Scenario-specific observations for regional snow avalanche warnings

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ABSTRACT
Avalanche forecasters are increasingly formalizing a risk-based approach to analyze different *avalanche problems* or scenarios. Since public danger warnings in Canada apply to large regions, users must down-scale the danger using local field observations. We conducted a field study in the mountains of western Canada on over 175 days. On each field day, an experienced team rated the local avalanche danger, identified the avalanche scenario of most concern locally, and observed a standard set of over 20 field observations. New snowfall over a two-day period correlated with local danger in all scenarios, but otherwise a unique set of observations correlated best with local danger for each scenario. The results provide an evidence-based selection of specific local observations for potential use in regional snow avalanche warnings. The identified observations may help recreationists make better informed decisions.

RÉSUMÉ
Les prévisionnistes avalanches sont de plus en plus de formaliser une approche fondée sur le risque d'analyser les problèmes ou des 'scénarios' d'avalanche. Depuis les avertissements de danger public au Canada s'appliquent à de vastes régions, les utilisateurs doivent à l'échelle du danger en utilisant les observations de terrain local. Nous avons mené une étude sur le terrain dans les montagnes de l'ouest du Canada sur plus de 175 jours. Sur chaque journée, une équipe de terrain expérimentés évalué le danger d'avalanche locaux, a identifié le scénario d'avalanche de la plupart des préoccupations au niveau local, et a observé un ensemble standard de plus de 20 observations. Neige nouvelle sur une période de deux jours en corrélation avec danger locales dans tous les scénarios, mais autrement, un ensemble unique d'observations le mieux corrélé avec le danger local pour chaque scénario. Les résultats fournissent une sélection fondée sur des observations spécifiques locales pour une utilisation dans régionale avertissements d'avalanche de neige. Les observations peut etre aider les amateurs de loisirs a recommandé de prendre de meilleures décisions éclairées.

1 INTRODUCTION

Snow avalanches are one of the most deadly slope hazards affecting Canadians, particularly those undertaking recreational activities in mountainous areas in winter. Jamieson et al. (2010a) have provided the most recent statistics: During the winters 1997-2007 (inclusive), 139 people lost their lives in 98 separate recreational avalanche accidents in Canada, mostly while skiing/snowboarding or snowmobiling. In contrast, over the same period there were 7 accidents resulting in 16 fatalities in non-recreational settings (e.g. residential, industrial, etc.). Ninety-two percent of the recreational accidents involved dry slab avalanches that were triggered by the victim or someone in their party.

Slab avalanches are those in which a relatively thick, stiff, and cohesive snow slab releases from a slope due to the failure of a weak - and often thin - underlying snowpack layer. While this general stratification is required for slab avalanche formation, the layering may take on several typical characteristics based on the conditions under which it formed. By far the most prevalent type in fatal accidents involves persistent weak layers (Jamieson et al. 2010a), so named because their recognizable grain structure may persist in the snowpack and release avalanches for weeks or months after their formation. These weak layers typically form at or near the snow surface, and are subsequently buried by snowfall. A bimodal distribution of slab thickness in fatal accidents with peaks at around 0.9 m and 1.5 m (Jamieson et al. 2010a) leads to the distinction between *persistent* (shallower) and *deep persistent* (deeper) avalanches. Some of the even shallower avalanches occur in newly fallen *storm* snow, or due to *wind*-generated slab conditions; in general, these lack persistent weak layers and the unstable configurations may persist for only a few days. Figure 1 shows the number of fatal avalanche accidents in Canada between 1997 and 2007 that occurred for each recognized avalanche type.

Avalanche forecasters are increasingly formalizing a risk-based approach to analyze different avalanche problems or scenarios (e.g. Statham et al. 2010). For example, avalanches that release on *deep persistent* weak layers tend to be much less frequent, although much larger and of greater consequence compared to those which release in *storm* snow. While the overall risk to recreational backcountry users is difficult to quantify (e.g. Jamieson et al. 2009a), professional forecasters and guides have long recognized the relative risks associated with different avalanche scenarios (Table 1).

