Understanding Avalanche Problem Assessments: A Concept Mapping Study with Public Avalanche Forecasters

by

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Abstract

Avalanche problems have become a fundamental component of avalanche hazard assessment and communication since the introduction of the Conceptual Model of Avalanche Hazard. However, the observations used to assess them are not explicitly defined and rely largely on avalanche forecasters' subjective judgements that are prone to noise and bias. This study uses concept mapping to develop a comprehensive understanding of factors influencing operational applications of avalanche problems in public avalanche bulletins in Canada. Interviews with 22 experienced forecasters revealed a diverse range of physical observations and additional considerations. While some of the observed inconsistencies can be attributed to physical differences among forecast regions, others originate from personal perspectives on risk communication considerations, approaches to dealing with uncertainty, and attributes of operational forecast systems. This research offers a starting point for the development of more objective criteria for adding and removing avalanche problems in public bulletins.

Keywords: avalanche problems; hazard assessment; avalanche forecasting; concept mapping

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List of Acronyms

AvCan	Avalanche Canada
Banff	Banff, Yoho, and Kootenay National Parks
CMAH	Conceptual Model of Avalanche Hazard
CR	Crusts
CT	Compression test
DF	Decomposing and fragmented precipitation particles
DH	Depth hoar
DL	Dry loose
DPS	Deep persistent slab
ECT	Extended column test
FC	Faceted grains
F, 4F, 1F, P, K	Hand test hardness codes (fist, four finger, one finger, pencil, knife)
Glacier	Glacier National Park
HST	Height of storm snow
Kananaskis	Kananaskis Country Provincial Park
PP	Precipitation particle
PS	Persistent slab
PST	Propagation saw test
PWL	Persistent weak layer
RB	Rutschblock test
RG	Rounded grains
SH	Surface hoar
SS	Storm slab
ST	Shovel shear test
SWE	Snow water equivalent
WS	Wind slab

Chapter 1.

Introduction

Snow avalanches are a natural hazard with the capability to be destructive and dangerous to people and infrastructure. In regions such as Canada where the combination of snow accumulation and terrain can produce avalanches, the detrimental impact to exposed elements of value is well established. Historically, avalanches in Canada have caused death, destruction, and economic losses in resource industries and worksites, along transportation corridors, energy and transmission, residential and public land uses, and recreational activities at ski areas and in the backcountry (Stethem et al., 2003). Currently, there is an average of ten avalanche fatalities each year in Canada (2012 to 2021) with the vast majority occurring during self-directed backcountry recreation (Avalanche Canada, 2021) where avalanche risk is accepted voluntarily.

To effectively manage avalanche risk both longer term planning and shorter term operational approaches can be applied depending on the context (Canadian Avalanche Association, 2016). For fixed assets such as roads, buildings, and utilities, long term planning such as site selection based on hazard mapping or permanent structural protection measures can be effective risk treatment options. However, complete avoidance of exposure to avalanche hazard or permanent protection are not feasible under all circumstances. Examples are highways crossing mountain passes where permanent protection can be too expensive, remote work sites (e.g., road construction, mines) where the exposure is temporary and can change continuously, or ski areas that are inherently located in avalanche terrain. Furthermore, permanent protection is not possible in many situations where the elements at risk are mobile such as recreational backcountry skiers, ice climbers, snowmobilers, and winter mountaineers.

In risk management contexts where long term planning measures are not feasible or unable to permanently reduce the risk to an acceptable level, avalanche forecasting becomes a critical component of the operational avalanche risk management process. Conventionally, avalanche forecasting has been described as a process primarily relying on inductive reasoning to evaluate the probability of avalanche release based on available meteorological, snow structure, and snow mechanics observations in the context of the relevant terrain (LaChapelle, 1980). While theoretical understanding of physical principles and snow mechanics help forecasters use deductive logic to interpret conditions, in practice forecasters are working under high levels of uncertainty that result in a reliance on subjective judgments primarily based on personal empirical experience (LaChapelle, 1966, 1980). To mediate the high degree of uncertainty, avalanche forecasting is applied as an iterative process of hypothesis testing and refinement based on redundant data sources that continues throughout the entirety of an avalanche season (LaChapelle, 1980). These practices of sequential updating and hypothesis testing can also leverage abductive reasoning processes where the best fitting hypothesis is selected based on incomplete information (Walton, 2004). In general, the use of experience-based heuristics help forecasters to operate effectively under complex and uncertain conditions, but these subjective human decisions are also susceptible to bias and error (Statham, Haegeli, et al., 2018). When heuristics are applied in inappropriate situations, these so called "human factors" have the potential to result in forecasting errors that can lead to severe consequences such as destruction of property, injury, or death (McCammon, 2004; McClung, 2002).

The Conceptual Model of Avalanche Hazard (CMAH) was developed as risk based framework to systematically assess avalanche hazard with the aim of reducing the influence of human errors, providing a consistent vocabulary for communication, and facilitating further study of forecasting expertise (Statham, Haegeli, et al., 2018). The CMAH was introduced into professional training programs in both Canada and the United States in 2008 and by 2013 was widely adopted and integrated into forecasting workflows and hazard communication across North America (Statham, Haegeli, et al., 2018). The CMAH divides the hazard assessment process into four distinct components (Figure 1.1) including the type of avalanche problem, which locations in the terrain the problem is situated, the likelihood that avalanches will occur, and the expected size of potential avalanches (Statham, Haegeli, et al., 2018).

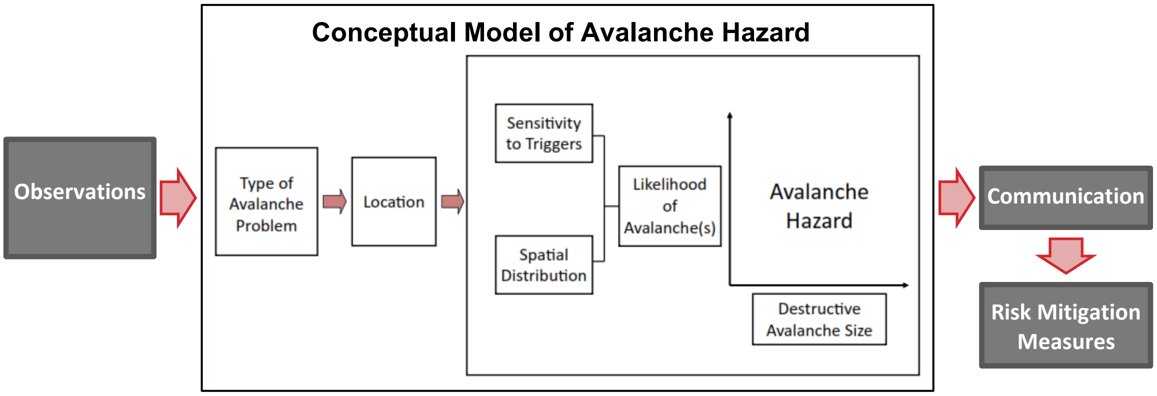

Figure 1.1 Avalanche forecasting process including the CMAH (imbedded figure from Statham, Haegeli, et al., 2018)

Fundamentally, the CMAH is built around the notion of distinguishable avalanche problems, which are used as a critical component to inform different mitigation approaches. Based on the structure of a snowpack, the character of different avalanche problems can be anticipated, providing important information that is not captured in stability ratings alone (Atkins, 2004). These problem types also dictate which observations are most valuable for the risk assessment process (Jamieson, Schweizer, et al., 2010). The CMAH defines nine avalanche problem types: dry loose, wet loose, storm slab, wind slab, persistent slab, deep persistent slab, wet slab, cornice, and glide slab (Statham, Haegeli, et al., 2018). Problem type definitions are based on the typical physical characteristics, formation, evolution and persistence, informative observation types, as well as effective mitigation options. However, the definitions are not explicitly prescriptive about what combination of conditions should be used to decide on the presence or absence of avalanche problems. Hence, forecaster judgement still plays an important role in the selection, ranking, and subsequent communication of the most relevant problems especially around indiscrete boundaries and transitions between avalanche problem types.

Avalanche forecasting takes place in many different operational settings such as ski resorts, backcountry guiding operations, transportation corridors, industrial and natural resource operations, and at public forecasting agencies. In the majority of theses settings forecasters use hazard assessments as a means to determine and implement appropriate risk treatment interventions such as preventing access to a hazardous area or the use of explosives to proactively control the severity of the hazard. Public forecasting agencies are an exception in that their mandate is to provide hazard information to the recreating public who are ultimately responsible for managing their own risk. In this context, forecasters apply the CMAH during their hazard assessment workflow (Statham et al., 2012), and key components of the CMAH including avalanche problems are subsequently shared with recreational backcountry users through the public avalanche bulletin (Klassen et al., 2013).

The avalanche bulletin is a central communication tool used by public avalanche forecasting agencies to engage with recreational backcountry users. Recreational backcountry users participate in variety of activities and are also diverse in the ways that they use the information presented in the public bulletin (St. Clair, 2019). To accommodate the diversity of users, public bulletins around the world use a tiered format beginning at the simplest level by communicating a regional danger rating and providing increasingly more detailed information in subsequent layers of the bulletin (European Avalanche Warning Service, n.d.; Statham & Jones, 2006). For the first tier, avalanche bulletins in Canada and the United States use the North American Public Avalanche Danger Scale to communicate avalanche hazard in the most concise and synthesized form. This danger scale uses five levels which are qualitatively defined by likelihood of avalanches, avalanche size and distribution, and is accompanied by a general travel advice statement (Statham et al., 2010). Although based off the CMAH risk assessment framework and terminology, the link between the hazard situation and the danger rating is another area where forecaster judgement is predominantly relied upon since no quantitative connection has been established to assign danger ratings. The second tier in the bulletins consists of avalanche problem information with up to three avalanche problems that are presented with their location in terrain (elevation and aspect), likelihood, expected size, and a brief description. The third and final tier of the bulletin includes more detailed information about avalanche activity, snowpack information, a weather summary, and an indication of the forecaster's confidence in the bulletin. A short text headline which forecasters use to convey an overarching message overlays all tiers of the bulletin.

An intentional by-product resulting from the implementation of the CMAH has been the generation of semi-quantitative datasets of hazard assessments that can offer insight into operational avalanche forecasting practices beyond what was previously possible. An early look at the application of the CMAH using data from two winters found that the maximum values for likelihood of triggering and avalanche size, and avalanche problem type were important indicators for predicting the danger rating, but also highlighted a strong influence of individual forecaster variation (Haegeli et al., 2012). A more comprehensive statistical examination of the not explicitly defined link between the CMAH and the North American Public Avalanche Danger Scale by Clark (2019) revealed more variability than could be explained by only considering the components of the CMAH. For example, avalanche problems with the same likelihood and consequence resulted in different danger ratings between different avalanche problem types and also based on the elevation band (Clark, 2019). Recently, the link between simulated weather and snowpack conditions and publicly forecasted avalanche problem types in Glacier National Park was investigated (Horton et al., 2020; Towell, 2019). Towell (2019) was able to confirm the relationship between anticipated snowpack and weather variables on avalanche problem type selection such as new snow amounts influencing the addition of storm slab problems, but the analysis also revealed considerable noise in the data. Furthermore, the rules for the removal of problems from forecasts that emerged from the analysis were much more vague, and the analysis was unable to link the removal of persistent avalanche problems to simulated weather and snowpack data (Towell, 2019). The author concluded from these results that additional factors beyond the defined physical characteristics affect the addition and removal avalanche problems in public avalanche bulletins. Shandro and Haegeli (2018), who studied the nature and variability of avalanche problems also noted operational practices and regional differences as possible influences on results.

Potential manifestations of differences in the undefined components of assessment approaches have also been reflected in studies that have focused on consistency. Lazar et al. (2016) revealed that, when presented with identical snowpack, weather, and avalanche occurrence data individual forecasters, even within the same forecasting operations, assign different danger ratings. Additionally, the study highlighted regional discrepancies between forecasters from Canada, the United States, and New Zealand despite using the same danger rating system and the CMAH. Notably, forecasters demonstrated a comparatively wider range in responses when presented with scenarios representing particular avalanche problems including incremental loading of a deep persistent weak layer (Lazar et al., 2016). Statham, Holeczi et al. (2018) investigated the application of avalanche problems among different avalanche warning services in the Canadian Rocky Mountains revealing substantial inconsistencies. Their study also highlighted that changes in the order and presence or absence of a problem can be linked to shift changes of forecasters.

Forecasting discrepancies of this nature are not limited to North America or the use of the CMAH framework. In the European Alps, inconsistencies between neighboring forecast regions along the borders of forecasting centers (including along national borders) were found to be higher than between regions within a forecasting center (Techel et al., 2018). In addition to differences in the avalanche conditions that may exist between regions, this suggests that differences in operational practices and cultures between forecast centers also impact avalanche forecasts despite the use of the same European Avalanche Danger Scale across these regions. Schweizer et al. (2020) also found that similar avalanche activity observed for different avalanche problem types (wet and dry) resulted in different danger ratings in the region around Davos, Switzerland. Widforss' (2021) exploration of automating Norwegian public avalanche bulletin components, including danger ratings and avalanche problems, using machine learning also exhibited challenges with targeting these variables that rely on human judgement. Model errors in differentiating wind-drifted and new snow avalanche problems, for example, were attributed to inconsistent application of these European avalanche problem types by forecasters (Widforss, 2021).

All these studies highlight that inconsistencies in avalanche forecasting is a widespread and substantial operational challenge. The potential consequences of inconsistencies between forecasters are a particular concern in public avalanche forecasting where the recreationists managing their personal risk are separate from the forecasters assessing the hazard. Systematic differences between forecast agencies and regions could also add to the challenge of recreationists who travel between forecast regions and are unlikely to recognize that information presented in a similar format could have a different meaning. In addition to providing insights about factors within the CMAH itself, the summarized studies have also brought to light additional factors not included in the model which play a role in assessment. While the CMAH has added some well-needed structure to the forecasting process, factors such as forecasting practices, rules-of-thumb, thresholds, and operational considerations that determine how the CMAH is actually operationalized remain largely undefined.

The objective of this study is to characterize the link between observations and forecasted avalanche problems by obtaining and representing knowledge about the avalanche problem type assessment process directly through discussions with experienced public avalanche forecasters. Having a more thorough and explicit understanding of what experienced forecasters consider when applying the avalanche problem type framework can identify opportunities to strengthen consistency between avalanche problem assessments and the subsequent risk communication in public bulletins used by backcountry recreationalists. Additional insights gained about forecasting practices and rules can also be a valuable step towards future development of practical operational tools to support avalanche forecasters in their assessments.

Chapter 2.

Methods

2.1. Background

Previous studies investigating the application of the CMAH have taken quantitative, statistical approaches to better understanding how public avalanche forecasters are assessing avalanche hazard (Clark, 2019; Haegeli et al., 2012; Lazar et al., 2016; Towell, 2019). While these studies have provided insights about the use of components of the CMAH in operational forecasting, they have also highlighted the likely influence of factors that are outside of the CMAH framework such as operation-specific forecasting practices and human influence. While the results of the existing studies have consistently highlighted this challenge, the quantitative approach stops short of providing a full explanation of the observed patterns and more comprehensive inventory of factors which are contributing to assessment decisions.

An alternate approach to gaining a more comprehensive understanding of how these decisions are made is offered through cognitive task analysis methods. Cognitive task analysis methods provide systematic processes for identifying and understanding the reasoning and knowledge that help people achieve outcomes (Crandall et al., 2006). Expert decision making within the avalanche practitioner domain has previously been investigated in a limited number of studies using cognitive task analysis approaches. These studies have demonstrated a capability to broaden the perspective of understanding avalanche assessments and decision making. Adams (2005) employed the critical decision method to explore human, physical, and environmental factors which influence avalanche practitioner's decisions. Maguire and Percival (2018) used artifact analysis and semi-structured interviews including protocol analysis to explore the subjective knowledge of avalanche forecasters working in a ski resort forecast application. Relevant to the current study, Maguire and Percival (2018) observed that explicit forecasting protocols and best practices do not capture the full range of cognitive activities critical to the forecasting process. A cognitive task perspective was also employed by Sättele et al. (2016) who developed an early warning system model which included critical parameters, experts' perception of these parameters, as well as their ability to evaluate the parameter based on personal and organizational factors.

Concept mapping is a cognitive task analysis method that is used to elicit and represent knowledge about events, processes, and procedures within a specific domain (Crandall et al., 2006). This method is a part of the knowledge elicitation branch of cognitive task analysis that has demonstrated the ability to collect and represent knowledge for applications in marketing, knowledge preservation, knowledge sharing, decision aiding, and revealing skill about procedures, heuristics, metacognitive strategies, and management of resources (Crandall et al., 2006). Concept maps create a graphical representation of knowledge by connecting pairs of concepts together using linking phrases to convey propositional phrases (Novak & Cañas, 2008). In Figure 2.1, for example, the propositional phrase *avalanche problems → are assessed by → avalanche forecasters* is made up of two concepts (*avalanche problems* and *avalanche forecasters*) which are connected by a linking phrase (*are assessed by*). Concept maps are also characterized by their semi-hierarchical structure and the use of crosslinks to connect and demonstrate interrelationships between concepts located in different segments of the concept map (Novak & Cañas, 2008).

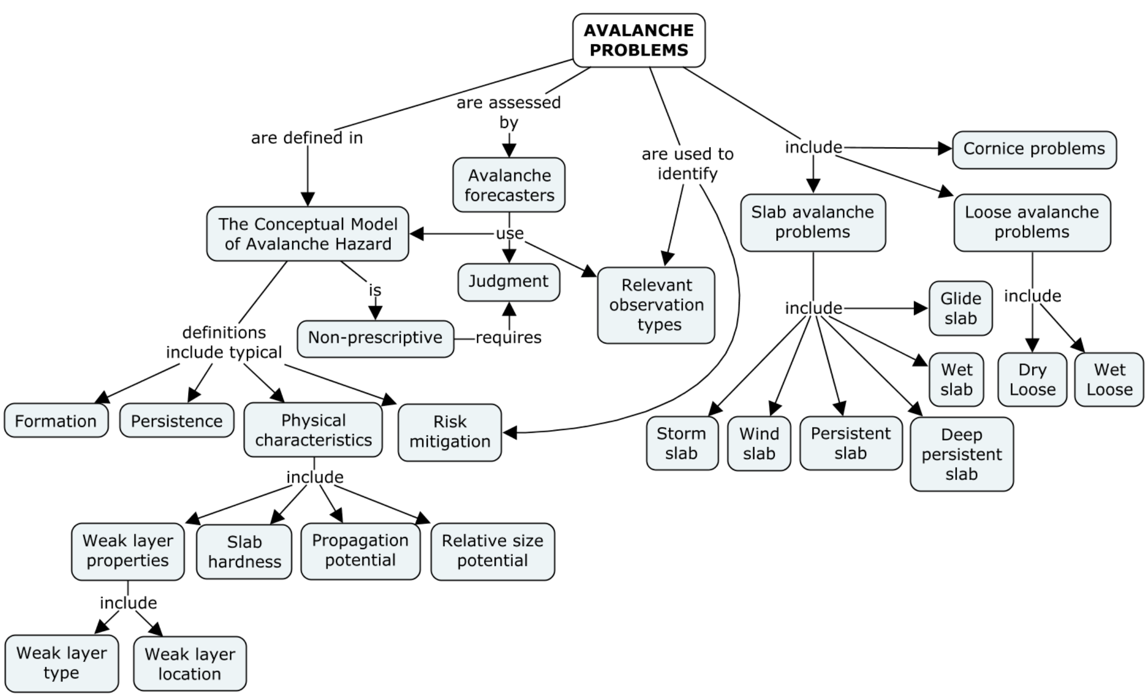

Figure 2.1 Example concept map describing avalanche problems

Concept mapping originates from the field of education where it was initially developed as tool in 1972 under consideration of the theory of meaningful learning (Novak & Cañas, 2006). Postulates of the theory of meaningful learning integrated into concept mapping include that new understanding is built on pre-existing knowledge of concepts and propositions that are organized into a hierarchical cognitive structure which becomes more detailed and interconnected when meaningful learning takes place (Novak & Cañas, 2006). Since its inception, concept mapping has been widely implemented and demonstrated as a useful tool in the educational field for research, curriculum development, and as a learning and knowledge evaluation tool in educational settings from pre-school to graduate programs (Novak & Cañas, 2010).

Concept mapping has also been applied extensively to capture and describe expertise in domains outside of purely educational settings. Example applications ranging from representation of terrain analysis information for military planning and operations, to making tacit knowledge explicit to provide a shared framework and resolve disagreements in the interpretation of business models, to preserving traditional knowledge about Thai silk weaving, to developing medical diagnostic decision aids for nuclear cardiology are detailed in Novak and Cañas (2010), Hoffman and Jameson (2013), Crandall et al. (2006), and Moon et al. (2011).

Concept mapping has also been used in fields closely related to the avalanche forecasting domain. Hoffman et al. (2017) applied the method in a project that modeled expert knowledge of U.S. Navy weather forecasters at a Meteorology and Oceanography Command forecasting and training facility (Hoffman et al., 2017). This project resulted in a knowledge model made up of over 150 concept maps detailing domain topics such as the developmental phases of thunderstorms in the Gulf Coast Region. In this context, concept mapping was used to elicit and preserve expert knowledge and the resulting concept maps were used to support trainees or relocated experienced forecasters who needed to develop local expertise (Hoffman et al., 2017). Although processes and procedures were not the focus of that project, the concept mapping method also resulted in the elicitation of heuristic rules and reasonings which were reflected in the knowledge model (Hoffman et al., 2006). This study provides an illustrative demonstration of how practitioners knowledge and beliefs can be expressed and represented within a domain that shares similar attributes to avalanche forecasting.

2.2. Data collection

2.2.1. Data collection approach

The primary goal of the data collection approach was to develop a more comprehensive perspective on the considerations that experienced public avalanche forecasters take into account when making decision about avalanche problems. This includes observation types, specific observation values and any other relevant factors. Concept mapping was selected as the primary method for expert knowledge elicitation and representation. To implement the concept mapping process, data collection involved two stages: an initial interview and a subsequent follow-up procedure. The individual interviews were used to introduce participating forecasters to the project and have an extended conversation about their forecasting practices regarding the avalanche problems in question. After the individual interviews, follow-ups were used to collaboratively refine and validate the draft concept maps that were developed during the initial interview.

2.2.1.1 Participating forecast agencies

In Canada, several non-government not-for-profit organizations and government agencies publish public avalanche bulletins. Four of these forecasting agencies in western Canada participated in this study including Avalanche Canada (AvCan), Glacier National Park (Glacier), Banff, Yoho, and Kootenay National Parks (Banff), and Kananaskis Country Provincial Park (Kananaskis). While all these agencies issue daily public avalanche bulletins using the same structure and components throughout the winter season, several organizational differences exist.

Avalanche Canada is a not-for-profit, non-government avalanche safety organization which provides forecasts to the widest range of regions within Canada. During our interview period in the 2020-2021 season a team of 13 avalanche forecasters produced daily bulletins for 14 forecast regions situated across British Columbia, Alberta, and Yukon (Avalanche Canada, 2021). In contrast to all other agencies in the study, Avalanche Canada utilizes an office-based forecasting strategy. Forecasters are centrally located in Revelstoke, British Columbia and are each typically responsible for generating avalanche bulletins for multiple remote forecast regions on a given day. In data sparse forecast regions where information is less readily available from sources including the industry wide information sharing system InfoEx (Haegeli et al., 2014), forecasters are supported by dedicated avalanche field teams.

The other three forecast agencies (Glacier, Banff, and Kananaskis) are government agencies who provide public avalanche forecasting within the bounds of national or provincial parks. Forecasters in these agencies are situated within their forecast region and participate in field-based forecasting activities. Avalanche forecasting teams in these regions also are also responsible for other forecasting applications such as highway avalanche control and visitor safety services including search and rescue. Forecast agencies based in Glacier and Banff are both a part of the federal Parks Canada agency. The Parks Canada forecast agencies publish their public avalanche bulletins bilingually on a Government of Canada platform using a slightly varied format from those published by Avalanche Canada's, although the tiered structure and components of the bulletin are the same. Kananaskis forecasters are public servants of the Alberta Provincial Government, who publish their forecasts using the platform of Avalanche Canada.

