USERS' AWARENESS AND RESPONSE TO UNCERTAINTY INFORMATION IN PUBLIC AVALANCHE FORECASTS

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ABSTRACT: Uncertainty is inherent in avalanche forecasting. On some days, the available evidence provides a clear picture of the existing hazard situation, while on other days, various unknowns can make it difficult to understand the conditions. Yet, uncertainty is currently not communicated in a consistent way in avalanche forecasts across the world, and to our knowledge, no research has explored how forecast users understand and respond to uncertainty information. To address this knowledge gap, we conducted a detailed online survey in collaboration with the Colorado Avalanche Information Center in the spring of 2024. The core of the survey consisted of an exercise where participants were presented with simplified but realistic avalanche forecasts that included different amounts of information about uncertainty from various sources. For each forecast scenario, participants were asked to assess the level of uncertainty in the forecast, and how the presented information would affect their approach to a typical backcountry trip. We also asked questions about the understandability, usefulness, and trustworthiness of forecasts that include uncertainty information. Our analysis of the responses from 1313 participants suggests that adding explicit statements about the magnitude and characteristics of the uncertainty in the forecast has a significant impact on readers' estimated amount of uncertainty, which then influences their decisions about whether to enter the backcountry. Our results also show that including this information increases trust in avalanche forecast centers as reliable sources of hazard information. These insights support the inclusion of uncertainty information in avalanche forecasts. Our study contributes to the growing body of applied research that aims to help avalanche forecasting centers improve the effectiveness of their communication products by explicitly testing different formats and approaches.

Keywords: Risk communication, uncertainty, public avalanche forecast, user research

1. INTRODUCTION

Uncertainty is inherent in avalanche forecasts that aim to predict and communicate the state of dynamic and variable avalanche conditions so that people traveling in this environment can make informed choices about their personal risk management. On some days, the available evidence provides a clear picture of the existing hazard situation, while on other days, various unknowns can make it difficult to understand the conditions. Yet, describing a day's uncertainty is not a consistent element in public avalanche forecasts, and the few avalanche warning services that do include information about uncertainty use different approaches. For example, Avalanche Canada adds predefined confidence statements at the very end of the public forecast to express the unknowns caused by specific conditions. (Avalanche Canada, n.d.). Other avalanche centers use a systematic checklist at the end of the forecasting process to evaluate the day's uncertainty without communicating them to the public (e.g., Øien et al., 2023; Varsom, n.d., Logan & Greene, 2023).

Backcountry recreationists' travel and terrain choices depend on their personal knowledge, experience, and preferences as well as situational and social context, and avalanche forecasts provide important information about the hazard conditions for their decision-making. However, if the limitations of forecasts, such as the amount of uncertainty characterizing the conditions, are not clearly communicated in the forecast product, it may impact the quality of decisions users can make or lead them incorrectly to believe that they are adequately informed (Morgan et al., 2002, p.4; Morss et al., 2008).

There is very little research on uncertainty in avalanche forecasts, and to our knowledge, no research has explored how forecast users

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understand and respond to uncertainty information. To fill this knowledge gap, we studied how users of public avalanche forecasts perceive, interpret, and respond to the uncertainty in forecasts using an online survey. More specifically, our research questions were:

1. How aware are forecast users about the overall magnitude and different sources of uncertainty in the forecast?

2. How does uncertainty information impact users' decisions to enter the avalanche terrain?

3. How does added uncertainty information impact the understandability, usefulness and trustworthiness of the forecast?

Improved understanding of user needs will help avalanche warning services create relevant and useful uncertainty communication to support forecast users' personal risk management.

2. UNCERTAINTY BACKGROUND

Uncertainty is the state, even partial, of deficiency of information related to understanding or knowledge of an event, its consequence or likelihood (ISO, 2018). This is distinctly different from confidence, which describes forecasters' belief that their assessments are correct based on the available evidence (Pouget et al., 2016)

While there are many ways to theoretically partition uncertainty (see e.g., Vick, 2002; CAA, 2016), we consider three types of uncertainty for our discussion of uncertainty in avalanche forecasts: complexity, probability, and ambiguity (Han, 2011). *Complexity* refers to the structural properties of a system that make it difficult to understand it completely. *Probability* refers to the inherent random behavior of the system that makes predictions about future events difficult. *Ambiguity* refers to a property of the information we have about a system, often conflicting or absent, that makes it difficult to understand or is prone to multiple different interpretations.

