AVALANCHE FATALITIES IN RELATION TO THE COVERAGE OF RECREATIONAL AVALANCHE FORECASTS IN THE UNITED STATES

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ABSTRACT: In the United States, avalanche forecasts for backcountry recreation are issued by a group of local and regional programs known as avalanche centers. These programs developed over time and were driven by community needs and resources. As a result, recreational avalanche forecasting is largely decentralized, with each operation managed and funded, at least in part, locally. This means that the coverage of recreational avalanche forecasts is focused on high-use areas and does not encompass all mountainous areas in a region or within the US. Although recreational avalanche forecasts covered just 3% of the mountainous regions in the US in avalanche year 2024, 77% of the avalanche fatalities occurred within those forecast areas. To examine the coverage of avalanche forecasts in relation to fatal avalanche accidents, we compiled a dataset of almost 200 accidents over a 10-winter period between October 2014 and June 2024. For each accident, we determined if the death occurred within an area covered by an avalanche forecast, outside of an area covered by a forecast, or at a location where the forecast was not applicable (in the United States, recreational avalanche forecasts do not apply to operating ski resorts or residential areas). There was no significant linear trend in the annual number of avalanche deaths outside of forecast areas. We analyzed the spatial clustering of avalanche accidents in the western United States at several scales. The accidents show a high degree of spatial autocorrelation with intensity peaks at several scales. The results of this analysis can be used to highlight areas where additional avalanche safety programs would have the most benefit and inform the spatial coverage of these programs. The scale breaks could be used to optimize the size of forecast zones for existing and future programs.

KEYWORDS: avalanche forecasting, avalanche accidents, spatial analysis, forecast coverage, forecast zone size

1. INTRODUCTION

Information on backcountry avalanche conditions in the United States is provided by a series of local and regional groups, collectively known as avalanche centers. Most of these groups are programs within the United States Forest Service (USDA FS), a federal government agency. In Colorado, this service is provided by a state government agency. In some places, this information is provided by non-profit groups. Even government avalanche centers rely heavily on private sector groups and stakeholders for funding and often partner with multiple entities for public engagement. This network of avalanche centers developed over time based on the needs and resources of individual communities. The result is a decentralized system that produces high-quality information on current avalanche conditions in specific, high-use areas.

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In some cases, the availability of that information varies in both time and space.

Avalanche centers issue summaries of current and future avalanche conditions that include one or more ratings from the North American Public Avalanche Danger Scale (NAPDS) (Statham et al., 2018). Most avalanche centers issue daily avalanche forecasts in the core of the snow season, but the coverage in the early fall and late spring varies based on local resources. According to national guidance, avalanche danger ratings are only valid for 24-hour periods (USDA FS National Avalanche Center, 2024). However, centers can issue products that describe conditions over multiple days as long as they do not assign a danger rating.

In 2024, recreational avalanche forecasts only covered about 3% of the mountainous regions in the United States. In the avalanche year 2024 (October 1, 2023, to September 30, 2024), 23% of the fatal avalanche accidents occurred outside areas not covered by recreational avalanche forecasts. This reality raises several questions. Does this rate mean that the coverage of avalanche forecasts in the US is adequate or inadequate? If adequate, how so? If inadequate, what changes do we make to reduce this value? The goal of this research is to better understand the spatial and temporal patterns behind these accidents and provide decision-makers with objective information to guide improvements to public avalanche safety in the United States.

2. DATA AND METHODS

The Colorado Avalanche Information Center (CAIC) maintains records of avalanche fatalities in the United States. We used fatal avalanche events from a ten-year period between October 1, 2014, and September 30, 2024 (avalanche years 2015 to 2024). Our data set included 197 avalanches that resulted in 225 deaths.

