ASSESSING AND COMMUNICATING LIKELIHOOD AND PROBABILITY OF SNOW AVALANCHES

Scott Thumlert[1], Martin Stefan[2], Stian Langeland[2]

Alpine Solutions, Canmore, Canada[1]
Wyssen Avalanche Control, Norway[2]

ABSTRACT: Forecasting avalanche hazard is the prediction of the magnitude, likelihood, timing, and location of potential avalanches. Assessing the likelihood of avalanches in absolutes is not currently possible due to a lack of scientific understanding of avalanche release processes, insufficient data describing snowpack structure, and the influence of weather; consequently, likelihood assessments represent subjective probabilities assigned by the forecaster. These subjective probability assessments are commonly communicated via verbal probability expressions on an ordinal scale: 1) Unlikely, 2) Possible, 3) Likely, 4) Very Likely, and 5) Almost Certain. Interpretations of verbal expressions of probability have been shown to vary drastically amongst individuals leading to communication problems, decreases in forecasting accuracy, and ultimately can compromise decision making. The verbal expressions of probability for avalanche forecasting have yet to be defined explicitly - both the meaning as a percentage chance of release and in rates of release expected for the spatial scale being forecasted - which has the potential to improve communication. In this paper, we propose a somewhat novel definition for likelihood of avalanches: *Likelihood of Avalanches: is the chance of the start zones being assessed releasing within the forecast time period, regardless of avalanche size.* Additionally, we propose a new ordinal scale of verbal expressions of probability complete with suggestions for percentage chance of release and frequencies of release. The definition: 1) can be effectively applied across all common spatial scales, which supports a core forecasting challenge, and 2) explicitly states a reference class (start zones being assessed) for the probability assessment which can improve understanding. The verbal expressions of probability are chosen given our existing understanding of what terms support operational avalanche risk mitigation decisions. The definitions of these terms in percentages are in line with common human interpretations and within the reasonable bounds of uncertainty when forecasting avalanches. Helpful frequency definitions are included because they naturally force the forecaster to explicitly explain the event and context (reference class). Finally, the amended scale is balanced and has more resolution at the lower end (avalanches are rare). The ultimate purpose of this paper is to promote discussion about forecasting the likelihood of avalanches and to elicit feedback from the community. Hence, we finish with an invitation to contribute via a survey.

KEYWORDS: Likelihood of avalanches, probability, avalanche forecasting, risk communication,

1. INTRODUCTION

"*Even if avalanche forecasting is probabilistic and includes uncertainty, it should be grounded in clear definitions, and uncertainty should not stem from nebulous terms but the nature of the problem.*" – Jürg Schweizer (Schweizer et al. 2019).

Forecasting avalanches is the prediction of the timing, location, and potential size over a specified region and time period. However, predicting avalanches in absolutes is not currently possible due to insufficient data describing the snowpack, the influence of weather, and a lack of scientific understanding of avalanche release processes; therefore, forecasters express their judgement of avalanche release using subjective probability assessments.

"The uncertainties facing geotechnical engineering are legion, so much so that they are cited as the chief feature distinguishing it from its sister civil engineering specialties" (Vick, 2002).

The level of uncertainty facing avalanche forecasters is comparable or greater to that of geotechnical engineers, therefore many of the concepts discussed and applied in this paper draw on the wealth of experience and knowledge from the geotechnical engineering field. Vick (2002) provides a robust explanation of subjective probability assessment by integrating three core elements: 1) uncertainty in knowledge, 2) inductive reasoning, and 3) individual expertise.

"Subjective probability requires integrating and synthesizing different kinds of information from different sources." (Vick, 2002).

Ultimately, avalanche forecasters assess their degree of belief about the probability of avalanches using subjective probabilities. The output of this subjective probability assessment is commonly communicated with an ordinal scale of verbal terms, e.g. from Statham et al. (2018): 1) Unlikely, 2) Possible, 3) Likely, 4) Very Likely, and 5) Almost Certain.