The way information is collected, processed, and shared can introduce uncertainty in different ways. For this study, we identified five distinct sources of uncertainty for avalanche forecasts. As a dynamic and complex natural phenomenon, the *avalanche system* itself has many unknowns regardless of our current level of understanding. For example, it is still inherently hard to know to a high level of precision and accuracy the probability of when and where avalanches happen (Schweizer, 2008). Different avalanche problems illustrate complexity as some avalanche problems are more difficult to predict than others (Statham et al., 2018). *Observations and models* represent the phenomenon but evidence about the actual conditions can be ambiguous, for example due to limited resolution, measurement errors, or observation challenges. *Avalanche forecasters* then interpret the data to create a subjective, qualitative assessment of the nature and severity of the conditions to produce a forecast. Individual forecasters' perception and knowledge as well as workflow procedures can add ambiguity in their assessments (McClung, 2002). The content and format of the *forecast product* can make the message about the nature and severity of avalanche hazard conditions ambiguous. In the end, the forecast is available to *forecast users*, who can choose to use the information when deciding how to act according to their preferred personal exposure to the avalanche hazard.

Accommodating uncertainty in avalanche risk management begins by acknowledging its existence; reducing it when practical; communicating the irreducible uncertainty; and reconciling its existence in decisions (CAA, 2016, p.2). Strategies commonly used to reduce uncertainty include identifying knowledge gaps, seeking targeted information/education, applying several ways to assess the risk, and pursuing independent opinions to help with the decisions.

3. METHODS

3.1 Survey design

The core of our survey consisted of an exercise where participants were presented with simplified but realistic avalanche forecasts that included different amounts of information about uncertainty from four sources: the present avalanche problem, the availability of observations, the understanding of the spatial distribution of the conditions, and the understanding of the timing of the condition. The information was presented in an abridged forecast format similar to how the Colorado Avalanche Information Center (CAIC) and other U.S. avalanche centers present their forecasts on their websites (Fig. 1).

The design of our scenarios started from eight simplified baseline avalanche forecasts that included a danger rating, an avalanche problem, and a generic description of the conditions. Following a statistical design, we then augmented the baseline forecasts to create 60 so-called