2.2.1.2 Avalanche problem types

To allow for a thorough exploration of the factors considered when making forecasting decisions about avalanche problems, only four of the nine avalanche problem types were selected as the focus of this exploratory study. Sets of avalanche problems that share indiscrete boundaries due to the nature of their formation and development were recognized as having the potential to provide valuable insights. In consultation with the collaborating avalanche warning services, storm slab, wind slab, persistent slab, and deep persistent slab avalanche problems (Table 2.1) were identified to be of particular interest. These problems are frequently used to describe avalanche hazard within western Canada. From the 2009/10 to the 2016/17 winter seasons, these four avalanche problem types accounted for 78% of forecasted problems in western Canada (Shandro, 2017). Furthermore, avalanches associated with these four avalanche problem types are responsible for the vast majority of avalanche fatalities in North America (Jamieson, Haegeli, et al., 2010; Langford & Haegeli, 2020; Logan & Greene, 2014). Based on the relationships between these problem types, two overarching discussion topics were formulated.

Storm slab (SS) and wind slab (WS) avalanche problems were combined into one interview script as both are situated near the surface of the snowpack and are often directly associated with a recent or ongoing weather event. SS problems are defined as short-term problems that result from soft, cohesive slabs of new snow reacting at the interface with an old snow surface or within the new snow itself (Statham, Haegeli, et al., 2018). WS problems are characterized as locally deep cohesive slabs of wind broken and packed snow particles (Statham, Haegeli, et al., 2018). Intense precipitation and wind are cited as conditions associated with peak instability of SS and WS problems respectively (Statham, Haegeli, et al., 2018). It is conceivable that these weather conditions frequently overlap in mountain environments, however practitioners in both Canada and the United States have made the case for not simultaneously listing these problems in the public bulletin (Klassen, 2014; Lazar et al., 2012). This practice was also reflected within the results of Towell (2019) who found the presence of a SS to be a more significant variable than any weather or snowpack variables for statistically derived decision rules around WS avalanche problems. Similarly, the initiation of this practice was reflected by a decrease in hazard scenarios containing both problem types identified by Shandro & Haegeli (2018).

Persistent slab (PS) and deep persistent slab (DPS) problem types were combined in the second interview script as they share similar characteristics in that they are both longer term problems associated with a slab overlying persistent weak layer buried deeper in the snowpack. The definition for PS problems identifies cohesive slabs overlying a weak layer that was formed at the snow surface which is susceptible to crack propagation (Statham, Haegeli, et al., 2018). DPS problems are characterized as involving thick, hard, cohesive, old snow slabs overlying a weak layer which was formed by metamorphosis within the snowpack (Statham, Haegeli, et al., 2018). The distinction between PS and DPS avalanche problems has also been a topic of discussion for practitioners (Klassen, 2014; Lazar et al., 2012) and notably, the avalanche problem types used in European public avalanche bulletins do not distinguish between these two avalanche problem types (European Avalanche Warning Service, 2017).

Table 2.1 CMAH avalanche problem definitions (adapted from Table 4 of Statham, Haegeli, et al., 2018)

	Description	Formation	Persistence	Typical Physical Characteristics	Typical risk mitigation
Storm Slab	Cohesive slab of soft new snow. Also called a direct-action avalanche.	Cohesive slab of new snow creates short-term instability within the storm snow or at the old snow interface.	Peaks of intense precipitation and tends to stabilize within hours or days following.	**Weak layer type:** DF, PP **Weak layer location:** In new snow or at new/old snow interface **Slab hardness:** Very soft to medium (F-1F) **Propagation potential:** Path **Relative size potential:** R1-5	Avoid avalanche terrain during periods of intense precipitation, and for the first 24-36 hours following. Assess for crack propagation potential in all avalanche terrain during and in the days following a storm.
Wind Slab	Cohesive slab of locally deep, wind-deposited snow.	Wind transport of falling snow or soft surface snow. Wind action breaks snow crystals into smaller particles and packs them into a cohesive slab overlying a non-persistent weak layer.	Peaks during periods of intense wind loading and tends to stabilize within several days following. Cold air temperatures can extend the persistence.	**Weak layer type:** DF, PP **Weak layer location:** Upper snowpack **Slab hardness:** Soft to very hard (4F-K) **Propagation potential:** Terrain feature to path **Relative size potential:** R1-4	Identify wind-drifted snow by observing sudden changes in snow surface texture and hardness. Wind erodes snow on the upwind side of an obstacle, and deposits it on the downwind side. They are most common on the lee side of ridge tops or gullies and are most unstable when they first form and shortly after.
Persistent Slab	Cohesive slab of old and/or new snow that is poorly bonded to a and does not strengthen or strengthens slowly conducive to failure initiation and crack propagation.	Weak layer forms on the snow surface and is buried by new snow. The overlying slab builds incrementally over several storm cycles until reaching critical threshold for release.	Often builds slowly and then activates within a short period for weeks or months but generally weeks.	**Weak layer type:** SH, FC, FC/CR combo **Weak layer location:** Mid to upper snowpack **Slab hardness:** Soft to hard (4F-P) **Propagation potential:** Path to adjacent paths **Relative size potential:** R2-4	Complex problem that is difficult to assess, predict and manage. Typically located on specific aspects or elevation. Identification and tracking of weak layer distribution and crack propagation propensity is key, along with a wide margin for error and conservative terrain choices.
Deep Persistent Slab	Thick, hard cohesive slab of old snow overlying an early-season persistent weak layer located in the lower snowpack or near the ground. Structure is conducive to failure initiation and crack propagation. Typically characterized by low likelihood and large destructive size.	Weak layer metamorphoses within the snowpack forming facets adjacent to an early-season ice crust, depth hoar at the base of the snowpack, or facets at the snow-glacier ice interface. The overlying slab builds incrementally over many storm cycles until reaching critical threshold for release.	Develops early in the winter and is characterized by periods of activity followed by periods of dormancy, then activity again. This on/off pattern can persist for the entire season until the snowpack has melted.	**Weak layer type:** DH, FC, FC/CR combo **Weak layer location:** Basal or near-basal **Slab hardness:** Medium to very hard (1F-K) **Propagation potential:** Path to adjacent paths **Relative size potential:** R3-5	The most difficult avalanche problem to assess, predict and manage due to a high degree of uncertainty. Low probability/high consequence avalanches. Triggering is common from shallow, weak snowpack areas, with long crack propagations and remote triggering typical. Weak layer tracking and wide margins for error are essential, with seasonal avoidance of specific avalanche terrain often necessary.

2.2.1.3 Forecast regions

Forecast regions focused on in this study (Figure 2.2) are situated within the transitional and continental snow climates of the Columbia Mountains and Rocky Mountains respectively. For the purposes of our study Avalanche Canada forecasters were asked to consider their responses from the perspective of the North Columbia and South Columbia forecast regions. This decision was made to maintain a more focused discussion with AvCan forecasters who regularly forecast for numerous different regional contexts across western Canada. Discussions with representatives from Avalanche Canada identified the North and South Columbia forecast regions as generally having a relatively rich availability of information for forecasters to leverage. While data sparsity is a common operational challenge in several AvCan forecast regions (Floyer et al., 2016; Storm & Helgeson, 2014), it was decided that examining the impact of data sparsity on avalanche problem type assessments was beyond the desired scope of this study. Additionally, the North and South Columbia forecast regions are both located within a single snow climate where they abut the Glacier National Park forecast region, which allows for interagency comparisons within the same snow climate region. A regional snow climate comparison can also be made where Banff and Kananaskis forecast regions neighbour each other within the Rocky Mountain Range.

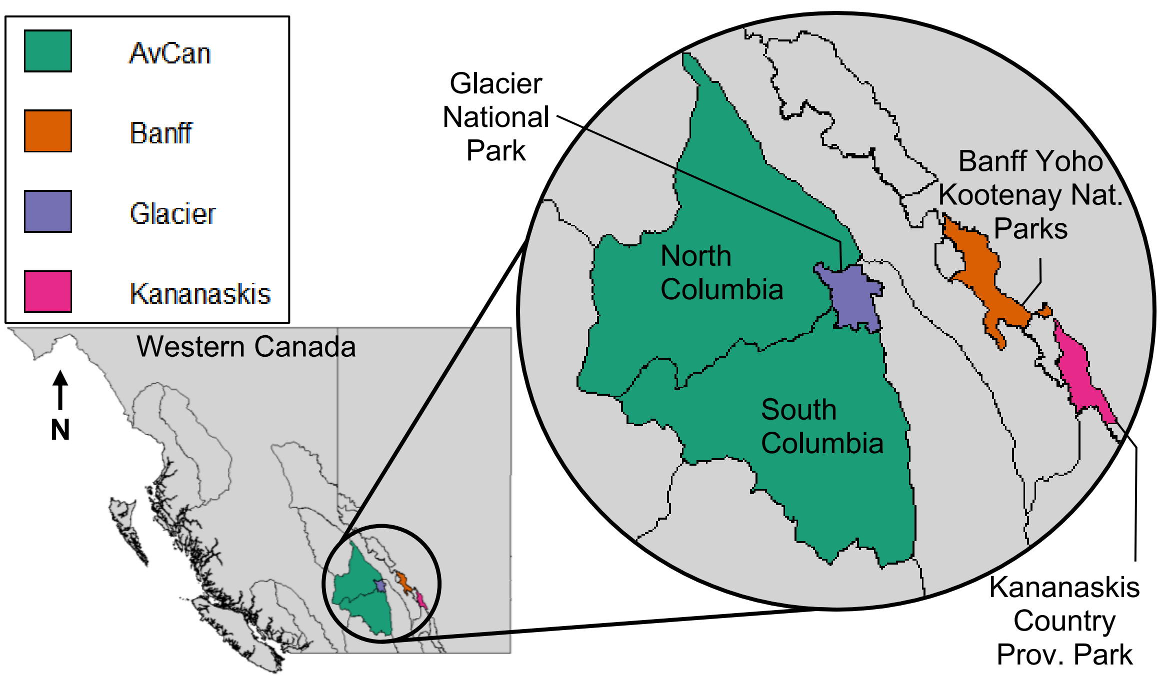

Figure 2.2 Location of forecast regions included in this study

The selected forecast regions are situated within two of the three major snow climate classifications (maritime, transitional, and continental) that are used to describe characteristic avalanche hazard conditions at the scale of the major mountain ranges of western Canada (McClung & Schaerer, 2006). The continental snow climate of the Rocky Mountains feature shallower snowpacks, colder temperatures, and often exhibits persisting structural instabilities (McClung & Schaerer, 2006). Comparatively milder temperatures and deeper snowpacks dominated by surface avalanche instabilities typically exist in maritime snow climate of the Coast Mountains (McClung & Schaerer, 2006). The transitional snow climate of the Columbia Mountains can present both maritime and continental dominated influences, often producing snowpacks with persistent instabilities associated with surface hoar and early season rain-on-snow generated facet-crust layers (Haegeli & McClung, 2003).

These climate regions have been linked to the prevalence of specific avalanche problem hazard scenarios (Shandro & Haegeli, 2018). Shandro and Haegeli (2018) found publicly forecasted DPS problems to be more prevalent in the Rocky Mountains and avalanche hazard scenarios involving PS problems more prevalent in the North and South Columbia forecast regions. Notably, the Glacier National Park forecast region did not exhibit the same increased prevalence of PS problems as the neighbouring Avalanche Canada forecast regions (Shandro & Haegeli, 2018). Including two forecast agencies within each of the transitional and continental snow climate regions in this study was intended to provide an opportunity to observe where such differences might exist that can be attributed to snow climate or to organizational context.

2.2.2. Concept mapping interviews

The interview design was established using the concept mapping procedure described in Crandall et al. (2006) and considering the skills described in Moon et al. (2011) and Coffey (2006). Interview and concept mapping procedures underwent a thorough pre-testing and refinement process including test interviews for each topic with avalanche professionals of varying backgrounds. The final interview design constituted of an approximately 1.5 hour interview process involving a team of two researchers and one forecaster. The interviews were conducted via a web-conferencing application.

Interviews began with a brief introductory presentation which elaborated on documentation describing the project and methods which was shared with participants prior to the interview. This introduction reiterated the goals and approach of the project and provided an overview and example of the concept mapping process.

The majority of each interview was devoted to the concept mapping process. To elicit and document expert knowledge during the interview most efficiently, the members of the two-person research team had distinct roles. One researcher focused on facilitating the conversation whereas the other researcher was focused on recording. The facilitator's primary purpose was to engage with the interviewee, focus the discussion, offer non-leading suggestions and probe questions, and to manage the pace to allow for concept map recording (Coffey, 2004; Crandall et al., 2006). The recorder was responsible for capturing and displaying the information in concept map format throughout the discussion (Coffey, 2004; Crandall et al., 2006). Web-conferencing allowed for the evolving concept map to be viewed by the interviewee and both members of the interview team throughout the discussion[1]. Concept maps were dynamically developed using CmapTools concept mapping software (Cañas et al., 2004).

The facilitated concept mapping process involved establishing the domain and focus of the concept map; characterizing key conditions, observations, thresholds and rules; identifying operational and personal practices; and concept map refinement. Focus questions are used in concept mapping to explicitly state the topic and guide what knowledge is most relevant (Crandall et al., 2006). A predetermined focus question was selected for each of the two interview topic areas based on project goals and interview pre-testing. To keep the conversations as focused as possible and use the interviewees' time most effectively, each interview focused on only one of the topics with half of the forecasters from each agency focusing on the SS and WS topic and the other half focusing on PS and DPS topic. The overarching focus question used for each topic were:

> **Storm slab and wind slab topic:** What are your considerations for deciding whether to add, keep, or eliminate a storm or wind slab avalanche problem from the public avalanche bulletin in <FORECAST REGION>?

[1] Interviewee connectivity issues resulted in audio only interviewee engagement during two interviews.

Persistent slab and deep persistent slab topic: What are your considerations for deciding whether to add, keep, or eliminate a persistent or deep persistent slab avalanche problem from the public avalanche bulletin in <FORECAST REGION>?

To further structure the interviews and get to the main questions of interest more quickly, a starting concept map (Figure 2.3) was developed for each topic to reflect common scenarios for adding, removing, and transitioning between problems in the bulletin. During the interview process forecasters were invited to add, remove, or make changes to the starting scenarios to reflect their own perspective.

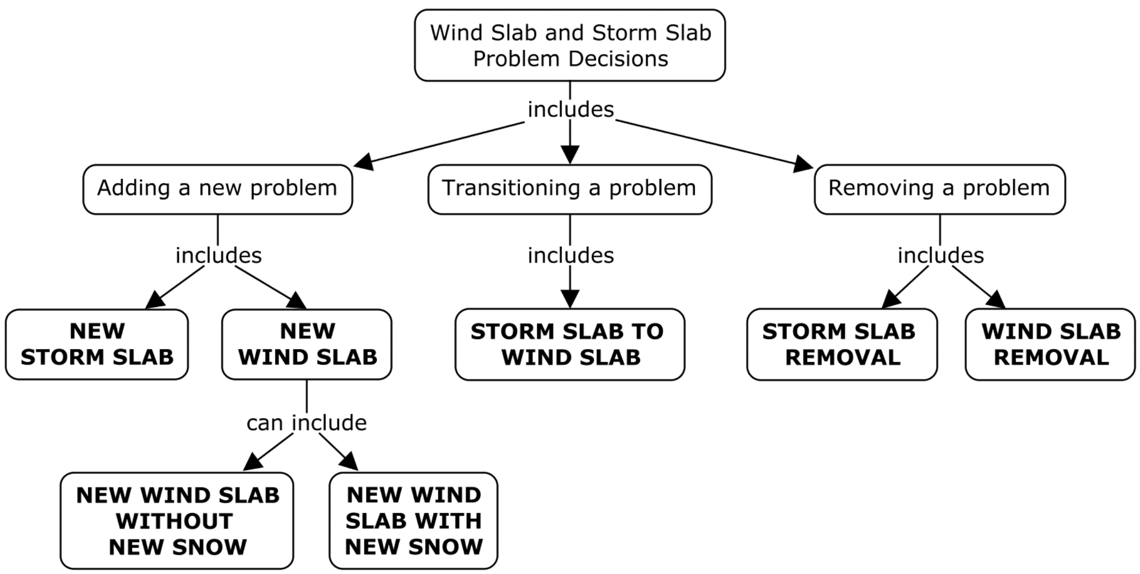

Figure 2.3 Example of starting concept map for storm slab and wind slab topic

For each scenario that the interviewee deemed as relevant, the following interview approach was used to develop a scenario specific branch of the larger concept map. To begin, the forecaster was asked to describe what observations and considerations they take into account for the specific scenario in the simplest terms. This question initiated the development of a "parking-lot" (Crandall et al., 2006) of unlinked concepts involving important observations and practices. These concepts were then further probed to understand relationships between concepts and to identify specific values, thresholds, examples, information sources, and personal or operational forecasting practices. Prompting questions about observation types aimed to elicit specific and quantifiable values where possible, although forecasters were not forced to provide this type of information if it did not readily come to them. As ideas were explored the concepts were rearranged and pairs of concepts were connected using linking phrases to create propositions that were assembled into a semi-hierarchical structure.

Once an initial round of discussion and concept map development had taken place for each scenario, forecasters were invited to make some preliminary refinements or elaborate on additional areas that had not been discussed. Avalanche Canada forecasters, who typically simultaneously prepare forecasts for multiple forecast regions, were also queried about where regional differences exist beyond the North and South Columbia specific concept map near the end interview.

Towards the end of the interview, each interviewee was asked to elaborate on how they decide to order the list of avalanche problems in the public bulletin. The CMAH indicates when more than one problem exists the forecaster should prioritize the problem types (Statham, Haegeli, et al., 2018). Factors which should be used to prioritize problems are not explicitly defined which provides opportunity for different perspectives between forecasters to emerge, as is reflected in the variability observed by Statham, Holeczi, et al. (2018). This open-ended question was intended to be an initial exploration of considerations that public forecasters hold in the prioritization of problems. Responses to the problem ordering question were recorded separately from the concept map that had been developed during the interview.

2.2.3. Follow-up and concept map refinement

The procedure of refining concept maps is iterative involving adding or removing concepts, and adjusting linking phrases connecting concepts (Crandall et al., 2006). Refinement of the concept maps largely took place following the initial interview process. As a first step in the refinement process, interview recordings were reviewed by the main researcher to capture any overlooked concepts and connections. The concept maps were also reviewed for quality by limiting cases where concepts are used more than once in the same concept map branch and resolving concept-linking phrase-concept triplets which did not form propositions. Additional questions and requests for clarifications about the concept map were formulated and presented back to the forecaster with an electronic version of the revised concept map draft for their review. Forecasters were encouraged to consider whether the concept map was an accurate representation or if corrections or elaborations could be made. Changes including addition, removal, editing, or restructuring of any content within the concept map was encouraged. The format of subsequent revisions to the concept maps varied between forecasters including updates over an exchange of emails, the use of sketches and markups, phone calls, and additional web-conferencing sessions. The majority of concept maps underwent one to two rounds of revisions to reach a suitable representation that was self validated by the forecaster. Some concept maps went through as many as four rounds of revisions and two forecasters did not have additional comments after the first concept map draft was presented.

2.2.4. Study participants

2.2.4.1 Participant selection

Our interview participants included 22 public avalanche forecasters whose recruitment was mediated through a senior staff member of each of the four participating forecasting agencies. Crispen and Hoffman (2016) identified that knowledge elicitation with genuine experts can be successfully achieved with a range of three to five participants and that additional experts provide diminishing returns on value of additional information yield. Six forecasters were recruited to participate from each of the AvCan, Banff, and Glacier forecast agencies. Due to their comparatively smaller forecast team size, four Kananaskis forecasters participated in the study. The sample size accommodates an expert knowledge perspective from four to six forecasters within each agency. The larger total number of individuals also provides a more comprehensive perspective to explore the variabilities between individual forecasters.

Selection of experts typically rely on three classes of proficiency including career, sociometric, and performance criteria (Crispen & Hoffman, 2016). Within the public avalanche forecasting domain performance criteria are difficult to determine as it is not easy to quantify the success of an avalanche forecast. As such, those who assisted with forecaster recruitment at each agency were asked to suggest experienced forecasters and/or forecasters who are recognized as a “go-to person” within the organization.

2.2.4.2 Participant backgrounds

A brief survey regarding participant backgrounds was distributed independently from the formal interview process and revealed a range of experience, roles, training levels, and personal experience contexts. On average forecasters had 19 years of experience working as an avalanche professional (range 10 to 33 years). Participants' experience in public forecasting varied between one to 27 years with an average of eleven years and they had spent an average of nine years (range of one to 18 years) at their current forecasting agency. All forecasters' roles involved active engagement in forecasting including eleven forecasters with senior or managerial positions (e.g., program coordinators, senior forecasters, managers, team leads) and two junior forecasters. All participants had a minimum Avalanche Operations Level 2 Industry Training Program certification through the Canadian Avalanche Association. Thirteen forecasters held an Avalanche Operations Level 3 certification which focuses on applied avalanche risk management and is the highest level of certification offered by the Canadian Avalanche Association. Some forecasters also disclosed relevant guiding certifications through the Association of Canadian Mountain Guides or International Federation of Mountain Guides Associations. Most commonly, personal backgrounds were described as involving guiding (15 forecasters). However, five forecasters described their backgrounds as including search and rescue; six as including forecasting for transportation corridors; four including public forecasting; one as an engineer; one as a forecaster for industrial settings; and two with backgrounds including ski patrolling. Forecasters indicated the snow climates that have shaped their perspectives as including continental (19 forecasters), transitional (20 forecasters), and maritime (7 forecasters). Most forecasters suggested that experiences in multiple snow climates have substantially shaped their perspective, with only one forecaster from each of the participating agencies specifying a single snow climate. Our sample included 19 male forecasters and three female forecasters with an age range of 34 to 57 years.

2.3. Analysis

2.3.1. Analysis of concept maps

The main objective of the analysis of the concept maps was to provide a comprehensive summary of the factors and values that are important for the assessment of the different scenarios within the topics discussed. Additionally, we were interested in using these summaries to examine differences between individual forecasters, forecasting agencies, and snow climate regions. A review of available methods and the project specific approach are discussed below.

2.3.1.1 Concept map analysis approaches from the education domain

As a knowledge elicitation method, concept maps on the same topic have not frequently been developed in replicate as in this study. However, concept mapping's rich history of use in the field of education presents examples of analysis approaches used for comparing multiple concept maps with the same focus. Methods for concept map analysis include evaluating concepts, categories of concepts and/or the structure or links between concepts using quantitative analysis (counts), similarity analysis (comparing to a reference concept map), holistic analysis (scoring content or structure using a rubric), and qualitative analysis (describing content or structure) (de Ries et al., 2021). The multitude of different approaches that have been used to evaluate open-ended concept maps in the education context reflects the challenge of analyzing these datasets which include semantically and structurally diverse representations of different individuals' understanding of a topic (de Ries et al., 2021).

Outcomes of the educational analysis methods at a general level focus on an evaluation of a student's knowledge or learning about a topic. These methods are not directly applicable in our context as the thorough understanding of the domain knowledge of the forecasters is not in question. However, these methods do provide some insights into techniques that have been used to work with concept map data. For example, some quantitative scoring methods reward higher counts of the number of valid propositions, levels of hierarchy, and cross-links between concepts as indicators of meaningful learning (Novak & Gowin, 1984). Since validity of concepts is not a concern in the context of expert knowledge elicitation, differences in total number of concepts between scenarios may provide a cautious impression of the relative breadth of domain knowledge for particular scenario. Similarity analysis where concepts and propositions are compared to a reference map are also of interest. However, rather than looking for overlap with a single expert concept map "answer key", we must consider the full array of expert concept maps more closely resembling the group similarity measure used by Beyerbach (1988). Many studies in educational setting have used more than one analysis method to achieve the study objectives (de Ries et al., 2021).

2.3.1.2 Concept map analysis approach used in this study

Building on the customized analysis approaches used in existing concept mapping research, this study employed an analysis approach that integrates both quantitative (frequency counts based) and qualitative (description of content based) methods that were tailored to the context this project. The analysis approach included data cleaning, data preparation, concept attribute coding, general concept map statistics, and developing a summary of content and consistency. Content and consistency were explored at the levels of observation types, observation values, and additional considerations.