Local avalanche centers or various governmental or private agencies compile data for each accident. In rare cases, CAIC staff use media reports to collect information. Each accident record includes a location recorded in the field by emergency service personnel or accident investigators. In some cases, the location was estimated by CAIC staff using descriptions from local contacts or media reports and mapping tools. Given the spatial scale of our analysis, the estimated locations provided sufficient precision, and we did not segregate by location quality.

We categorized the forecast relevance for each accident (Table 1, Figures 1 and 2). If the avalanche occurred within a forecast area with an issued danger rating, we recorded the danger relevant to the accident.

We used spatial statistics to identify the location and intensity of accident clusters. Kernel density estimates (KDE) (Baddeley et al., 2016) are a common way of identifying clusters in point patterns. KDE intensity measures the number of values included and the tightness of a cluster. The K-function computes spatial autocorrelation, the degree to which observations are closer or further apart compared to a spatially random process. The L-function is a transformation of the K-function and can help identify spatial structures within the autocorrelation (Baddeley et al., 2016). Previous spatial analysis of accidents used a coarser spatial resolution in the United States (Spencer and Walker, 2011), the municipality scale in Austria (Pfeifer et al., 2018), or regional groupings in Switzerland (Techel et al., 2014)

Table 1: Forecast relevance categories, brief descriptions, number of events, and color codes for figures in this paper.

Category	Description	Number of events	Color in figures
Danger rating not applicable	Inside a municipality or within the boundary of an operating ski resort.	14	
Outside forecast area	In a backcountry location not covered by an avalanche center.	42	
Inside forecast area - no valid danger	Inside the forecast area of an avalanche center, but when there was no valid avalanche danger rating. Often before or after the main season of forecasting.	4	
Inside forecast area - multi-day forecast	Inside the forecast area of an avalanche center, but in a place covered by a multi-day description of the avalanche conditions. No valid avalanche danger rating.	10	
Inside forecast area - valid danger rating	Inside the forecast area of an avalanche center when there was a valid avalanche danger rating for the accident location.	126	High (4) Considerable (3) Moderate (2) Low (1)
Unknown	Location and other details were insufficient to determine if there was a valid avalanche danger rating at the time and place of the accident.	1	