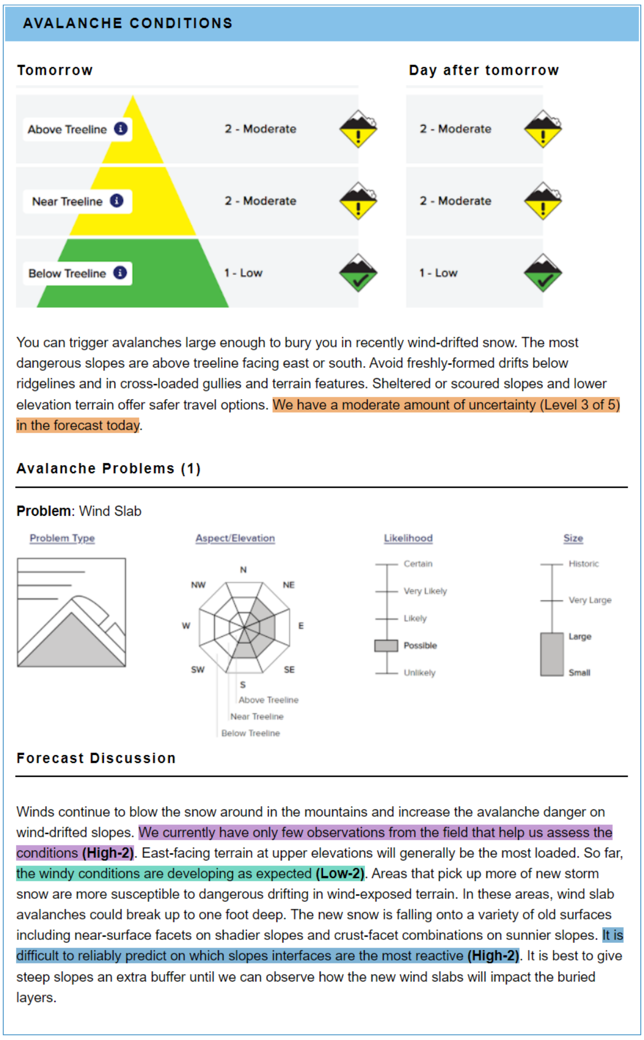

Figure 1: Example treatment avalanche forecast with a moderate danger rating, a wind slab problem, a magnitude statement present (orange highlight), high degrees of uncertainty from observations (purple highlight) and spatial distribution (blue highlight), a low degree of uncertainty from timing (green highlight), and the guidance statement for how to deal with the uncertainty absent. Highlighting and labels are only for illustration and were not shown to participants

Table 1: Attributes and levels for avalanche forecasts.

Attribute	Levels	Implementation
Danger rating*	Moderate Considerable	Moderate, moderate, low Considerable, considerable, moderate
Uncertainty from avalanche problem*	Low High	Storm slabs, wind slabs Persistent slabs, wet slabs
Uncertainty from observations	Low High	e.g., many professional observations available e.g., limited visibility prevents observations
Uncertainty from spatial distribution	Low High	e.g., similar conditions across entire forecast region e.g., difficult to reliably predict most reactive locations
Uncertainty from timing	Low High	e.g., all weather models agree on timing e.g., difficult to predict when conditions deteriorate
Explicit statement on uncertainty magnitude	Absent Present	n/a e.g., We have a moderate amount of uncertainty (Level 3 of 5) in the forecast today
Guidance on how to manage uncertainty	Absent Present	n/a e.g., track amount of new snow locally

* Included in baseline scenarios

treatment forecasts with varying levels of uncertainty from the four sources, with or without a statement about the overall magnitude of uncertainty (based on the number of uncertainty sources at level High), and with or without a guidance statement for how to deal with the existing uncertainty. While Table 1 lists the attributes included in the statistical design and provides examples of their implementation, the statements in the actual forecast scenarios (e.g., Fig. 1) were adjusted to ensure they made sense in the context of the given danger rating, avalanche problem and hazard description.

Each survey participant was presented with a baseline scenario first and then with three consecutive treatment scenarios with different levels of overall uncertainty. For each scenario, participants answered the following questions:

- *How much uncertainty do you think the forecaster faced when producing this forecast?*
  Rated on a scale from 0 (No uncertainty at all) to 100 (Extreme uncertainty)
- *Would you consider traveling in the backcountry under these conditions at all?*
  Answered with Yes or No
- *How useful was the presented avalanche forecast for your decision?*
  Rated on a scale from 0 (Not at all useful) to 100 (Extremely useful)

In addition, we asked participants *how difficult it was for them to understand the presented information* (rated on a scale from 0 (Not at all difficult) to 100 (Extremely difficult)) separately for the baseline scenario and after all three treatment scenarios combined. And finally, we asked participants in the debrief following the exercise *how much the integration of explicit uncertainty information in avalanche forecasts would affect their trust in their avalanche center as a reliable source of avalanche safety information* using a 7-level Likert-scale ranging from 'much decreased trust' to 'much increased trust'.

To provide context for our analysis, the survey also included the standardized background questions proposed by Haegeli et al. (2023) to collect information on participants' backcountry activities and experience, formal avalanche safety training, and avalanche forecast use.

3.2 Survey implementation and dataset

We collected data March 7 – May 15, 2024. The survey was promoted through extensive outreach by CAIC, which included targeted invitation emails to the members of Snowpool, the CAIC forecast user research panel, and general outreach through CAIC website, email, and social media channels. In addition, the invitation to participate was promoted by the U.S. National Avalanche Center to their network of other avalanche warning services in the United States.