To allow for more adaptable and robust data manipulation and analysis, refined concept maps were exported from CmapTools and imported into R statistical software (R Core Team, 2021). Within R, a custom package of tools was developed to access and manipulate concept maps, individual concepts, linking phrases, and attributes of the concept maps (e.g. forecaster identifiers, concept map topic, agencies).

Data cleaning was required to prepare the concept maps for meaningful further analysis. This was primarily focused on creating a higher degree of cross-compatibility between concept maps. The open-ended nature of the interviews, where concepts and linking phrases were intentionally non-confined, resulted in a variety of concepts with synonymous meanings. A dictionary identifying these instances was developed to look up and replace synonymous phrases or concepts. For example, all derivatives of the term temperature (temp, temperature, temperatures) were simplified so concepts containing this term could be more directly queried and compared. In some cases, manual adjustments to the concept maps were required to increase the specificity within the hierarchy of observation types. For example, if a concept map contained the following proposition: *snowpack properties → considers → weak layer depth* it would be updated to include *snowpack properties → considers → weak layer properties → includes → weak layer depth.* The addition of the *weak layer properties* observation type was then able to be recognized in comparisons to other concept maps where *weak layer properties* were also relevant but focused on a different sub-observation type such as *weak layer formation*. All manual changes were tracked and were carefully implemented only where it was perceived to not alter the meaning of the content contained within concept maps.

During concept map development, the concepts used to represent each forecaster's considerations within their concept map were categorized and colour coded based on the type of information they contain. These concept types were further refined and utilized to structure the analysis approach. Concept types included information sources, observation types, observation values, assessment, special considerations, examples, key conditions, problems, regions, and scenarios (Table 2.2).

Table 2.2 Concept types and colour coding format (bolded rows indicate observation types that are the primary focus of the subsequent analysis).

Concept Type	Description	Example
SCENARIO	concepts describe the general circumstances where a problem is added or removed from the bulletin	adding a persistent slab problem
Key conditions	broad categories that provide structure for individual concept maps	snowpack properties
Observation types	**physical properties that can be objectively observed or inferred by forecasters**	**air temperature**
Observation values	**quantitative or qualitative values or ranges of values associated with an assessment or observation type. Often linked using a qualitative likelihood or frequency descriptor such as 'typically', 'sometimes', 'rarely', or 'not when'.**	**greater than 0ºC**
Assessment	includes elements of the assessment process which require substantial forecaster judgement to interpret from physical observations	danger rating
Examples	provide additional explanation or are used where forecasters did not generalize observation values	
Information source	data sources used by the forecaster	InfoEx
Regions	geographic or forecast regions	Purcells
Problem types	avalanche problem types	Storm Slab Problem
Special considerations	**additional factors outside of the more physically based observation types, these include subjective considerations, considerations related to practices or processes, and explanatory concepts that provide additional context**	**message fatigue**

The analysis of the considerations important for avalanche problem type decisions was broken down into twelve major scenarios that were discussed by participating forecasters (Table 2.3). To prepare each major scenario for the analysis, the branch of each individual's concept map that contained information describing that scenario was isolated from the individual's larger concept map. To start the analysis, an aggregated set of summary statistics was calculated which included the overall number of concepts, the number of linking phrases, the number of connections between concepts, and the proportion of concept types for each scenario.

Table 2.3 Major analysis scenarios by topic

Storm Slab and Wind Slab Problem Major Scenarios	Persistent Slab and Deep Persistent Slab Problem Major Scenarios
- Adding storm slab - Adding wind slab with new snow - Adding wind slab without new snow - Transitioning storm slab to wind slab - Removing storm slab - Removing wind slab	- Adding persistent slab - Adding deep persistent slab - Removing persistent slab - Removing deep persistent slab - Reactivating persistent slab - Reactivating deep persistent slab

To explore the observations, heuristics, practices, and other factors that influence forecasters avalanche problem type assessments, the main analysis of the concept maps for each major scenario was guided by the following three questions each focusing on a separate concept type:

Question 1: What *observation types* are relevant to the scenario?

Question 2: For observation types that are frequent for each scenario, what *observation values* do forecasters consider?

Question 3: What *additional considerations* exist and is there potential conflict between these?

To explore Question 1, the observation types were identified and filtered to only include those that were mentioned by at least two forecasters. Observation types which were only considered by one forecaster were iteratively reviewed to capture and correct any synonymous observation types which may have been missed during the initial data cleaning process. All observation types included by at least two forecasters were then summarized by calculating how often they were mentioned across all concept maps, by region, agency, and individual forecaster. These quantitative frequency statistics for each scenario were represented using a combined heat map and bar chart figure where observation types were arranged based on their information class (LaChapelle, 1980) as instability conditions, snowpack conditions, weather conditions, or as spatial and temporal factors.

Once relevant observation types had been identified, we explored Question 2 by examining the values associated with these observation types for each scenario. Any concepts directly linked to each observation type were considered at this stage. Observation values often included different levels of detail, units, or additional context which needed to be accounted for. For example, values for an observation type such as new snow might include simply the presence or absence of new snow; or might include sub-observation types for new snow (observed or forecasted) expressed as accumulation (cm) or snow water equivalence (mm); and these values might include specific thresholds or ranges over different time frames. To account for context, the “path” of propositions from the root concept of the scenario to the observation type was considered. Including the path of propositions from the scenario root to the observation type made it easier to distinguish between cases where, for example, some wind values in a particular scenario were related to wind loading and others were related to the impact of wind at the time of weak layer formation. A qualitative summary of observation values for each observation type was developed in the form of summary tables that also suggest a general qualitative evaluation of the consistency between observation values. Due to variability between the observation types and the variety of observation value formats (quantitative, categorical, ranges, thresholds, sub-categories, etc.) this measure can only indicate a rough impression of the alignment of values by suggesting a weak, moderate, or strong consistency (Table 2.4). The total number of observation values should also be considered when reviewing the qualitative consistencies.

Table 2.4 Qualitatvie value consistency labels

Label	Description
Weak	wide range of values or multiple conflicting values
Moderate	moderately wide range of values, or multiple values agree with one value conflicting
Strong	narrow range of values with no conflicting values

The final step of the analysis was Question 3, which explored the additional considerations that were included in the avalanche problem type decisions associated with each scenario. These types of considerations were found within the special consideration concepts. The special consideration concepts for each scenario were extracted and aggregated with their connected propositional statements and paths to provide context. A qualitative analysis of these propositions then involved inductive coding to extract common themes in participants' considerations. A consistent coding scheme was used for all scenarios to allow for more broadly applicable considerations to be compiled and summarized across scenarios and concept map topics. This allowed, for example, additional considerations related to approaches for dealing with uncertainty described in an individual removing PS problem scenario to be considered more holistically across the different contexts of adding and removing other avalanche problem types.

2.3.2. Analysis of ordering problems question

The ordering problems question was analyzed separately from the concept maps. All discussions pertaining to the ordering problems question for each forecaster were transcribed. An inventory of factors used to decide the order of avalanche problems presented in the bulletin were identified from the transcripts of all forecasters. For each interviewee the factors they described as considerations were identified and, where included by the forecaster, the relative weights between factors and descriptive examples of associated problem orders were also compiled.

Chapter 3.

Results

Interviews and follow-ups resulted in two sets of concept maps: One set of eleven concept maps describes the SS and WS avalanche problems topic, and a second set of eleven concept maps describes the PS and DPS avalanche problems topic. The results of each set of concept maps are presented by describing the observation types, observation values, and additional considerations that forecasters mentioned during the interviews for adding, removing, transitioning (only SS to WS), and reactivating (PS and DPS only). The results section concludes by discussing additional, more general considerations that are applicable to both SS/WS and PS/DPS avalanche problems and considerations around ordering problems that were shared by the interviewees.

3.1. Storm slab and wind slab scenarios

Interviews about SS and WS avalanche problems elicited descriptions of several scenarios that result in a change of the status of a problem in the public avalanche bulletin (Figure 3.1). All interviews resulted in a representation of a scenario for adding and removing each problem type (add SS, add WS, transition SS to WS, remove SS, remove WS). In some cases, more specific sub-scenarios were included to illustrate more specific scenarios, such as the difference between adding a new WS with or without new snow.

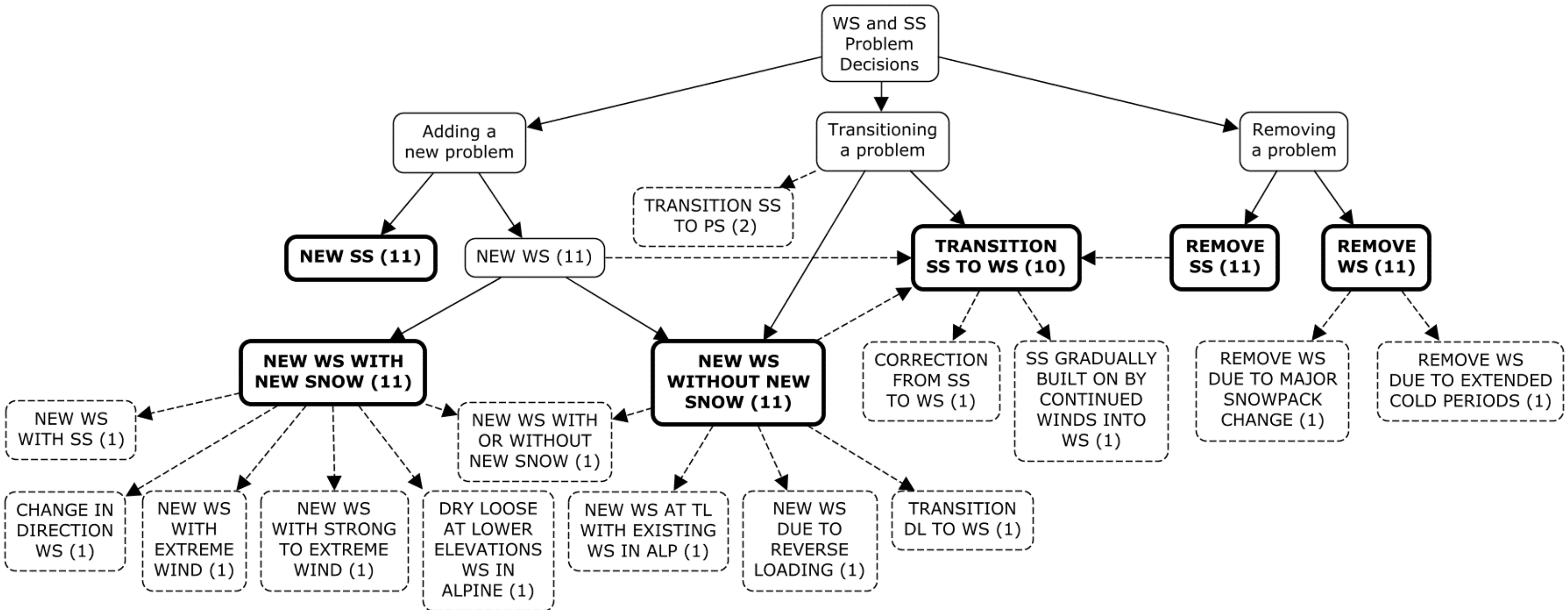

Figure 3.1 **Storm slab and wind slab scenarios (major analysis scenarios bolded; sub-scenarios dashed; values in parenthesis indicate number of forecaster interviews including the scenario).**

Concept maps focused on SS and WS decisions were comprised of a total of 3122 concepts, 2249 linking phrases, and 5786 connections between concepts. The number of concepts, linking phrases, and connections that make up each base scenario varies across scenarios and between forecasting agencies (Figure 3.2). On average the removal scenarios contain fewer concepts than scenarios for adding a problem.

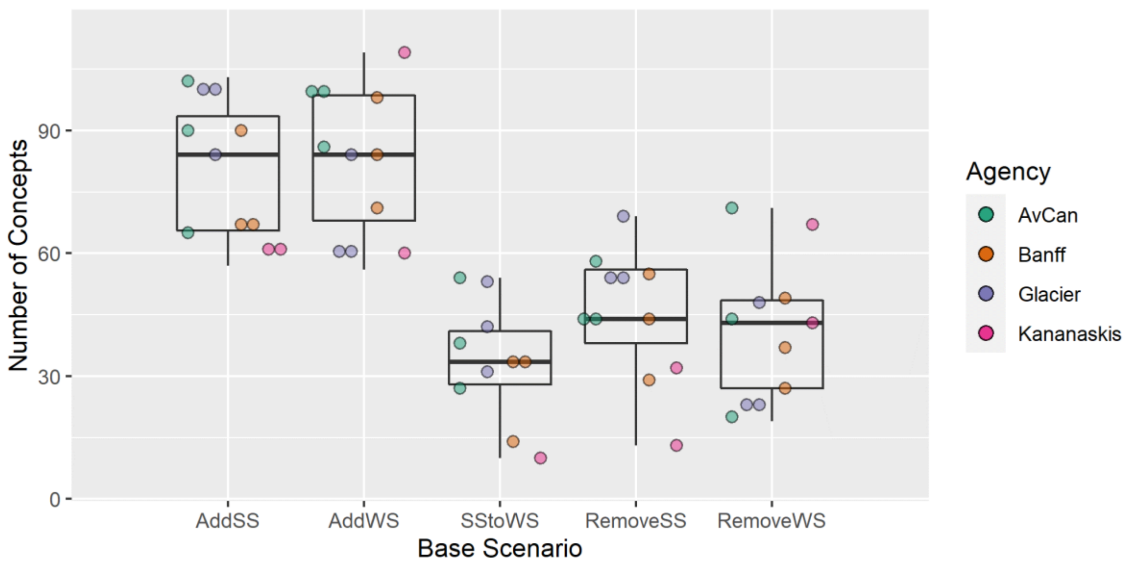

Figure 3.2 Number of concepts by scenario and agency for storm slab and wind slab problems

Observation types, observation values, and special considerations made up the majority of the concepts used to describe the decisions to add and remove these problem types (Figure 3.3).

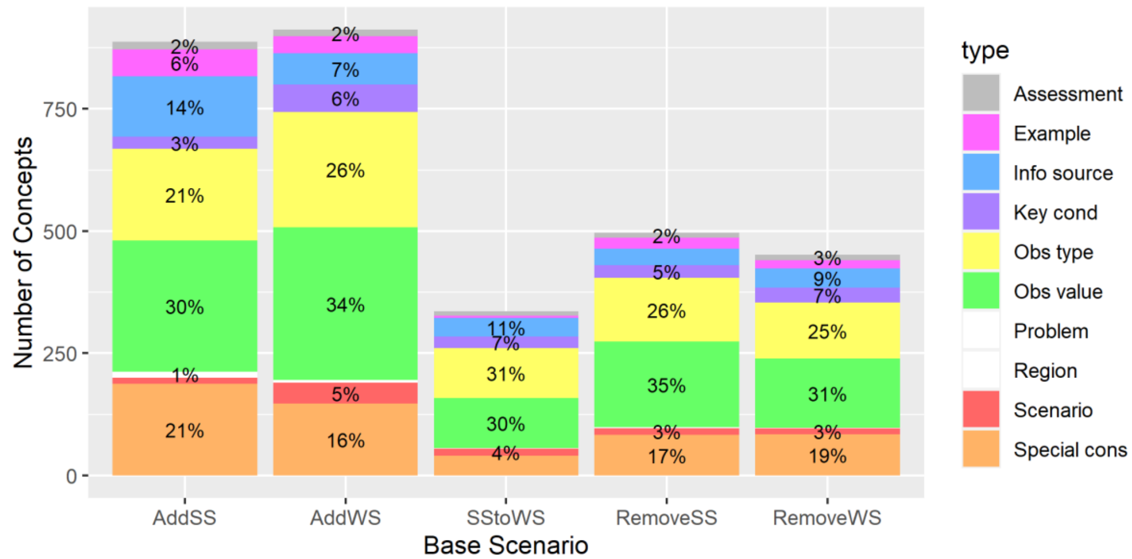

Figure 3.3 Total number and proportions of concept types by scenario for storm slab and wind slab problems

On average 60% (range of 53% to 64%) of concepts discussed in each scenario were related to observation types, observation values, and assessments. The observation types primarily include physical observations and related to weather, snowpack, and instability conditions as well as spatial or temporal considerations (Figure 3.4). Special considerations on average made up 17% of the concepts for each scenario.

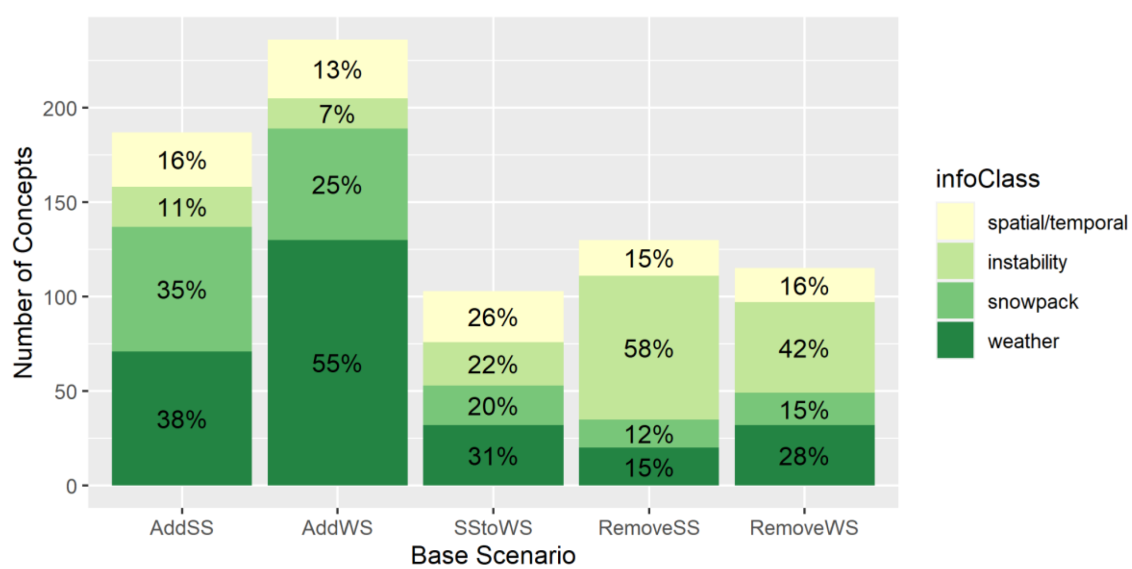

Figure 3.4 Observation type information classes by scenario for storm slab and wind slab problems

3.1.1. Storm slab avalanche problems

Concept map interviews centered on SS problems focused on considerations for adding and removing SS avalanche problems in the bulletin. The transition of SS to WS is discussed separately in Section 3.1.2. These discussions generated a total of 1383 concepts, 986 linking phrases, and 2539 connections.

3.1.1.1 Adding SS problems

The addition of storm slab problems to the public bulletin was discussed in all eleven interviews. However, the frequency of occurrence for SS problems was noted to be very rare by both forecasters in Kananaskis, and less frequent than other regions by one Banff forecaster (B4)[2]. On average, the adding SS scenarios included 81 concepts. As the name of the problem suggests, the initiation of this problem type is closely tied to the direct development of avalanches from new snow deposited by individual storm events. The following section further elaborates on the considerations of forecasters when initiating this problem type.

Observations

Observations for adding a SS problem to the bulletin most consistently included weather conditions but also involved instability, snowpack, and spatial and temporal considerations (Figure 3.5).

[2] Forecaster identifiers use an anonymized alphanumeric forecaster code where the letter indicates the agency (A – AvCan, G – Glacier, B – Banff, K – Kananaskis) and an individual identifier (1-6).

Figure 3.5 Observation types mentioned by at least two forecasters as a consideration for adding SS avalanche problems. Dark colored grid squares indicate that a forecaster noted the observation type. The total number of forecasters who discussed the observation type across all agencies is presented as bar charts on the right.

The following subsections describe the observation types and values for adding a SS avalanche problem in detail organized according to the information classes weather observations, snowpack observations, instability observations, and spatial and temporal considerations. Each of these sections is accompanied by an overview table (e.g., Table 3.1) that summarizes the observation types and values. Each row in the overview table represents an individual observation type relevant for the scenario that was mentioned by at least two forecasters. More specific observation types are grouped and indented under more general observation types (e.g., ***new snow accumulation*** under ***new snow***) for ease of navigation and understanding. However, it is important to note that the information presented in these tables does not represent a true hierarchy where the number of mentions of the sub-observations add up to the total number of mentions of the observation type. The main reason for this is that the paths to the presented sub-observation types can differ between concept maps, (e.g., if ***rain*** is included as a consideration in a concept map it is possible that ***loading*** more generally was not mentioned). Additionally, forecasters may mention the main observation type without including sub-observations or may include multiple sub-observations. Coloured pie charts are included in the table to indicate the proportion of forecasters from each agency who included the scenario that mentioned the observation type. All tables correlate with an associated heat map figure for each scenario (e.g., Table 3.1 correlates to Figure 3.5) where more information can be found on which individual forecasters included each observation type. A general impression of the consistency of the observation values as defined in Table 2.4 is also provided in these summary tables.

Weather observations

When considering adding a new SS problem, all forecasters mentioned weather conditions associated with new snow, air temperature, and wind conditions (Table 3.1).

Table 3.1 **Summary of weather observations, frequencies, and values for adding SS avalanche problems. Coloured pie charts indicate the proportion of forecasters who mentioned each observation type out of those whose interview included the scenario from each agency. More specific observation types are grouped under more general observation types for ease of navigation, but frequencies do no need to add up due to differences in concept maps. Agencies: A=Avalanche Canada, B=Banff, G=Glacier, K=Kananaskis. Total number of forecasters who discussed the scenario at each agency noted in parentheses.**

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
new snow	11	●	●	●	●	considers *accumulation, SWE, forecasted, received, distribution, and intensity of new snow*	*n/a*
new snow accumulation	9	◐	◐	●	●	threshold range of ≥ 10 to 30 cm (see Figure 3.6 for more detail)	moderate
forecasted SWE	2	◐	◐	○	○	threshold range of 10 to 25 cm	strong
air temperature	11	●	●	●	●	more likely when warmer (-10ºC to 0ºC); less likely when colder (≤-10ºC to -20ºC)	strong
air temperature trends	3	○	◐	◐	◐	more likely when cold to warm than when warm to cold	strong
wind	11	●	●	●	●	typically or almost always “some wind” (AvCan); requires no wind transport (K4)	weak
wind speed	8	○	●	●	●	not when no wind; typical ranges from calm to strong winds; sometimes extreme winds (see Figure 3.7 for more detail)	weak

Regarding ***new snow***, nine of eleven forecasters (all agencies) quantified thresholds for new snow ***accumulation*** in depth of new snow while the remaining two forecasters (A4, G4) quantified thresholds for forecasted ***snow water equivalent*** (SWE). The typical threshold values for new snow accumulation ranged between 10 cm to 30 cm (Figure 3.6). Some forecasters further specified combinations of typical conditions also including wind or temperature values that adjust the new snow threshold. For example, two Glacier forecasters (G5, G6) indicated a typical threshold of 10 cm of new snow when there is wind, compared to a threshold of 20 cm without wind (G5) or when temperatures are -5ºC to -10ºC (G6). Notably, despite some forecasters indicating that less snow accumulation can be relevant in the Rocky Mountains, thresholds from Banff represented the highest typical thresholds of at least 30 cm (Figure 3.6). Two forecasters in the Columbia

Mountains (G5, A5) noted that incremental loading is less likely to lead to a SS problem or at least slows the development, whereas one forecaster in the Rocky Mountains (B4) stated that it occurs quite often. The range of threshold values provided by forecasters who indicated focusing on forecasted SWE was 10 to 25 mm, which is consistent with the thresholds for depth of new snow assuming a density of new snow of roughly 100 kg/m^3.