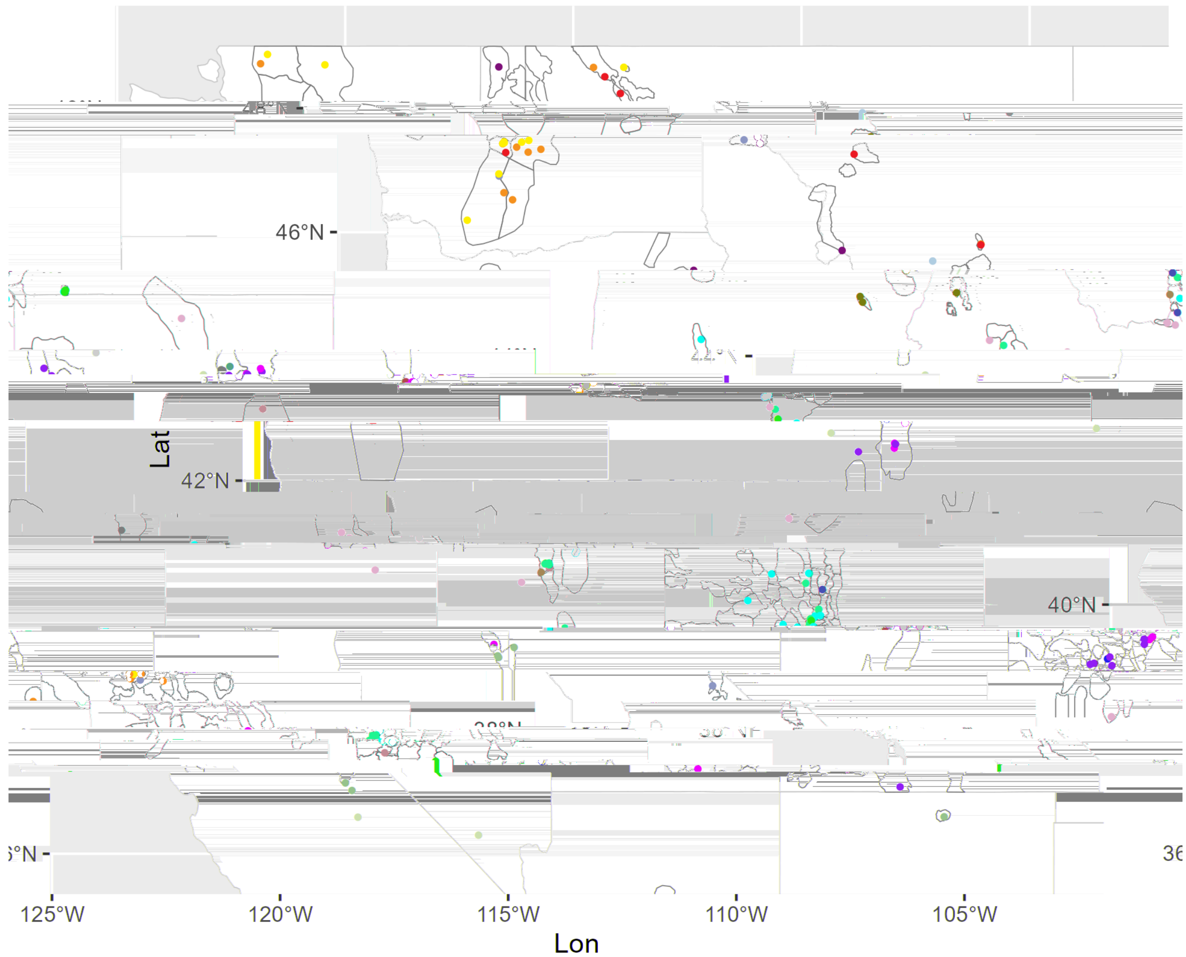

Figure 1. Fatal avalanche accidents in the western United States for avalanche years 2015 to 2024. Accidents are color-coded by forecast relevance categories in Table 1. Forecast areas shown in black include all types supported by avalanche centers in 2024, from daily forecasts to areas with an organized observation-sharing program but no forecast program.

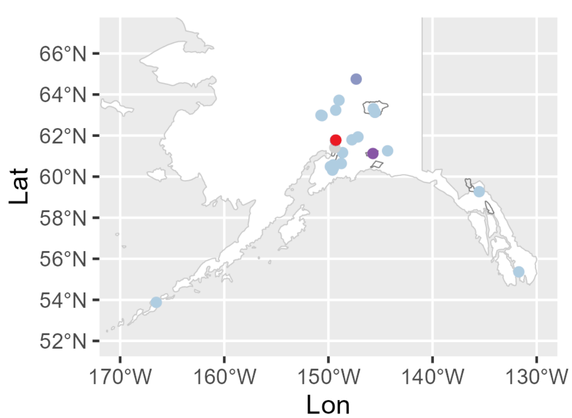

Figure 2. Fatal avalanche accidents in Alaska for avalanche years 2015 to 2024, as in Figure 1.

3. RESULTS AND DISCUSSION

Sixty-four percent of accidents in our dataset occurred inside an avalanche center's forecast area when there was a valid danger rating. About 21% of accidents occurred outside of a forecast area (Figure 3). Alaska and Idaho were the states with the most accidents outside of forecast areas. During our study period, Washington, Colorado, and New Hampshire did not have accidents outside of a forecast area. The single avalanche accident in New Mexico occurred within the boundary of an operating ski area; thus, the backcountry danger rating was not applicable.

The annual number of accidents outside forecast areas did not significantly ($p > 0.1$) change over time during this period (Table 2), consistent with previous findings (Birkeland et al., 2017). For our dataset, space-time cluster analysis at the annual scale did not add value to the spatial cluster analysis. Previous work has examined accidents at shorter temporal scales (Logan and Witmer, 2013).