The Canadian Avalanche Centre (CAC) produces public avalanche warnings or bulletins every 3 to 7 days for several geographic areas in western Canada. Many of these 'bulletin regions' are greater than 10,000 km^2 in area, while the area traveled during a typical recreational backcountry journey may involve exposure to ~10 km^2 of terrain. The avalanche danger for each region is specified

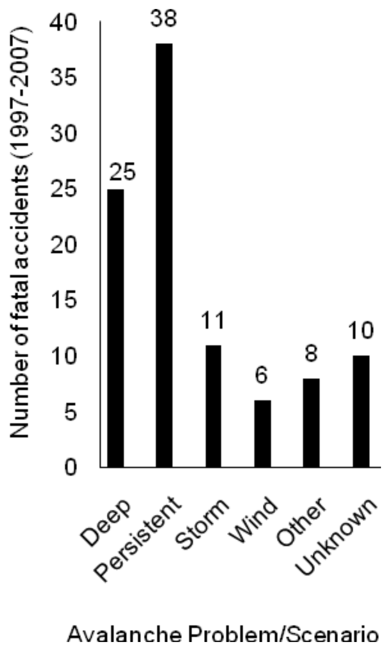

Figure 1. Distribution of fatal recreational avalanche accidents in Canada for different avalanche scenarios (1997-2007; after Jamieson et al. 2010a).

on a five-level scale; each level includes the forecaster's expectation about the likelihood of natural and human-triggered avalanches occurring, as well as the expected range of avalanche size; this gives users some indication of the overall risk. Recent research has shown that, given the large size of many bulletin regions and the fact that spatial variability in the snowpack layering and weather results in variability in the avalanche danger (Schweizer et al. 2008; Jamieson et al. 2008a), the recreational traveler should – if practical - 'localize' the avalanche danger by making certain avalanche, snowpack, and weather observations during their journey (e.g. Jamieson et al. 2006, 2008b).

While professional guides and other avalanche workers can make almost continuous technical field observations and synthesize the results implicitly to localize the avalanche danger, the target user of avalanche warnings typically has little technical training or experience (e.g. McCammon et al. 2008), and may rely heavily on the avalanche warning for guidance and decision support while in the field. Professional decision-makers rely preferentially on particular field observations depending on the predominant avalanche scenario. Experience and technical training tend to guide the choice of observations (and site selection for snowpack tests); the typical recreationist lacks both of these.

As the risk-based analysis of avalanche scenarios has increased (e.g. Statham et al. 2010), so has their mention in public avalanche warnings. In fact, CAC forecasters currently identify in each bulletin, using graphics and keywords, one to three prominent avalanche scenarios. The forecaster usually relies on their own experience to recommend observations or signs that a recreational traveler might pay attention to in the field to localize the regional danger under each scenario, although no protocol exists to guide or support these suggestions. Several decision support tools exist to direct field observations and help amateurs recognize the signs of increased avalanche danger (e.g. the Avaluator; Haegeli 2010), although these are not scenario-specific beyond noting that the *persistent* and *deep* conditions are more dangerous.

The purpose of this paper is to provide evidence-based recommendations of which simple observations made during a backcountry journey in avalanche terrain are most appropriate to localize the avalanche danger under different avalanche scenarios. Since the risk of avalanche depends on the predominant avalanche

Table 1. Avalanche scenarios included in this study. Descriptions after Atkins (2004) and Haegeli (2010).

Slab Avalanche Scenario	n (days)	Description	Frequency (Relative)	Consequence (Relative)
Deep	17	Thick, hard slab and persistent weak layer buried near the base of snowpack. May be dormant for weeks and months, and may require only light triggers to release very large dangerous avalanches. Very difficult to predict.	Low-Moderate	Very High
Persistent	82	Slabs generally less than 1 m thick, and persistent weak layers buried in the upper to mid-snowpack. Responsible for most fatal avalanche accidents. May release sporadically, with light triggers, or during changes in weather.	High	High
Storm	18	Soft but cohesive slabs of fresh snow, where weak layer is within or at base of fresh storm snow. Tend to stabilize quickly, so avalanching peaks during a storm, and tapers off shortly after.	Low-Moderate	Moderate
Wind	42	Cohesive slab of wind-deposited snow over an underlying weak layer or interface. Tend to be spatially variable, but usually found in alpine and treeline areas, next to ridges, ribs, etc.	Moderate	Low

scenario, so should the factors governing recreational decision-making.

