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Field observations for estimating the local avalanche danger in the Columbia Mountains of Canada

Bruce Jamieson [a,b,*], Pascal Haegeli [c,d], Jürg Schweizer [e]

[a] Department of Civil Engineering, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada T2N 1N4
[b] Department of Geoscience, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada T2N 1N4
[c] REM, Simon Fraser University, Burnaby, BC, Canada
[d] Avisualanche Consulting, Vancouver, Canada
[e] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

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ABSTRACT

Snow avalanche danger can vary considerably within the forecast regions, especially large regions. Experienced recreationists routinely use the regional forecast along with local observations to estimate the local avalanche danger. However, some less experienced recreationists are unsure how to interpret the various field observations. To assess a systematic approach, we conducted a field study during the winters of 2006–07 and 2007–08 in the Columbia Mountains of western Canada. Experienced observers rated the local avalanche danger and made 24 observations of weather, avalanche activity and simple manual snowpack tests on approximately 130 location-days. Since the local danger was often rated separately for the elevation bands alpine, treeline, and below treeline, the observations could be applied to 272 individual local danger ratings. Fourteen of the potential predictors yielded significant rank correlations with the local avalanche danger. Reflecting their larger scale, many of the weather variables correlated better with the regional danger forecast than with the local rating. In contrast, some snowpack observations including the hand shear and ski pole test correlated better at the local scale than the regional scale. Classification trees using the regional rating plus three of the local observations exhibited a better agreement with the local danger rating than did the regional rating by itself.

1. Introduction

Regional avalanche bulletins generally provide an expert assessment of the avalanche danger in a given forecast region. However, the regional danger is a forecast that can differ from the local danger when traveling in the backcountry—which needs to be assessed. Several factors can contribute to a difference between the local nowcast and the regional forecast:

- the avalanche danger is spatially variable (e.g. Schweizer et al., 2008),
- large forecast regions do not allow specifying the danger in more detail, so that local avalanche danger can vary considerably within these regions (Jamieson et al., 2008a),
- the relevant and/or accurate data, including weather and snowpack data, might not have been available at the time of the forecast,
- imperfect assessment of current and future weather and snowpack conditions by forecasting models and human forecasters, and
- in some areas the bulletin is not published on a daily basis, so that there is the potential for the avalanche danger to have changed since the bulletin was published.

During a typical day of backcountry snowmobiling, snowboarding or ski touring, recreationists are exposed to avalanche paths within an area of roughly 10 km^2. Although snowmobilers can cover much more distance than people on touring skis or split snowboards, in the Columbia Mountains many snowmobilers make valley bottom approaches along snow roads with few avalanche paths. Their main exposure to avalanches is often at the head of the valley where they spend much of the day. Hence, the rough estimate of 10 km^2 does not differ substantially for motorized and non-motorized recreation. (Examples of trips in the Columbia Mountains which are popular with snowmobilers, skiers and snowboarders are listed under Trip Planner at www.avalanche.ca).

It seems reasonable for recreationists traveling in the backcountry to use the regional forecast as initial estimate of the local avalanche danger in the area of the day's recreation. For low risk travel it is essential to check whether the danger as forecasted prevails [also called verification of the bulletin]. However, verification is usually difficult, requires expert knowledge and often observing snow profiles as well as performing stability tests (e.g. Schweizer et al., 2003). In

* Corresponding author. Department of Civil Engineering, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada T2N 1N4. Tel.: +1 403 220 7479; fax: +1 403 282 7026.
E-mail address: bruce.jamieson@ucalgary.ca (B. Jamieson).

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general, to assess the local avalanche danger during a backcountry trip, recreationists have three potential sources of information:

a. the regional avalanche bulletin (where available)
b. various local weather, snowpack and avalanche observations that do not require digging a pit, and/or
c. snowpack observations, notably stability tests, that do require digging one or more pits.

Whereas avalanche educational books emphasize many qualitative indicators of instability, there is little guidance available for recreationists how to weigh these factors and adjust the regional forecast. Munter (2003) proposed that at least Considerable avalanche danger should prevail when either a critical amount of new snow (about 20–50 cm depending on conditions) is reached or when whumpfs, shooting cracks or recent avalanche activity are observed. Remotely triggered avalanches would indicate High danger. Schweizer (2003) made an attempt to relate the frequency of signs of instability to the danger levels Moderate, Considerable and High.

Our objective was to identify observations that could be used, in combination with the forecasted regional danger level, to estimate the local avalanche danger during a day of backcountry recreation in the Columbia Mountains of western Canada.

This study was conducted in the Columbia Mountains, which have a transitional snowpack with a maritime influence in which the midwinter snowpack at treeline is often about 3 m thick. Every winter, surface hoar (frost) buried by subsequent snowfall results in several persistent snowpack weaknesses in the Columbia Mountains (Haegeli and McClung, 2007).

While the study of Jamieson et al. (2006) focused on the value of stability tests that require digging, this study examines the value of various simple weather, snowpack and avalanche observations, which do not require digging, for estimating the local avalanche danger in area where a regional bulletins is available.

Jamieson et al. (2008b) presented an analysis of observations from treeline and below treeline areas in the Columbia Mountains during the winter of 2006–07. For the winter of 2007–08, the study was expanded to include alpine areas above treeline. In this paper, we analyze the data from the Columbia Mountains during winters of 2006–07 and 2007–08.