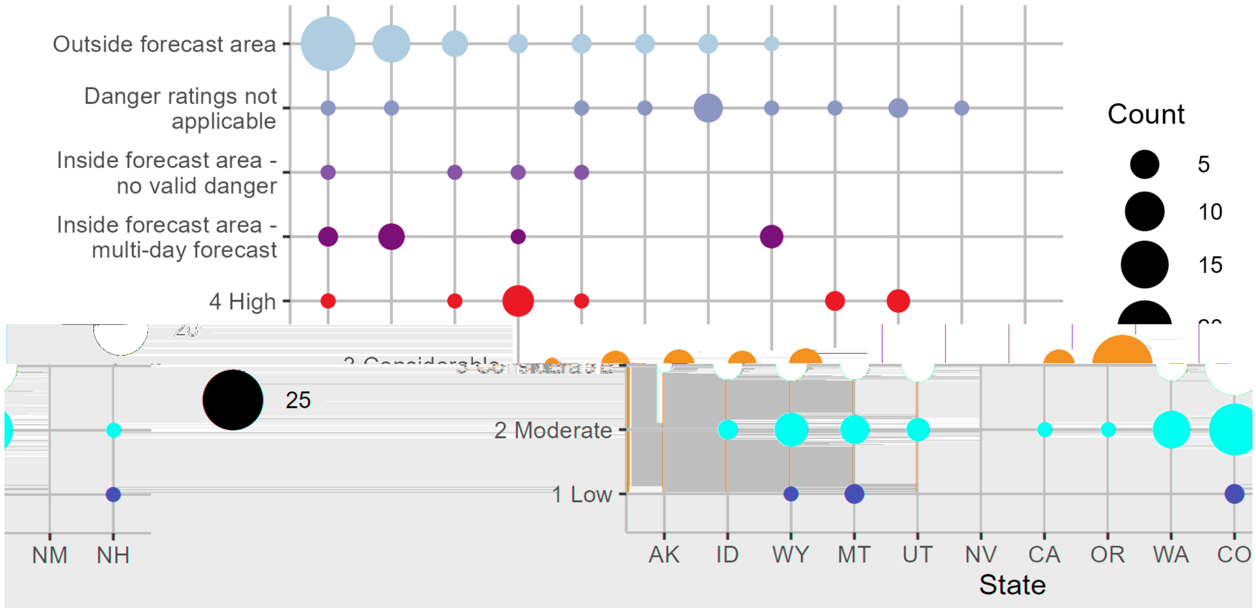

Figure 3. The number of avalanche accidents by state, color-coded by forecast relevance category according to Table 1. A single accident in the Unknown relevance category is not included.

3.1 Kernel Density

Visual interpretation of the KDE provides insight into cluster location and size. The clusters with the highest intensities are in the CAIC's Southern Mountains region, the Utah Avalanche Center's Salt Lake Area Mountains, and the Gallatin National Forest Avalanche Center's Cooke City area in Montana (Figure 4). The CAIC's Central and Northern Mountain regions and the Northwest Avalanche Center's Snoqualmie Pass zone have less intense clusters. All intense clusters of avalanche accidents are included within avalanche center forecast areas. Avalanche accidents in Alaska are widely dispersed. Given the number of accidents and the spatial dispersion, KDE does not indicate clustering in Alaska.

Table 2: The forecast relevance categories for avalanche accidents by avalanche year.