Likelihood of avalanches is often combined with an estimation of avalanche magnitude to estimate

* *Corresponding author address:*
Scott Thumlert, Alpine Solutions, Canmore, AB, Canada, T1W1B3;
tel: +1 403-700-4393
email: sthumlert@avalancheservices.ca

hazard. The estimation of avalanche hazard is core to the daily process for avalanche risk management and is a fundamental skill for avalanche forecasters. It follows that both the assessment and communication of likelihood of avalanches is critical for sound decision-making in practical avalanche risk management operations.

This paper proposes a novel definition for the likelihood of avalanches, presents a new ordinal scale of likelihood terms, and defines these terms robustly as probabilities and frequencies. The objectives are to reduce dependence on spatial scale and to improve the interpretation and communication of likelihood between forecasters. The following sections provide background on the concepts applied in the development of the scale and definition.

2. VERBAL EXPRESSIONS OF PROBABILITY

Verbal expressions of probability involve using qualitative terms such as Likely, Unlikely, and Rare to describe the likelihood of events and to communicate uncertainty. These expressions are often preferred over numerical probabilities because they are more intuitive, and they enable efficient communication. Also, people find words easier and more natural to use than numbers because they conform better to the internal process of weighing arguments, as opposed to computation (e.g. Zimmer, 1984).

However, there is a depth of research showing large differences in the ways individuals understand, communicate, and use these types of verbal expressions of probability (e.g. Nakao and Axelrod 1983; Brun and Teigen, 1988; Theil 2002). Discrepancy between interpretations of likelihood expressions has been shown to create communication problems (Fischer and Jungermann 1996), reduce forecasting accuracy (e.g. Rapoport et al. 1990) and ultimately compromise decision making (Friedman et al. 2018). The challenges with using verbal expressions of probability are evident in avalanche forecasting as discovered by Thumlert et al. (2022) who found a startling wide range in probabilities associated with the likelihood terms from a survey of avalanche professionals.

Verbal expressions for likelihood commonly used in avalanche forecasting are not currently defined with translation into numerical probabilities or frequencies (e.g. Statham et al. 2018).

3. ON THE TRANSLATION OF VERBAL EXPRESSIONS INTO PROBABILITIES AND FREQUENCY STATEMENTS

It has been well-established that translating or defining verbal expressions of probability into numerical values improves interpretation and communication. A few key studies across multiple fields highlight this conclusion:

- Budescu et al. (2009) examined how providing numerical ranges of verbal probability expressions used by the Intergovernmental Panel on Climate Change enhances the clarity and effectiveness of communication.
- Budescu et al. (2014) further explored the impact of translating verbal expressions into numerical probabilities on the understanding and interpretation of climate change reports.
- Fischer and Jungermann (1996) showed how defining verbal probability expressions in medical contexts can reduce misunderstandings and improve patient communication.
- The comprehensive book by Morgan et al. (2002) provides comprehensive insights into how clear definitions and numerical translations of verbal probabilities can improve risk communication.
- Nakao and Axelrod (1983) highlighted the benefits of using numerical probabilities over verbal expressions in medical communication to enhance understanding and decision-making.
- Teigen and Brun (1999) examined how numerical definitions of verbal probabilities can improve probabilistic reasoning and decision-making.

Translating verbal expressions of probability into frequency statements also significantly improves communication by necessitating the definition of the reference class. The reference class is a well-defined group or category to which the probability statement applies. A frequency statement expresses probability by specifying how often an event occurs out of a total number of opportunities or trials. For example, the reference class in the frequency statement “*On average, a basketball player makes 45 out of 100 free-throw attempts*” is the 100 free-throw attempts. A few studies showing the communication improvement using frequency statements:

- The book by Gigerenzer (2002) explains how using frequency formats can enhance understanding of risks and probabilities, making it easier for people to grasp complex statistical information.
- Koehler (1996) reviews how presenting statistical information as frequencies rather than probabilities helps individuals avoid common reasoning errors such as the base rate fallacy.
- Hoffrage et al. (1996) discusses the advantages of using frequency statements over probabilities in communication, highlighting how they lead to better understanding and more accurate decisions.