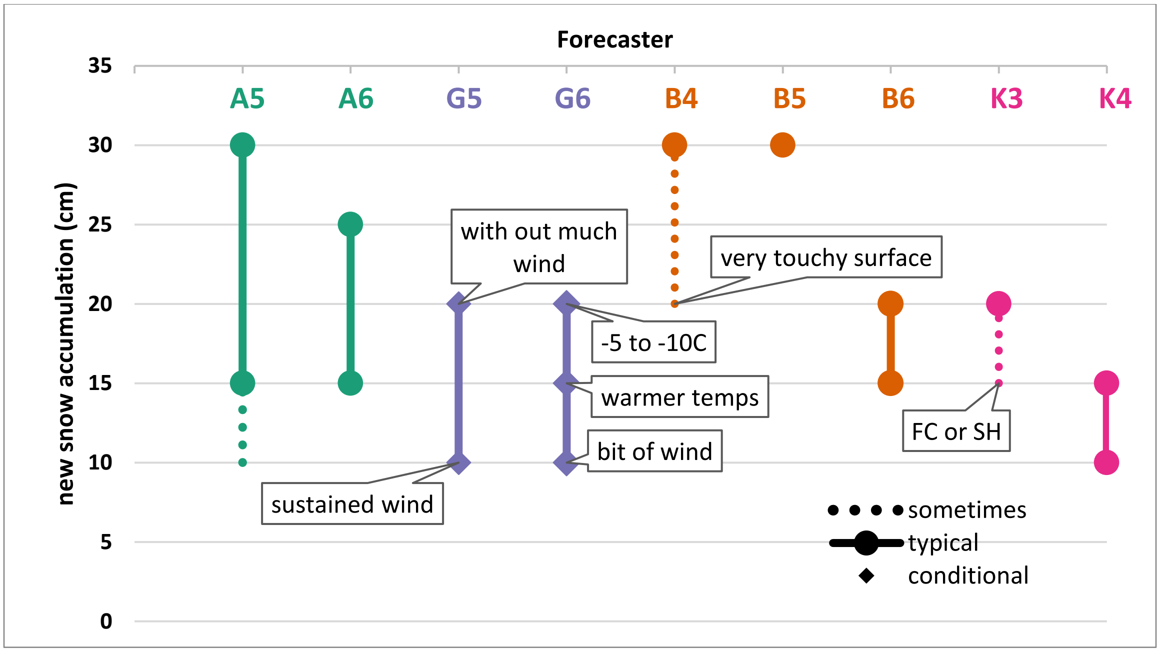

Figure 3.6 Range of new snow accumulation thresholds for adding a SS problem. Each line indicates values provided by an individual forecaster, colour coded by agency (AvCan: green, Glacier: purple, Banff: orange, Kananaskis: pink).

Forecasters from all agencies agreed that storm slabs are more likely to be initiated when ***air temperatures*** are warmer than with colder temperatures. Typical air temperatures that were indicated as more likely to lead to SS avalanche problems ranged from -10ºC to 0ºC. Quantified ranges for colder air temperatures of less than -10ºC to less than -20ºC were indicated to make SS problem initiation less likely. Some forecasters also specified the ***trend in air temperatures*** as important with SS problems more likely when the trend during a storm goes from cold to warm or if it warms up after the storm and less likely when a storm comes in warm and ends cold.

All forecasters indicated that ***wind*** is a consideration when deciding to add a SS problem, but the mentioned values for typical wind conditions varied widely. All of the office-based AvCan forecasters noted that there is typically or almost always “some wind” and only rarely no wind or occasionally very little wind. However, none of these forecasters further quantified wind speed values. All eight forecasters from the field-based agencies (Glacier, Banff, Kananaskis) specified ***wind speed*** values though their described values cover the entire spectrum of possibilities (Figure 3.7). Typical wind speed values for Glacier forecasters included light (15 to 20 km/hr), moderate, and strong winds ("not when no wind", and "sometimes when extreme"). Banff forecasters indicated typical values in the light to moderate range, where as Kananaskis forecasters mentioned that winds need to be in the calm to light range, but also noted that these conditions occur extremely rarely in that region.

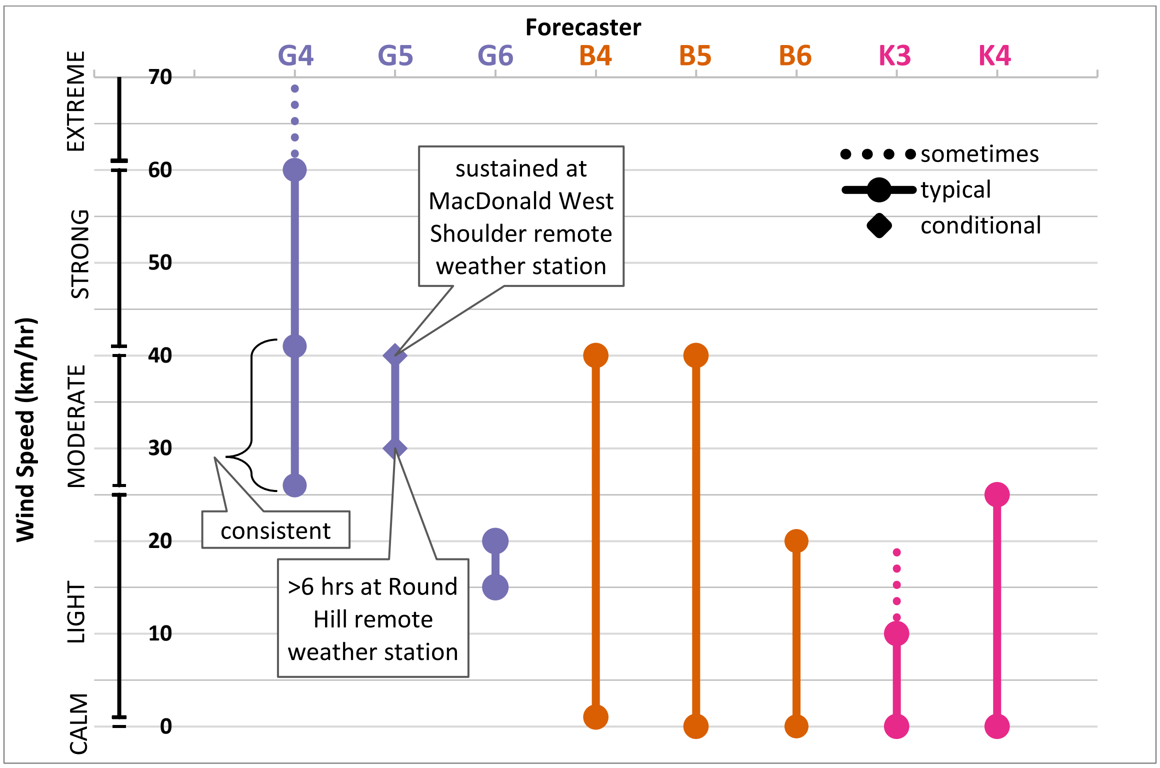

Figure 3.7 **Range of wind speed values for adding SS problems. Each line indicates values provided by an individual forecaster, colour coded by agency (Glacier: purple, Banff: orange, Kananaskis: pink).**

Snowpack observations

Relevant snowpack properties (Table 3.2) included consideration of both the properties of the slab and the underlying surface or weak layer. ***Grain type of the underlying surface or weak layer*** was the most frequent consideration (10 interviews; all agencies). The most frequently mentioned grain types were surface hoar (8 interviews; all agencies), facets (6 interviews; all agencies) and crusts (6 interviews; all agencies).

Some forecasters noted that these grain types are typically more concerning and make the decision more obvious. Forecasters also mentioned stellars (4 interviews; AvCan, Glacier, Banff), decomposing and fragmented particles or old snow surfaces (3 interviews; AvCan, Banff) but less frequently. Two forecasters (AvCan, Glacier) also mentioned ***density changes*** at the interface with the weak layer or underlying surface.

Relevant ***slab properties*** were mentioned by 9 interviewees (all agencies). Four of them explicitly highlighted cohesion (AvCan, Glacier, Banff) but other relevant slab properties including hardness, density, settlement, distribution, feeling, depth, thickness, snowpack temperature, and surface grain type of the slab were also mentioned. Regarding ***slab formation*** (6 interviews; all agencies) forecasters from all agencies generally agreed that settlement, new snow loading, or pressure sintering contributes to storm slab formation. However, the role of wind in slab formation included some conflicting perspectives with forecasters from Kananaskis indicating that SS problems are not added to the forecast when slab formation is driven by wind, and forecasters from all other agencies indicating that wind can be the driving factor of SS problem formation. ***Slab hardness*** minimum threshold values mentioned by the interviewees (6 interviews; all agencies) ranged between fist to one finger minus. ***Slab density*** was also included by four forecasters (AvCan, Banff, Kananaskis) but only quantified by one forecaster (A6) as greater than 100 kg/m^3. A second forecaster mentioned that the density of the new SS is typically greater than that of the underlying surface. One of two forecasters who included ***slab depth*** as a consideration specified typical values of greater than 20 cm (A4), which aligns well with new snow accumulation values specified by other AvCan forecasters. Two forecasters from Kananaskis indicated the ***feeling of the snow while traveling across terrain*** as a factor including signs of instability (cracking/whumpfing), feeling of a well settled storm slab, and changes in density when breaking trail.

Table 3.2 Summary of snowpack observations, frequencies, and values for adding SS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
slab properties	9	●	◔	●	●	requires cohesion (4); also considers *hardness, density, settlement, distribution, feeling, depth, thickness, snowpack temperature, and surface grain type of the slab*	*n/a*
slab formation	6	◕	◔	◔	●	influenced by temperature, settlement, loading/pressure sintering, and wind (AvCan, Glacier, Banff) or no wind (Kananaskis)	weak
settlement	4	○	◔	◔	●		*no values*
slab hardness	6	◕	◔	◕	◐	fist to one finger minus	moderate
slab density	4	◔	○	◔	●	> 100 kg/m³ relative density of new snow greater than underlying slab	moderate
slab depth	2	◕	○	○	○	rarely < 10 cm; sometimes 10-20 cm; typically > 20 cm; always after ≥ 30 cm	*single value*
feeling of snow while traveling through terrain	2	○	○	○	●	signs of instability (cracking/whumpfing), feeling of a well settled storm slab, double ski penetration when breaking trail	moderate
underlying surface	8	◕	●	◕	◐	considers *grain type, distribution, age, density changes*	*n/a*
weak layer properties	2	◔	○	◔	○	considers *grain type, sensitivity*	*n/a*
weak layer/ underlying surface grain type	10	●	●	●	◐	surface hoar, facets, crusts, stellars, decomposing and fragmented particles and old snow surfaces (in order of frequency indicated)	moderate
density changes	2	◔	◔	○	○	typically related to higher density snow over lower density snow, melt freeze crusts, and wind hardened surfaces, FC or SH with a crust	moderate

Instability observations

Instability condition observations (Table 3.3) were less commonly mentioned as playing a role for adding a new SS problem. Relevant ***avalanche observations*** (4 interviews; AvCan, Glacier, Banff) involved consideration of ***trigger types*** and destructive avalanche size. Forecasters indicated that natural and skier triggered avalanches are relevant although two forecasters disagreed on the relevance of explosives triggered results with one indicating that they sometimes occur (B5) and another explicitly mentioning that the likelihood of avalanches being triggered by explosives is generally left out of their decision making (A5). The most commonly mentioned ***avalanche size*** was small slabs large enough to hurt somebody (larger than size 1). Two forecasters (B5, G5) also noted ***snowpack tests*** such as burp tests and shear tests as being relevant to their decision to add a SS.

Table 3.3 Summary of instability observations, frequencies, and values for adding SS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
avalanche observations	4	◔	◔	◕	○	considers *size and trigger type*	*n/a*
trigger type	4	◔	◔	◕	○	natural, skier, sometimes or does not include explosives	moderate
avalanche size	3	◕	◔	○	○	typically small slabs > size 1	strong
snowpack tests	2	○	◔	◔	○	*burp tests and shear tests*	moderate

Spatial and temporal observations

Spatial and temporal considerations for adding a SS problem to the bulletin were primarily related distribution (Table 3.4). Most frequently forecasters referred to the ***distribution of the avalanche problem*** (6 interviews; all agencies), and there was general agreement that the problem should be more widespread than very isolated or only lee features. Two additional forecasters more specifically mentioned ***weak layer distribution*** and ***slab distribution***, but they agreed with the other forecasters that the distributions had to be fairly widespread. Forecasters from Banff noted that the avalanche problem distribution can be aspect (B4) or elevation (B5) dependent, and mentioned ***wind distribution*** as a consideration (B5, B6). These forecasters also described the SS scenario with wind being communicated in two different ways: Either listing a SS with notes cautioning about more cohesive slabs at upper elevations (B5) or concurrently listing a WS problem in the alpine and a SS problem at lower elevations (B6). Two forecasters mentioned regional ***distribution of new snow*** (Glacier, Banff) as a relevant observation for adding a SS avalanche problem, which is linked to comments about ***spatial variability***

(2 interviews; Banff, Kananaskis). Forecasters indicated adding a new SS is typically more likely when the new snow distribution is consistent across whole region, while it is less likely when new snowfall is concentrated in one small zone.

Timing of the storm with respect to the forecast period relative to when the forecast is issued was discussed by three forecasters (AvCan, Glacier, Banff) who noted that SS problems are typically added to the bulletin either when an anticipated storm is still incoming or after the storm has arrived (for example overnight storms at Glacier where forecasts are issued in the morning). Two forecasters (B5, K4) also mentioned anticipated ***persistence time of storm slab problems*** with typical ranges within one to three days. For one of these forecasters (B5) the anticipated persistence time was related whether the problem should be directly initiated as a PS problem instead of a SS problem.

Table 3.4 Summary of spatial and temporal observations, frequencies, and values for adding SS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
distribution of avalanche problem	6	◕	◔	◕	◐	unlikely when very isolated or only in lee features, likely when widespread, sometimes aspect or elevation dependent	strong
slab distribution	2	◔	○	◔	○	almost always or typically everywhere; sometimes by elevation band (B6)	strong
distribution of weak layer	2	◔	◔	○	○	with respect to aspect, elevation, terrain features	*single value*
wind distribution	2	○	○	◕	○	light to moderate alpine wind leading to SS problem that is more cohesive at higher elevations; sustained alpine winds only > 20km/hr leading to concurrent alpine WS and lower elevation SS	moderate
distribution of new snow	2	○	◔	◔	○	related to regional and spatial variability typically when fairly consistent across whole region, less likely when one small zone	moderate
spatial variability	2	○	○	◔	◐		*no values*
timing of the storm	3	◔	◔	◔	○	incoming and arriving storms	moderate
storm slab persistence time	2	○	○	◔	◐	typical ranges include 1-3 days	strong

Additional considerations and practices

Discussions around initiating SS problems in the public bulletin also revealed additional factors beyond the physical properties and observations outlined above. Other avalanche problem types were frequently mentioned as an important consideration when deciding whether to add a SS problem. The influence of how many problems exist and the specific interactions between listing SS and WS problem types came up throughout all adding, removing, and transitioning scenarios. These topics are summarized later in Sections 3.3.1 and 3.1.4 respectively.

In addition to the interaction between SS and WS problems, which we elaborated on above when describing the role of wind speed for adding an SS avalanche problem, some forecasters also referred to interactions with dry loose (DL) and persistent slab (PS) problems. Several forecasters mentioned using a SS problem to also describe concurrent DL problems but highlighting the additional problem in the descriptive text instead of listing it. This rational of selecting a SS problem over a DL problem was described as more conservative by one forecaster (A5) who also indicated that they never simultaneously list SS and DL problems to avoid confusion.

> I would say there is an inherent bias for me personally to go with the storm slab [over a DL problem] because as a forecaster that is the more conservative decision … If I list that as a dry loose avalanche problem and then someone gets buried in a slab avalanche, I blew it in my mind. Whereas if I write that there is a storm slab problem and then I get feedback that yeah there were no slab properties actually and it was just amazing skiing, then I can much easier live with that error, erring on the side of caution, than the other way. (A5)

Related to PS problems, consideration was given to whether some problems should a) be directly initiated as a PS, or b) a SS problem should be forecast first to give the forecaster more time to assess the problem that could later be transitioned into a PS problem. Three forecasters (Glacier, Banff) stated that they always (G4) or almost always (G5, B6) begin with a SS problem before transitioning to a PS problem. While two other forecasters from Banff agreed that a PS problem can be transitioned out of a SS, they also described directly forecasting PS problems if there is a high confidence in the persistent nature of the interface and its distribution (B4) or to avoid public confusion (B5). One forecaster also mentioned that going directly to a PS problem allows for a shorter problem description, which they viewed as desirable for keeping people's attention (B4). These preferences on initiating or transitioning to PS problems align well with similar considerations described in the PS and DPS focused interviews (see Sections 3.2.1 and 3.2.2).

Some specific challenges with office-based forecasting were expressed related to initiating SS problems in the bulletin. Amongst these challenges are understanding the conditions preceding a storm (A4), such as uncertainty in the distribution of snow surface conditions, and the inability to identify whether a storm interface developed within the storm snow based on weather data alone (A5). Additionally, the validation of wind conditions from weather stations was noted as a challenge due to a limited number of stations with wind sensors and the potential for instrumentation malfunction (A4).

The timing of a storm with respect to the forecast period was also a factor for some forecasters. In Glacier National Park where forecasts are issued daily in the morning, some forecasters (G4, G6) indicated they will sometimes pre-emptively add a SS problem in anticipation of upcoming forecast periods. One forecaster's reason for this practice was their desire to provide users with problem information for planning their trips on the following day rather than waiting until the next morning and potentially missing them because they are already on their backcountry excursions by the time the bulletin for the day is published (G6). One AvCan forecaster also shared that storms that "trickle in" during the forecast period are more challenging to forecast and require more nuanced messaging that empowers users to make their own observations (A4).

3.1.1.2 Removing SS problems

Forecasters discussed several reasons for considering the removal of a SS problem: stabilization, transitions into other problem types (PS or WS), and as a correction because forecasted conditions did not materialize. Regionally, forecasters from Kananaskis indicated that the removing a SS problem scenario occurs very rarely due to the rare occurrence of SS problems to begin with, their average number of concepts (22 concepts) for this scenario was notably lower than the overall average (45 concepts).

Observations

Analysis of the concept maps for removing SS problems revealed that the most frequently considered observations across agencies are related to instability conditions, whereas observations related to snowpack, weather, and spatial or temporal considerations were mentioned much less frequently (Figure 3.8).

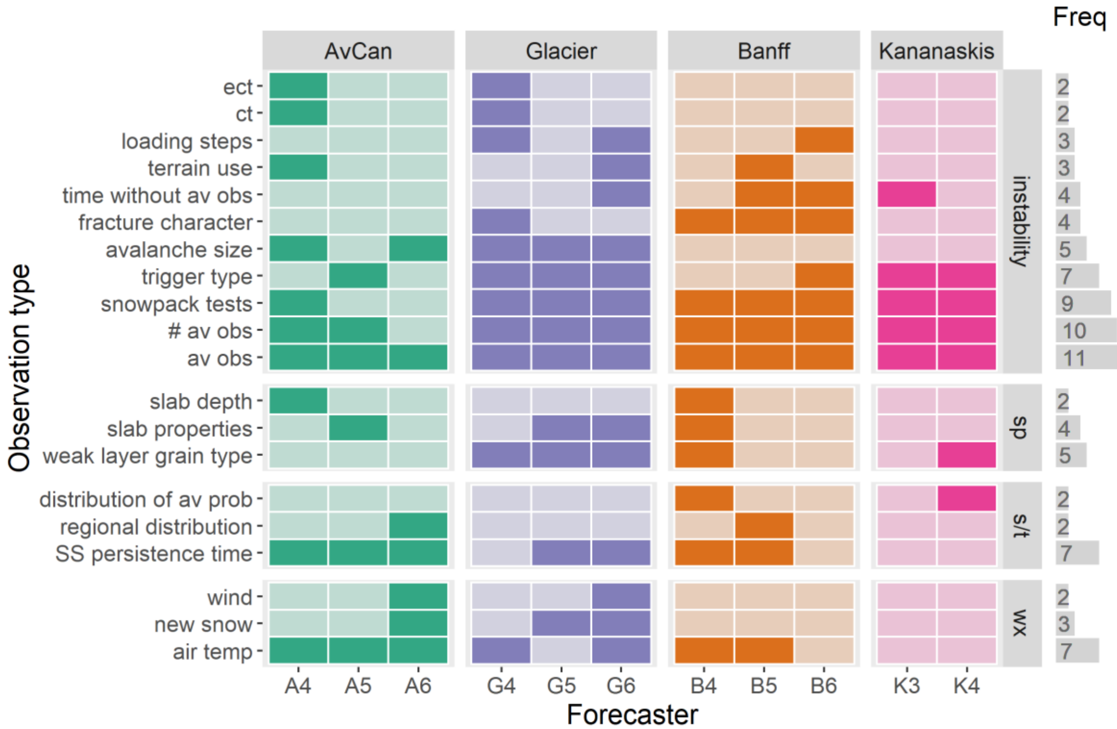

Figure 3.8 Observation types mentioned by at least two forecasters as a consideration for removing SS avalanche problems. See caption of Figure 3.5 for detailed explaination of figure presentation.

Instability observations

Instability conditions (Table 3.5) were most frequently related ***avalanche observations*** (all interviews) and snowpack tests (9 interviews; all agencies). Forecasters (all agencies) commonly agreed that there should be a decreasing trend in the ***number of avalanche observations***. While three forecasters (B5, B6, G6) indicated that they require no avalanche observations in their region, four others (A5, B4, G4, G5) indicated that some level of avalanche activity can continue when removing a SS problem. Examples of acceptable amounts of activity were three or fewer observations in the entire forecast region (A5) or one to two observations every couple of days (G4). Avalanche observations with skier and natural ***trigger types*** (7 interviews; all agencies) were consistently indicated as relevant for the decision to remove a SS problem. Five forecasters (AvCan, Glacier) indicated that destructive ***avalanche size*** was relevant, but only the Glacier forecasters provided explicit values about the size of acceptable occurrences (isolated events such as a couple of size 1 to 1.5s in really steep extreme or unskiable terrain, or size 1.5 loose avalanches not triggering a slab). ***Terrain use*** considerations (3 interviews; AvCan, Glacier, Banff) included both public and professional users and related to people starting to ski more aggressive features with no signs of instability. Four forecasters (Glacier, Banff, Kananaskis) indicated that they typically wait for at least one or two ***days without observed activity*** (G6, B5, B6) or a few days of no or diminishing activity (K3) before removing the problem.

A variety of different ***snowpack tests*** were described with compression tests (2 forecasters) and extended column tests (2 forecasters) being mentioned more frequently. Despite the differing snowpack tests that forecasters indicated, there was general agreement that test results should generally produce hard results with resistant, non-planar or broken fractures, or no results at all.

Table 3.5 Summary of instability observations, frequencies, and values for removing SS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
avalanche observations	11	●	●	●	●	considers *number, trigger type, time without, size, distribution, and type of observations*	*n/a*
– number of avalanche observations	10	◕	●	●	●	none, few to none, continued activity, decreasing trend	moderate
– trigger type	7	◔	●	◔	●	skier and naturals	strong
– avalanche size	5	◕	●	○	○	size 1.5 or big isolated results acceptable in really steep extreme or unskiable terrain	moderate
– time without observed activity	4	○	◔	◕	◑	1-2 days or a few days of diminishing activity	moderate
terrain use	3	◔	◔	◔	○	professionals and/or public skiing more aggressive features without signs of instability	strong
snowpack tests	9	◔	●	●	●	considers *compression test, extended column test, burp test, hand shear, rutschblock test, shear test, and testing small features*	*n/a*
– fracture character	4	○	◔	●	○	typically resistant, non-planar, or broken; not when sudden (collapse or planar)	strong
– loading steps	3	○	◕	◔	○	typically hard or no results	strong

Snowpack observations

Snowpack properties (Table 3.6) were less frequently mentioned as relevant factors for removing SS problems from the bulletin. Mentioned snowpack observations were related to ***slab properties*** (4 interviews; AvCan, Glacier, Banff) and the grain type of the weak layer (5 interviews; Glacier, Banff, Kananaskis). Loss of cohesion of the slab (e.g., faceting out of the surface snow) was a consistent indicator for removing the SS avalanche problem. One forecaster noted that the slab is more likely to facet out when the ***slab depth*** is thin (B4) and another (A4) agreed that a SS problem is easier to remove when the slab depth is thinner (no greater than 50 cm) and more challenging as it becomes deeper (60 to 120 cm). When considering the ***weak layer grain type***, forecasters made a distinction between persistent and non-persistent weak layers with some noting that SS problems with underlying persistent weak layers are more likely to be transition to PS problems.