2. Dataset

2.1. Regional danger ratings

Regional avalanche bulletins in western Canada include danger ratings and several short paragraphs of text. The text typically explains

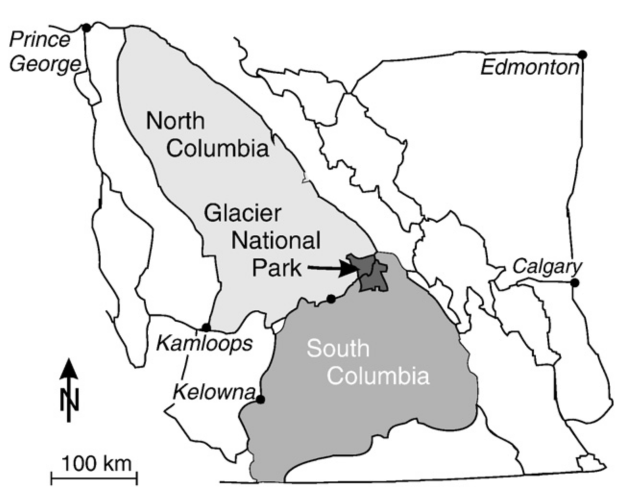

Fig. 1. Avalanche bulletin regions in which the observations were made.

Table 1
Summary of data for local nowcasts and regional forecasts.

Number of cases (Alp/TL/BTL)	Sites for local nowcasts	Forecast region (Fig. 1)
4 (0/2/2)	North Purcell Mountains	South Columbia Mountains
130 (3/54/73)	Cariboos near Blue River, BC	North Columbia Mountains
138 (21/56/61)	Highway corridor in Glacier National Park	Highway corridor in Glacier National Park

how the weather and snow conditions are contributing to the avalanche danger and discusses the avalanche danger in terms of the terrain. The forecast (or bulletin) rates the regional avalanche danger (RF) as either Low (1), Moderate (2), Considerable (3), High (4) or Extreme (5) (Dennis and Moore, 1996). One difference between European and Canadian definitions of the five danger levels, is that Canadian definitions refer only to the probability of avalanches and make no reference to the expected size of avalanches. In western Canada, ratings are published for three elevation (vegetation) zones: below treeline (BTL), treeline (TL) and alpine (Alp).

In western Canada, forecast regions vary from 100 km^2 to about 25,000 km^2 (Jamieson et al., 2008a). The largest regions are approximately 2500 times larger than the scale of a ski tour, which is approximately 10 km^2. In the winters of 2006–07 and 2007–08, we made local observations in the forecast regions for the North Columbia Mountains (24,000 km^2), Glacier National Park (450 km^2) and the South Columbia Mountains (25,000 km^2), as shown in Fig. 1 and summarized in Table 1. For the analysis we used the latest regional danger rating available to recreationists in the morning of the observation day. Glacier National Park produces a daily bulletin in the mornings. In the North and South Columbia Mountains, the bulletin was often published 1 to 2 and occasionally 3 days before the field observations and rating of local avalanche danger. Jamieson et al. (2008a) showed the agreement between the regional danger rating and the local danger rating increased as the lead time for the regional bulletin decreased or the forecast area decreased.

2.2. Simple field observations

There are many simple weather, snowpack and avalanche observations that are potentially relevant to assessing the local avalanche danger. For this study, we focused on variables (Tables 2 and 3) based on their inclusion in avalanche books for recreationists (e.g. Tremper, 2001, pp. 88–170; McClung and Schaerer, 2006, pp. 197–206), and their ease of observation. Values were assigned to achieve repeatable observations by different observers, or, in few cases, based on observation guidelines (Greene et al., 2004; Canadian Avalanche Association, 2007). Observers were trained in all procedures and provided with custom field books that specified the acceptable observations as summarized in Table 2. For all but the categorical variable for snow surface condition, we ordered the values or levels based on their expected correlation with avalanche danger. For example, when probing the top 50 cm of the snow surface with a ski pole, gradually increasing resistance is rarely associated with slab avalanching, a sudden increase in resistance due to a buried crust is sometimes associated with slab avalanching, and feeling decreasing resistance indicative of hard layers over softer layers is more often associated with slab avalanching.

The rightmost column of Tables 2 and 3 shows the data type: categorical, ordinal or ratio. Although SkiPen, PrecipRate, HN24, HN48 and TempTr24 have the ratio and hence interval property (meaning it is possible to measure the difference between values), we analyzed them as ordinal variables because their values were estimated and for consistency with the analysis of other variables.

A few of the variables in Tables 2 and 3 deserve some explanation. A whumpf is an audible collapse of the snowpack typically induced by movement of a person or oversnow machine. It occurs under similar

Table 2
Avalanche and snowpack observations.

Variable name	Description	Values	Data type[a]
Avalanche observations			
LoosAvCur[b]	Loose release(s)	None, one or more	Ordinal (+)
SlabAvCur[b]	Slab release(s)	None, one or more	Ordinal (+)
LoosAvRec[b]	Deposit from loose avalanche	None, 24–48 h old, <24 h	Ordinal (+)
SlabAvRec[b]	Deposit or crown from slab avalanche	None, 24–48 h old, <24 h	Ordinal (+)
Passive snowpack observations			
HN24	Height new snow, last 24 h	cm	Ratio (+)
HN48	Height new snow, last 48 h	cm	Ratio (+)
Refreeze	Snow surface refreeze since thaw on previous day	Yes, no	Ordinal (+)
Whumpf[b]	Shooting cracks, whumpfs	None, one or more	Ordinal (+)
Crack[b]	Snow surface cracks at skis	None or rarely, common	Ordinal (+)
PinWheel[b]	Pinwheeling (today)	None, one or more	Ordinal (+)
TreeBomb[b]	Snow clumps falling from trees	None, one or more	Ordinal (+)
Drifts[b]	Deposits of drifted snow	None/old, 24–48 h, <24 h	Ordinal (+)
Scour[b]	Wind scouring/sastrugi	None, one or more affected area/patch	Ordinal (+)
SurfCond	Snow surface condition	Dry fresh, dry settled refrozen crust, wet coarse, sticky, wind affected	Categorical
CrustThick	Thickness of surface crust	cm (0 if no surface crust)	Ratio (+)
Active snowpack observations			
SkiPen[b]	Avg. ski penetration	cm	Ratio (+)
PoleProbe[b]	Ski pole probing in top 50 cm	Gradually increasing resistance, buried crust, hard over softer layer	Ordinal (+)
HShearR[b]	Hand shear resistance	Easy, moderate, hard, no fracture	Ordinal (−)
HShearDep[b]	Hand shear depth	cm	Ratio (+)
HShearCh[b]	Hand shear character	No planar fracture, resistant planar fracture, sudden planar fracture	Ordinal (+)