We expect that different field observations correlate better with local danger under different avalanche scenarios. The observations or signs preferred by experts are likely related to the mechanisms of triggering and release of the different avalanche types, e.g. recent snowfall amounts when *storm* avalanches are of most concern, or signs of fracturing for *persistent* avalanches, although we are aware that with experience comes a tacit understanding of the avalanche phenomenon that may be difficult or impossible to quantify.

2 METHODS AND DATA

University of Calgary avalanche research (ASARC) field workers collected data for this study during the winters of 2009 and 2010. Field workers all had extensive technical avalanche training, and were qualified to make field observations and provide expert-level local danger ratings. For this study, observations and danger ratings were made on over 175 days in the Coast, Columbia, and Rocky Mountains of British Columbia and Alberta. We filtered the dataset to omit days with wet or loose snow avalanches as a primary avalanche problem, leaving 159 days available for analysis. On each of these days, field teams identified the avalanche scenario(s) that most influenced the local danger rating. In the case of a tie between two scenarios we chose as the primary one the scenario listed first. Each field worker rated the local avalanche danger according to Canadian standards (Canadian Avalanche Association 2007) for three elevation bands (below treeline, treeline, alpine). These ratings were based on *all* available information, including: discussions with colleagues at a morning meeting, recent observations shared by neighbouring operations, recent and current snowpack, weather, and stability observations, snowpack tests, etc. This cumulative process for rating the local danger is important, although only usually possible within professional operations. While travelling to a major decision-point in their trip, usually near treeline (on skis or occasionally by snowmobile or helicopter), workers made a standard set of about 25 observations (see Jamieson et al. 2010b for more details). Following completion of other research priorities, workers travelled back to the trailhead and continued making observations. At the end of the day, they rated the local danger again.

The data were grouped into the four prominent dry slab avalanche scenarios: *deep persistent, persistent, storm, wind.* Table 1 summarizes the scenarios and data used for this study. Within each group, for the local danger we chose the most conservative (highest danger) rating for treeline at the end of the day. This is expected to maximize the number of observations available for analysis, and the end of day rating includes influences from other observations made throughout the day (e.g. snow profiles, snowpack tests, etc). In a few cases, the local danger was not specified for treeline at the end of day, so instead we used the end of day below treeline (n = 5) danger, the mid-day below treeline rating (n = 2), or the mid-day treeline rating (n = 8). Ratings were converted to ordinal scale from 1 to 5, corresponding to increasing local danger.

Each of the observation variables has an implied or expected monotonic relationship with avalanche danger. Values for most were converted to ordinal scale with increasing values expected to relate to higher danger (Table 2). For several intrinsically ratio-scale variables (e.g. recent snowfall, crust thickness etc.) we used the raw data. For most of the variables, we chose the maximum value observed, regardless of whether it was a mid-day or end of day observation. We combined all avalanche observations into two categories (slab, loose) regardless of their trigger or timing. Table 2 summarizes the field observations and their treatments.

We used the non-parametric Spearman rank correlation to test the relationship between the field observations and the local danger under each scenario. The correlation coefficient (R) ranges from -1 (perfect negative correlation) to 0 (no relationship) to 1 (perfect positive correlation). Significance of R refers to the probability (p) that the observed relationship arose in the sample by chance. For this study, significant correlations have $p < 0.05$. Note that the local danger is considered the independent variable in this study, and we test which field observations are most dependant on it under different avalanche scenarios. The expert-rated local danger incorporates the field observations, but it is not based primarily on them (Jamieson et al. 2009b).

3 RESULTS

Table 3 shows the Spearman rank correlation coefficients and significance for each variable under each scenario. Significant ($p < 0.05$) correlations are marked in bold, and highly significant ($p < 0.01$) are marked in bold and italic.

When the *deep* slab avalanche scenario was the main problem, two observations had highly significant correlations with local danger: snow clumps falling from trees (R = 0.87), and snow height in the last 24 hours (R = 0.65). These are also both relatively strong, positive correlations, which means that more snow was observed falling from trees and more snow fell in the previous 24 hours during periods of higher danger. Significant correlations were deposits of drifted snow (R = 0.54) and 48 hour snowfall (R = 0.52). Again, these were both positive and relatively strong correlations.

