Simple calculations of avalanche risk for backcountry skiing

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ABSTRACT: The avalanche risk from backcountry skiing and its dependence on the regional danger ratings have not been estimated—notably in North America. To get around this data gap, we have tried to calculate the risk using an event tree which breaks the avalanche risk to backcountry skiers into the probability of triggering, the probability of being caught in a triggered avalanche, and the probability of death if caught. An expert survey estimated the probability of triggering a potentially fatal avalanche while making fresh tracks in a trigger zone for each level of regional avalanche danger. A previous study found that 40% of people who trigger a potentially fatal avalanche are caught. Based on accident reports, the probability of being killed depends on the avalanche size, the distribution of which is known for skier-triggered avalanches in Canada. To calculate the daily risk, we modelled making fresh tracks in a specified number of trigger zones as an encounter probability. Based on our assumptions, a person can directly ski a dozen or so trigger zones in a day while the regional danger is Low or Moderate with comparable risk to kayaking. For a person skiing directly 5-10 trigger zones while the avalanche danger is Considerable, the daily risk is likely higher than kayaking and in the range of rock climbing or mountaineering.

KEYWORDS: avalanche risk, backcountry skiing, comparative risk, skier-triggering, regional avalanche danger

1. INTRODUCTION

The empirical risk of death from a day of ski touring has not been estimated in North America. In Switzerland, Munter (2005) estimated the avalanche risk in Switzerland to be between 1:50,000 for all ski-touring and 1:5,000 deaths per skier-day for skiing avalanche terrain with limited caution when the danger is not Low. Using skier frequency data from Zweifel and others (2006), we recalculated the avalanche risk from skiing in two backcountry areas near Davos, Switzerland to be about 1:70,000 deaths per skier-day.

This paper takes a different approach. We used an event tree to break the risk down by the regional danger rating and by the number of trigger zones skied. We defined an exposure as making fresh tracks while skiing directly up, down or across one trigger zone (which may only be common for Low danger). So in our search for a simple risk calculation, triggering by the second or third or tenth person in the same up-track was ignored. Skilled route selection was excluded partly because the level of skill and its effect on the triggering probability are even more difficult to estimate. We also wanted to establish a baseline and a framework upon which factors like skilled route selection and recognition of local conditions could be later applied.

We chose to keep our first risk calculation simple by concentrating on one strong factor: the regional avalanche danger rating. We first calculate the risk for skiing a single trigger zone and then for skiing n trigger zones in a day.

The numerous simplifying assumptions mean that our results are not suitable for slope-scale risk assessments. At best, the results represent an index of backcountry skiing risk at the regional scale.

2. EXPLORATORY RISK ANALYSIS FOR SKIING ONE TRIGGER ZONE

To break down the risk into components, we used an event tree (e.g. Walpole et al., 2007) in which at each branch of the tree there are a fixed number of outcomes for which the (conditional) probabilities can be estimated (Figure 1). The tree first branches into the five levels of regional danger, 1 (Low) through 5 (Extreme). Next the tree branches by the type of involvement: skier triggered, caught in a natural avalanche, or not involved (No Invol). For both these types of involvements, the tree branches according to the five classes of avalanche size on the Canadian scale, S_1 through S_5 (McClung and Schaerer, 2006,

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p. 322). For each size, the person is either caught or not. Those caught may be either killed or not.

Some assumptions are required to simplify the tree and its components:

- We excluded the risk from spontaneous (natural) avalanches from our calculations for two reasons: First, accident data show that overall the risk due to natural avalanches is about 10% of the risk due to human-triggered avalanches (Tremper, 2008, p. 15). Second, the risk of death from natural avalanches likely increases with the danger level but data to quantify this effect are not available. Hence, we ignored the part of the tree for natural avalanches.
- At higher levels of avalanche danger, avalanches with greater destructive potential (larger size) may be more likely but we ignore this effect because avalanche size is not explicitly part of the danger scale used in North America from 1996 to 2009 (Dennis and Moore, 1996). For more on this point, see Jamieson (2009).
- The probability of being caught (*C*) in a triggered avalanche (*T*) is assumed to be $P_{C|T}$ = 0.4 (Schweizer and Lütschg, 2001), and independent of avalanche size.