[a] Sign in brackets indicates sign of expected correlation.
[b] Recorded after the ascent to the decision point and at the end of the day.

snowpack and loading conditions as cracks that shoot out from the skis (Fig. 2). Both these phenomena indicate that the properties of the slab and underlying weak layer are favourable to propagating fractures in the weak layer (van Herwijnen and Jamieson, 2007). In contrast, cracking at skis indicates that the snow surface layer is cohesive and stiff but does not indicate the presence of a critically weak layer. Pinwheeling occurs when a small volume of moist or wet surface snow rolls downslope accumulating a spiral shape or "pinwheel" (Fig. 3).

A hand shear test (e.g. Tremper, 2001, p. 146–147) is a simple test in which a column, with a cross section about 30 cm by 30 cm, is manually isolated about 40 cm deep; a slope parallel force is manually applied to create slope parallel fractures ("shears") in known or unknown weak layers (Fig. 4). The force to cause a fracture is subjectively rated as easy, moderate or hard (Table 2). For this study, we also noted the character of the fractures, i.e. whether the fractures were planar or not.

2.3. Rating the local danger

On each day of field observations, a team of two or three skilled observers traveled on touring skis for at least 15 and sometimes more than 60 min to a relatively sheltered opening in the forest below or at treeline, conducting simple weather, snowpack and avalanche observations as they travelled. To simulate the site selection of recreationists, the field teams tried not to use local knowledge or expert site selection. At the sheltered site, they recorded the active snowpack observations listed in Table 2. Also at this site, a snow profile was often observed and stability tests conducted as described in Jamieson et al. (2006). From this decision point, the team sometimes continued to travel on touring skis into terrain more exposed to avalanches, typically above treeline. In addition, the team had access to weather, snowpack and avalanche observations from the hosting operation and from neighboring avalanche safety programs. Further, the field observers were working regularly in the area, accumulating their knowledge of the avalanche conditions over the winter.

Using all available information, the field team agreed on a danger rating for the local drainage and the current day, called the "local nowcast" (LN). The local ratings of avalanche danger used the same five-level scale and definitions as the regional danger ratings (Dennis and Moore, 1996). In the winter of 2006–07, these local danger ratings were recorded for the treeline elevation band where the forest opens (TL) and below treeline (BTL), provided both could be done with confidence. In

Table 3
Weather observations.

Variable name	Description	Values	Data type[a]
SnowfallRate[b]	Snowfall rate	0, <1, 1, 2, 3+ cm/h according to CAA (2007)	Ordinal (+)
WindSpeed[b]	Typical ambient wind speed	Calm, light, moderate, strong/ extreme; according to CAA (2007)	Ordinal (+)
SnowBlow[b]	Blowing snow	None, at ridges, below ridges,	Ordinal (+)
Sky	Cloud cover	Clear, few, scattered, broken, overcast/obscured	Ordinal (+)
TempTr24	24 h change in max air temperature	°C	Ratio[c] (+)
TempTrTdy	Daytime temp. increase	<normal, normal, > normal[d]	Ordinal (+)
ReachZero	Air temp to 0 °C	No, yes	Ordinal (+)

[a] Sign in brackets indicates expected sign of correlation.
[b] Recorded after the ascent to the decision point *and* at the end of the day.
[c] Ratio variable but the values were estimated and hence the variable was treated as ordinal for analysis.
[d] <normal, or >normal implies unusual or anomalous.

Fig. 2. Photograph of a crack that suddenly shoots out from a ski. This indicates the presence of a slab and weak layer both of which are favourable to skier-triggered slab avalanches.

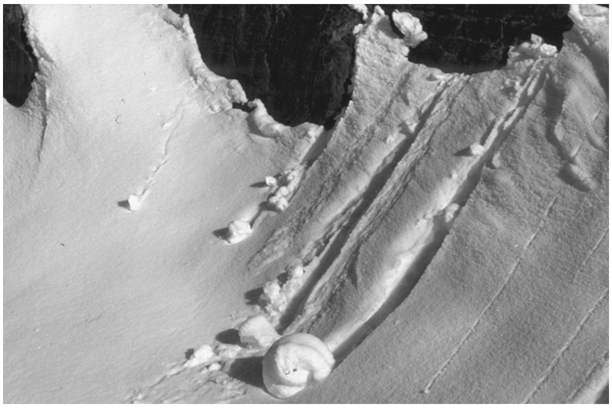

Fig. 3. Pinwheels: rolls of moist or wet surface snow on a slope.