An effective scale to assist forecasters with assessing and communicating their judgement and uncertainty about potential avalanche releases would use verbal expressions of probability along with the translation of the terms into numerical probabilities and frequency statements.

4. ON SPATIAL SCALE

Assessing the likelihood of avalanches is also complicated by the varying spatial scales of the forecast region that forecasters often assess (e.g. Schweizer, 2008). The scale of the forecast region varies between single slopes or start zones (i.e. micro scale < 1 km^2), mountain drainages (i.e. meso scale > 100 km^2), to mountain ranges or regions (i.e. synoptic scale > 10,000 km^2).

Ideally a robust definition and scale for expressing forecaster's likelihood assessments would be mostly independent of the spatial scale and could be applied effectively and consistently across all scales. To achieve this independence from the spatial scale the definition and frequency statement must specify a reference class that automatically adjusts to the spatial scale being assessed.

As an example, consider the forecaster assessment of a Persistent Slab avalanche problem as Likely (60% chance). When applied to a single avalanche path, this means that the main start zone where this Persistent Slab avalanche problem is expected to exist has a 60% chance of releasing during the forecast time period. When applied at a regional scale, this means that all the start zones where the Persistent Slab is expected to exist have a 60% chance of releasing. Therefore, on average the forecaster is expecting to see about 6 out of 10 of these specific start zones release an avalanche.

5. THE DEFINITION OF LIKELIHOOD OF AVALANCHES

Here we propose a somewhat novel definition for the likelihood of avalanches.

Likelihood of Avalanches **is the chance of the start zones being assessed releasing within the forecast time period, regardless of avalanche size.**

This definition specifies a reference class - the avalanche terrain (start zones) being assessed. While this may sound obvious to the experienced forecaster, explicitly stating a reference class and clearly describing the structure and context of the probability assessment helps people understand and compute the relevant probabilities (e.g. Neace et al. 2008).

Many forecasters have found value describing the type of avalanche they are assessing with Avalanche Problems (e.g. Lazar et al. 2012; Klassen et al. 2013). Framing the likelihood assessment around a specific avalanche problem helps the forecaster define start zones where the problem is expected to exist, informs the type of anticipated avalanche activity, and helps the decision of what risk management techniques are most appropriate (Statham et al. 2018). The proposed likelihood definition is designed to work using the core concept of avalanche problems by simply defining the "avalanche terrain being assessed" as the terrain where the avalanche problem is expected to exist. The forecaster defines the likelihood assessment as the chance that the start zones where the avalanche problem is expected to exist will release within the forecast time period, regardless of size.

6. AN ORDINAL SCALE FOR COMMUNICATING LIKELIHOOD OF AVALANCHES

Here we propose a novel ordinal scale for communicating the results of the forecaster's subjective probability assessment (Table 1). The scale uses six terms balanced around lower and higher probabilities, provides numerical probabilities and frequency descriptions, and provides multiple options for the verbal probability expressions. The multiple verbal options are presented because we recognize that cultural and linguistic differences across the worldwide professional avalanche community may interpret these terms differently. For example, in Norway the term Fair Chance might be interpreted as a higher probability (i.e. 70 to 90% chance), whereas in North America the same term often implies a roughly even probability (i.e. ~50%).

Table 1: Proposed scale describing the Likelihood of Avalanches.