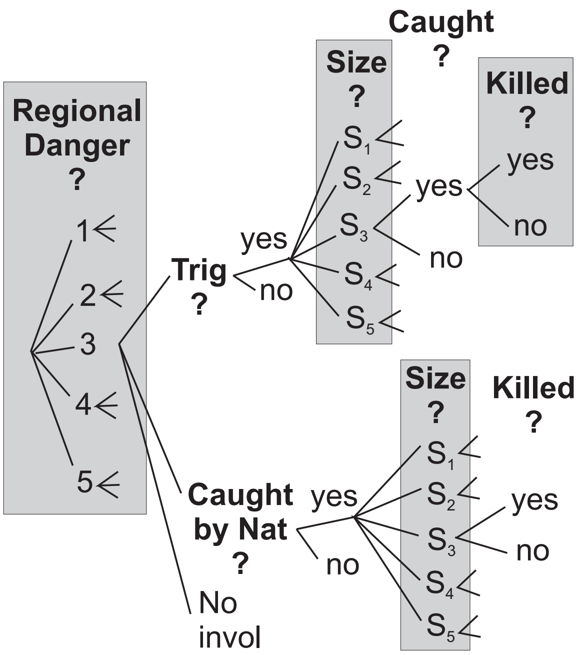

Figure 1. Tree of events including the sequences that can lead to death. The levels of regional danger are 1 *(Low) through* 5 *(Extreme).* S_1 *through* S_5 *are for avalanche size on the Canadian scale. Some branches which are similar to others are not shown. Except for the branches for the regional danger rating, which is fixed for a region on a specific day, probabilities can be estimated for the other branches.*

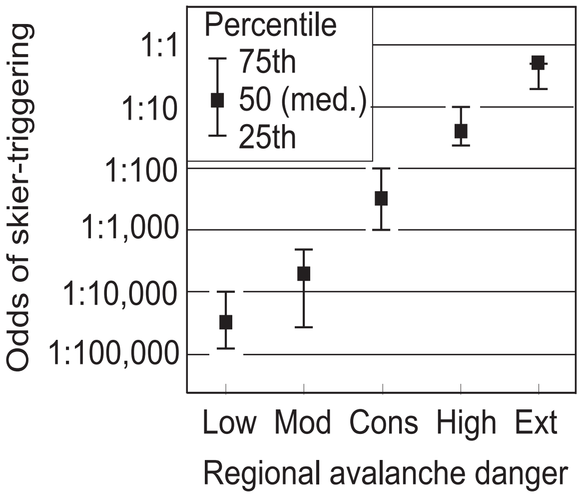

Figure 2. For each level of the regional avalanche danger, the graph shows the estimated odds of skier-triggering a potentially fatal avalanche while making fresh tracks in one trigger zone without skilled route selection. The whisker or bar shows the range of the middle 50% of estimates, i.e. from the 25th to the 75th percentile (Q1 to Q3). A square marks the median or 50th percentile.

Working only with the upper part of the tree for skier-triggered avalanches, two key components need to be estimated: the probability of triggering a potentially fatal avalanche at danger level *d*, $P_{T|d}$; and the probability of being killed (*K*) if caught (*C*), $P_{K|C}$. A survey of 23 experts in North America (Jamieson, 2009) gave the estimates for $P_{T|d}$ shown in Figure 2. The survey shows a roughly 10-fold increase in triggering odds with each level of regional danger. (For reference, Munter (2006) estimated that the total area of trigger spots and hence the risk would double with each level of danger. Using data from the Austrian Tyrol, Pfeifer (2009) found the increase in the frequency of skier triggering to be close to Munter's estimate and lower than from Jamieson's (2009) North American survey.)

From accident data reported to the Canadian Avalanche Association from 1984 to 1996, the relative frequencies for size 2, 2.5 and 3 skier-triggered avalanches are 0.71, 0.18, 0.11, respectively (Jamieson and Geldsetzer, 1996; Table 1).