Avalanche Year	Danger ratings not applicable	Outside forecast area	Inside forecast area - no valid danger	Inside forecast area - multi-day forecast	Inside forecast area - valid danger rating
2015		3	1		6
2016	1	7		3	18
2017	2	2			8
2018	1	4	1	1	14
2019	2	6			15
2020	2	3		1	13
2021		4		1	23
2022	1	2	1		10
2023	4	7			14
2024	1	4	1	4	5

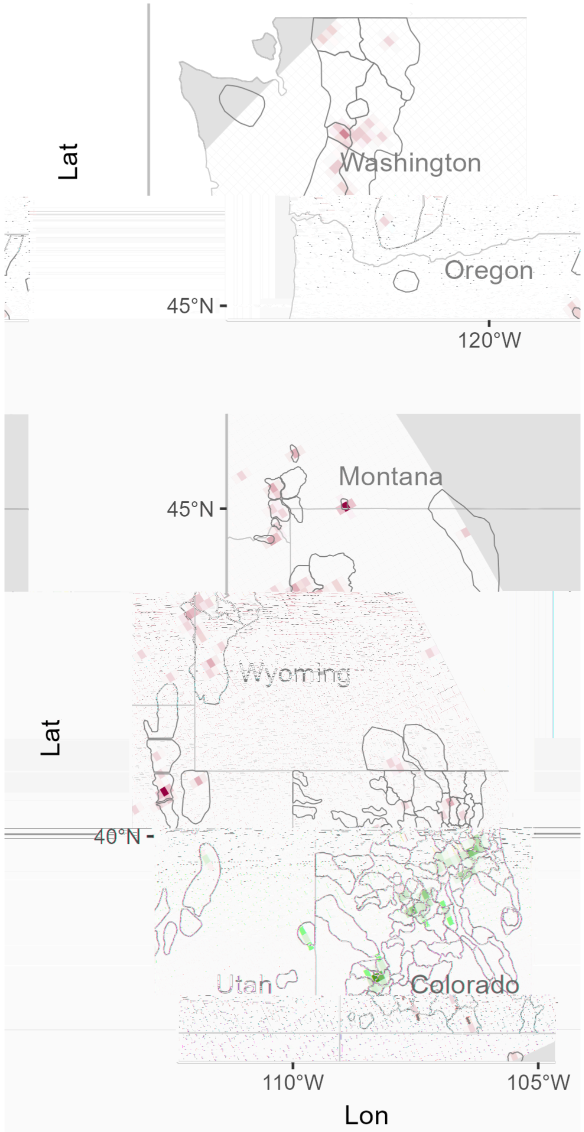

Figure 4. Kernel density estimates for avalanche accidents for select parts of the western US. Increasing intensity is shown with darker shades of magenta. Forecast areas are shown in gray. The areas shown include all types of coverage, from daily forecasts with danger ratings to organized data-sharing programs.