Four observations had highly significant correlations with local danger when *persistent* avalanches were the main concern: average ski penetration (R = 0.44), recent slab avalanches (R = 0.42), 48 hour snowfall (R = 0.34), and hand shear resistance (R = 0.34). While not strong, these were all positive correlations. Significant correlations were also found between local danger and shooting cracks or whumpfs (R = 0.28), pinwheeling (R = 0.23) and

Table 2. Variables and definitions observed in this study in this study. See Jamieson et al. (2010b) for more detail.

Variable	Description (values expected to relate to increasing danger)
Local Danger	(Low, moderate, considerable, high, extreme)
Avalanche observations	
Recent loose avalanches(s)	(None, 1, 2, 3+)
Recent slab release(s)	(None, 1, 2, 3+)
Shooting cracks, 'whumpfs'	Observations of weak layer fracture propagation without avalanche release, suggests avalanching possible (None, 1, 2, 3+)
Snow surface cracks at skis	Suggests 'slab' present (None, Occasional, Frequent)
Passive snowpack observations	
Pinwheeling (today)	Moist surface clumps rolling/snowballing down slopes (0, 1-2, 3+)
Snow clumps falling from trees	'Tree bombs', when accumulated snow on coniferous branches is shed, usually during windy and/or warm weather (None, Occasional, Frequent)
Deposits of drifted snow	(None, 24-48 hrs old, <24 hrs old)
Thickness of surface crust	Thickness in cm (decreasing)
Overnight freeze after thaw	(No thaw, yes, no)
Blowing snow	(None, at ridge, below ridge)
Wind scouring/sastrugi	(None, 24-48 hrs old, <24 hrs old)
Active snowpack observations	
Avg. ski penetration	Average skier standing still, in cm (increasing)
Ski pole probing in top 50 cm	(increasing resistance, buried crust, hard over soft = obvious weak layer)
Hand shear resistance	Qualitative testing of the bond of near surface slab and weak layers (no result, hard, moderate, easy)
Hand shear depth	Depth of failure plane in cm (increasing)
Weather observations	
Cloud cover	(Clear, few, scattered, broken, overcast, obscured)
Typical ambient wind speed	(Calm, low, moderate, strong, extreme)
Snowfall rate	cm/hour (none, <1, 1, 2, 3+)
Snow height last 24 h	cm (increasing)
Snow height last 48 h	cm (increasing)
24 h change in max air temperature	°C, increase positive, decrease negative (increasing)
Air temp to 0°C	(no, yes)

observations of air temperature rising to 0°C (R = -0.23). Of these, only the latter shows a negative correlation with local danger, so lower danger was associated with air warming to 0°C.

When the main problem facing observers was the *storm* avalanche scenario, one variable had a highly significant correlation with local danger: snowfall rate (R = 0.69). Three others had significant correlations: 48 hour snowfall (R = 0.57), air temperature warming to 0°C (R = -0.57), and cloud cover (R = 0.49). In the *storm* scenario group, all of the significant correlations are relatively strong; however, as in the *persistent* group, temperature rising to 0°C is a negative correlation with local danger.

Five variables correlate significantly with local danger in the *wind* slab group. Average ski penetration (R = 0.58) and 48 hour snowfall (R = 0.44) had highly significant correlations with local danger, while 24 hour snowfall (R = 0.33), air temperature warming to 0°C (R = -0.33), and thickness of surface crust (-0.31) had significant correlations. The ski penetration and 48 hour snowfall were strong and positive, and the 24 hour snowfall was also positive. The others were negative, so days with thinner crusts or warming to 0°C were observed more often during lower local danger.

We also combined the data from days with the *deep* scenario dominating local danger with the data from days with a *persistent* scenario. We felt that this was important, given the fact that no established or de facto threshold exists where a *persistent* avalanche becomes a *deep* one, and field observers and forecasters may not agree on which scenario is prevalent. The correlations are included in Table 3. Significant correlations were similar to those found in the two constituent groups, although one additional significant but weak variable is added: snow surface cracking at skis (R = 0.20).