During this period, no larger skier-triggered avalanches were reported. We exclude smaller avalanches since, by definition, they are relatively harmless. The same source gives the probability of death for these sizes of avalanches (all triggers) as 0.05, 0.17 and 0.35, respectively (Table 1). The frequency-weighted probability of death if caught in a skier-triggered avalanche is 0.11, the same as reported by Schweizer and Lütschg (2001) in a Swiss study. However for the

Table 1. Frequency and death rate by avalanche size, Canada, 1984-96				
Avalanche size (Canadian)	Rel. freq. of skier-triggered avalanches (102 reports)	Probability of death (all triggers)		
		Assumed reporting rate for non-fatal avalanches		
		all	1 in 10	1 in 20
2	0.71	0.05	0.0052	0.0018
2.5	0.18	0.17	0.020	0.0041
3	0.11	0.35	0.051	0.011
> 3	0	-	-	-
Probability of death if caught in a skier-triggered potentially fatal avalanche, $P_{K\|C}$		0.11	0.013	0.0066

Canadian study, these probabilities are too high since many non-fatal avalanches were likely not reported as accidents. Schaerer (1987, p. 2) estimated that about half of non-fatal avalanches were reported. However, to estimate more realistic fatality rates, we assumed that only 1 in 10 to 1 in 20 of potentially fatal avalanches were reported as accidents to the Canadian Avalanche Association between 1984 and 1996. These assumed reporting rates result in the adjusted probabilities shown in Columns 4 and 5 of Table 1. Hence, the frequency-weighted probability of being killed for a skier who is caught in any potentially fatal skier-triggered avalanche, $P_{K|C}$, likely lies between 0.0066 to 0.013 (roughly 1/100) based on Canadian data from 1984 to 1996.

Including the assumptions noted above, the risk of death while directly skiing **one** trigger zone at danger level *d* is

$$R_{SKI}(1, d) = P_{T|d}\, P_{C|T}\, P_{K|C} \qquad (1)$$

For the middle 50% of triggering odds at Considerable danger, this calculated risk ranges from approximately 1 death per 20,000 to 1 per 200,000 trigger zones skied, assuming that 1 in 10 non-fatal avalanches were reported.

3. EXPLORATORY RISK ANALYSIS FOR SKIING *n* TRIGGER ZONES IN A DAY

Using $P_{T|d}$ for the probability of triggering a potentially fatal avalanche while skiing a single trigger zone at regional danger *d* (Figure 2), the probability of not triggering such an avalanche in *n* independent exposures is $(1- P_{T|d})^n$. Although a day of recreation would likely stop when a potentially fatal avalanche was triggered, we wish to know the probability of one or more deaths for a day in which skiing *n* trigger zones is typical. This is the encounter probability $1-(1- P_{T|d})^n$ (e.g. LaChapelle, 1964; McClung, 1999). (For Low, Moderate and Considerable danger, the triggering probability, $P_{T|d}$, is less than 0.01 and the encounter probability is well approximated by $n\, P_{T|d}$, which is the first non-zero term in the McLaurin expansion. Although we do not use this approximation in subsequent calculations, it does explain the near-linear increase in risk with exposures in Figure 3.)

Using the numerous assumptions described above, we approximate the risk of death from directly skiing *n* trigger zones in a day at danger level *d* as

$$R_{SKI}(n, d) = [1-(1-P_{T|d})^n]\, P_{C|T}\, P_{K|C} \qquad (2)$$

4. COMPARISON OF SKIING RISK TO RISK DUE TO OTHER MOUNTAIN RECREATION

In Figure 3, we compared our sloping lines for the calculated risk of death from making fresh tracks while skiing directly *n* trigger zones in a day (Eq. 2) with horizontal lines for Munter's (2005) estimate for skiing avalanche terrain with limited caution when the danger is not Low (1:5,000 per day), Sowby's (1964) risks from kayaking (1:20,000 for a 5-hour day), rock-climbing (1:5000 for a 5-hour day) and mountaineering (1:1500 per day).