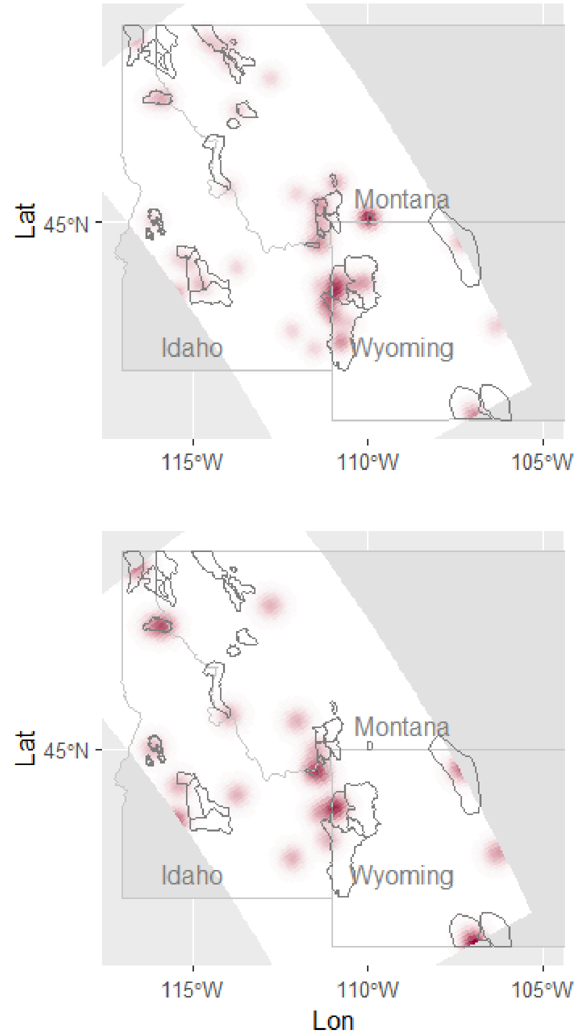

Figure 5. Kernel density estimates for all avalanche accidents (top) and only those outside forecast areas (bottom) in Idaho, Montana, and Wyoming. Increasing cluster intensity is shown with darker shades of magenta.

In Idaho, Montana, and Wyoming, there were a number of accidents outside of, but near, forecast areas with valid danger ratings. Figure 5 compares the KDE for all accidents in those states (top) to the KDE for accidents outside forest areas (bottom). There is a cluster of accidents in the Bitterroot Mountains along the northern Idaho-Montana border. Although the current forecast boundaries encompass all of these accidents, the cluster includes accidents that occurred before the zone was designated. There are two clusters of accidents along the Idaho-Wyoming border. One is near Island Park (near areas covered by the Gallatin National

Forest Avalanche Center) and the other is in the Big Hole mountains (near areas covered by the Bridger-Teton Avalanche Center). The cluster of accidents in the Island Park area include an accident in a residential area, accidents prior to daily forecasts, and accidents 5 to 10 km outside current forecast zones. In the Big Hole mountains, cluster intensity is driven by accidents about 10 km outside forecast boundaries. The cluster in the Snowy Range of southeastern Wyoming is near but outside of the Colorado Avalanche Information Center's forecast area.

3.2 K- and L-functions

We compared autocorrelation for accidents in the western United States, the Montana-Idaho-Wyoming region, and Colorado (Figure 6). The empirical K and L functions indicate strong spatial autocorrelation for avalanche accidents, which is expected for scattered locations concentrated in mountainous areas. K-functions (Figure 6, top) indicate changes in autocorrelation around 1 km, 5 km, and 8 km across all three datasets. The L-function estimate (Figure 6, bottom) shows an increase in autocorrelation beyond 125 km for both the western United States and Montana-Idaho-Wyoming.

The spatial autocorrelation suggests size breaks for forecast areas that most effectively capture avalanche accident clusters. The Gallatin National Forest Avalanche Center's Cooke City zone is approximately 10 km east to west and 18 km north to south and captures the cluster of fatalities in that area--a combination of access and use restrictions concentrate use into a limited area, and accidents have occurred in just a few nearby mountains. Large forecast areas begin to encompass entire mountain ranges and therefore cluster all accidents within the range. The Bridger Teton Avalanche Center's Greys River area along the Wyoming/Idaho border is an example.

The CAIC's smallest base elements used to create daily forecast zones are about 5 to 16 km across. CAIC uses a spatial schema that aggregates base elements into zones and regional groupings. The autocorrelation in Colorado suggests that clusters of avalanche accidents could be effectively captured by forecast zones less than 20 km across, around 50 km across, or larger than 125 km across.