Our analysis sample of participants with complete responses included 1313 participants who assessed 5252 avalanche forecast scenarios. It primarily consisted of backcountry skiers and snowboarders (82%), but we also had substantial participation from snowshoers (8%), out-of-bounds skiers and snowboarders (5%) and snowmobilers (3%). Participants' backcountry experience was evenly distributed with 23% having 3-5 years of experience, 23% 6-10 years, 20% 10-20 years, and 27% more than 20 years. Only 8% of the sample was in their first or second year of winter backcountry activities. Similarly, we had a range of dedication to winter backcountry activities in the sample, which was evenly split between participants who spend more or less than 20 days in the backcountry each winter. The sample had a relatively high degree of formal avalanche safety training with only 14% of participants having no training at all; the most common course level was an introductory course (44%). Reported avalanche forecast use was also high among our participants with 43% reading the forecast daily, and another 41% checking it before every trip and sometimes in between. The CAIC was identified as the "home" avalanche center by 46% of our sample. Another 15% came from the Northwest Avalanche Center, 6% from the Bridger-Teton, 6% from the Gallatin, and 5% from the Sawtooth avalanche centers. The remaining 22% of the sample frequent other avalanche forecast centers.

3.3 Statistical analysis

We conducted our entire analysis in R (version 4.3.2; R Core Team, 2024) and started with basic descriptive statistics and simple comparisons (e.g., Pearson's chi-squared test, Wilcoxon rank-sum test, paired t-test) to explore the nature of our dataset. We then estimated a series of generalized linear mixed effects models (Brooks et al., 2017) to explore participants' responses to the avalanche forecast exercise questions in more detail. For this paper, we only examined our survey dataset as a whole and did not yet account for potential heterogeneities within our sample population.

To reflect the nature of our response variables, we employed beta regression models to examine response variables with values from 0 to 100 (amount of uncertainty, usefulness of forecast) and a logistic regression model to analyze the question of whether to enter the backcountry at all under the given conditions. In addition to using statistical significance (p-value < 0.05) for deciding what variables to keep for our final models, we also only included predictor variables that exhibited substantial effect sizes with the potential for practical implications.

We used effects plots from the effect package (Fox and Weisberg, 2019) to visualize the results of our regression analyses. Effects plots illustrate the differences in the dependent variable between levels of a predictor variable of interest while holding all other predictor variables constant at their base levels. It is therefore more informative to look at the differences between the attribute levels of the predictor variable of interest than the absolute values since these charts only illustrate the magnitude of the effect.

4. RESULTS

4.1 Uncertainty assessments

Across the entire dataset, participants estimated the uncertainty that forecasters faced when they produced the forecast at a median of 30/100 (interquartile range (IQR): 20-60) for the baseline scenarios (n = 1313) and at a median of 48/100 (IQR: 20-70) for the treatment scenarios (n = 3939). This means that estimated amount of uncertainty increased by 18 units simply by adding information about it in the forecast (Wilcoxon rank-sum test: p-value < 0.01).

Examining the treatment scenarios in more detail revealed that all sources of uncertainty and their interactions with the explicit magnitude statement influenced participants' estimates. The estimates were neither affected by the danger rating nor the presence or absence of the guidance statement. The blue lines in Fig. 2, which depict the effect sizes without the uncertainty magnitude statement, show that the low and high uncertainty statements themselves result in different estimates. The information about uncertainty from observations had the biggest impact with a 9.3-unit difference between the high and low statements in the effects plots, followed by avalanche problem type (6.5-unit difference), spatial distribution (5.0), and timing (3.8). Of the avalanche problem types, the persistent slab avalanche problem was considered to have more associated uncertainty than the other problem types included in the experiment. The orange lines in Fig. 2 illustrate the effect of the explicit uncertainty magnitude statement (highlighted in orange in Fig. 1) on participants' uncertainty estimates. As expected, the statement significantly increased the differences between the low and high uncertainty statement for all sources. It also significantly increased the awareness of the uncertainty associated with wet slab avalanche problems, which did not stand out when the statement was absent.

In addition to raising participants' awareness of the individual sources of uncertainty, having the uncertainty magnitude statement also improved participants' understanding of the additive nature of uncertainty. Without the magnitude statement, uncertainty estimates were approximately equivalent for 2-4 sources of uncertainty at level High (Fig. 3: blue box plots). However, they continued to increase linearly with cumulative numbers of sources when the statement was present (Fig. 3: red box plots).