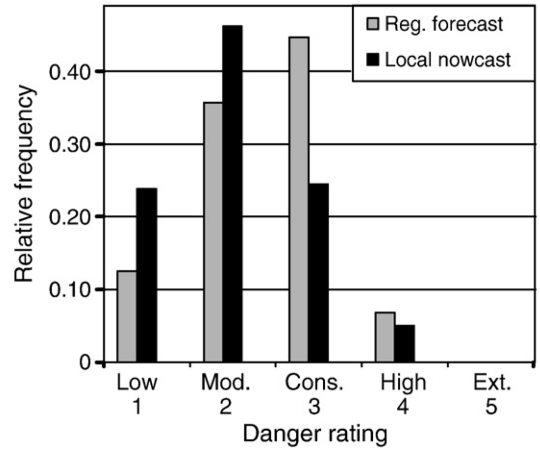

Fig. 5. Relative frequencies of regional and local avalanche danger rating.

the winter of 2007–08, the local danger in the alpine (Alp, above tree line) was also rated if it could be done with confidence. Where one or more of the team members had travelled by touring skis and made observations in the preceding day or two in a specific elevation zone, confidence was usually high and consequently the local danger was rated for the elevation zone. During the two winters, the local danger was rated for the below treeline zone (BTL) on 136 of 140 field days (97%), and for the treeline zone (TL) on 112 of 140 field days (80%). In the second winter, the local danger was rated for the above treeline zone (Alp) on 24 of 76 of field days (32%), reflecting the less frequent travel and observations above treeline.

In most days of winter backcountry recreation, groups ascend through terrain less prone or exposed to avalanches and then make a decision about whether to advance into more exposed avalanche terrain or remain in more sheltered terrain. To assess whether the early observations in less exposed terrain were as helpful as the subsequent observations, relevant observations were recorded at the decision point, which often occurred around 11 am, and again at the end of the day. Except for the analysis of the sufficiency of the decision point observations in Section 3.5, we used the combined morning (decision point) and afternoon observations, taking the value which indicated higher avalanche danger.

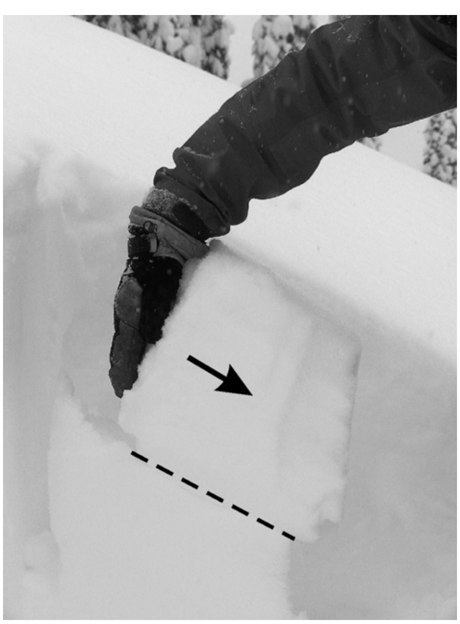

Fig. 4. Hand shear test. A column, approximately 30 cm by 30 cm, is isolated about 40 cm deep by hand or with a ski pole. The column is manually pushed downslope and any slope parallel fractures noted.

3. Results and analyses

3.1. Distributions of regional and local avalanche danger ratings

The distributions of the regional and local avalanche danger ratings for the 272 cases in this study are shown in Fig. 5. The regional danger rating was rated Considerable for 44% of the cases. This frequency is close to the long term frequency of 47% for the three vegetation zones combined in the North Columbia Mountains from 1996 to 2006 (Canadian Avalanche Centre data). While the local danger was rated Low or Moderate more often than the regional rating, the regional rating was rated High or Considerable more often. We suspect the generally higher ratings in the regional forecast are caused by the spatially limited

Table 4
Spearman rank correlations of potential predictors with local (LN) and regional avalanche danger ratings (RF).

Potential predictor		LN		RF	
	n	R_{LN}	p	R_{RF}	p
RF	272	**0.46**	10^{-15}	–	–
LoosAvCur	272	−0.06	0.31	**0.16**	0.01
SlabAvCur	272	**0.14**	0.02	0.08	0.19
LoosAvRec	272	0.06	0.31	**0.17**	10^{-3}
SlabAvRec	272	**0.29**	10^{-6}	**0.20**	10^{-3}
Whumpf	272	**0.34**	10^{-8}	**0.18**	10^{-3}
Crack	269	**0.28**	10^{-6}	0.08	0.21
PinWheel	272	0.03	0.59	0.04	0.50
TreeBomb	272	0.01	0.87	0.09	0.14
Drifts	265	**0.22**	10^{-4}	**0.22**	10^{-4}
Scour	272	0.01	0.85	−0.09	0.16
SkiPen	261	**0.18**	10^{-3}	**0.35**	10^{-8}
PoleProbe	272	0.08	0.17	−0.01	0.85
CrustThick	268	0.01	0.89	−0.08	0.19
HshearR	254	**0.22**	10^{-4}	0.01	0.81
HShearDep	226	0.07	0.26	0.09	0.18
HShearCh	191	**0.25**	10^{-3}	0.05	0.51
HN24	223	**0.35**	10^{-7}	**0.32**	10^{-6}
HN48	178	**0.38**	10^{-7}	**0.37**	10^{-7}
SnowfallRate	265	**0.20**	10^{-3}	**0.32**	10^{-7}
WindSpeed	271	0.09	0.13	0.04	0.52
SnowBlow	270	**0.14**	0.03	**0.19**	10^{-3}
Sky	255	**0.14**	0.03	**0.28**	10^{-6}
TempTr24	222	0.05	0.45	0.09	0.20
TempTrTdy	248	−0.06	0.33	0.00	0.96
ReachZero	248	**0.14**	0.03	0.07	0.27
Refreeze	259	0.00	0.99	0.02	0.78

Correlations for which $p < 0.050$ are marked in bold (although at most 2 decimal places are shown in the table).

data available to the regional forecasters, scale issues in the data (Haegeli and McClung, 2004) including the regional focus of the bulletin, the uncertain weather in the days following the publication of the regional forecast, focusing on the high use areas (where our teams made few observations), and perhaps "erring on the side of caution" by the public avalanche forecasters (Jamieson et al., 2008a).

