups do not show significant changes through time, possibly because there is no change, seasonal variability is large, or the number of fatalities per group is small. These trends do not indicate directly changes in the fatality rate of the user groups. We do not have the congruent changes in user numbers to calculate the rate of fatalities per user day. Combining the fatalities with user days, or proxy of user days, is an obvious but non-trivial direction for future research.

Avalanche accidents tend to occur closely together in time. The temporal clustering of fatalities is tighter over the United States than it is in Colorado. This suggests that synoptic weather patterns link avalanche fatalities in the United States, with storms creating dangerous conditions over many mountain ranges. There is a bimodal cluster period in Colorado. That suggests some fatalities clustered within an avalanche cycle. The longer cluster corresponds roughly to the periodicity of storms. As an avalanche professional who tracks accident occurrences, the temporal clustering substantiates the feeling that accidents often come in quick succession.

The spatial locations of accidents in Colorado are tightly clustered. The densest accident distributions are in areas with good access and a large concentration of ski areas. This probably corresponds with a large number of users, and many opportunities for the users to reach backcountry avalanche terrain.

Somewhat surprisingly, there are few “killer paths” where multiple fatalities occurred during the study period. There are certainly “killer areas” where extensive avalanche terrain and high recreational traffic create a tight cluster of fatalities. Many of the clusters in CO are in terrain accessed from ski areas. These clusters support the recent efforts across the western US to educate side-country riders, skiers and snowboards who exit from ski areas into the backcountry.

Also surprisingly, there was little difference among user groups in the minimum distance to roads. Many avalanche professionals assumed that accidents involving Snowmobilers would be farther from roads. The distance non-motorized users can travel is limited compared to a snowmobile. The lack of difference may be a function of Colorado geography and road access. Support for this comes from the significant differences in minimum distances from roads when compared by forecast zone. Many of those differences can be attributed to the zone shape and road density.

The space-time cluster detection provided ambiguous results. The most significant space-time clusters were not apparent solely from the spatial data. In that sense, the methodology worked. The accident data may be too sparse temporally for the scan statistic to offer much additional utility or insight over purely spatial clustering. Future space-time cluster detection may be improved by incorporating additional data. The additional data might also allow for spatial modeling of the avalanche accidents.

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