4 DISCUSSION

4.1 Non-specific correlations

The 48-hour snowfall height had a relatively strong correlation with local danger in all scenarios included in this study, meaning that more snow was associated with higher local danger, independent of the particular problem or scenario. This is not surprising, as avalanche activity of all types is known to peak during or shortly after snowfall events. Two days worth of new snow may overload any weak layers in the snowpack, stormy periods are often associated with strong winds and transportable snow, and accumulations of storm snow are required for the *storm* scenario to dominate.

The air temperature warming to 0°C had a significant negative correlation with local danger in all but the *deep* scenario; it was strongest in the *storm* group, and weaker yet significant in the *persistent* and *wind* group. The effect of warm, above freezing air on the snowpack is known to both enhance stability (e.g. by homogenizing snowpack layers via equilibrium metamorphism over time) and reduce stability (e.g. by reducing the stiffness of slab layers in the short term, and thereby increasing the penetration depth of skier induced stresses and natural creep rates; McClung and Schaerer 2006, p. 97-98), particularly of near-surface layers. In this study the stabilization effects of warming were more prominent, since for shallower slab scenarios warming to the freezing point was related to lower local danger. Short term warming of the air would likely have no impact on the

Table 3. Spearman rank correlation coefficients (R) between observations and local danger rating for each avalanche scenario. Valid cases (n) and significance (see footnote) are indicated.

	Deep		Persistent		Storm		Wind		Deep & Persistent	
	n	R	n	R	n	R	n	R	n	R
Avalanche observations										
Recent loose avalanches(s)	17	~	82	-0.19	18	0.05	42	0.07	99	-0.14
Recent slab release(s)	17	0.40	82	***0.42***[1]	18	0.32	42	0.28	99	***0.42***
Shooting cracks, whumpfs	17	0.27	82	**0.28**[2]	18	0.38	42	0.12	99	***0.30***
Snow surface cracks at skis	17	0.05	82	0.21	18	-0.13	42	0.26	99	**0.20**
Passive snowpack observations										
Pinwheeling (today)	17	0.45	82	**0.23**	18	0.29	42	0.04	99	***0.26***
Snow clumps falling from trees	17	***0.87***	82	0.17	18	0.31	42	0.17	99	***0.29***
Deposits of drifted snow	17	**0.54**	82	0.06	18	0.21	42	0.03	99	0.14
Thickness of surface crust	17	-0.26	82	-0.11	18	~	42	**-0.31**	99	-0.16
Overnight freeze after thaw	17	-0.35	82	0.09	18	-0.38	42	-0.09	99	0.05
Blowing snow	17	0.44	82	0.05	18	0.32	42	-0.07	99	0.12
Wind scouring/sastrugi	17	-0.45	82	0.04	18	-0.08	42	-0.04	99	-0.05
Active snowpack observations										
Avg. ski penetration	17	0.36	82	***0.44***	17	0.46	42	***0.58***	99	***0.44***
Ski pole probing in top 50 cm	17	0.13	82	-0.13	18	-0.28	42	-0.08	99	-0.08
Hand shear resistance	16	0.40	79	***0.34***	17	0.22	42	0.11	95	***0.35***
Hand shear depth	13	0.19	72	0.15	14	-0.12	36	0.32	85	0.16
Weather observations										
Cloud cover	17	0.43	81	0.08	18	**0.49**	42	-0.05	98	0.15
Typical ambient wind speed	17	0.41	82	0.02	18	0.22	42	0.00	99	0.11
Snowfall rate	17	0.29	82	0.06	18	***0.69***	41	0.29	99	0.11
Snow height last 24 h	17	***0.65***	82	0.07	18	0.42	42	**0.33**	99	0.17
Snow height last 48 h	17	**0.52**	82	***0.34***	18	**0.57**	42	***0.44***	99	***0.38***
24 h change in max air temperature	17	0.20	80	0.14	18	-0.06	42	-0.04	97	0.13
Air temp to 0°C	17	-0.35	82	**-0.23**	18	**-0.57**	42	**-0.33**	99	**-0.24**

[1]Correlatons marked in bold and italic are significant with $p < 0.01$

[2]Correlations marked in bold are significant with $p < 0.05$

lower part of the snowpack (Schweizer and Jamieson 2010; Bakermans and Jamieson 2009), which may explain why this variable was not correlated with danger in the *deep* group. The expert interpretation of warming may relate mostly to the first day it occurs, and usually with fresh snow on the surface. Of course, some key factors are probably not captured by the simple observations in this study.