Table 3.6 Summary of snowpack observations, frequencies, and values for removing SS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
weak layer grain type	5	○	●	◔	◐	persistent and non-persistent	strong
slab properties	4	◔	◕	◔	○	lack of cohesion/faceting out of surface	strong
slab depth	2	◔	○	◔	○	more likely to facet and easier to gauge removal when thinner	moderate

Weather observations

Weather conditions (Table 3.7) were also less frequently mentioned as considerations for removing SS problems. Only air temperature (7 interviews; AvCan, Glacier, Banff), new snow (3 interviews; AvCan, Glacier) and wind (2 interviews; AvCan, Glacier) were noted by multiple forecasters. Most forecasters who mentioned ***air temperature*** as a consideration highlighted cold temperatures such as cold clear nights, cooling trends, and extreme cold (below -20ºC). Two forecasters also indicated that air temperatures conducive to bonding of new layer onto an old layer and big diurnal temperature swings would promote stabilization and therefore the removal of the SS avalanche problem. There was strong agreement between forecasters who brought up

new snow as a consideration that they are more likely to maintain a SS problem if there is continued new snow. ***Wind*** was raised by two forecasters, but only one of them provided a value indicating that a lack of wind typically shortens for how long a SS problem persists.

Table 3.7 Summary of weather observations, frequencies, and values for removing SS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
air temperature	7	●	◑	◑	○	cold (clear nights, cooling trend, extreme cold) (5), conducive to bonding (1), strong diurnals (1)	moderate
new snow	3	◑	◑	○	○	problem is more likely to be maintained in the bulletin when there is continued new snow	strong
wind	2	◑	◑	○	○	no wind reduces persistence time	*single value*

Spatial and temporal observations

Spatial and temporal observations (Table 3.8) were most commonly related to persistence time (7 interviews; AvCan, Banff, Glacier) followed by distribution of the problem (2 interviews; Banff, Kananaskis). The typical ***persistence times*** for SS avalanche problems described in the interviews ranged from two to four days. Interestingly, while some forecasters indicated that persistence time varies regionally with snow climate such that longer time frames are expected in the Rocky Mountains, two forecasters from the Rocky Mountains (B4, B5) mentioned persistence times of two days, which were among the shortest in our sample. ***Distribution*** of the avalanche problem and the regional distribution were each brought up by two forecasters. Values related to distribution included narrowing trends with activity no longer widespread or widespread regionally. Regionally forecasters indicated that they may remove the problem if it only exists in specific, sporadic, or pocketed areas in the region (e.g., only a single operation in the region is seeing activity).

Table 3.8 Summary of spatial and temporal observations, frequencies, and values for removing SS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
storm slab persistence time	7	●	◕	◕	○	range of typical values 2-4 days	moderate
distribution of avalanche problem	2	○	○	◔	◐	no longer widespread, diminishing distribution trend (K4)	*single value*
regional distribution	2	◔	○	◔	○	must no longer be a widespread regional problem; specific areas in the region (sporadic, pocketed, for example only a single operation in the region seeing activity)	strong

Additional considerations and practices

Several additional considerations beyond the physical observation types described above play a role in forecasters decision to remove SS problems. Relative to other problem types, including WS and PS problems, some forecasters stated that they find SS problems easier to remove from the public bulletin. Explanations for the relative ease of removal take into account being less conservative for lower consequence problems (A6) and the transition of a SS into a different problem type acting as a buffer (B4, G4, G6). Other forecasters implied higher confidence in removing SS problems indicating that they are comfortable relying more on previous experience, training, and typical persistence times from the CMAH when avalanche observations are unavailable (A6) or that weather conditions on their own can sometimes provide enough information to remove the problem (G6). The value of the immediacy and exact timing of avalanche observations from the remote detection system in Glacier National Park was also noted for low visibility conditions (G5). The practice of removing the problem and continuing to mention it elsewhere in the bulletin was mentioned by two forecasters (B4, B5), although another forecaster (B6) stated that practice is less common for SS problems compared to longer lasting problems. Two field-based forecasters (G4, K4) also described relying on a gut feeling or a “witch doctor type thing” for removing SS problems. Whereas one office-based forecaster (A4) noted that they resort to gleaning this type of qualitative information from the reports and the travel and terrain use of other professionals. A forecasting team consensus was a factor for one forecaster (K4) for removing the problem.

> This is kind of where I end up taking a lot of stuff and throwing it into the sorcerer's bowl … mixing it up and coming up with some sort of answer. (G4)

While forecasts also mentioned the number of other problems that exist, character limitations in the bulletin, and user context as important considerations, they relate to the all types of avalanche problems and are therefore discussed in the Section 3.3.

3.1.2. Transitioning storm slab problems to wind slab problems

Decisions around transitioning SS problems into WS problems were discussed by ten of the eleven forecasters whose interviews focused on storm and wind slab avalanches. The forecaster who did not cover this scenario in their interview (K4) was based out of Kananaskis where both forecasters (K3, K4) indicated that this transition is very rare because they hardly ever include SS problems in their forecasts. In total, the conversations about this scenario generated 336 concepts, 238 linking phrases, and 600 connections.

This transition scenario incorporates both the removal of a SS problem and the addition of a WS problem. The transition from SS to WS scenario was described by some forecasters as a product of the public forecasting practice of initially grouping WS problems within an emerging SS problem. Because SS problems typically having a shorter persistence time than a coexisting WS problem, the transition generally occurs when the SS problem subsides, and the residual WS problem needs to be communicated separately. The development of a new WS problem due to a wind event following a relatively windless storm is another possible progression for this scenario, but that situation is primarily described by the adding a WS problem in Section 3.1.3.1.

3.1.2.1 Observations

Observation types considered by forecasters who elaborated on the SS to WS transition included a combination of instability, snowpack, weather and spatial and temporal factors (Figure 3.9).

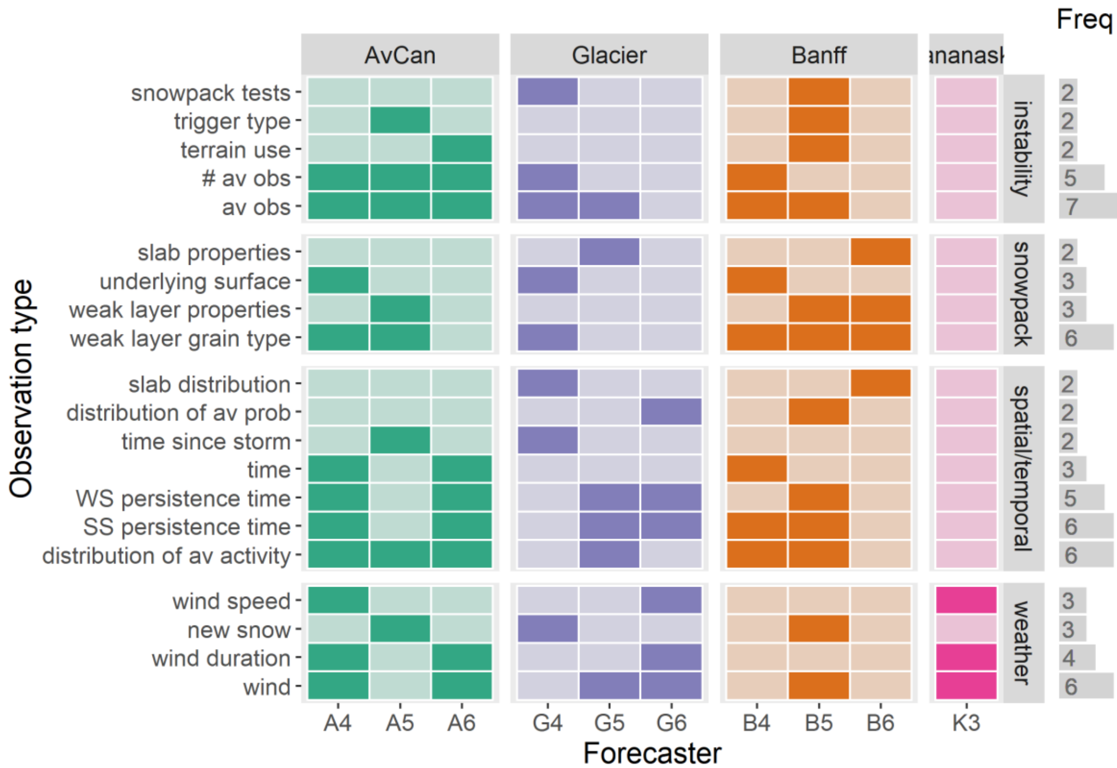

Figure 3.9 **Observation types mentioned by at least two forecasters as a consideration for transitioning a SS to a WS avalanche problem. See caption of Figure 3.5 for detailed explaination of figure presentation.**

Instability observations

Forecasters discussing the transition from a SS to a WS problem most frequently cited instability conditions (Table 3.9). Instability observations were primarily focused on ***avalanche observations*** (7 interviews; AvCan, Glacier, Banff). The typical ***number of avalanche observations*** (5 interviews; AvCan, Glacier, Banff) were indicated to be either continued activity (A4, G4) and/or marked by a decreased amount of activity (A5) specifically related to storm slabs in areas not affected by wind (B4, A6). Two forecasters (A5, B5) agreed that avalanche observations should include skier ***triggering***, with one of these forecasters (B5) also noting explosive triggering.

Snowpack tests were mentioned by only two forecasters, with one looking for results that indicate an improved or indetectable SS interface (B5). The other noted that snowpack tests are less useful for this decision because differentiating between SS and WS in snowpack test observations can be vague (G4).

Table 3.9 Summary of instability observations, frequencies, and values for transitioning a SS to a WS avalanche problem. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (10)	A (3)	G (3)	B (3)	K (1)	Values	Value Consistency
avalanche observations	7	●	◕	◕	○	considers *number, distribution, trigger, and size, of observations*	*n/a*
number of avalanche observations	5	●	◔	◔	○	decreased activity (storm slab), continued activity (wind slab)	moderate
trigger type	2	◔	○	◔	○	skier (2), explosives (1)	moderate
terrain use	2	◔	○	◔	○	related to *distribution of avalanche activity (Table 3.12)*	strong
snowpack tests	2	○	◔	◔	○	indicate lack of or improved SS interface	*single value*

Snowpack observations

Snowpack properties (Table 3.10) were less frequently discussed by forecasters, but some of them did mention that they consider weak layer and slab properties. ***Weak layer grain type*** was mentioned by six forecasters (AvCan, Glacier, Banff), and four of them (A4, A5, G4, B4) indicated that they were less likely to transition the problem to a WS if the weak layer is of persistent nature (in one case specifically surface hoar). Others mentioned that potential persistent weak layers that did not preform can be transitioned to WS problems (B6) and that faceted grains can influence the longevity of a WS problem (B5). Forecasters who touched on ***slab properties*** (G5, B6) agreed that the problem might be transitioned if the SS lacks cohesion, either because the slabs did not develop and the problem type needs to be corrected or if the slab faceted out. One of these forecasters also noted that the problem may still be transitioned if the SS is cohesive, but the SS stabilizes more quickly leaving a residual WS problem that was initially combined under the label of SS.

Table 3.10 Summary of snowpack observations, frequencies, and values for transitioning a SS to a WS avalanche problem. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (10)	A (3)	G (3)	B (3)	K (1)	Values	Value Consistency
weak layer properties	3	◔	○	◕	○	considers *grain type and detectability of weak layer*	*n/a*
underlying surface	3	◔	◔	◔	○	considers *weak layer grain type*	*n/a*
weak layer/ underlying surface grain type	6	◕	◔	●	○	less likely when persistent grain types; more likely/typically non-persistent or old snow interface; can include persistent grain type that does not preform; facets increasing *WS persistence time*	moderate
slab properties	2	○	◔	◔	○	typically lack of cohesion, can include cohesive slabs	moderate

Weather observations

Weather observations (Table 3.11) mentioned by our interviewees primarily focused on ***wind*** observations (6 interviews; all agencies). Three forecasters (A4, G6, K3) noted that to transition the problem to a wind slab they typically see or require multiple days or continued winds since the storm that initiated the SS problem. These three forecasters agreed that continued winds should be at least moderate (more than 25 km/hr) or return to typical (Kananaskis) winds of 30 to 50 km/hr. Alternatively, one forecaster (A6) indicated that if there was considerable wind during the initial storm, no substantial subsequent wind is required.

New snow was brought up as a consideration by three forecasters (A5, G4, B5), and precipitation more generally was mentioned by one additional forecaster (G5). However, how new snow was considered differed between these forecasters. One forecaster (A5) considers the snowfall accumulation during the initial storm as a measure for snow available for transport. Another forecaster (G4) focuses on the intensity of snowfall because in their opinion transitioning to a WS requires the storm to have ended or have a substantial break with only flurries or less than 1 mm/hr snowfall intensity. The final forecaster who talked about new snow (B5) was interested in how the new loading will influence the persistence time of the WS.

Table 3.11 Summary of weather observations, frequencies, and values for transitioning a SS to a WS avalanche problem. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (10)	A (3)	G (3)	B (3)	K (1)	Values	Value Consistency
wind	6	◕	◕	◔	●	considers *duration, speed, distribution, current, previous, and loading due to wind*	*n/a*
wind duration	4	◕	◔	○	●	multiple days, ongoing or steady since the storm; requires wind during initial storm but can include no substantial new wind	weak
wind speed	3	◔	◔	○	●	at least moderate (> 25km/hr) (G6, A4); return to typical 30-50 km/hr	strong
new snow	3	◔	◔	◔	○	considers *accumulation, transport, intensity, loading of new snow*	*n/a*

Spatial and temporal observations

Some forecasters also stated that they pay attention to spatial and temporal conditions (Table 3.12) including the time of the transition and the distribution of other properties. The ***distribution*** of slabs, observed activity, or the SS/WS problem more generally was mentioned by nine of ten forecasters who discussed this scenario. The observation values for distribution were non-conflicting and generally indicated distributions becoming more specific to the alpine elevation band and/or lee aspects and specific terrain features.

Interviewees also alluded to temporal considerations such as ***time*** to transition, time since the storm, and SS and WS ***persistence times***. One or more of these time considerations were mentioned by eight of the ten forecasters. Forecasters agreed that SS problems typically persist for one to two days following the storm or a shorter time period than the typical persistence time for WS problems. Values were less precise for WS persistence time with quantified values ranging from typically longer than two days (A4, G5) to typically four days or sometimes longer than four days (B5). Values for time to transition and time since the storm generally aligned with the end of SS persistence times with typical values ranging between two to three days.

Table 3.12 Summary of spatial and temporal observations, frequencies, and values for transitioning a SS to a WS avalanche problem. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (10)	A (3)	G (3)	B (3)	K (1)	Values	Value Consistency
distribution of avalanche activity	6	●	◔	◕	○	typically alpine and lee aspects or terrain features, decreased in areas that are not wind effected typically tapering off at lower elevations	moderate
distribution of avalanche problem	2	○	◔	◔	○	no longer widespread/all aspects, becomes more specific and limited to lee features	strong
slab distribution	2	○	◔	◔	○	limited to upper elevations	*single value*
time (to transition)	3	◕	○	◔	○	typical range 2-3 days, sometimes range 2-5 days	moderate
time since storm	2	◔	◔	○	○	typically 2-3 days, greater than 2 days	strong
storm slab persistence time	6	◕	◕	◕	○	typically 1 to 2 days	strong
wind slab persistence time	5	◕	◕	◔	○	longer than SS, > 2 days (A and G), typically 4 days (B), longer when built on by continued wind, shorter when no additional inputs	moderate

3.1.2.2 Additional considerations and practices

The SS to WS transition scenario conceptually and many of the associated additional considerations shared around it are rooted within the discussion of SS and WS interactions found in Section 3.1.4. However, one forecaster (A6) explicitly elaborated on the influence of the forecast application and described how this transition might be less common in an operational forecast application where the practice of combining WS and SS problems is less common and the number of simultaneous avalanche problems is less constrained in favour of being more realistic. Another forecaster (G4) also noted that one of the factors influencing when they will transition a SS problem is the perceived relevance to the user after a storm has ended.

> I don’t want to hold onto storm slab for too long, because if people are looking outside and it is a beautiful blue sky, once again you got to try and keep it relevant, like “storm? storm snow? It is not storming, what are they talking about?”. (G4)

3.1.3. Wind slab avalanche problems

Our interviews focusing on decisions related to WS problems discussed considerations for adding and removing WS problems in the bulletin (SS transition to WS discussed separately in Section 3.1.2). These discussions generated a total of 1364 concepts, 969 linking phrases, and 2494 connections.

3.1.3.1 Adding WS problems

During most interviews, a distinction was made between scenarios for adding a WS problem with and without new snow. Only one forecaster (G5) did not differentiate between these two adding WS cases and shared their considerations using a single scenario for both. Because of this, the combined scenario of forecaster G5 is included in the results for both scenarios discussed below. Some forecasters described additional sub-scenarios which are included within each of these major scenarios (Figure 3.1).

The adding WS with new snow scenario was indicated as the primary mechanism responsible for new WS problems in Kananaskis (K3, K4) and to sometimes occur by one Banff forecaster (B4). Adding a WS without new snow scenario, on the other side, was described as often occurring by a Banff forecaster (B4) but only rarely or occasionally the mechanism for a new wind slab in Kananaskis. On average forecasters included 83 concepts for adding WS problems (incudes concepts for both the with wind and without wind scenarios).

Observations for adding a WS problem with new snow

All eleven forecasters included a scenario for initiating a new wind slab problem to the bulletin in the presence of new snow. Two forecasters further divided this scenario into the following sub-scenarios:

- new WS with a small amount of new snow (A6),
- new WS with (strong to) extreme wind (A4, A6),
- change in direction WS (A4), and
- DL at lower elevation and WS in alpine (A4).

One forecaster described the scenario as a new WS problem with a SS problem (G4). The following presentation of the results for the adding a WS problem with new snow includes the considerations for these sub-scenarios. Overall, observations for initiating a WS problem in the presence of new snow in the bulletin primarily involved weather observations. Snowpack, instability, spatial and temporal considerations were also included by some forecasters, but they were mentioned considerably less frequently and, with the exception of distribution observations, less consistently (Figure 3.10).

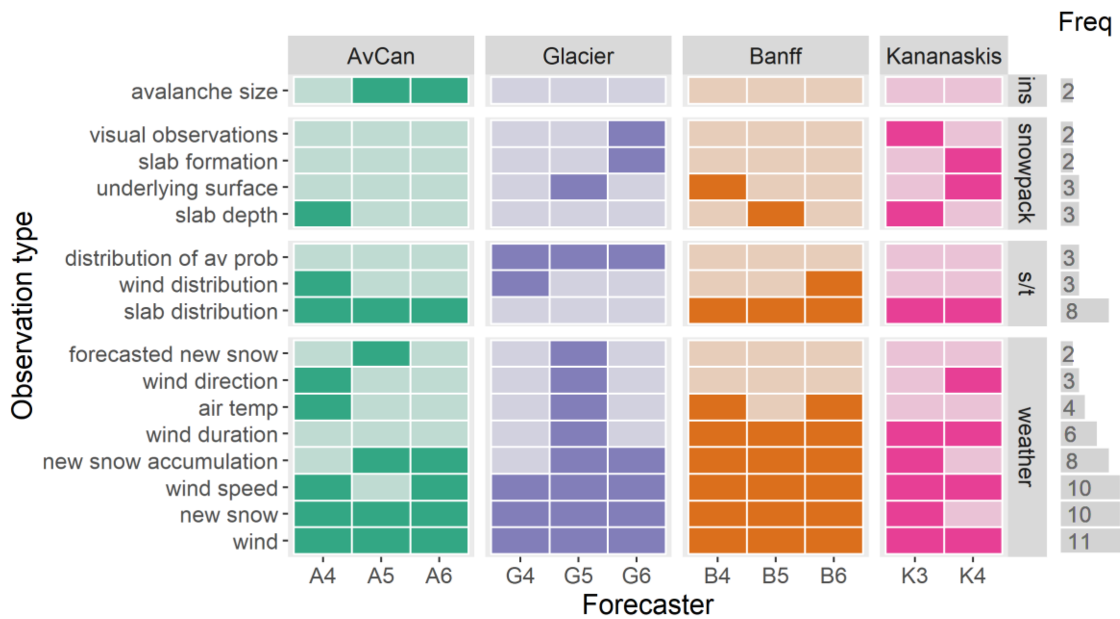

Figure 3.10 Observation types mentioned by at least two forecasters as a consideration for adding WS avalanche problems with new snow. See caption of Figure 3.5 for detailed explaination of figure presentation.

Weather observations

Observed or forecasted wind, new snow, and air temperature conditions were the most frequently referenced weather considerations by forecasters for initiating a new wind slab problem in the presence of new snow (Table 3.13). All forecasters considered ***wind***, and most (10 interviews; all agencies) provided a quantification of typical ***wind speeds***. Most forecasters (all agencies) specified typical threshold values that fall within the moderate to strong range of wind speeds (26 to 60 km/hr). Two forecasters in the Rocky Mountains (B5, K3) had a lower threshold beginning at 20 km/hr, although one (B6) noted this lower threshold for sustained winds was typically accompanied by gusts in the 30 to 40 km/hr range. Three forecasters included extreme winds (A4, A6, B4). Rationale of the Banff forecaster who noted extreme winds was that slabs will be built in lower elevation ski terrain where the wind speed is lower. The two AvCan forecasters who discussed the sub-scenario focused on new wind slabs with (strong to) extreme winds stated that wind speeds needed to be greater than 60 km/hr (A6) or in the 60 to 90 km/hr range (A4). Alternatively, one forecaster (G6) shared that in some rare cases extreme winds can create a "moonscape" that leads to removal of all problems rather than initiating a wind slab.

Wind duration (6 interviews; Glacier, Banff, Kananaskis) values varied between forecasters. Both Kananaskis forecasters simply indicated that winds constantly exist almost non-stop within the region. Forecasters from Banff all specified consideration for duration but values ranged for sustained winds from most of an hour (B6) to greater than 5 to 6 hours (B4). Other forecasters provided wind speed specific values for wind duration such as at least 2 hours for moderate winds, 4 to 6 hours for 40 km/hr winds (G5), and gusts for strong winds (B5). Some forecasters also mentioned that a ***change in wind direction*** was relevant for initiating new wind slabs with new snow (A3, G5, K4).

New snow (10 interviews; all agencies) was most frequently related to ***new snow accumulation*** (8 interviews; all agencies). Most forecasters had an upper limit for typical new snow accumulation. Upper limits included less than 10 cm (A5, B5, K3), less than 15 cm (A6, G6, B6), and less than 20 cm (G5, B4). Two Banff forecasters indicated a range implying typical lower limits of 5 cm (B4) and 10 cm (B6). One forecaster (K3) mentioned that any amount of new snow can lead to a wind slab. Two situations were identified when higher new snow accumulation can lead to a new WS problem: a) more than 20 cm in combination with a SS problem (B4), or b) at least 15 cm with strong to extreme winds (A6). New snow was also quantified using snow water equivalent of typically between 10 to 20 mm (A4). Two forecasters (A5, G5) agreed that if there is incoming snow in the weather forecast, they are less like likely to add a new WS problem.

Air temperature values (4 interviews; AvCan, Glacier, Banff) varied from cold to mild temperatures. Three of four forecasters (A4, G5, B6) indicated that new wind slabs with new snow typically are initiated with cold air temperatures which one forecaster quantified as -10ºC and colder. Another forecaster (B4) deemed milder temperatures between 0ºC and -10ºC more concerning. Forecaster G4 also agreed that mild temperatures are possible but typically require higher wind speeds for slab formation. Two forecasters from Banff (B4, B6) explicitly indicated that air temperature is a less important consideration for WS formation compared to SS formation.