3.2. Correlations of ordinal variables with LN

Avalanche danger and most of the potential predictors were analyzed as ordinal variables, with the exception of the categorical variable, SurfCond, for the snow surface condition. To assess associations between the ordinal predictor variables and the regional and local danger ratings we used the Spearman rank correlation coefficient *R* (e.g. Walpole et al., 2007, pp. 690–691). Moderate wind speed is often reported to transport more snow into release zones than higher wind speed (e.g. Tremper, 2001, pp. 96–97). However, graphs of LN against SnowBlow and WindSpeed (not included) did not show non-monotonic trends, perhaps because we had few observations of strong wind.

RF exhibited a stronger correlation with LN than any of the field observations (Table 4), indicating the value of the regional danger rating for assessing the local avalanche danger. Since none of the field observations exhibited a comparable correlation with LN, no single variable is a promising predictor of the local avalanche danger.

Based on Table 4, the following variables correlated equally or more strongly with RF than with LN: LoosAvCur, LoosAvRec, Drifts, SkiPen, SnowfallRate, SnowBlow and Sky. Also, HN24 and HN48 correlated almost as strongly with RF as with LN. Accordingly, these nine variables are not promising for estimating the local avalanche danger. The variables SnowfallRate, SnowBlow, Sky, HN24 and HN48 likely reflect regional scale weather processes which are usually well anticipated by regional avalanche forecasters.

For estimating the local avalanche danger, we selected the ordinal variables which correlated significantly with LN and for which $|R_{LN}| - |R_{RF}| > 0.05$ if R_{RF} is significant, otherwise for which $|R_{LN}| > 0.20$. This rule selects Whumpf, Crack, SlabAvRec, HShearR and HShearCh.

3.3. Univariate analysis of a categorical variable

In this section we analyze the categorical variable, SurfCond. The graph in Fig. 6 summarizes the LN values for SurfCond. The lowest median value of LN (1) is for a wet coarse-grained surface, whereas it is higher (2–2.5) for the other five classes. Also, there are substantial overlaps between the interquartile ranges for crust, sticky, wind-stiffened and dry fresh. A larger dataset—preferably including more observations during the spring—might reveal if wet coarse and perhaps settled snow is usually associated with lower levels of LN. However, with the data available in this study, the snow surface condition does not appear promising for estimating the local danger.

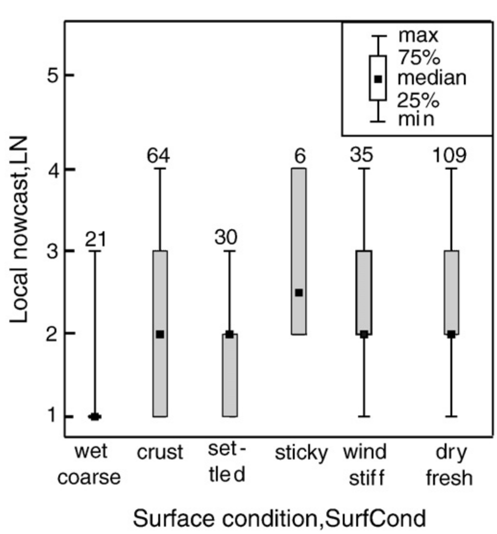

Fig. 6. Box and whisker plot of local avalanche danger for six classes of snow surface condition. The number of cases is shown above each of the box and whisker plots.

Although the variable Sky is ordinal since it represents increasing cloud cover, the amount of cloud cover may not have a monotonic relationship with avalanche danger. Overcast or obscured sky is common during precipitation, which is associated with avalanching, whereas clear sky is also sometimes associated with warming of the snow surface by short wave radiation and potential avalanching. A box plot (not shown) displayed an increasing trend in avalanche danger as cloud cover increased from Few clouds (FEW) to Overcast (OVC). However, the median avalanche danger was higher for Clear sky than for Few clouds. Had more observations been made in the spring when the short wave radiation during the longer days can potentially warm the snow surface more, it is possible that higher danger—especially above treeline—would have been associated with Clear sky or Few clouds. However, given its weak monotonic trend, we are satisfied with treating Sky as an ordinal variable (Table 4), and with its exclusion as a good predictor for estimating the local avalanche danger.

Table 5
Bias check for presence of reader in field team.

No. readers	*N*	Spearman rank correlation			Hit rate
		R	*t*	*p*	
0	212	0.45	7.32	$<10^{-6}$	0.40
>0	32	0.56	3.75	$<10^{-6}$	0.53

3.4. Observer bias

Some of the field teams included one or more persons who had read the regional bulletin before going into the field for the day, potentially biasing the rating of the local nowcast. Out of 244 cases for which the number of bulletin readers was recorded, one or more team members had read the bulletin in 32 cases. The results of the Spearman rank correlation between RF and LN as well as the hit rate for cases with and without bulletin readers are summarized in Table 5. Both the rank correlation coefficient *R* and the hit rate were higher for cases in which one or more bulletin readers were present. A significance test comparing the *t*-values from the two rank correlations yields a *p*-value of 0.44 for a 2-sided test and 0.21 for the 1-sided test; hence, there is no evidence that the presence of a bulletin reader influenced the ratings of the local nowcast.