Verbal Probability Terms	*Numerical Probability*	*Frequency description (or rates of release) **
VERY LIKELY, ALMOST CERTAIN, HIGHLY PROBABLE, ALMOST CERTAINLY	> 75%	More than 75 out of every **100 paths or start zones** in the region release.
LIKELY, PROBABLE, GOOD CHANCE, QUITE PROBABLE	50 - 75%	50 to 75 out of every **100 paths or start zones** in the region release.
FAIR CHANCE, EVEN CHANCE, UNCERTAIN, NOT CERTAIN, POSSIBLE	5 - 50%	5 to 50 out of every **100 paths or start zones** in the region release.
UNLIKELY, NOT LIKELY, PROBABLY NOT, IMPROBABLE, DOUBTFUL, QUITE UNLIKELY	0.1 - 5%	1 to 50 out of every **1000 paths or start zones** in the region release.
HIGHLY UNLIKELY, REMOTE CHANCE, ALMOST NO CHANCE, NEARLY IMPOSSIBLE, HIGHLY IMPROBABLE	< 0.1%	***At most*** 1 out of every **1000 paths or start zones** in the region release.
EXCLUDED, OMITTED, DISREGARDED	0.0001%	***At most*** 1 out of every **1,000,000** paths or start zones in the region release. This means that it is as close to impossible as we can imagine.

**Frequency descriptions are not very useful when forecasting for single path or area with few paths - use numerical probability ranges or verbal probability terms. When assessing a single path or an area with a few paths, forecasters may find it useful to replace the spatial reference class in the frequency description with a temporal one. The forecaster would then assess how many days with similar conditions would release avalanches. For example, the forecaster may expect that the start zone would release on about 1 out of 100 days with similar conditions.*

7. INTEGRATION WITH EXISTING ASSESSMENT METHODS - CONCEPTUAL MODEL OF AVALANCHE HAZARD

While the evaluation of likelihood of avalanches ultimately represents the forecaster's subjective probability assessment, there have been methodologies proposed to help guide the assessment process.

The conceptual model of avalanche hazard (CMAH) proposed by Statham et al. (2018) considers two factors that contribute to the likelihood assessment: 1) sensitivity to triggers, and 2) spatial distribution. Sensitivity to triggers describes "*snowpack instability separately from the size of the avalanche by gauging the triggers necessary for avalanche release*" on a four-level ordinal scale: Unreactive, Stubborn, Reactive, Touchy. And spatial distribution describes "*the spatial density and distribution of an avalanche problem and the ease of finding evidence to support or refute its presence"* on a three-level ordinal scale: Isolated, Specific, Widespread. The model then integrates these spatial distribution and sensitivity to trigger scales using a table to form the assessment of likelihood of avalanche(s) (Figure 1). It is critical to recognize that this assessment functions with the definition of likelihood: *"is the chance of an avalanche releasing within a specific location and time period, regardless of avalanche size"*, where the forecaster is apparently assessing the likelihood of a single avalanche regardless of the spatial scale being assessed.

The assessment of the "*chance of an avalanche releasing within a specific location and time period*" (single avalanche) specifies a reference class that makes the likelihood assessment highly dependent on the spatial scale being assessed. For example, Statham et al. (2018) states "*The probability of an avalanche on a single slope of 0.01 could be considered likely, while the probability of an avalanche across an entire region of 0.1 could be considered unlikely*". The reference class used in this definition naturally means that the likelihood of an avalanche increases as the spatial scale increases, assuming consistent conditions.

The proposed definition in this paper uses a reference class that attempts to capture the expert forecasting process in that higher likelihood assessments results in the intuitive conclusion that the forecaster expects to see more avalanches. For example, consider a Widespread x Touchy (Almost Certain) assessment for a reactive persistent slab avalanche problem with a significant warm storm forecast for a regional spatial scale (e.g. South Columbia range). If the forecaster was able to observe all potential start zones where the persistent slab problem was expected to exist after the storm and observed only a single avalanche release, most experienced forecasters would consider their forecast incorrect. In other words, most experienced forecasters would have been expecting to see a widespread avalanche cycle (i.e. numerous avalanches).

Figure 2 explores how the proposed definition and scale could potentially integrate with the assessment process proposed in the CMAH. Let's explore the output from a couple example likelihood assessments using Figure 2:

a) **Wind Slabs -** Widespread x Reactive = Likely (50 - 75%) - up to Size 2 - ridgetop lee features.