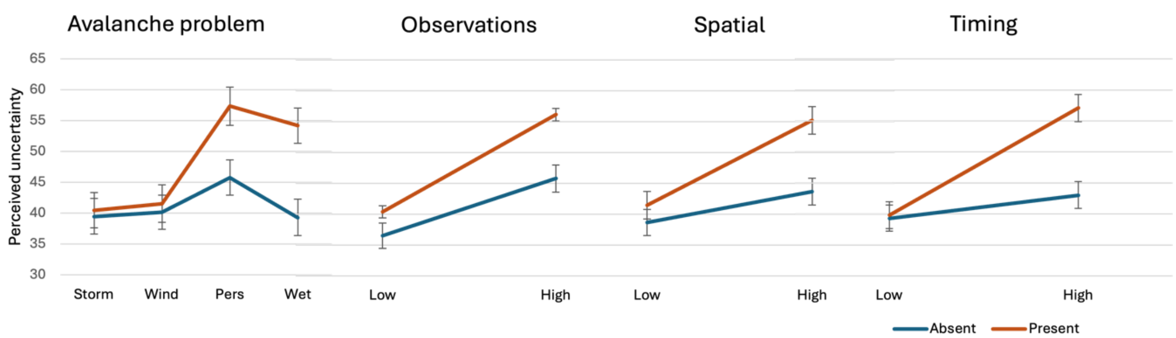

Figure 2: Effects plots of uncertainty assessment model for treatment scenarios and the uncertainty magnitude statement absent (blue) or present (orange).

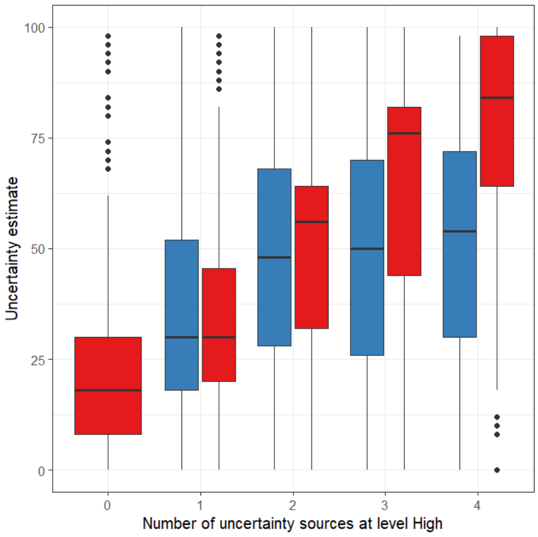

Figure 3: Participants' uncertainty estimates as a function of the number of uncertainty sources at High and the uncertainty magnitude statement absent (blue) or present (red).

4.2 *Whether to enter the backcountry at all*

Overall, participants chose not to enter the backcountry under the given conditions in 21% of the cases with no significant difference between the baseline and treatment scenarios (Pearson's chi-squared test: p-value = 0.102). To examine these choices in more detail, we created a combined model for all scenarios that included the danger rating, the avalanche problem type, the estimated uncertainty stated by participants in the preceding question, and whether it was a baseline or treatment scenario as predictors. The analysis revealed that a) participants were more likely to enter the backcountry under a moderate danger rating, and b) higher estimated amounts of uncertainty made participants go into the backcountry less. This effect was more pronounced at a considerable danger rating (all comparisons: Type II Wald chi-square test: $p < 0.001$).

4.3 *Usefulness of forecast information*

With an overall median of 82/100, participants' ratings of the usefulness of the forecast for their decision on how to proceed under the given conditions was very high, but the baseline scenarios received a slightly higher rating than the treatment scenarios (84 vs. 82; Wilcoxon rank-sum test: p-value = 0.049). Our regression analysis revealed that the usefulness of the forecast was significantly higher under Considerable than Moderate, and it detected a similarly large but negative relationship between the estimated amount of uncertainty and the usefulness of the forecast. This means that the higher the estimated uncertainty, the less useful the information for trip planning.

4.4 *Difficulty of understanding*

Participants generally found it easy to understand both the forecast information and our questions, and the inclusion of uncertainty information did not complicate their understanding. On a scale from 0 (Not at all difficult) to 100 (Extremely difficult), participants' median difficulty ratings were 16 for the baseline forecasts (n = 913) and 18 for the treatment scenarios (n = 999). The mean of participants' difference between their two ratings was -0.02 (n = 831), and a t-test showed no significant difference from zero. This means that across the entire dataset, there was no difference in the perceived difficulty of the forecasts with or without uncertainty information.