3.5. Sufficiency of data gathered during ascent to decision point

Eighteen of the observations listed in Tables 2 and 3 were recorded at the decision point, and again at the end of the day. To assess whether the observations made prior to the decision point were sufficient for estimating the local avalanche danger, each observation recorded at the decision point and the observation for the entire day (taking the pre- and post-decision point observation favouring higher danger) was correlated with the local avalanche danger in Table 6. Only cases which were observed before and after the decision point were included in the correlations so the number of cases for some variables is slightly reduced compared to Table 4. Only the variables with significant correlations with LN in Table 4 are included in Table 6. Except for SlabAvCur, all the observations that were significant over

Table 6
Rank correlations of LN with observations at the decision point and after the full day.

Potential predictor		Decision point		Full day	
	n	R_{LN}	p	R_{LN}	p
SlabAvCur	270	0.08	0.18	**0.14**	0.02
SlabAvRec	270	**0.28**	10^{-6}	**0.29**	10^{-6}
Whumpf	270	**0.32**	10^{-8}	**0.34**	10^{-8}
Crack	265	**0.28**	10^{-6}	**0.29**	10^{-6}
Drifts	265	**0.24**	10^{-4}	**0.22**	10^{-4}
SkiPen	259	**0.22**	10^{-4}	**0.18**	10^{-3}
HShearR	246	**0.31**	10^{-6}	**0.22**	10^{-4}
HShearCh	152	**0.30**	10^{-4}	**0.23**	10^{-3}
SnowfallRate	264	**0.16**	10^{-2}	**0.20**	10^{-3}
SnowBlow	268	**0.13**	0.03	**0.13**	0.03

Correlations for which $p<0.050$ are marked in bold.

the full day were also significant prior to the decision point, with similar values of the correlation coefficients.

3.6. Effect of vegetation zone on the correlations with the local nowcast

Field teams produced local nowcasts for below tree line (BTL) and at tree line (TL) for two winters but only did so for the alpine zone in the second winter. Correlations with LN for those observations that were significant for the full day and all vegetation zones in Table 4 are shown in Table 7 by vegetation zone. Only 17 to 24 cases were available for the alpine zone and none of the correlations were significant, indicating the need for more observations. About four to five times as many cases were available for below treeline and treeline zones. Of the 14 observations (excluding RF) that were significant for all vegetation zones combined, 11 were significantly correlated with LN below treeline, and 8 were significantly correlated in the treeline zone. Of the five observations (excluding RF) selected for estimating the local avalanche danger in Section 3.2, all were significantly correlated with LN in below treeline and treeline zones.

4. A multi-predictor model for estimating the local avalanche danger

The objective of this study was to see if selected field observations could be combined with RF to estimate the local avalanche danger, LN. Since RF has the strongest rank correlation with LN, we seek a combination of RF and field observations to yield LN*, which is the output or "predicted" class of LN. The predictors are combined with a classification tree algorithm.

Table 7
Rank correlations of observations with LN for the three elevation zones.

Potential predictor	BTL			TL			ALP		
	N	R	p	N	R	p	N	R	p
RF	136	**0.45**	$\mathbf{10^{-8}}$	112	**0.33**	$\mathbf{10^{-4}}$	24	0.19	0.38
SlabAvCur	135	0.15	0.08	111	0.08	0.38	24	0.28	0.18
SlabAvRec	135	**0.26**	$\mathbf{10^{-3}}$	111	**0.27**	$\mathbf{10^{-3}}$	24	0.24	0.26
Whumpf	135	**0.45**	$\mathbf{10^{-7}}$	111	**0.29**	$\mathbf{10^{-3}}$	24	0.14	0.52
Crack	133	**0.27**	$\mathbf{10^{-3}}$	109	**0.34**	$\mathbf{10^{-4}}$	23	0.16	0.45
Drifts	133	**0.18**	**0.04**	109	**0.30**	$\mathbf{10^{-3}}$	23	−0.02	0.91
SnowfallRate	133	**0.24**	$\mathbf{10^{-3}}$	109	0.18	0.06	24	0.04	0.84
SnowBlow	134	0.08	0.35	110	0.17	0.08	24	0.19	0.36
SkiPen	129	**0.25**	$\mathbf{10^{-3}}$	107	0.10	0.30	23	0.27	0.21
HShearR	125	**0.25**	$\mathbf{10^{-3}}$	101	**0.21**	**0.03**	20	0.17	0.48
HShearCh	72	**0.25**	**0.03**	62	**0.26**	**0.04**	18	−0.26	0.30
HN24	113	**0.42**	$\mathbf{10^{-6}}$	93	**0.35**	$\mathbf{10^{-4}}$	17	0.30	0.24
HN48	91	**0.46**	$\mathbf{10^{-5}}$	75	**0.41**	$\mathbf{10^{-4}}$	12	−0.03	0.93
Sky	128	**0.21**	**0.02**	106	0.09	0.36	21	−0.28	0.22
ReachZero	124	0.14	0.13	103	0.12	0.24	21	0.38	0.09

Correlations for which $p<0.050$ are marked in bold.

Table 8
Misclassification costs.