The 24-hour snowfall was correlated significantly with avalanche danger in two groups (*deep and wind)*. This, combined with the observation that it was not significantly correlated in the other two groups is difficult to explain with physical arguments; it is possible that only when considered as part of a set of observations does the 24-hour snowfall value become meaningful.

4.2 Scenario-specific correlations

4.2.1 Deep

In order of strength of the significant correlations, the observations associated with higher local avalanche danger when *deep* avalanches were of most concern were more snow clumps falling from trees (also known as 'tree bombs'), deeper 24 hour snowfall, more recent deposits of drifted snow, deeper 48 hour snowfall.

Snow clumps falling from trees typically occurs during periods of warming or windy weather, usually the first time such conditions appear after several winter storms. A causal relationship to deep slab avalanching is not expected (e.g. triggering of slopes by falling clumps); however, the correlation is very strong and highly significant, and some connecting process may exist. For example, under the same conditions cornices may be expected to fail and trigger large slopes. Note that in this study, deep slab avalanching was not necessarily observed, but local avalanche danger was rated higher at times when 'tree bombs' were falling and observers were concerned with a *deep* slab problem.

The variables related to drifting snow and snowfall totals suggest that the local danger was higher when additional loads were added to a potentially unstable snowpack. A direct causal relationship is expected between loading and deep slab avalanche release, although deep slabs often 'surprise' forecasters and professionals during periods of apparently fair weather.

4.2.2 Persistent

In order of strength of the significant correlations, the observations associated with higher local avalanche danger when *persistent* avalanches were of most concern were higher average ski penetration, more frequent recent slab avalanches, deeper 48 hour snowfall, less hand shear resistance, more whumpfs and shooting cracks, more pinwheeling, and no warming to 0°C.

The five strongest correlations are related to either the condition of the slab, the weak layer, or both together. Higher average ski penetration may be related to recent snowfall totals, since skis penetrate deeper in softer (usually fresher) snow or to the potential thickness of a slab over a weak layer as settlement occurs. Similarly, higher loads on the weak layer and potentially thicker slabs would be related to deeper 48 hour snowfalls. Observations of slab avalanches are a clear indicator of unstable conditions, as are whumpfs and shooting cracks. Each of these correlations are expected to have a physical relationship with more likely avalanche release, and therefore local danger.

The relationship of more pinwheeling yet no warming to 0°C appearing together is problematic as they seem contradictory, i.e. pinwheeling requires a moist or wet surface, and warming to 0°C would tend to cause that. Further exploration of the data show that it was usually snowing and overcast when pinwheels were observed, and in all but one case clumps of snow were falling from trees. Further exploration here is not warranted, as we have few data with observed pinwheeling and we may be observing the effects of an unbalanced dataset.

4.2.3 Storm

In order of strength of the significant correlations, the observations associated with higher local avalanche danger when *storm* avalanches were of most concern were higher snowfall rate, deeper 48 hour snowfall, no warming to 0°C, and increasing cloud cover.

The important variables in the *storm* group were all related to loading by storm snow, as would be expected. The rate of snowfall at the time of the observation was best correlated with local danger, while the others suggest that longer winter stormy periods occur during higher danger when instabilities in storm snow are of concern. Rapid snowfall is known to trigger avalanches within the storm snow, while 48 hour snowfall, cloudy skies, and no warming to 0°C all relate to periods of winter storms. As expected, variables related to stormy weather are observed more when the local danger due to *storm* snow avalanches is higher.

4.2.4 Wind

In order of strength of the significant correlations, the observations associated with higher local avalanche danger when *wind* avalanches were of most concern were higher average ski penetration, deeper 48 hour snowfall, deeper 24 hour snowfall, no warming to 0°C, and thinner surface crusts.