   Applied at a drainage scale with approximately 100 total start zones and the avalanche problem being expected to exist on ~16 of those start zones (Alpine and Treeline on North through East aspects). The likelihood assessment would translate to an approximate 50 - 75% chance of the 16 start zones where the wind slabs are expected to exist releasing, and on average the forecaster would expect about 8 to 12 avalanches. Note, if the forecaster was assessing for human triggering (and likely subsequently avoiding these features) there may be no avalanches if no humans ski or ride those start zones.

b) **Deep Persistent Slabs -** Specific x Stubborn = Unlikely (0.1 - 5%) - up to Size 3.5 - thin snowpack areas.

   Applied at a regional scale with approximately 1000 total start zones and the deep slab problem being expected to exist on only 50 thin areas of the snowpack (roughly 5% of the total 1000 start zones are thin). The likelihood assessment of Unlikely would mean a 0.1 - 5% chance of release for those 100 paths, and on average the forecaster would expect somewhere between none and 3 avalanches across the entire region.

   A relevant question to evaluate the CMAH likelihood assessment process with the proposed definition and scale is: do these estimates of avalanches at the spatial scales specified above align with your forecasting process?

Spatial Distribution	Unreactive	Stubborn	Reactive	Touchy
Wide-spread	Unlikely	Possible	Very Likely	Almost Certain
Specific	Unlikely	Possible	Likely	Very Likely
Isolated	Unlikely	Unlikely	Possible	Likely

Sensitivity to Triggers

Figure 1: The integration of sensitivity to triggers and spatial distribution table presented in the conceptual model of avalanche hazard presented by Statham et al. (2018).

Spatial Distribution	Unreactive	Stubborn	Reactive	Touchy
Wide-spread	Unlikely (0.1 - 5%)	Fair Chance (5 - 50%)	Likely (50 - 75%)	Very Likely (> 75%)
Specific	Unlikely (0.1 - 5%)	Unlikely (0.1 - 5%)	Fair Chance (5 - 50%)	Likely (50 - 75%)
Isolated	Highly Un-likely (< 0.1%)	Unlikely (0.1 - 5%)	Unlikely (0.1 - 5%)	Fair Chance (5 - 50%)

Sensitivity to Triggers

Figure 2: A potential integration of sensitivity to triggers and spatial distribution table presented in the conceptual model of avalanche hazard (Statham et al. 2018) with the likelihood definition and scale proposed in this paper.

8. DISCUSSION AND CONCLUSIONS

This paper proposes a somewhat novel definition for likelihood of avalanches and a corresponding ordinal scale for communicating forecaster's likelihood assessments that draw on well-established concepts from the fields of risk communication and probability assessment. These systems aim to capture and support the experienced avalanche forecaster's tacit and natural mental process, and to support operational risk management decision making.

8.1 *Application for Varying Spatial Scales*

The definition reduces the dependance on the spatial scale and can be applied across the common forecasting spatial scales (e.g. slope, drainage, region). For a single start zone (or avalanche path), the forecaster simply assesses the question: what is the chance that the start zone will release within the forecasting time period?

The terrain-based frequency statements (Table 1) may be difficult to conceptualize for single start zones, and forecasters may find value shifting to a temporal reference class by considering the following assessment question:

- On how many days with snow and weather conditions just like today would this avalanche path release?

To apply the definition at larger spatial scales, the forecaster uses the following logic:

- Imagine the potential avalanche start zones or terrain where you expect the avalanche problem to exist. The visualization of the terrain being assessed is what establishes the reference class for the forecaster's probability assessment.
- What is the chance that those start zones will release? Note, this is an average likelihood assessment applied roughly equally across all those specific start zones. The assessment is NOT the chance of a single avalanche releasing from the assessed start zones, nor is it an assessment that all of those start zones will release. For the lowest probability classes, many regions will be too small to contain all the start zones mentioned in the frequency statements provided in Table 1 (e.g. 1000 paths or start zones at Highly Unlikely). In this case, many days when these low probabilities are forecasted there will be no avalanches at all.