Predicted LN	Observed LN			
	1	2	3	4
1	–	2	3	3
2	1	–	2	3
3	1	1	–	2
4	1	1	1	–

4.1. Classification tree algorithm (CTA)

Given a list of ordinal and categorical variables, classification trees iteratively form splits into two branches by selecting the variable for each split that "best" classifies the response variable. We used Gini's diversity index as the splitting criterion (Breiman et al., 1984, p. 28). Our response variable was LN. To reduce possible overfitting, we set the minimum node size to 5 cases. Partly because of the small sample size, we checked that every split in the tree was consistent with our experience and published interpretation of the observation (e.g. Tremper, 2001, 88–170; McClung and Schaerer, 2006, pp. 197–206).

4.2. Selection of cases

We chose to exclude the 18 cases for which RF = 4 because we wanted to assess a model for RF = 1 to 3 since backcountry travel for non-professional recreationists is not recommended when the danger level in the regional forecast is 4 or 5 (Dennis and Moore, 1996; www.avalanche.ca, 2008). The remaining dataset included 11 cases for which LN = 4 (i.e. LN > RF) but no cases with LN = 5.

4.3. Misclassification costs

Any simple classification scheme for estimating the local danger will misclassify some of the cases used to build the scheme. However, underestimating the local danger can have higher consequences (costs) than overestimating the local danger. To reduce the frequency of underestimating danger compared to overestimating it, we applied the misclassification costs shown in Table 8. A misclassification cost of 1 was applied to overestimation of the local danger. A cost of 2 is applied to underestimation of the local danger by one level. A cost of 3 is applied to underestimation of the local danger by two or more levels.

4.4. Combining predictors

Two hundred and fifty-four cases for which RF ≤ 3 were available from the winters of 2006–07 and 2007–08, as shown in Table 9. To maximize the size of the dataset used to build the tree, we used only the highly ranked predictors. There were 251 cases for which RF, RecSlab, Crack and Whumpf were available. HShearR and HShearCh were only available for 236 and 175 cases, respectively, and were not selected by the CTA. The resulting tree is shown in Fig. 7. Notably, this tree does not predict LN* = 1, which is likely a result of the misclassification costs.

Table 9
Frequency of LN ratings by RF.

RF	Observed LN				Total
	1	2	3	4	
1	16/16	16/16	4/4	0/0	36/36
2	37/37	51/50	10/10	1/1	99/98
3	11/11	58/58	42/41	8/7	119/117
Total	65/64	129/124	65/55	13/8	254/251

Numbers after the slash represent the cases selected for the tree in Fig. 7.

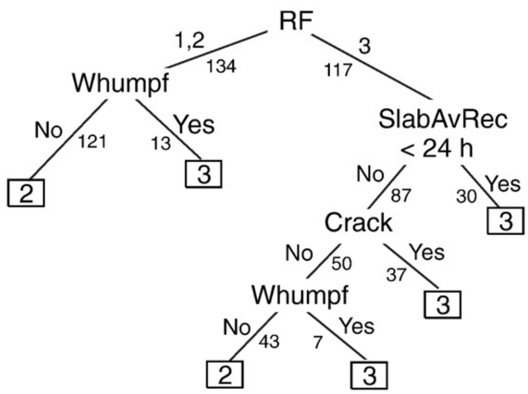

Fig. 7. Classification tree for the Columbia Mountain data. Output values of LN* are in the boxes. Numbers below the branches are the number of cases in the learning sample that take the particular branch.

Also, the tree does not predict LN* = 4, likely since LN = 4 only occurred in eight cases. The structure of the tree can be simplified by using OR conditions within an IF statements. Specifically, the right side of the tree could be changed to: IF (SlabAvRec < 24 h OR Crack OR Whumpf) then LN* = 3 ELSE LN* = 2. However, our current goal was *not* to develop a tree for recreational use, but rather to identify field observations which could, potentially, be combined with RF for estimating the local avalanche danger.

For the first split, the CTA selected RF, which has the highest rank correlation with LN. In the second level, the algorithm selected SlabAvRec and Whumpf which are regarded as primary indications of instability (e.g. Tremper, 2001, p. 167; McClung and Schaerer, 2006, pp. 172–173). Crack is selected at the third level, and Whumpf appears again at the fourth level.

The tree has some terminal nodes (leaves) with LN* < RF and some with LN* > RF, thus it can rate the local danger higher or lower than the regional danger rating. The tree is conservative because we chose higher misclassification costs for under-estimation of local danger than for over-estimation (Table 8).

Symmetric skill score such as the Hanssen–Kuipers discriminant (Wilks, 1995, p. 249) could be used to assess the tree's output (e.g. Jamieson et al., 2008b). However, we prefer to assess the rates of hits, overestimations and underestimations separately because we chose the asymmetric misclassification costs to reduce underestimations of local danger.

The classification matrix for this tree is shown in Table 10. Of note, there are two cases for LN = 4 and LN* = 2. In one of these cases, the local rating was influenced by stability test results which strongly indicated an unstable layer 45 cm below the surface. In the other case, one or more fresh slab avalanches were observed, contributing to LN = 4 although RF = 2. With the applied misclassification costs, local danger was correctly classified in 134 cases (53%), over-estimated in 97 cases (39%) and under-estimated in 20 cases (8%). Using RF only to predict LN* (Table 9), local danger was correctly classified in 107 cases (43%), over-estimated in 106 cases (42%) and under-estimated in 38 cases (15%). Thus, the classification tree in Fig. 7 increased the hit rate by 10 percentage points, decreased the overestimation rate by 3 and decreased the underestimation rate by 7 percentage points. A 10-fold cross validation yielded a hit rate of 51%, an overestimation rate of 41%, and an underestimation rate of 8%, all of which are improvements over using RF as the only estimator for LN.