We expected that during times of *wind* slab problems, observations related to wind would be best correlated with local danger, e.g. deposits of drifted snow, blowing snow, wind speed, etc. However, none of these had significant correlations. In fact, we found that all of the significant correlations were also significant in the *persistent* group, with the notable exception of thinner crusts. One possible explanation for the poor group discrimination and an apparently unrelated correlation (surface crusts) is that most of the backcountry journeys for this study were limited to treeline or sub-alpine elevations, where wind effects are less prominent. Often the terrain features most susceptible to the development of *wind* slab problems are steep, exposed, or otherwise inaccessible during conservative field work. Therefore, the workers may have been most concerned about a *wind* slab scenario on a given day, but were unable to make the type of observations that might have the expected correlations with local danger.

4.2.5 Deep and Persistent

When we tested correlations between the observations and local danger for the *deep* and *persistent* groups together, we found nine variables with significant correlations. Figure 1 shows that at least 64% (to a maximum of 74%) of fatal, recreational avalanche accidents occurred because of *deep* or *persistent* avalanches. Given this prevalence, as well as the prevalence of these two scenarios in the current dataset, forecasters may suggest that backcountry travelers focus on the following observations as indicators of higher local danger on most days that persistent weak layers are known to be buried in the snowpack (listed in order of strength of significant correlations): increasing average ski penetration, more frequent recent slab avalanches, deeper 48 hour snowfall, lower hand shear resistance, more frequent whumpfs or shooting cracks, more frequent snow clumps falling from trees, more pinwheeling, no warming of the air to 0℃, and more common snow surface cracks at skis.

While this list may be intractable given its length and complexity for inclusion in a public avalanche bulletin, a few of the observations on this list are fortunately already recommended to recreationists: the Avaluator decision-support tool (Haegeli 2010) lists recent slab avalanches, signs of instability (i.e. whumpfs, instability tests, cracking), recent loading (i.e. 48 hour snowfall) as key warning signs for avalanche danger. The Avaluator tool also includes critical warming to 0℃ as a warning sign, but with the reverse relationship as found here, i.e. warming means higher danger. In any case, it may be appropriate to avoid the long list of combined variables in this group in favour of a more focused, scenario-specific approach. In that way, the recommendations of the forecaster and those of other tools or products would not be in conflict.

4.3 Limitations

The first and most important limitation of this study is that it is a preliminary analysis, with limited and often unbalanced data, although many of our findings are supported by physical arguments or the findings of other studies.

The set of observations with relatively strong, significant correlation with local danger under each scenario are not meant to be an exclusive list that recreationists should follow, and ignore all other factors. They are simply those that *could* receive particular attention by recreationists in order to localize the avalanche danger.

In this study, we chose to focus on one dominant avalanche scenario per day; however, on most days the public avalanche bulletin lists two or more scenarios that a recreationist could encounter in the field. As such, it is vital that backcountry recreationists recognize that on any given day they may be tasked with managing more than one avalanche problem and that a combination scenario requires more numerous observations and more difficult decision-making.

One further limitation of this study is that it is applicable to recreational backcountry travel and amateur decision-making in the Coast, Columbia, and Rocky Mountains of western Canada, although data from the Rocky Mountains and Coast Mountains are limited. Late-season observations are also limited, which may at least partly explain some surprising results for warm conditions (e.g. pinwheeling, surface warming). We did not consider the avalanche danger and scenarios affecting transportation, energy, or utility corridors, property, or other persons (e.g. public, workers, etc.).

5 CONCLUSIONS

Our results suggest that:

- A small number of field observations correlated with local avalanche danger in more than one scenario. In particular, deeper 48-hour snowfall was correlated with higher avalanche danger under every scenario;
- A unique set of four to seven field observations correlated with local danger under each of the four different avalanche scenarios we studied;
- Combining two of the most common and dangerous scenarios simply expanded the list of correlated observations, which was close to recommendations provided by some decision-support tools;
- The significant negative correlation between air temperature warming to 0℃ and local danger is counter-intuitive and opposite to the recommendation by decision-support tools. This may be a peculiarity of our sample rather than a true effect.

We have identified evidence-based recommendations of which simple observations made during a backcountry journey in avalanche terrain are most appropriate to localize the avalanche danger under different avalanche scenarios. These could help avalanche forecasters instruct users of public avalanche warnings or bulletins on which observations to pay most attention to in the field; however, no recommendation or decision-support tool can reduce the risk of avalanche to zero, nor replace training, experience, and sound judgement.

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