Applying the definition at the larger scale also results in the intuitive conclusion that higher likelihood assessments (e.g. Very Likely) should result in more avalanches.

8.2 Different Types of Triggers

Depending on the nature of the avalanche risk management program, forecasters may have to assess likelihood for different types of triggers: natural releases, human triggers, explosives, or some combination of these. For example, some remote paths very rarely if ever experience human triggers in the start zones, which means the forecaster is only assessing for natural avalanches. Whereas in a guided backcountry skiing program, where people are often skiing and riding avalanche terrain, the forecasters often assess for both human triggers and natural avalanches. This assessment for both human triggers and/or explosives is complicated by the fact that it is a conditional probability assessment - the forecaster must first assume that the human triggers or explosives will dynamically load the start zone, and then assess the likelihood of avalanches assuming the loading. Avalanche start zones assessed with a higher likelihood due to the loading are often then avoided, which makes the evaluation of assessment challenging if no avalanches are observed.

During times of Low and High avalanche hazard (see Avalanche Canada, 2024) the likelihood of natural releases and human triggering may be similar. That is, at Low hazard both natural and human triggered avalanches may be Unlikely. Conversely, at High hazard both natural and human triggered avalanches may be Likely. Forecasters often combine the assessment for both types of triggers during these times and may separate the assessment for naturals and human triggering during periods of Moderate or Considerable hazard. For example, a Moderate hazard due a buried weak layer of surface hoar during a stable weather pattern without any significant inputs may result in natural avalanches being assessed as Unlikely, but human triggering could be assessed as Likely if the skiers center-punched start zones where the buried surface hoar existed.

A useful technique applied in practice is to assess for human triggering on slopes that may be skied separately from natural avalanches that may release from overhead terrain and run onto the ski terrain.

8.3 Low Frequency of Avalanhce Release over Larger Spatial Scales

Recently Schweizer et al. (2020) analyzed a 20-year avalanche occurrence dataset for an approximate 300 km^2 region around Davos Switzerland and found relatively low average number of avalanches per day, even during periods of High avalanche hazard. That is, avalanches were rare, or in other words, low probability events for any given day. The proposed definition for likelihood of avalanches supports this finding and captures the professional forecaster's expertise by focusing the probability assessment on specific terrain (e.g. avalanche problems). The key part of the definition for this is the "start zones being assessed" or "the start zones where the avalanche problem is expected to exist".

An example may help to visualize this concept. Let's consider the same ~300 km^2 region near Davos and assume that there are ~1000 start zones total. The forecaster expects that Persistent Slabs due to a buried sun crust are located on only south aspects at treeline and alpine elevations and assesses them as Likely (60% chance) to release. This assessment is applied only to those specific start zones which constitute approximately 165 out of the potential 1000 (1000 x 0.66 only treeline and alpine elevations x 0.25 only south aspects). Further the assessment of Likely would mean each of those 165 has an approximate 60% chance of releasing and on average we may expect about 100 avalanches. The expected 100 avalanches are significantly less than the 600 that would be expected if the Likely (60% chance) was applied to ALL the ~1000 potential start zones in the region. We believe that this terrain-based reference class captures the natural and intuitive process used by most experienced forecasters.

Hafner et al. (2021) analyzed avalanche activity during two extreme avalanche situations for a region in Switzerland near Davos and found avalanche activity in 13% of the potential release areas. This proportion of the potential release area analysis uses a slightly different reference class than we have proposed which is the proportion of the number of potential start zones, which may partially help explain the low areal proportion of released start zones. For example, a smaller relative avalanche size where ~25% of the potential start zone released would count as 1 / 1 (100%) for our reference class but would count as 25% in the Hafner et al. (2021) analysis.