5. Discussion

There is the potential that certain observations such as SlabAvRec or Whumpf might have a strong influence on the assessment of the local danger rating and therefore should not be used as independent predictors of the local avalanche danger. Although observations such as recent avalanches and whumpfs are important, the influence of an individual observation or variable on the local danger rating is likely weak because:

- The observers were working continuously in the area and were rarely surprised by any one observation. This is like asking a forecaster: How often are you so surprised by a single observation that you decide to change the danger rating? Informal conversations with forecasters suggest it does happen but is rare.
- Local danger ratings were based on a variety of correlated variables.
- In a related study of snowpack stability tests, Jamieson et al. (2006) rated the local danger before and after doing the stability tests, and found that they only changed their local danger rating due to the stability test results in 5 to 8% of the cases.

In the context of avalanche danger verification without digging, Schweizer (2003) associated the frequency of whumpfs, skier triggering, remote triggering and natural avalanching with Moderate, Considerable and High danger based on expert judgment and the usage of the danger levels in Switzerland (Table 11). It is interesting to compare this table with the output from the classification tree (Fig. 7). If whumpfs (or shooting cracks) are observed, the tree outputs Considerable danger and never Low or Moderate danger, while the table reports these observations are typical for Considerable danger. With regard to slab avalanching, we focus on skier triggering since remote triggering is a special case of skier triggering and Table 11 implies natural avalanching is less common than skier triggering. When recent slab avalanching including skier triggering is observed in the Columbia Mountains, Fig. 7 outputs Considerable local danger, while Schweizer (2003) reported skier triggering is typical for Considerable danger in the Swiss forecast regions, which are much larger than 10 km^2. Schweizer (2003) also pointed out that, in Switzerland, verification of the danger levels Considerable and High is possible with observations such as whumpfs, but that downgrading the danger to Moderate or Low is more difficult and usually requires snow profiles and/or stability tests. However, in the absence of recent avalanches, whumpfs or cracking around skis, the tree based on data from the Columbia Mountains (Fig. 7) outputs LN* = 2 when RF = 3, and agrees with LN for 30 of 43 cases (70%). Thus, in spite of differences in the definitions of avalanche danger between Canada and Switzerland, differences in snow climate and spatial scale, we see rough agreement and no inconsistencies between the Swiss table and the tree for the Columbia Mountains.

Table 10
Classification matrix for tree in Fig. 7.

Pred. LN	Observed LN				
	1	2	3	4	Total
1	0	0	0	0	0
2	59	91	12	2	164
3	5	33	43	6	87
4	0	0	0	0	0
Total	64	124	55	8	251

Table 11
Frequency of signs of instability for Moderate, Considerable and High avalanche danger in Switzerland (Schweizer, 2003).

Danger level	Signs of instability			
	Whumpfs, cracks	Skier-triggering	Remote triggering	Natural avalanching
Moderate	Occasional	Occasional	Rare	Rare
Considerable	Typical	Typical	Occasional	Occasional
High	Frequent	Frequent	Typical	Typical

6. Summary and conclusions

On about 130 location-days in the winters of 2006–07 and 2007–08, a set of 24 potential predictor variables (easy weather, snowpack and avalanche observations) were observed concurrently with local ratings of the avalanche danger in one or more elevation/vegetation zones in the Columbia Mountains, yielding 272 records or cases. Of the 23 potential ordinal or ratio predictor variables, 14 exhibited significant rank correlations ($p<0.05$) with the local avalanche danger. A categorical variable representing the snow surface conditions showed little predictive merit.

The danger rating from the regional bulletin, RF, correlated with the local danger rating, LN, better than any single the field observation. This indicates the value of the regional forecasts, even for large regions. To supplement RF for estimating the local avalanche danger, the observations Whumpf, Crack, SlabAvRec, HShearR and HShearCh correlated substantially better with LN than with RF.

When recorded at the late morning decision point, nine of the ten potential observations for estimating the local avalanche danger, including all three observations selected by the classification tree algorithm, appear useful. This suggests that many useful observations were obtained in the morning, before venturing into more serious avalanche terrain.

We used an established algorithm to construct a classification tree that would have less underestimations of local avalanche danger than overestimations. The tree used the regional danger rating, as well as observations of recent slab avalanches, whumpfs and cracking around skis. Compared to using only the regional danger rating for local rating, the classification tree increased the hit rate from 43 to 53%, decreased the overestimation rate from 42 to 39% and decreased the underestimation rate from 15 to 8%. This suggests that regional danger rating can be combined with the local observations to estimate the local avalanche danger in the Columbia Mountains. Nevertheless, the classification tree (Fig. 7) should be regarded as preliminary and is not recommended as a basis for decisions at this stage. Some limitations include: the tree is sensitive to the frequencies of RF and LN during our field days, as well as the splitting rule and misclassification costs. Also, the data used to construct the tree may not be representative of the diverse weather and snowpack conditions in the Columbia Mountains—for examples, few of our data were obtained during spring conditions, and few of the local danger ratings were for the alpine zone.

The snowpack observations in this study focus on the surface and near surface layers. However, deeper layers can also play an important role in avalanche formation. Jamieson et al. (2006) analyzed the usefulness and predictive merit of snowpack tests of deeper layers. These tests require digging a pit, are slower and therefore less appealing to some recreationists than the easy observations considered in this paper. However, a future aid for estimating the local avalanche danger may need to include both types of observations to be effective under a wide variety of snowpack conditions.

The data for this study were obtained in the Columbia Mountains. The results may not be applicable for other snowpack types in Western Canada including the maritime snowpack of the Coast Range or the continental snowpack of the Rocky Mountains.

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