Table 3.13 Summary of weather observations, frequencies, and values for adding WS avalanche problems with new snow. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
wind	11	●	●	●	●	considers wind *speed, direction, duration, and distribution*	*n/a*
wind speed	10	◕	●	●	●	values range from 20-90 km/hr	moderate
wind duration	6	○	◔	●	●	values range from gusts to at least 6 hours (Banff, Glacier); constant winds (Kananaskis)	weak
wind direction	3	◔	◔	○	◐	change in direction	strong
new snow	10	●	●	●	◐	considers *accumulation, forecasted, SWE, precipitation type and slab depth of new snow*	*n/a*
new snow accumulation	8	◕	◕	●	◐	typical values range from less than 10 to less than 20 cm; potentially any snow; sometimes > 20 cm in combination with SS or ≥ 15 cm with strong to extreme wind	moderate
forecasted new snow	2	◔	◔	○	○	typically none	strong
air temperature	4	◔	◔	◕	○	includes cold (≤ -10ºC) and mild (-10ºC to 0ºC); less likely when warm	moderate

Snowpack observations

Forecasters consider snowpack properties (Table 3.14) substantially less frequently when deciding whether to add a WS problem. Forecasters who included the ***underlying surface*** as a consideration (G5, B4, K4) discussed persistent grain types including facets, surface hoar, crusts and "good sliding surfaces" in addition to non-persistent grain types such as rounded grains and "fairly good bonding surfaces". While forecasters indicated that either persistent or non-persistent underlying surfaces can be possible, some were divided on whether a persistent grain type would make them more likely to initiate a PS problem rather than a WS, initiate a WS that may transition to a PS later, or simply initiate a WS that is expected to be more persistent and more reactive. ***Slab depth*** was mentioned by three forecasters, two of which quantified a typical threshold value of 10 cm, with one having a lower limit of 5 cm (B5) and the other an upper limit of 30 cm (A4). A Kananaskis forecaster (K3) described relative slab depths with deposit zones double or quadruple the new snow depth. Two forecasters (G6, K4) agreed that ***slab formation*** should be wind driven process. ***Visual observations*** of scouring, loaded features, and blowing snow were also important in two interviews (G6, K3).

Table 3.14 Summary of snowpack observations, frequencies, and values for adding WS avalanche problems with new snow. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
underlying surface	3	○	◔	◔	◐	can be persistent (facets, surface hoar, crusts) or non-persistent (rounded grains) grain types	moderate
slab formation	2	○	◔	○	◐	wind driven (wind transport, wind pressing, mechanically broken up by wind)	strong
slab depth	3	◔	○	◔	◐	typically 10-20 cm; must be < 30 cm; not when < 5 cm; 2-4 times as deep in deposit zones	strong
visual observations	2	○	◔	○	◐	scouring, loaded features, blowing snow	strong

Instability observations

Instability observations were not frequently cited as important considerations for the adding a new WS problem with new snow scenario. Only destructive ***avalanche size*** was discussed by more than one forecaster (2 interviews; AvCan), who agreed that avalanches needed to be greater than size 1 to be relevant. One of these forecasters (A5) also mentioned that problems with anticipated size 1 avalanches are sometimes listed a problem in the forecast if there are no other problems present.

Spatial and temporal observations

Spatial and temporal considerations for adding a WS problem in the presence of new snow (Table 3.15) primarily related to ***distribution*** characteristics. All forecasters commented on either the distribution of slabs (8 interviews; AvCan, Banff, Kananaskis) or the avalanche problem (3 interviews; Glacier). Forecasters described similar distribution characteristics for both based on elevation bands, terrain features, and aspect. Alpine elevations were consistently the focus while treeline and below treeline elevations were described to be less typical for WS formation. Common terrain features included cross-loaded and immediate lee features, and aspects were described as lee aspects, sometimes more than lee aspects, and for one Kananaskis forecaster (K3) typically not west and southwest aspects (windward aspects that are blown down to rock). The three Glacier forecasters (G4, G5, G6) all indicated that the distribution of the avalanche problem is typically not widespread. High elevation winds with a distribution that is not as significant below the alpine vegetation band were also mentioned by three forecasters (A4, G4, B6).

Table 3.15 Summary of spatial and temporal observations, frequencies, and values for adding WS avalanche problems with new snow. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
slab distribution	8	●	○	●	●	*elevation bands:* typically alpine sometimes treeline and below treeline *terrain features:* cross loaded and immediate lees *aspects:* lee aspects, sometimes more widespread than lee aspects	strong
distribution of avalanche problem	3	○	●	○	○	typically specific, isolated to immediate lees, aspect dependent, alpine and sometimes treeline elevations bands; not when widespread	strong
wind distribution	3	◐	◐	◐	○	high elevation winds	strong

Observations for adding a WS problem without new snow

The scenario for WS problems that develop without concurrent snowfall events was discussed in all interviews. Some scenarios were further dissected into the following sub-scenarios:

- new WS at treeline with an existing WS in alpine (K3),
- new WS due to reverse loading (K3), and
- transition DL to WS (A5).

Observations for initiating a WS problem in the absence of new snow in the bulletin primarily involved weather and snowpack conditions, with instability and spatial and temporal considerations coming up considerably less frequently (Figure 3.11).

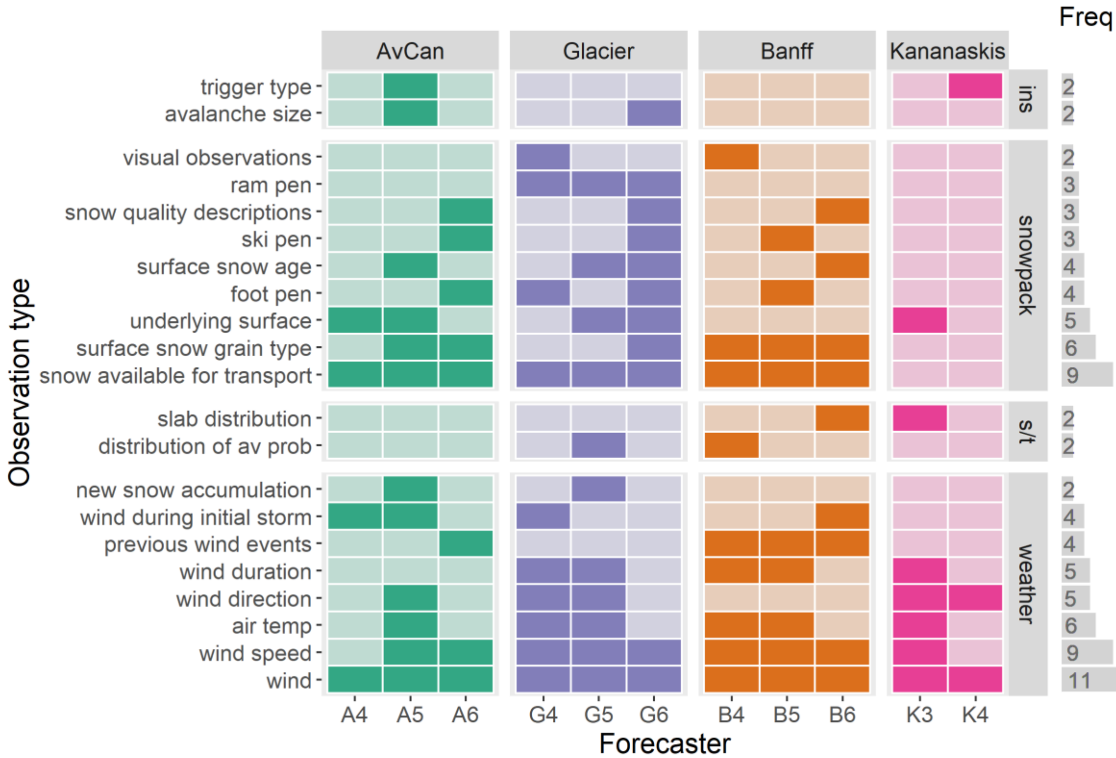

Figure 3.11 Observation types mentioned by at least two forecasters as a consideration for adding WS avalanche problems without new snow. See caption of Figure 3.5 for detailed explaination of figure presentation.

Weather observations

Weather observations (Table 3.16) were predominantly focused on ***wind*** conditions with all eleven forecasters describing wind as a component of there decision. Some forecasters further specified interest in differences or big changes in wind conditions over time including wind during the preceding storm, since the most recent storm, current conditions, and forecasted conditions. Starting with preceding wind conditions, forecasters agreed there should be no or little wind during the initial storm (4 interviews; AvCan, Glacier, Banff) and there should not be a preceding strong to extreme wind event that has scoured or stripped surfaces (4 interviews; AvCan, Banff). For example, a week of wind scouring alpine surfaces would not lead to this scenario (B5). One forecaster (A5) also indicated that between the storm and an initiating wind event winds should be less than moderate and include no change in direction. Forecasters discussing current or forecasted wind conditions associated with adding a new WS problem mentioned paying attention to wind speed, direction, and duration. ***Wind speed*** (9 interviews; all agencies) values generally agreed between forecasters who quantified them. The lower threshold of typical wind speeds varied but were all within the moderate range (26 to 40 km/hr). Five forecasters (Glacier, Banff, Kananaskis) noted ***wind duration*** should be sustained, only three quantified values which included at least two hours (B5), several hours (G4), and four to six hours (G5). Five forecasters (AvCan, Glacier, Kananaskis) who indicated ***wind direction*** all agreed that a change of direction leading to reverse loading can be important.

Other relevant weather considerations that were noted in more than one interview included ***air temperature*** (6 interviews; all agencies) and new snow accumulation during the preceding storm (2 interviews; AvCan, Glacier). Conditions that are less likely to result in a new WS problem without new snow include temperatures around freezing (A5 greater than or equal to 0ºC; B4 warmer than -5ºC) or when it is very cold (B5 at or below -20ºC). Comparatively, adding a new WS problem was indicated as being more likely with mild temperatures (B5 -5ºC to -10ºC). Stated typical values for ***snow accumulation*** during the initial storm were 15 to 20 cm (A5) and less than 20 cm (G5).

Table 3.16 Summary of weather observations, frequencies, and values for adding WS avalanche problems without new snow. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
wind	11	●	●	●	●	considers *speed, duration, direction,* of *previous, current, and/or forecasted winds*	*n/a*
wind speed	9	◕	●	●	◐	≥ moderate (26-40 km/hr), 30 km/hr, 40 km/hr, higher than initial storm	strong
wind duration	5	○	◕	◕	◐	sustained (≥ 2, several, 4-6 hours)	moderate
wind direction	5	◔	◕	○	●	includes reverse loading (all), typical west wind events (only G4)	moderate
wind during initial storm	4	◕	◔	◔	○	none, not much, little wind during initial storm	strong
previous wind events	4	◔	○	●	○	less likely following previous strong to extreme events that have scoured or stripped surfaces	strong
air temperature	6	◔	◕	◕	◐	less likely when warm (≥ 0ºC or > -5ºC) or cold (≤ -20ºC); more likely when -5ºC to -10ºC or closer to 0ºC	moderate
new snow accumulation	2	◔	◔	○	○	15-20 cm HST (A5), < 20 cm (G5)	strong

Snowpack observations

Snowpack properties (Table 3.17) were primarily related to the presence and properties of snow available for transport. ***Snow available for transport*** (9 interviews; AvCan, Glacier, Banff) was elaborated on using penetration values, surface snow properties, and snow quality descriptions. Surface penetrability was discussed by forecasters in the form of ***foot penetration*** (4 interviews; AvCan, Glacier, Banff), ***ski penetration*** (3 interviews; AvCan, Glacier, Banff), and ***ram penetration*** (3 interviews; Glacier). Typical value ranges were greater than 5 cm to mid-boot for foot penetration, greater than 5 cm to greater than 10 cm for ski penetration, and 25 to 40 cm for ram penetration. An additional perspective was that while all these penetration values are available, it is easiest to get a feel for the snow available for transport by being out in the field rather than relying of specific measurements (G6). ***Grain type of the surface snow*** was another frequent consideration (6 interviews; AvCan, Glacier, Banff) with forecasters consistently indicating that this scenario is less likely when crusts (in fetch, widespread, to ridgetop), faceted snow (sometimes possible), and previously wind pressed surfaces exist. Surface forms indicated to make a new WS problem more likely were decomposing and fragmented precipitation particles and recently fallen storm snow. ***Age of the surface snow*** was described as an indicator by four forecasters (AvCan, Glacier, Banff) with snow available for transport that is often “newish” (G6), typically older than 24 hours (A5), or possible with new or older snow (G5, B6). Three forecasters (AvCan, Glacier, Banff) also agreed on ***snow quality descriptions*** with amazing, powder, and good ski conditions as positive indicators for snow available to transport and breakable crusts, difficult or poor ski conditions, and personally not wanting to ski there as negative indicators. ***Visual observations*** of blowing snow at ridgetops was brought up as making the scenario more likely by two forecasters (B4, G4).

The only other relevant snowpack observation type that multiple forecasters mentioned was the nature of the ***underlying snow surface*** on which the wind transported snow is deposited on (5 interviews; AvCan, Glacier, Kananaskis). Most forecasters noted underlying crusts as relevant, other grain types included facets, rounded grains, surface hoar, and previously wind modified surfaces. Two forecasters (G6, A5) noted that it is often hard to know what the surface is going to look like that the wind slab is sitting on.

Table 3.17 Summary of snowpack observations, frequencies, and values for adding WS avalanche problems without new snow. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
snow available for transport	9	●	●	●	○	considers *foot/ram/ski penetration, grain type, quality descriptions,* and *age* of snow available for transport	*n/a*
foot penetration	4	◔	◕	◔	○	typically > 10 cm (B5), knee high (G4); unlikely when ≤ 5 cm (A6) or mid-boot (G4)	moderate
ram penetration	3	○	●	○	○	typically 25-40 cm (G4); more likely 30 cm (G5); less likely 10 cm (G5)	strong
ski penetration	3	◔	◔	◔	○	typically > 10 cm (B5); unlikely when ≤ 5 cm (A6)	moderate
surface snow grain type	6	◕	◔	●	○	less likely crusts and facets; more likely PP and DF	strong
surface snow age	4	◔	◕	◔	○	typically > 24 hrs, new or newish; can include older	moderate
snow quality descriptions	3	◔	◔	◔	○	more likely with amazing, powder, good ski conditions; less likely with breakable crusts, difficult or poor ski conditions, or not willing to ski there	strong
visual observations	2	○	◔	◔	○	blowing snow at ridge tops	strong
underlying surface	5	◕	◕	○	◐	includes crusts, facets, rounded grains, surface hoar, previously wind modified surface	moderate

Instability observations

Instability observations were not frequently cited as important considerations for the adding a new WS problem without new snow scenario. ***Avalanche size*** was discussed in two interviews (AvCan, Glacier). One AvCan forecaster (A5) indicated that when the destructive avalanche size is greater than size 1 it is more likely to be listed as a problem in the forecast, while a Glacier forecaster (G6) was interested in snow available for entrainment but did not quantify a size. Two forecasters (AvCan, Kananaskis) also noted ***trigger type*** where they agreed skier triggering was relevant but were divided on the likelihood that this scenario would produce a natural cycle.

Spatial and temporal observations

Spatial and temporal considerations for adding a WS problem in the absence of new snow to the bulletin were not frequently discussed indicators. However, a few forecasters did note some ***distribution*** characteristics. Two forecasters (Banff, Kananaskis) discussed the distribution of slabs which they broke down into elevation bands and aspects. Another two forecasters (2 interviews; Glacier, Banff) mentioned that adding a new WS problem required the issue to be distributed more widely distributed than only in really specific extreme terrain, typically isolated to immediate lees, and not a widespread problem.

Additional considerations and practices

Several additional considerations beyond the physical observation types were also cited as playing a role in the decision to add a WS problem. Specifically in Kananaskis, multiple WS problems were often said to be grouped together to avoid confusion. The result is a continuous adjustment of an already existing WS problem rather than the initiation of a new problem. Analogously to forecasters in other regions who use SS problems to transition through before adding a PS problem, in Kananaskis WS problems were described as providing more time to assess a potential transition to a PS problem.

> We have a lot of buried wind slabs to worry about. We tend to get layer, after layer, after layer, after layer. It is not uncommon to have 3 or 4 buried wind slabs that you have to somehow articulate to people. And generally, once those are on, they kind of stay on in one form or another they’re on the bulletin. (K4)

Recreationists’ use of terrain with respect to WS problems was also a consideration that came up during or interviews. During periods of lower hazard, one forecaster (G5) recognizes that users are more likely to be skiing in extreme terrain making WS problems more relevant. The lower danger ratings at these times also provide more opportunity to talk about WS problems due to lower relative hazards. Another forecaster pointed out that wind slabs are easier to feel making them easier to manage and avoid (A4).

Other considerations for this scenario that emerged in the interviews included the presence of other avalanche problems, considerations of the interactions between listing SS and WS problems, the number of problems, and default problems. Because these considerations are more general and relate to a broader set of avalanche problems, they are elaborated on in Section 3.1.4.

3.1.3.2 Removing WS problems

Removing WS problems was discussed in all interviews. On average the removing WS scenario generated 41 concepts. One forecaster specified two sub-scenarios for removing a WS due to a major snowpack change and removing WS due to extended periods of cold temperatures (K4).

Observations

Our analysis of the concept maps for removing WS problems revealed that the most frequently considered observations across agencies are related to instability conditions, and less frequently related to observations of snowpack conditions, weather, and spatial or temporal considerations (Figure 3.12).

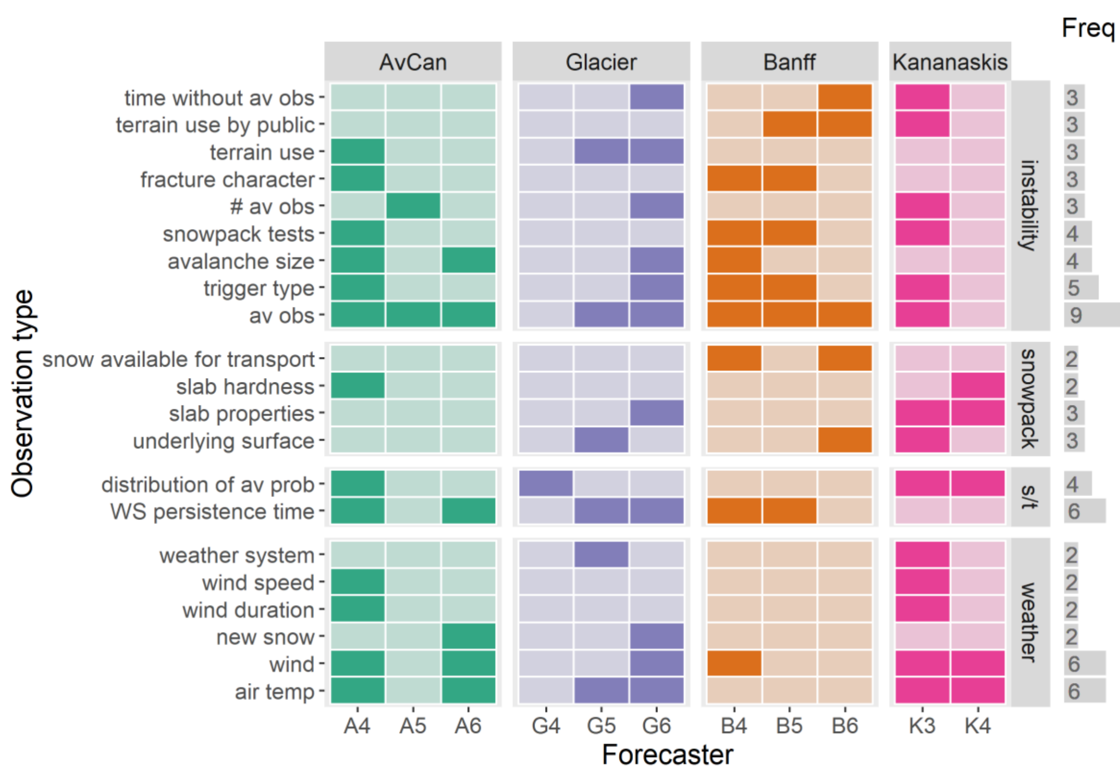

Figure 3.12 Observation types mentioned by at least two forecasters as a consideration for removing WS avalanche problems. See caption of Figure 3.5 for detailed explaination of figure presentation.

Instability observations

Instability conditions (Table 3.18) were cited most frequently as considerations for removing a WS problem. ***Avalanche observations*** (9 interviews; all agencies) commonly involved consideration of trigger type, destructive avalanche size, number of avalanche observations, and time without observed activity. Forecasters who mentioned ***trigger types*** (5 interviews; all agencies) agreed that a decrease in skier and natural activity was a relevant indicator. One forecaster (B5) also stated that more explosive triggered activity can be present. With respect to ***avalanche size*** (4 interviews; AvCan, Glacier, Banff), one forecaster noted that up to size 1.5 avalanches might be acceptable (B4), and another mentioned that there should not be any step downs (G6). The ***number of avalanches*** that are acceptable was noted by three forecasters (A5, G6, K3) who agreed no activity, or a strong trend of diminishing activity can be an indicator. Although, some activity was acceptable if removing the WS would not result in a no problem scenario (A5). Required ***length of time without observed activity*** (3 interviews; AvCan, Glacier, Kananaskis) varied between forecasters from at least one day (G6), to few days (K3), to a lot of days (B6).

Six forecasters (all agencies) mentioned that they pay attention to ***terrain use*** by the public and/or professionals when deciding to remove a WS problem. They are specifically looking for expanded terrain use including extreme terrain, suspect features, big lines, and alpine heli-ski “poster runs” being skied without slab avalanches occurring. ***Snowpack test*** results were discussed by four forecasters (AvCan, Banff, Kananaskis) with a focus on ***fracture character*** becoming more resistant, non-planar or progressive collapse (3 interviews; AvCan, Banff). The value placed on information coming from snowpack tests was mixed. One forecaster suggested that they rely less on snowpack tests for surface problems than with deeper problem types (B5), and another mentioned that it might outrank avalanche observations due to avoidance strategies and because professionals will focus on collecting relevant instability information to support their move into alpine terrain (A4).

Table 3.18 Summary of instability observations, frequencies, and values for removing WS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
avalanche observations	9	●	◕	●	◑	considers *trigger, number, time without, size, distribution, and type of avalanches*	*n/a*
trigger type	5	◔	◔	◕	◑	decrease natural and skier triggering more explosives	strong
avalanche size	4	◕	◔	◔	○	≤ size 1.5 wind slabs; no step downs	moderate
number of avalanche observations	3	◔	◔	○	◑	none, > none and other avalanche problems, few days of strong trend of diminishing activity	moderate
time without observed activity	3	○	◔	◔	◑	at least one day (G6); a few days of no or strong trend of diminishing activity (K3); a lot of days (B6)	weak
snowpack tests	4	◔	○	◕	◑	forecasters mentioned *compression tests, ski cuts and slope tests*	*n/a*
fracture character	3	◔	○	◕	○	resistant, non-planar, progressive collapse, not sudden	strong
terrain use	3	◔	◕	○	○	heli-ski poster runs, whether operations are avoiding terrain	strong
terrain use by public	3	○	○	◕	◑	expanded terrain use, extreme terrain, not triggering suspect features for WS, big lines	strong

Snowpack observations

Snowpack properties (Table 3.19) seem to only rarely factor into the decision to remove a WS problem. Three forecasters (Glacier, Kananaskis) pointed out the loss of cohesion through faceting out of ***slab properties***. ***Slab hardness*** (2 interviews; AvCan, Kananaskis) was included by one forecaster (K3) who noted wind slabs are less likely to facet out and be removed if they are really hard to begin with. The other forecaster who included slab hardness stated that when the problem is removed, slabs are sometimes relatively soft (fist plus) but more typically stiffer. Two forecasters from Banff indicated that ***snow available for transport*** is a consideration. One noted that WS problems might be removed when everything is wind hammered and blown out at treeline and in the alpine (B6), while the other described that snow available for transport and continued winds can prolong the persistence time of the WS problem (B4). The ***underlying surface*** was relevant to three forecasters (G5, B6, K3), two of whom indicated persistent weak grain types including facets can extend the duration of problem.