8.4 Components of the Likelihood Scale

There are important concepts that influenced the design of the proposed likelihood scale:

- The ordinal scale of likelihood terms (e.g. Highly Unlikely, Fair Chance, Very Likely) should be chosen to support the decisions being made with their use. That is, the selection of the number of terms, whether the terms should be balanced evenly around 0.5 probability or skewed to higher or lower probabilities, what probability ranges each term should represent, etc. should be selected to be effective for operational decision making. For example, we recognize that the low probability - high consequence situation (e.g. large destructive deep slab avalanches) is a common problem for forecasters, and therefore we included a low probability term: Highly Unlikely, Remote Chance, Almost No Chance, Nearly Impossible, Highly Improbable. One of these likelihood terms could be chosen on a day where the forecaster is aware of a deep weakness in the snowpack, but there are no strong weather inputs forecast that would increase the chance of avalanches. Also, we understand that forecasters experience times with high levels of uncertainty, and therefore we included a term that represents a lot of uncertainty and a wide range of probabilities: Fair Chance, Even Chance, Uncertain, Not Certain, Possible. A useful question that remains is whether the two more probable levels - Likely and Very Likely - are useful or would one be sufficient?
- Avalanches are rare (Section 8.3). Therefore, an important remaining question is whether the probabilities and resulting frequencies suggested in the proposed likelihood scale (Table 1) are too high to accurately represent the reality of avalanche release rates?
- The probability ranges represented by the likelihood terms (e.g. 50 - 75% for Likely) should fall within the normal intuitive range for how most people interpret these terms. That is, one should NOT select values less than 50% for Likely because most people associate the word Likely with a greater than 50% chance. We attempted to choose ranges for the terms that fall within the normal intuitive range, however as discussed above, these values may be too high given actual avalanche release rates.
- The likelihood terms and associated probability ranges should fall within the reasonable bounds of uncertainty for forecasting avalanches. In other words, differentiating between a 10 and 11.5% chance of avalanches is not normally achievable with any confidence. This concept provides an upper boundary on the number of likelihood terms in the scale.

Overall, the numerical values proposed in the scale should be considered as a first suggestion and basis for discussion, rather than a final result. Novel and more accurate studies on avalanche activity rates using the reference class proposed here would provide data to better inform the probabilities and frequencies. The probability ranges and frequencies can and should evolve. The core concept and question explored in this paper is what do avalanche forecaster's subjective probability assessments of the likelihood of avalanches actually represent in terms of forecasting avalanche releases across terrain?

8. SURVEY INVITATION

Given the evolving nature of this topic and potential vast application of subjective probability assessment for snow avalanche release around the world, we have crafted a survey to better inform some of the concepts presented in the paper. We invite you to contribute your thoughts here:

Avalanche Likelihood Survey

ACKNOWLEDGEMENTS

The authors would like to thank Grant Statham and Bruce Jamieson who have been directly involved in the development of the concepts presented here. The guiding team at the CMH Adamants lodge and Eric Ostopovich have provided excellent feedback on the probability concepts applied to practical avalanche risk management in the field. Pascal Haegeli and Andrea Mannberg reviewed and consequently improved the survey. The avalanche technician team at Alpine Solutions has displayed a lot of patience and valuable feedback while being peppered with questions about their mental processes for industrial avalanche forecasting.

The concepts are not simple and the application to the avalanche patch is equally complex, however it is imperative we get this right.

REFERENCES

Avalanche Canada, 2024. Avalanche Canada - Glossary - Avalanche Danger Scale. https://avalanche.ca/glossary/terms/avalanche-danger-scale. Website accessed August 1, 2024.

Budescu, D., Broomell, S., Por, H., 2009. Improving communication of uncertainty in the reports of the Intergovernmental Panel on Climate Change. Psychological Science, 20(3): pp. 299-308.

Budescu, D., Por, H., Broomell, S., 2014. Effective communication of uncertainty in the IPCC reports. Climatic Change, 124(1-2): pp. 317-328.