The area between our sloping lines includes some of the uncertainty in the triggering probability and in the probability of death. The uncertainty in the triggering probability is represented by the range from the first to third quartile from the survey (Figure 2). The uncertainty in the probability of death is represented by the range of reporting rates for non-fatal avalanches in Table 1. The lower uncertainty line for risk is based on the first quartile of the triggering odds from the survey *and* on 1 in 20 non-fatal avalanches being reported in accident data (Q1 1:20 non-fatal). The upper uncertainty line is based on the third quartile (Figure 3) *and* on 1 in 10 non-fatal avalanches being reported (Q3 1:10 non-fatal). The upper uncertainty line for Moderate danger is shown as well as both lines for Considerable and High danger. The lines for Extreme danger are off the graph.

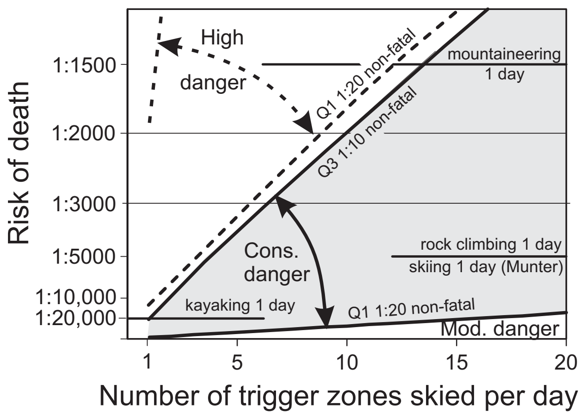

Figure 3. Calculated risk of death by number of trigger zones skied per day for Moderate, Considerable and High danger. The uncertainty zone from "Q1 1:20 non-fatal" to "Q3 1:10 non-fatal" is explained in the text. For comparison, daily risk from kayaking, rock climbing and mountaineering (Sowby, 1964) as well as skiing avalanche terrain with limited caution (Munter, 2005) are shown as horizontal lines.

5. SOME TENTATIVE INTERPRETATIONS

In the following interpretations, various simplifying assumptions including those outlined in this paper have been made, and "skiing" means making fresh tracks while directly skiing trigger zones in the backcountry:

- The calculated avalanche risk from skiing increases roughly 10-fold with each level of regional avalanche danger. This follows from the approximate 10-fold increase in triggering probability when the regional danger increases by one level (Figure 2, based on the survey).
- As indicated by the almost straight lines in Figure 3, the skiing risk at Moderate or Considerable danger is roughly proportional to the number of exposures. This is also true for Low danger although the uncertainty lines are not shown.
- The calculated risk from skiing fewer than 20 trigger zones at Moderate danger is roughly comparable to a published risk for kayaking. The calculated risk for directly skiing fewer than 20 trigger zones while the regional avalanche danger is Low (not shown) tends to be lower than for kayaking.
- At Considerable danger, the risk from directly skiing 10 or more trigger zones per day is likely greater than kayaking and more in the range of risk while rock climbing or mountaineering (~1960 data). However, there is considerable uncertainty in this comparison.
- Munter's (2005) estimate for skiing avalanche terrain with limited caution when the danger is not Low is in the middle of the range that we calculated for directly skiing 5-15 trigger zones at Considerable danger.
- At High danger the calculated risk from directly skiing more than about five trigger zones per day is at least as high as mountaineering.

6. DISCUSSION AND SUMMARY

Our assumption of directly skiing trigger zones tends to make our estimates of avalanche risk higher than for typical backcountry skiing. The exception is for Low danger, for which we observe many people skiing directly down trigger zones.

At Considerable avalanche danger, skilled route selection—which requires experience—may be important to reduce the risk to a level comparable to kayaking or rock climbing.

For these calculations, there is an underlying assumption that trigger points are randomly distributed on avalanche slopes in a forecast region. For a skier who skis different avalanche slopes without skilled route selection on each run, and is thereby exposed to many different trigger zones, the assumption may be reasonable. However, the risk calculations probably overestimate the avalanche risk for a person repeatedly skiing the same few trigger zones without skilled route selection.