Table 3.19 Summary of snowpack observations, frequencies, and values for removing WS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
slab properties	3	○	◔	○	●	faceting out of slabs	strong
slab hardness	2	◔	○	○	◑	sometimes F+; typically stiffer; less likely to facet out when really hard wind slabs to begin with	moderate
snow available for transport	2	○	○	◕	○	wind hammered blown out at treeline and in alpine; can prolong problem	moderate
underlying surface	3	○	◔	◔	◑	problem maintained longer with persistent weak layer, deep persistent week layer, facets	strong

Weather observations

Weather conditions (Table 3.20) were primarily related to ***air temperature*** (6 interviews; AvCan, Glacier, Kananaskis) and ***wind*** (6 interviews; all agencies). Forecasters were aligned in considering cold temperatures including extreme or extended cold (at least -20ºC), or cold clear nights (3 to 4 days of -10ºC and clear skies) can lead to faster removal of WS problems. Melt-freeze cycles or strong diurnal swings were also an air temperature condition promoting the removal of WS mentioned by two forecasters (K4, G6). Three forecasters (B4, G6, K3) described calm conditions with no new wind inputs as a relevant consideration for the removal of WS problems. One forecaster (K4) noted that a huge wind event could also potentially lead to a major change in the snowpack that creates a bridging layer. ***New snow*** was a consideration for two forecasters, but only quantified by one who indicated that new snow accumulation of more than 15 cm can be a reason for removal because it is very rare to have wind slabs triggered once the are buried (G6). An arctic outbreak without wind (K3), omega blocks (K3), and benign weather systems with good visibility (G5) were mentioned as ***general weather situations*** that reduce the persistence of WS avalanche problems.

Table 3.20 Summary of weather observations, frequencies, and values for removing WS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
air temperature	6	◕	◕	○	●	cold/extreme cold/extended cold/cold clear nights; big swings/melt-freeze cycles; mild	moderate
wind	6	◕	◔	◔	●	no new wind inputs	moderate
wind duration	2	◔	○	○	◑	couple of days (K3)	*single value*
wind speed	2	◔	○	○	◑	calm (K3)	*single value*
new snow	2	◔	◔	○	○	*accumulation* >15 cm	*single value*
weather system	2	○	◔	○	◑	arctic outbreak without wind, benign weather systems with good visibility, and omega blocks	moderate

Spatial and temporal observations

Relevant spatial and temporal observations (Table 3.21) included wind slab persistence time (6 interviews; AvCan, Glacier, Banff) and distribution of the avalanche problem (4 interviews; AvCan, Glacier, Kananaskis). With the exception of one forecaster, a regional split appeared in the ***wind slab persistence time*** values with two forecasters from Banff (B4, B5) suggesting typical values of 3 to 4 days, while two forecasters in the Columbia Mountains indicated 5 to 6 days (A6) and 5 to 7 days (G5). The other Columbia Mountain Range based forecaster (A4) stated 1 to 2 days as a typical persistence time for wind slabs and rarely greater than 3 days. The interviewed forecasters exhibited strong agreement in their perspective on how the ***distribution of the avalanche problem*** affects their decision to remove WS problem (4 interviews; AvCan, Glacier, Kananaskis). They typically or sometimes remove the problem when it becomes isolated and trends towards allowing more travel, and they tend not to remove the problem when its distribution is widespread or specific.

Table 3.21 Summary of spatial and temporal observations, frequencies, and values for removing WS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
wind slab persistence time	6	◕	◕	◕	○	*Banff:* 72-96 hrs (3-4 days), 1-2 days longer than SS *AvCan/Glacier:* 5-7 days, 5-6 days; typically 1-2 days and rarely >3 days post wind event;	moderate
distribution of avalanche problem	4	◔	◔	○	●	not when specific or widespread sometimes/typically ≤ isolated, allowing more travel	strong

Additional considerations and practices

In addition to the physical observations described above, interviewees also discussed other considerations for removing WS problems. While WS specific additional considerations are the focus of this section, more general additional considerations such as the influence of other avalanche problem types are further elaborated on in Section 3.1.4.

Forecasters expressed that WS problems are harder to remove than SS problems or other problem types more generally. Glacier forecasters (G5, G6) attributed the challenge to remove WS problems to more limited direct field observations compared to SS problems. Additionally, because WS problems are less likely to be transitioned to a different problem, they require more certainty and more information to be removed (G4). One of the Kananaskis forecasters (K3) stated that the extreme variability of terrain and winds in their region makes it hard to extrapolate and generalize observations. Similarly, a forecaster from Banff (B6) indicated WS problems as being one of the hardest problems to remove because of the large amount of alpine terrain in their forecast area that is continuously affected by wind, even when wind speeds are only light.

> Of any problem that we are redescent to get rid of, and we always seem to want to get rid of, but we never really seem to be able to pull the trigger, it is the wind slab. And that is because I think we are dealing with a huge amount of alpine. If you consider the surface area of alpine represented in our tenures versus most of the others through British Columbia, I am sure you would find we deal with a hell of a lot of it. And so, it is pretty easy for a light wind up there to be moving snow a lot of the time. (B6)

Some forecasters drew comparisons to removing PS problems (A5, K3). The generally lower consequence or lower uncertainty associated with WS compared to PS problems was indicated to lead to easier or faster removal from the bulletin.

> In my mind how dangerous or hazardous a problem is will also affect how long I leave it in my bulletin before removing it. And so, you know for example, a persistent slab problem I am likely going to leave in my bulletin as a front page problem for longer than I would a wind slab problem, even with the same data … and that is a function of uncertainty … the other thing that factors into that decision for me is the consequence of me being wrong removing that persistent slab problem and having a fatality. You know if someone triggers a deep persistent slab or a persistent slab the likelihood of there being severe consequence you know if we can speak in general terms is generally higher than a wind slab. (A5)

Preferences varied in relation to adjusting the attributes of an existing WS problem versus removing the existing WS problem to add a new one. One AvCan forecaster (A4) suggested that it is more meaningful if a WS problem can be removed as soon as it is gone and then to add new WS problem rather than instigating confusion over an old lingering WS that has morphed into something else.

> If I think it can be gone today, I would take it off today. Because if there is something changing, I think that gives me the opportunity to write a fresh wind slab problem that's going to be more relevant, as opposed to one that just morphed into something else for the future days. So, if I think a problem is done, and I mean, yeah, it's tough, because done doesn't have to mean impossible either. (A4)

> It's really easy to have a forecast that covers your butt, and just like leave lingering wind slabs in the alpine forever. Because you could probably make a case that you could always go out and find a wind slab problem in the Columbias. It might just be confined to extreme terrain, immediately below ridge crest, like full on tiger country. But I bet 80% of the time, maybe even higher, that if your one goal was to find wind slabs, you could probably find them in the winter season. So, yeah do you just leave it there forever, or do you actually kill it at some point, just knowing that wind slabs … and extreme terrain are an inherent part of backcountry travel and objective hazard in the mountains in the winter. (A4)

This perspective was contrasted by a forecaster from Banff (B5) who prefers to maintain WS problems in anticipation of another wind event (B5). In Kananaskis both forecasters (K3, K4) described the practice of continuously adjusting and cycling between different WS problems rather than removing the problem from the bulletin. This enduring cycle of WS problems was a reason that forecasters in Kananaskis indicated for rarely removing these problems from the bulletin (K3). The forecast team was also self described as fairly conservative and reluctant to remove WS problems (K3). Achieving a forecasting team consensus to remove the WS problem was also brought up by one forecaster (K4).

> Although we may actually technically have a new wind slab, we aren't adding a new wind slab problem to the bulletin because it is already there. Right, so we could certainly have that event, well certainly the two kind of ones that came to my mind was the reverse wind loading or a high alpine wind slab problem that eventually turns into a tree line elevation problem as well. So, they are technically a new wind slabs without new snow, but they are not really blowing into the bulletin in that same fashion right, they are just going to be another version of what we have already got there. (K3)

Bulletin users' terrain use and their capabilities to recognize and avoid WS problems were also brought up by two forecasters (A4, G4). One of these forecasters (G4) stipulated that users who are looking for bolder more extreme ski lines are typically capable of identifying wind slabs in extreme terrain even if they are not included in the bulletin. Hence, they are not the users who they are focusing on when deciding to remove a WS problem from the bulletin.

3.1.4. General additional considerations and practices for storm slab and wind slab problems

3.1.4.1 Storm slab and wind slab problem interactions

Variable perspectives were expressed throughout the interviews about the relationship between SS and WS avalanche problems and how they are best represented in the public bulletin. Discussions about the interactions between forecasters' risk communication objectives and the nature of simultaneous developing SS and WS problems during stormy periods revealed some diverging practices.

The practice of combining SS and WS problems and communicating them as a single problem in the public bulletin was described in some way by forecasters at all agencies. Most commonly when combining these problems forecasters indicated that initially a SS problem is typically used to also encompass a coexisting WS problem. SS problems are preferred as the representative problem type over WS problems because they cover a wider distribution (B6) and acknowledge a change in the snowpack compared to the previous forecast period (G4). Often forecasters noted these combinations would be further explained within the forecast text using terms like “wind stiffened storm slab” (A4) or “caution in wind affected terrain at treeline and in the alpine which may make the SS more cohesive” (B5). Differing degrees of aversion to simultaneously including both SS and WS problem types in the bulletin were expressed. The range included never listing them together (A5), less likely but possible (A6), trying to avoid it (A4, B6), typically use only one (B4, G5), or sometimes simultaneously use both problems (G4, B5).

> In my mind the definition of storm slab also includes those lee features where the slabs might be thicker and harder. I would still … identify those features as a storm slab problem. … When I use the word "storm slab problem" that also encompasses what could technically be considered wind slabs (A5)

The rationales for using the SS problem to also describe concurrent WS problems involved a) keeping the communication simple (A6) and avoiding confusion (A5), b) the fact that the distinction between these problems can be irrelevant during large storms with slab avalanches everywhere (G6) and because most storms have a wind component (A4, A5, G5, B4), c) the difficulty of being fine-tuned enough to meaningfully distinguish between the two problems in large forecast regions (A4), and d) the limitation of a maximum of three problems that can be listed in the forecasting software (G6 and B5). One AvCan forecaster (A6) also describes the practice of combining SS and WS problems as coming from public forecasting specific training and mentorship implying that it is less common practice in other forecast applications where the number of simultaneous avalanche problems is less constrained and there is a stronger focus on being technically precise. Similarly, a Kananaskis forecaster (K4) provided an example of using a more nuanced problem type selection to communicate internally between forecasters for a very isolated SS that would typically be communicated to the public as part of a WS problem.

> I would say the reasoning for only including the one [storm slab or wind slab problem] is largely training or mentorship for me. It is the people that I have worked with that have you know sort of guided me to only include one of the problems versus in a you know more of an operational setting you want to be as realistic as possible … even if it means you have five avalanche problems. Because I guess as a professional, we have the mindset that we can break those out a lot easier than a class A or class B recreationist. (A6)

Forecasters who were more likely to use both problem types in the same forecast cited that it is sometimes helpful to communicate differences (distribution and likelihood) between the problems (G4, G5) especially in light of character limits on forecast text (G5).

A scenario of multiple storms with a lot of strong wind was also described as a potential reason for keeping the WS problem in place in addition to a SS (B4).

Practices in Kananaskis provided an exception to the typical approach of initially using a SS problem to also describe a concurrent WS problem. Instead, the Kananaskis forecasters stated that WS problems were the more dominant problem for their region. Both Kananaskis forecasters also shared the atypical perspective that SS problems should only be used for pure settlement slab problems without any wind influence. They further provided examples of potential situations when these problem types may be combined in the public bulletin. One of these examples is using a WS to also describe a very isolated SS problem (K3). Alternatively, if an avalanche problem is developed under lighter than normal winds a SS problem may be used to differentiate the new problem from a pre-existing WS problem. However, this scenario is sometimes also described using a single WS problem with further differentiation made within the forecast text.

> I feel like the way that I define these slabs is that they would be better defined as a settlement slab versus a storm slab. (K4)

When initiating a new problem related to a forecasted or ongoing storm, forecasters in some regions referred to a default avalanche problem type they typically use to describe these conditions in their forecast region. Special or unusual circumstances and possibly additional information such as field confirmation rather than inference from a weather forecast would be required to convince them that a different problem type was more relevant to the bulletin. AvCan forecasters considering the North and South Columbia forecast regions all expressed that their default condition is to initiate a SS problem. Similarly, some forecasters in the neighboring Glacier forecast region (G4, G5) indicated that they typically lean towards forecasting SS problems initially. In contrast to the Columbia Mountains, both forecasters from Kananaskis indicated that WS problems are their default problem type when there is new snow, and that the vast majority of the time the regional snowpack can be described with a DPS problem and WS problem. The statements of the interviewed forecasters from Banff National Park indicate that their region is somewhere between these situations. They described storm scenarios where they tend to group WS problems into a SS problem initially, but they also consistently mentioned that SS problems occur less frequently and WS problems more frequently compared to other regions due to more wind and smaller snowfall amounts.

3.1.4.2 Weather information sources

Weather conditions including air temperature, wind, and new snow were common forecasting considerations, especially for the adding WS and SS scenarios. Typical information sources included both weather forecast information and weather actuals from remote weather stations, weather plots, and field observations. The uncertainties associated with this information, which includes both the inherent uncertainty associated with the information source and the uncertainty associated with particular weather events, was described as a considerable influence for adding both SS and WS problem types and has the potential to lead forecasters to arrive at different problem types.

In the Columbia Mountains, AvCan and Glacier forecasters indicated that weather forecasts are typically what is available to them at the time that they are writing the bulletin. Additional weather actuals were less important for adding problems but considered when available (i.e., storm begins before forecast is issued) or to later increase confidence or validate their forecasts. Some forecasters indicated a high confidence in the reliability of precipitation forecasts for initiating SS problems (G4, G6), whereas there was less trust in the forecasts of wind events (G6, A4). Removing SS or WS problems from the bulletin was sometimes indicated to be a correction for when forecasted weather conditions from the previous day did not materialize (A6, B4).

Forecasters in the Rocky Mountains had less confidence in forecasted precipitation events (B5) and indicated that weather forecasts seem to generally perform poorly for the Kananaskis region (K3). One of the Banff forecasters explained that they primarily rely on weather stations for adding SS problems and are cautious of extrapolating personal field weather observation to the regional scale (B6). Another indicated that there is often more debate within the team over adding a WS without new snow based on wind speed if there is a lack of relevant field observations above 2700 m (B4). In Kananaskis, more reliance was placed on field observations and field validating of forecasted or weather station snowfall values before adding a SS problem (K3). While weather stations were deemed most untrustworthy for wind, one forecaster noted it is almost always windy in Kananaskis anyways when considering adding a WS problem (K3).

> I feel like for the Rockies the wind is a pretty important player. You know, often we can get some new snow, dribs and drabs, and we don't see an avalanche cycle until we also see the wind kick up, and then we start to see things move or it might even wake up deeper layers … I would be rich if I got you know 100 bucks every time we got promised snow and we just got wind (B5)

3.1.4.3 Forecaster context

One's personal risk tolerance, confidence, and experience was mentioned by several forecasters when discussing to how quickly a SS or WS problem will be dialed back or removed (A4, A5, B5).

> I think of how if I am new to an area, I'd want to know of the things that I should be looking for. Like if I think it is something that I have to manage then I want the problem in there … My litmus test really is like: do I think if I go out there, am I going to be thinking of about this in where I go, and would I take [a child]? And if I think if my answer is yes, then I want to leave it in. So, I'm not, I am maybe a little more conservative in terms of wanting to pull things out until I am confident in that I can pull it. (B5)

Additionally, the first day of a forecasting shift was sometimes a reason for forecasters to avoid changing a problem type unless there were major changes in the conditions (A4, A5, B5).

3.2. Persistent slab and deep persistent slab scenarios

All persistent slab and deep persistent slab avalanche problem topic interviews resulted in a representation of a scenario for adding and removing each problem type from the bulletin (add PS, add DPS, remove PS, remove DPS). In some cases, adding a PS or DPS was described more specifically as transitioning from a different problem type or directly adding the problem (Figure 3.13). Several forecasters also included separate scenarios for reactivating a pre-existing problem for either or both PS and DPS problems (reactivate PS, reactivate DPS).

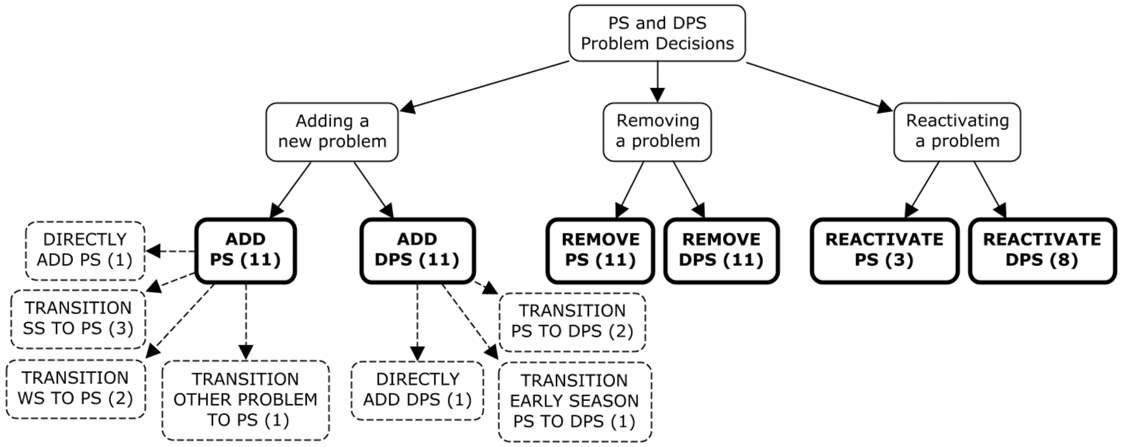

Figure 3.13 Persistent slab and deep persistent slab scenarios (major analysis scenarios bolded; sub-scenarios dashed; values in parenthesis indicate number of forecaster interviews including the scenario).

Concept maps focused on PS and DPS decisions were comprised of a total of 2863 concepts, 2004 linking phrases, and 5209 connections between concepts. The number of concepts, linking phrases, and connections that make up each base scenario varies across scenarios and between forecasting agencies (Figure 3.14). On average, the PS problem scenarios contain more concepts than DPS problem scenarios, and the descriptions of the adding scenarios include more concepts than their corresponding removal scenarios. The reactivation scenarios, which were only discussed by a portion of forecasters, resulted in the fewest average number of concepts.

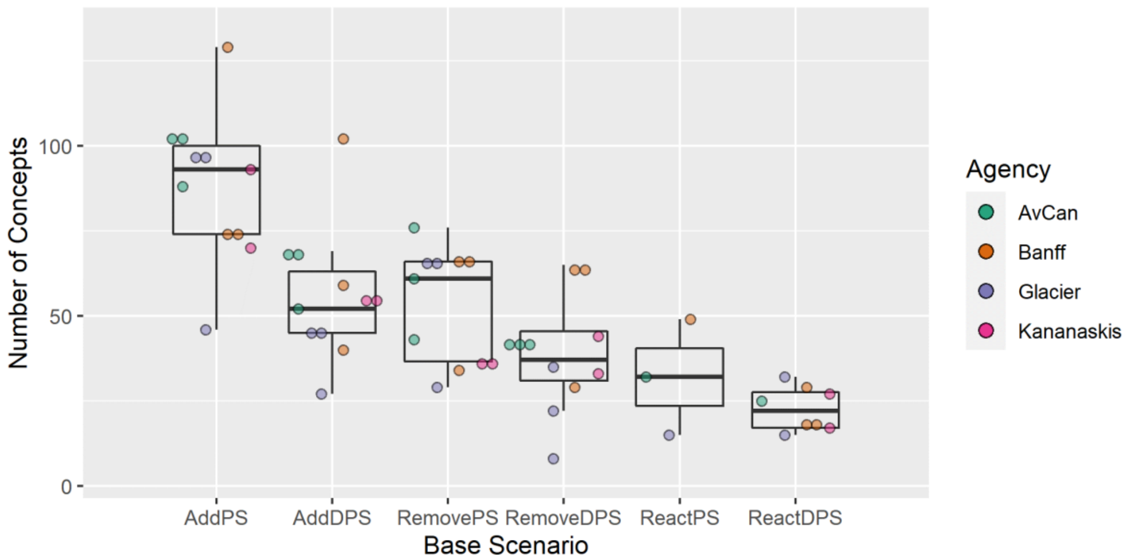

Figure 3.14 Number of concepts by scenario and agency for persistent slab and deep persistent slab avalanche problems topic

Observation types, observation values, and special considerations make up the majority of concepts used to describe the decisions to add and remove the PS and DPS problem types (Figure 3.15).

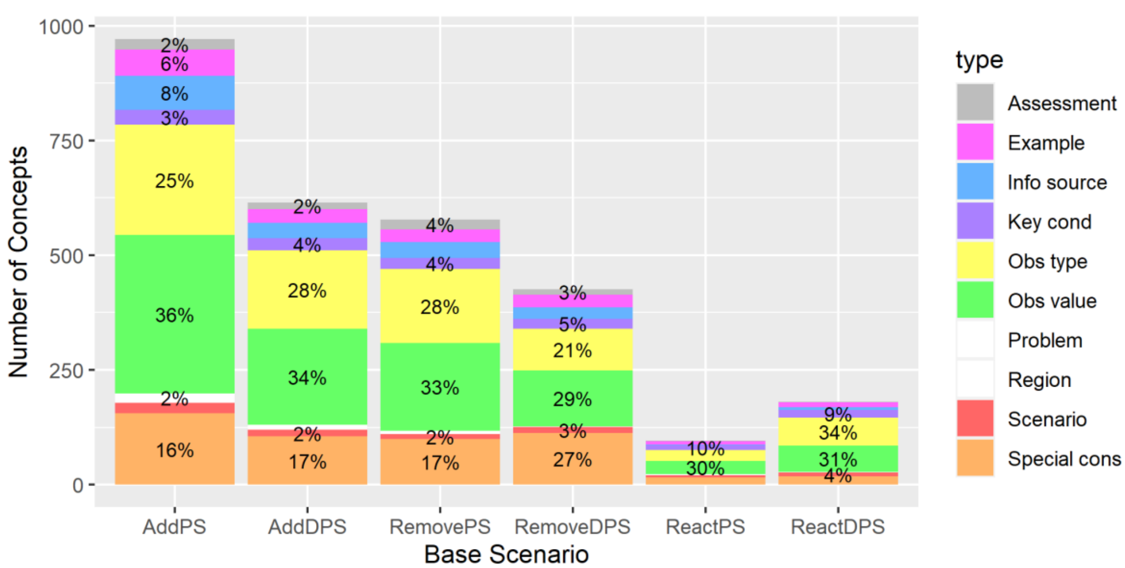

Figure 3.15 Total number and proportions of concept types by scenario for persistent slab and deep persistent slab problems

On average 61% (range 53 to 66%) of concepts included in each scenario were related to observation types and observation values. These concepts primarily include physical observations types and values related to weather, snowpack, and instability conditions (Figure 3.16). Special considerations made up an average of 17% of the concepts for each scenario with the removing DPS and reactivating DPS scenarios as outliers (27% and 10% respectively).