Brun, W. and Teigen, K. H. 1988. Verbal probabilities: Ambiguous, context-dependent, or both? Organizational Behavior and Human Decision Processes, 41(3): pp: 390–404.

Fischer, K., Jungermann, H., 1996. Rarely occurring headaches and rarely occurring blindness: Is rarely = rarely? The meaning of verbal probability expressions in specific medical contexts. Journal of Behavioral Decision Making, 9(3): pp. 153-172.

Friedman, J., Baker, J., Mellers, B., Tetlock, P., Zeckhauser, R., 2018. The Value of Precision in Probability Assessment: Evidence from a Large-Scale Geopolitical Forecasting Tournament. International Studies Quarterly, Volume 62, Is-sue 2, June 2018: pp. 410–422.

Gigerenzer, G., 2002. Reckoning with risk: Learning to live with uncertainty. Penguin Books.

Hafner, E., Techel, F., Leinss, S., Buhler, Y., 2021. Mapping avalanches with satellites - evaluation of performance and completeness. The Cryosphere, 15: pp. 983–1004.

Klassen, K. Haegeli, P., Statham, G., 2013. The role of avalanche character in public avalanche safety products. Proceedings of the International Snow Science Workshop 2013, Grenoble, France: pp. 493-499.

Koehler, J., 1996. The base rate fallacy reconsidered: Descriptive, normative, and methodological challenges. Behavioral and Brain Sciences, 19(1): pp. 1-53.

Lazar, B., Greene, E., Birkeland, K., 2012. Avalanche problems and public advisories. Avalanche Review 31(2): pp. 1, 14–15, 23.

Morgan, M., Fischhoff, B., Bostrom, A., Atman, C., 2002. Risk communication: A mental models approach. Cambridge University Press.

Nakao, M., Axelrod, S., 1983. Numbers are better than words: Verbal specifications of frequency have no place in medicine. The American Journal of Medicine, 74(6): pp. 1061-1065.

Neace W., Michaud S., Bolling L., Deer K, Zecevic L., 2008. Frequency formats, probability formats, or problem structure? A test of the nested-sets hypothesis in an extensional reasoning task. Judgment and Decision Making. 3(2): pp. 140-152.

Rapoport, A., Wallsten, T., Erev, I., Cohen, B. 1990. Revision of opinion with verbally and numerically expressed uncertainties. Acta Psychologica. 74: pp. 61–79.

Schweizer, J., 2008. On the predictability of snow avalanches. Proceedings ISSW 2008, International Snow Science Workshop, Whistler BC, Canada, 21-27 September 2008, 688-692, 2008.

Schweizer, J., Mitterer, C., Techel, F., Stoffel, A., Reuter, B. 2019. On the relation between avalanche occurrence and avalanche danger level, The Cryosphere Discussions.

Schweizer, J., Mitterer, C., Techel, F., Stoffel, A., Reuter, B., 2020. On the relation between avalanche occurrence and avalanche danger level. The Cryosphere, 14, 737–750, 2020.

Statham, G., Haegeli, P., Birkeland, K., Greene, E., Israelson, C., Tremper, B., Kelly, J., Stethem, C., McMahon, B., White, B., 2018. A conceptual model of Avalanche hazard. Natural Hazards 90: pp. 663–691.

Teigen, K., Brun, W., 1999. The directionality of verbal probability expressions: Effects on decisions, predictions, and probabilistic reasoning. Organizational Behavior and Human Decision Processes, 80(2), 155-190.

Theil, M., 2002. The Role of Translations of Verbal into Numerical Probability Expressions in Risk Management: A Meta-Analysis. Journal of Risk Research 5 (2): 177–186.

Thumlert, S., Jamieson, B., Statham, G., 2022. Communicating Likelihood and Probability for Operational Snow Avalanche Forecasting. Canadian Geotechnique Volume 3 (4): pp. 54 - 57.

Zimmer, A., 1984. A model for the interpretation of verbal predictions. International Journal Main-Machine Studies, 20: pp. 121-134.