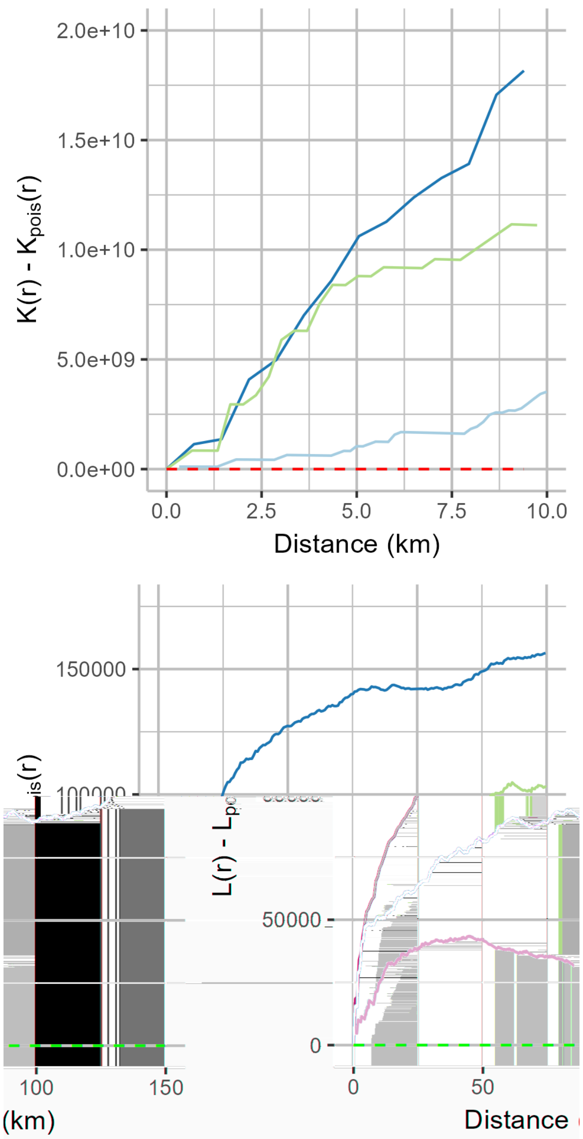

Figure 6. Empirical K-function (top) and L-function (bottom) for all western accidents (dark blue), accidents in Montana, Idaho, and Wyoming (green), and Colorado (light blue). Values have been centered around the theoretical functions (red), so more positive values indicate greater autocorrelation.

All three datasets show changes in autocorrelation at similar distances. This finding suggests that the spatial scale of topographic factors like drainage size, regional climate zones, and human factors like distance traveled from access points may be similar across the western United States.

4. CONCLUSIONS

Fatal avalanche accidents in the United States have high spatial autocorrelation and are tightly clustered. The source of autocorrelation in avalanche fatalities likely includes both human and physiographic processes. Avalanches occur in specific types of terrain, and in the winter, people access these areas from common starting points. Thus, it is not surprising that fatal accidents are clustered in space.

The cluster locations and spatial autocorrelation analysis offer insight into where the expansion of avalanche safety programs would be most impactful and, to some degree, the size of the area these programs should address.

About three-quarters of accidents occurred within areas covered by existing avalanche forecasts. The most intense spatial clusters are encompassed by existing avalanche forecasts. In the areas where there are accident clusters outside of avalanche center forecast areas, the avalanche safety community has already implemented other approaches — such as observation sharing and education programs — to address known avalanche safety issues. That said, these methods are not a substitute for daily avalanche forecasts, and more resources are needed to address the problem adequately.

The spatial autocorrelation of accidents could be used to inform forecast zone size or justify targeted data collection in certain areas of larger zones. In the US, there is no standard approach to determining the size and shape of a forecast zone. Avalanche centers often consider access points, recreational use patterns, weather patterns, snow climates, and other location-specific features to draw forecast zone boundaries. Changes in correlation at 2.5 km, 5 km, and 8 km suggest minimum dimensions for forecast zones that would capture clusters of avalanche accidents. Topographically, those size breaks also reflect individual or associated drainages, giving physiographic support for forecast zones of this size. In our analysis, autocorrelation increases at longer distances. This scale is much larger than a drainage and closer to a mountain range.

In areas where smaller forecast zones are not practical, a historical approach is to designate a whole terrain feature or mountain range as a single zone. This is an effective way of capturing the cluster of avalanche accidents with spatial autocorrelation over 125 km. That said, optimizing avalanche forecast zones is more complex than accident trends. Other factors such as terrain, mode of access, user types and behaviors, and snow climate are also clear considerations.

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