4.5 *Trust in avalanche forecast center*

Participants' responses to our question of how including explicit uncertainty information in avalanche forecasts would affect their trust in their avalanche forecast revealed strong support. Overall, 69.6% of participants stated that it would increase their trust (Slightly increased trust: 16.2%; Increased trust: 38.5%; Much increased trust: 14.9%), a quarter of the sample (25.2%) stated that their trust would remain the same, and only 5.2% indicated that their trust would decrease.

5. DISCUSSION

Our experiment of adding explicit uncertainty information in avalanche forecasts reveals important insights on participants' understanding and response to uncertainty. First, we can see limitations to their current perceptions, since participants' uncertainty ratings increased substantially when the forecast included some explicit uncertainty information. Second, participants also struggled to combine the effects of the different sources without the explicit magnitude statement showing their limited comprehension of the cumulative severity of the uncertainty.

Another key finding is that higher levels of estimated uncertainty result in more conservative choices related to entering the backcountry at all. However, increased estimated uncertainty is also associated with lower usefulness of the forecast for personal decision making. On the other hand, adding uncertainty information did not make the forecast text more difficult to understand.

And finally, participants' trust in the avalanche center would mainly increase if uncertainty information was included in their forecasts. This aligns with van der Bles et al. (2020) reassurance that science communicators can be more open and transparent about the limitations of their knowledge and still considered trustworthy.

5.1 Limitations

While these insights provide a detailed picture of how our participants perceive and response to uncertainty information in avalanche forecasts, there are several limitations to consider when extrapolating our results. Our sample of the participants was dominated by more committed and experienced consumers of avalanche forecasts, and we only examined the sample as a whole. However, we suspect that forecast users with different backgrounds might respond to uncertainty information in particular ways. Hence the next stage of our analysis aims to identify typical response patterns and relate them to participant characteristics to learn more about the uncertainty information needs and preferences of different user segments.

Furthermore, our present analysis used the simple decision of whether to enter the back-country or not as a metric for users' response to the uncertainty information. In reality, however, there are numerous other actionable options for managing uncertainty. When participants chose to enter the backcountry in our experiments, the survey presented them with numerous follow-up questions to further explore their coping strategies, which we will examine in more detail in the next stage of our analysis.

5.2 Implications for user support

The overarching conclusion of our analysis is that, based on our sample, there are no drawbacks to adding uncertainty information in the public forecast. The information heightens user's awareness of uncertainty, supports more conservative decision making, and increases the trust in the forecast center. The uncertainty information is more beneficial for users when it includes descriptions of the different sources and an explicit statement of the overall magnitude of uncertainty. These illustrate the full uncertainty conditions more clearly.

However, forecast centers and avalanche educators need to offer guidance on how to use uncertainty information. The observed negative relationship between the estimated amount of uncertainty and the usefulness of the forecast in our sample reflects a rather basic perspective that a more uncertain forecast is inherently less helpful for trip planning. However, avalanche professionals have highlighted that understanding the source and the magnitude of uncertainty is critical for making informed risk management decisions (Sykes & Atkins, 2023). Useful starting points for these educational efforts are establishing common vocabulary for communicating about uncertainty, designing travel and terrain advice statements with practical suggestions for how to reduce uncertainty, and educating backcountry travelers on how to define and discuss uncertainty effectively (e.g., Stock, 2024).

6. CONCLUSION

Currently information about uncertainty is not presented in a consistent way in public avalanche forecasts. We studied how forecast users perceive and interpret uncertainty information in hypothetical forecast scenarios to understand the basic impact of uncertainty statements for users. The presented results suggest that adding explicit statements about the magnitude and characteristics of the uncertainty of the hazard conditions has a significant impact on the readers' perception of the amount of uncertainty, and that their perception of the uncertainty influences their decision to enter the backcountry. These insights support the inclusion of uncertainty information in avalanche forecasts with few downsides.

The next step in our research is to examine the results of our survey in more detail to better understand participants' coping mechanisms and variabilities within the sample. Following that, we will conduct qualitative research to identify relevant channels, content, and formats for uncertainty information that supports the diverse needs of forecast users, which will ultimately help avalanche forecast centers to create more effective avalanche safety information products and services.

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