The uncertainty lines for avalanche risk in Figure 3 are based on simple assumptions of uncertainty and are not upper and lower limits. In the future, we plan to model uncertainty with a Monte-Carlo simulation.

We have made many assumptions to obtain these simple calculations of avalanche risk for various levels of regional avalanche danger. Hopefully, the event tree will provide a framework for more realistic calculations. We hope the tree can be modified to include other factors or observations including those used in decision support schemes (e.g. terrain ratings) and in bulletins (e.g. avalanche type). Also, the experts who responded to the survey made many suggestions such as including avalanche size, the area of the forecast region, and skilled route selection in a future survey of triggering odds.

The triggering odds for a snowmobiler are likely higher than for a skier since snowmobiles are likely more effective for initiating fractures in weak layers (T. Exner, in preparation). Also, snowmobilers can access more trigger zones in a day than a self-propelled backcountry skier or snowboarder.

In time it may be possible to validate some of our calculations. For the present, we invite experienced recreationists to comment on the comparison of our calculated skiing risk with other recreational risks in Figure 3.

Our numerous assumptions mean that our calculations are exploratory and not suitable for risk assessments, especially on the scale of individual slopes or ski runs. We hope these exploratory calculations promote discussion, better analyses, better estimates of avalanche risk during winter recreation and, ultimately, better informed decisions.

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REFERENCES

Dennis, A., M. Moore. 1996: Evolution of public avalanche information: The North American experience with avalanche danger rating levels. Proc. Internat. Snow Science Workshop, Banff, Alberta, 1996, 60-72.

Exner, T. In preparation. Field studies of snowpack stress and deformation due to surface loads and temperature effects. PhD thesis, Dept. of Geoscience, University of Calgary, Calgary, Canada.

Jamieson, B. 2009. Regional danger ratings and the odds of triggering a potentially fatal avalanche, avalanche.ca - The Journal of Canada's Avalanche Community, 89: 56-69. Also in press for The Avalanche Review.

LaChapelle, E.R. 1966. Encounter probability for avalanche damage. USDA Forest Service, Misc. Rep. 10.

McClung, D.M. 1999. The encounter probability for mountain slope hazards. Can. Geotech. J. 36: 1-2.

McClung, D.M., P.A. Schaerer. 2006. The Avalanche Handbook, 3rd edition. The Mountaineers Books, Seattle, Washington, USA.

Munter, W. 2005. Formel statt Floskel. Bergundsteigen - Zeitschrift fuer Risikomanagement im Bergsport. Oesterreichischer Alpenverein, Innsbruck, Austria, 14(4): 38-41.

Munter, W. 2006. 3x3 Avalanches - La gestion du risque dans les sports d'hiver. Éd. Club Alpin Suisse

Pfeifer, C. 2009. On probabilities of avalanches triggered by alpine skiers. An empirically driven decision strategy for backcountry skiers based on these probabilities. Natural Hazards 48: 425–438.

Schaerer, P.A. 1987. Avalanche Accidents in Canada III. A Selection of Case Histories, 1978-1984, National Research Council of Canada, Inst. Res. Construction, No. 1468, NRCC publication 27950.

Schweizer, J., M. Lütschg. 2001. Characteristics of human-triggered avalanches. Cold Reg Sci Technol. 33: 147–162

Sowby, F.D. 1964. Radiation and other risks. In F.J. Neary (ed.) Proc. Symposium on the Transporting of Radioactive Materials, Bournemouth, 13-15 April 1964, H.M. Stationary Office, London, UK.

Tremper, B. 2008. Staying Alive in Avalanche Terrain, 2nd edition. The Mountaineers Books, Seattle, Washington, USA.

Walpole, R.E., R.H. Myers, S.L. Myers, K. Ye. 2007. Probability and Statistics for Engineers and Scientists, eighth edition. Pearson Prentice Hall, Upper Saddle River, New Jersey, USA.

Zweifel, B., A. Raez, T. Stucki. 2006. Avalanche risk for recreationists in backcountry and in off-piste area: Surveying methods and pilot study at Davos, Switzerland. In Gleason, A. (ed.) Proc. International Snow Science Workshop 2006, Telluride CO., 733-741.