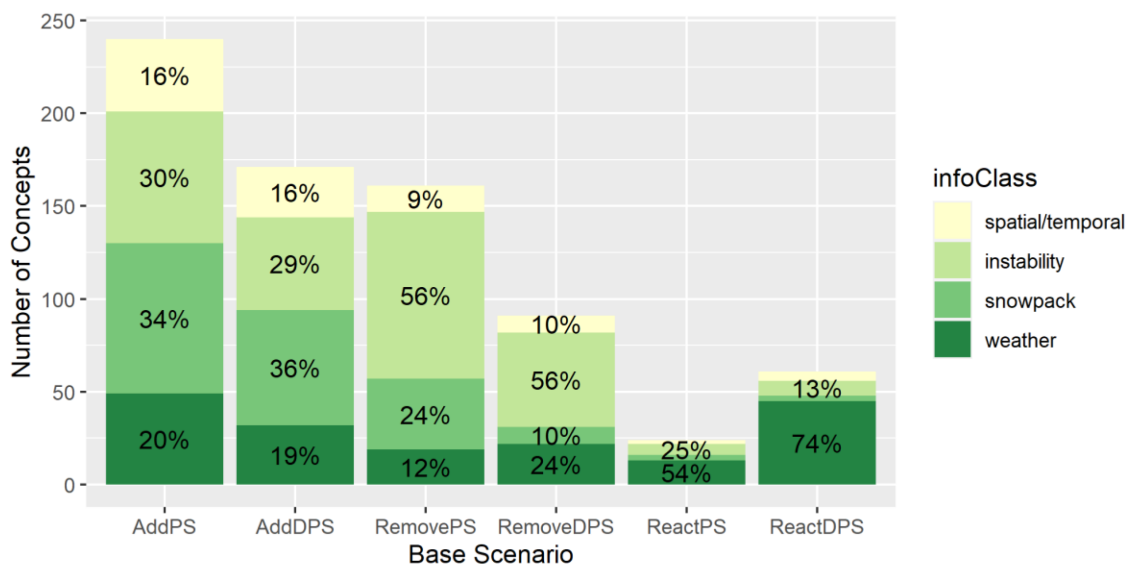

Figure 3.16 Observation type information classes by scenario for persistent slab and deep persistent slab problems

3.2.1. Persistent slab avalanche problems

Interviews focused on decisions around PS problems included discussions around considerations for adding, removing, and reactivating PS problems in the bulletin. These discussions generated a total of 1645 concepts, 1139 linking phrases, and 2963 connections.

3.2.1.1 Adding PS problems

The scenario for adding PS problems was discussed by all forecasters in this topic, on average these discussions generated 88 concepts. Interviews with forecasters from all regions and agencies revealed a typical progression for initiating new PS problems involving a transition from another problem type. However, some differences in this problem progression emerged between agencies. All Glacier forecasters stated that PS problems always transition from a SS problem, while all other agencies indicated that PS problems will occasionally, sometimes, or rarely be directly initiated in the forecast. Forecasters from Kananaskis indicated that PS problems commonly transition from a WS problem, while PS problems are typically transitioned from SS problems in all other agencies.

The rationales for making the decision to transition through another problem over directly initiating a PS problem were related to a) keeping communication simple and that it is not initially important to users which problem type it is, b) maintaining consistency throughout an organization, and c) providing the forecasters more time to assess the problem before committing to a PS problem (i.e., avoid confusion of removing a PS problem that does not persist).

> The storm slab is very often used as the vehicle to set us up for the persistent slab, like that is one reason we would … use it to transition through it to get us up for the persistent slab … it can happen pretty quick but we can be burned with that. (B6)

Reasons for directly adding the PS problem included physical conditions such as when a slab is formed through incremental loading and there was not a widespread SS problem to start with, or risk communication considerations including avoiding confusion and getting people to think about the problem sooner.

> For me it's just all about how that snow is failing. You know, if it is failing on the surface hoar and there is a slab there and it's going to persist then I'll call it. I just feel it is important especially with public warnings to get people thinking about it the sooner the better. (B2)

Observations

Observations for adding a PS problem to the bulletin involved instability, snowpack, and weather conditions (Figure 3.17). The most frequently mentioned observation types were weak layer properties including grain type and avalanche observations.

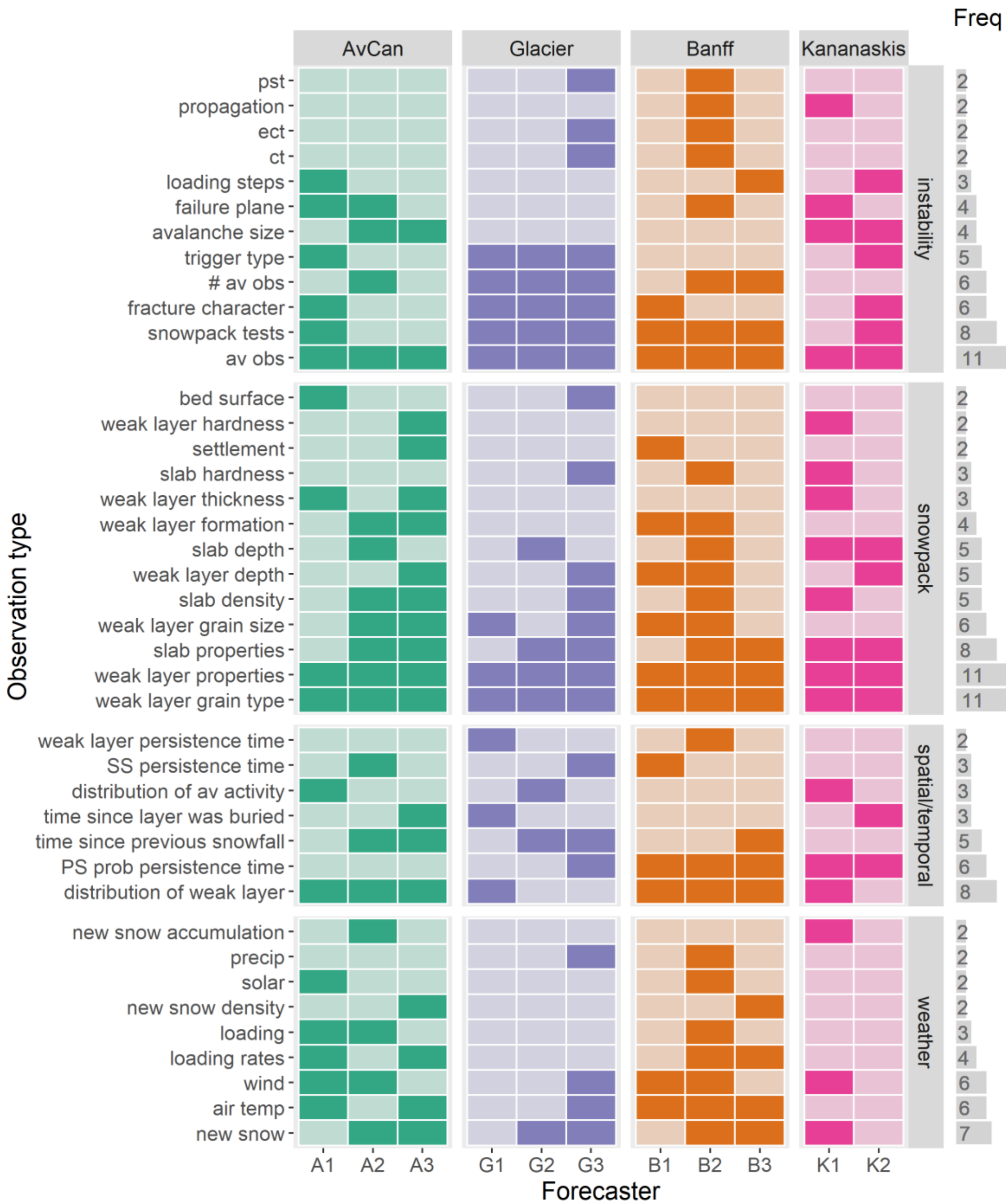

Figure 3.17 Observation types included by at least two forecasters as a consideration for adding PS avalanche problems. See caption of Figure 3.5 for detailed explaination of figure presentation.

Instability observations

The most frequently discussed instability conditions when considering adding a PS problem to the bulletin (Table 3.22) were ***avalanche observations*** (11 interviews) and

snowpack tests (8 interviews; all agencies). The ***number of avalanche observations*** when initiating a PS problem differed between forecasters including no observations, continued observations following a storm cycle, or a decreasing trend of observations. Two forecasters from Banff (B2, B3) indicated that PS problems can be added in either the presence or absence of avalanches noting that the problem might be added while it is developing. Some forecasters mentioned that they are looking for the presence of avalanches (G3) or maintained activity following a storm cycle (A2, G1). Two of three forecasters from Glacier (G1, G2) stated that avalanche observations are typically present but with a decreasing trend in the number of observations. Regarding ***trigger types*** (5 interviews; AvCan, Glacier, Kananaskis) most interviewees agreed that avalanche observations with skier triggering are relevant, while observations with other trigger types were more variable. Individual forecasters indicated looking for maintained sensitivity to large triggers (G2), step downs from shallower avalanches with decreasing skier triggering and natural activity (K2), or that they are less likely to initiate a PS problem when trigger types are explosive compared to skier accidentals and remote triggering (A1). Destructive ***avalanche size*** (4 interviews; AvCan, Kananaskis) values included at least size 2 (A2, K2), or “quite large” (A3). One forecaster indicated adding the problem when it is producing size 1 avalanches is also possible, and that size is a more valuable indicator for DPS problems (K1). Four forecasters (AvCan, Banff, Kananaskis) noted the ***failure planes*** of observed avalanches should include persistent interfaces and not be a surface or storm interface or be stepping down to ground. ***Propagation*** was also mentioned by two forecasters (B2, K1) one of whom described the qualities of propagation with respect to the sound of surface hoar failures and the speed and glazed surface resulting from propagation over a crust.

Snowpack tests including compression tests, extended column tests (ECT), propagation saw tests (PST), shear tests (ST), and rutschblock tests (RB) were consistently mentioned to be relevant if they produce sudden or planar ***fracture characters*** (6 interviews; all agencies) that indicate propagation or continued persistence. Relevant ***loading steps*** (3 interviews; AvCan, Banff, Kananaskis) typically include easy to moderate results.

Table 3.22 Summary of instability observations, frequencies, and values for adding PS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
avalanche observations	11	●	●	●	●	considers *number, trigger, distribution, failure characteristics, and recorded types of avalanches*	*n/a*
number of avalanche observations	6	◔	●	◕	○	presence or absence of observations, continued activity following a storm cycle, decreasing trend of activity	weak
trigger type	5	◔	●	○	◐	skier, natural, large triggers, step downs, explosives, remote and accidentals	moderate
avalanche size	4	◕	○	○	●	range of at least size 1 to at least size 2; quite large	moderate
failure plane	4	◕	○	◔	◐	persistent interfaces, crusts, crust-facets, wind slabs stepping down onto persistent interface not surface or storm interface or stepping down to ground	strong
propagation	2	○	○	◔	◐	qualities of propagation include the sound of surface hoar, and the fast speed and hard glazed surface of failure over a crust	*single value*
snowpack tests	8	◔	●	●	◐	includes *ECT, CT, PST, RB, ST.*	*n/a*
fracture character	6	◔	●	◔	◐	sudden results, planar results, indicates propagation, continued persistent character	strong
loading steps	3	◔	○	◔	◐	easy to moderate, less likely when hard to no results, one example includes hard and sudden planar	moderate

Snowpack observations

Snowpack properties (Table 3.23) frequently included ***weak layer properties*** (11 interviews) and ***slab properties*** (8 interviews; all agencies). Forecasters strongly agreed on relevant ***weak layer grain type*** including surface hoar, facets, crusts, and facet-crust combinations. Regional variation in the frequency of occurrence of these grain types was present with forecasters located in a continental snow climate (Banff, Kananaskis) noting surface hoar as occurring sometimes or less commonly, crusts occurring often or sometimes, and facets occurring most commonly. Some forecasters located in a transitional snow climate described surface hoar as the most prevalent (A2) and facets as occurring less commonly (G3). Typical ***weak layer grain size*** (6 interviews; all agencies) values ranged between at least 5 mm to 15 mm for surface hoar and at least 0.5 mm to at least 2 mm for facets. Quantified typical ***weak layer depth*** values included at least 25 cm (B1), 70 to 100 cm (A3), 40 to 100 cm (G3), and the top third of the snowpack (K2). One forecaster from Banff (B2) discussed weak layer depth in the context of protection of the weak layer from wind (at least 15 to 20 cm deep) and solar (at least 5 cm deep) while the problem is developing. Four interviewees (AvCan, Banff) concurred that ***weak layer formation*** should occur at the surface. ***Weak layer thickness*** was mentioned three times (AvCan, Kananaskis) with two forecasters quantifying values for surface facet thickness of 5 to 10 cm (A3) and at least 10 to 20 cm (K1). Other relevant weak layer properties that were specified by more than one forecaster included, ***hardness*** (2 interviews) that was "softer" (A3) or fist to four finger (K1), and ***bed surfaces*** including crusts (A1, G3).

Slab density was the most frequently considered slab property (5 interviews; all agencies) for making a decision whether to add a PS avalanche problem or not. However, only one forecaster (G3) provided a specific threshold value (greater than 100 kg/m^3). Three forecasters did specify typical ***slab hardness*** values of four finger to one finger (B2), one finger minus or a two-step change in resistance (G3), and at least one finger (K1). Typical minimum ***slab depth*** thresholds (4 interviews; all agencies) were notably smaller than the typical weak layer depths indicated for this scenario and included at least 10 cm (G2), 15 cm (K1), 20 to 40 cm (K2), 20 cm (A2), and 30 cm (B2). Two interviewees (A3, B2) also mentioned ***settlement*** was relevant, but neither elaborated on specific values.

Table 3.23 Summary of snowpack observations, frequencies, and values for adding PS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
weak layer properties	11	●	●	●	●	considers *grain type, depth, distribution, time since burial, formation, grain size, density of weak layer*	*n/a*
weak grain type	11	●	●	●	●	surface hoar, facets, crusts, facet-crust combinations	strong
weak layer grain size	6	◕	◕	◕	○	*surface hoar* typical range 5-15 mm; *facets* typical range ≥ 0.5 to ≥ 2 mm	moderate
weak layer depth	5	◔	◔	◕	◐	range includes ≥ 25 cm to ≤ 100 cm	weak
weak layer formation	4	◕	○	◕	○	surface formation	strong
weak layer thickness	3	◕	○	○	◐	surface facets range ≥ 5-20 cm	moderate
weak layer hardness	2	◔	○	○	◐	“softer”, F to 4F	strong
bed surface	2	◔	◔	○	○	more likely crusts or hard smooth surfaces, less likely new snow	strong
slab properties	8	◕	◕	◕	●	includes or requires cohesion; considers *slab density, depth/thickness, hardness, and slab type (wet/dry)*	*n/a*
slab density	5	◕	◔	◔	◐	> 100 kg/m3	*single value*
slab hardness	3	○	◔	◔	◐	typically 1F-, 4F to 1F, two step change in resistance; not when F to 4F	moderate
slab depth	5	◔	◔	◔	●	typical ranges > 10 cm to > 40 cm	moderate
settlement	2	◔	○	◔	○		*no values*

Weather observations

Relevant weather conditions considered for adding PS problems to the bulletin related to several different contexts including weak layer development, slab development, and problem initiation. The weather observations most frequently considered when adding a PS problems to the bulletin included new snow, wind, and air temperature (Table 3.24).

New snow (7 interviews; all agencies) was included as a consideration for the progression of how the problem is initiated, as an impact on problem distribution, and as an input that relates to slab development. ***New snow accumulation*** values for adding a new PS avalanche problem differed between AvCan and Kananaskis with an example of 15 cm with wind over surface hoar in Kananaskis (K1) and typically 25 to 30 cm in the North and South Columbia regions (A2). The AvCan forecaster (A2) also indicated that less than 25 cm might not be enough load to trigger persistent slab avalanche activity and that storms larger than 30 cm have the potential to change the distribution of the problem by cleaning surface hoar layers out of many areas. Two forecasters (A3, B3) mentioned the ***density of new snow*** as an important consideration for the formation of the slab but did not further elaborate on it. Comments on relevant ***loading rates*** commonly referenced incremental loading (A3, B3, B2). Larger storms with loading rates that can form a slab on their own were also mentioned (B3) especially if these storms occur after incremental loading events (B2). An AvCan forecaster was also interested in rapid loading more generally as an initiating factor (A1). Loading and precipitation more generally were also mentioned in three and two interviews respectively.

Wind was mentioned as a relevant observation related to problem development and problem initiation. Rapid relative changes (A1) and typically sustained winds of 20 to 30 km/hr (B2) were discussed as a loading factor for problem initiation by two forecasters (AvCan, Banff). With respect to problem development, “some wind” was indicated to increase sensitivity and slab density in addition to influencing what kind of problem the PS will transition from (WS versus SS). Wind over an unprotected (exposed or shallow) weak layer can also destroy it and prevent the problem from developing (B2).

References to ***air temperature*** as an important indicator (6 interviews; AvCan, Glacier, Banff) were related to problem development and problem initiation. One forecaster from Glacier (G3) highlighted cold air temperatures during weak layer (facet) development (e.g., -20ºC for 10 days), while others discussed that PS problem development is more likely when warmer temperatures (0ºC and high humidity) exist during the storm that builds the slab and less likely with colder periods following a storm that may cause a slab to facet (B3). Changes in air temperature that are considered relevant for initiating a PS avalanche problem include warming (A1); rapid temperature rise (A3); and swings of at least 5 to 10ºC in warmer temperature regimes especially around 0ºC (e.g., a change from -20ºC to -5ºC, a change from -12ºC to -5ºC overnight) (B2). ***Incoming solar radiation*** was also mentioned as a consideration in two interviews (A1, B2).

Table 3.24 Summary of weather observations, frequencies, and values for adding PS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
new snow	7	◕	◕	◕	◑	considers *accumulation, density, and cohesion, and loading rates of new snow*	*n/a*
new snow accumulation	2	◔	○	○	◑	typically 25-35 cm; less obvious < 25 cm or > 35 cm (A2); 15 cm with wind over SH (K1)	weak
new snow density	2	◔	○	◔	○	enough to form a slab	*single value*
loading rates	4	◕	○	◕	○	incremental new snow loading; especially rapid changes or incremental snowfall followed by a storm	moderate
wind	6	◕	◔	◕	◑	*initiating/loading:* rapid relative changes, 20-30 km/hr sustained *influence on problem development:* wind as a factor in slab formation or can destroy the layer while at the surface	moderate
air temperature	6	◕	◔	●	○	*weak layer development:* for example -20ºC for 10 days *slab development:* more likely with warmer temperatures during the storm or with warmer temperature regimes than colder temperatures following a storm or in colder temperature regimes *initiating*: rapid rise in temperature throughout the day	moderate
incoming solar radiation	2	◔	○	◔	○		*no values*
loading (general)	3	◕	○	◔	○	considers *wind, new snow, precipitation, and rates of loading*	*n/a*
precipitation (general)	2	○	◔	◔	○	considers *new snow and rain*	*n/a*

Spatial and temporal observations

Spatial and temporal factors that emerged as relevant for the decision to add a new PS avalanche problem included considerations around both times and distribution (Table 3.25). Considerations around ***time*** were pertaining to the time since the layer was buried or the end of the preceding storm in addition to the anticipated persistence time of the problem and the weak layer. ***Time since the previous snowfall event or since the layer was initially buried*** was discussed by seven forecasters including all agencies (Figure 3.18). Typical values mentioned by AvCan forecasters included at least two days after the storm ends (A2) or the second avalanche cycle that occurs on the layer (A3). In neighboring Glacier National Park, typical values included at least 48 hours (2 days) (G1), at least 36 hours (1.5 days) to 4 days (G2), and 3 to 4 days (G3) after the storm ends. One forecaster from Glacier (G2) specifically noted that they typically will not initiate a PS problem while it is snowing since the problem will be considered a SS problem at that point. Values for the forecasters in the Rocky Mountains included longer typical time frames including up to one week (7 days) (B3); at least 10 days up to two weeks (14 days) without new snow or more recently with a new avalanche problem on top; and a few days after a storm with wind or with a sequence of storms that leads to a new layer of wind slabs (K2).

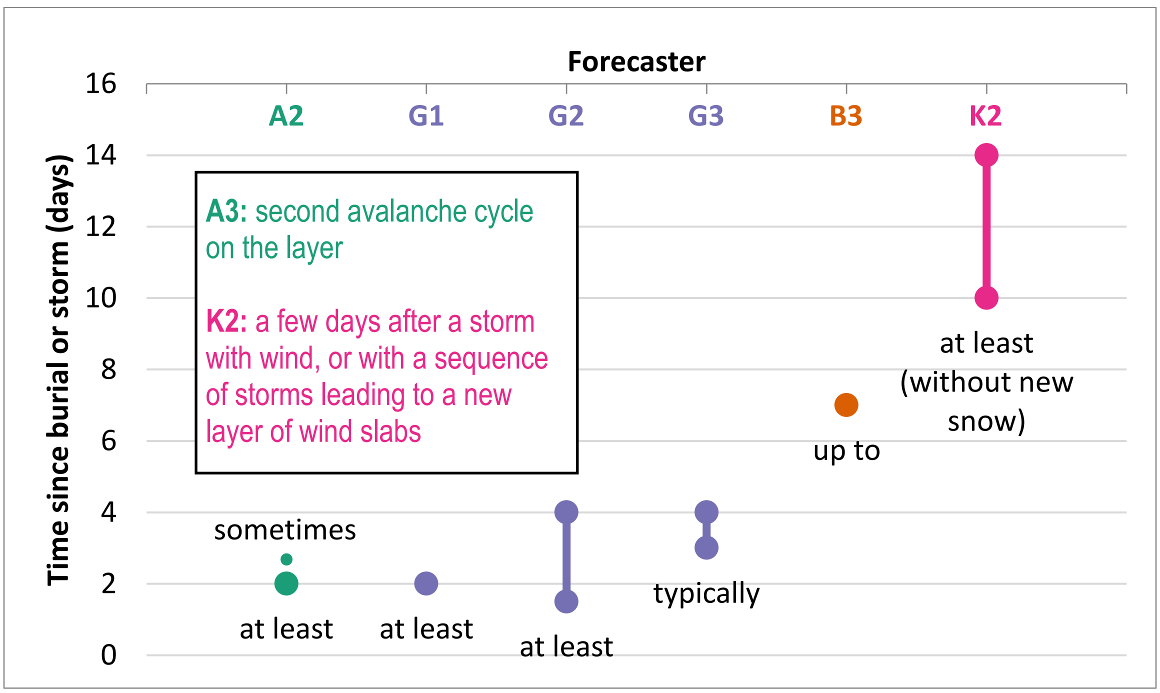

Figure 3.18 Typical time since burial or since the preceding storm for adding a PS problem

Anticipated ***persistence time of the PS problem*** was discussed by six forecasters (Glacier, Banff, Kananaskis) and included a range of values from at least two days and up to months. Two forecasters elaborated on the anticipated persistence time of the weak layer specifically, and one of them (B2) explicitly stated that they expect relevant weak layers to persist for up to six weeks, which is in a similar range as other forecasters' perspective on anticipated problem persistence. Three forecasters (A2, B1, G3) also included a comparison to ***SS problem persistence*** times of typically hours to days.

Weak layer distribution was mentioned as a relevant observation for adding PS avalanche problems (8 interviews; all agencies) with values typically being specific or widespread and only sometimes isolated. In some cases, the distribution was further broken down into elevation band (sometimes or less commonly alpine, often or typically at treeline and below treeline), aspect, and regional distribution. The ***distribution of avalanche activity*** (3 interviews) included values of typically widespread initially then narrowing.

Table 3.25 Summary of spatial and temporal observations, frequencies, and values for adding PS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
weak layer distribution	8	●	◔	●	◐	typically specific or widespread and sometimes isolated. In some cases this distribution is further broken down into elevation band (3), aspect (1), and regional distribution (1).	moderate
distribution of avalanche activity	3	◔	◔	○	◐	typically widespread initially then narrowing	moderate
PS problem persistence time	6	○	◔	●	●	typical range from at least 2 days up to months	moderate
SS persistence time	3	◔	◔	◔	○	typically hours to days	strong
weak layer persistence time	2	○	◔	◔	○	typically anticipated to be ≤ 6 weeks	*single value*
time since previous snowfall	5	◕	◕	◔	○	typical range greater than 1.5 days up to 7 days	moderate
time since layer was buried	3	◔	◔	○	◐	> 2 days up to 2 weeks; second avalanche cycle	weak

Additional considerations and practices

In addition to the physical conditions specified by the observation types and values discussed above, forecasters also described other factors that they take into consideration when making the decision to add a PS problem to the public avalanche bulletin.

Forecasters highlighted the relevance of several compound components of the hazard and risk assessment process that cannot be directly observed including consequence (3 interviews; Glacier, Kananaskis), sensitivity (4 interviews; AvCan, Banff, Kananaskis) and likelihood (3 interviews; AvCan, Glacier). Adding a PS is only considered when the consequences of a problem are deemed significant or not when a problem is generally inconsequential to people except in very specific locations. The sensitivity of a new PS avalanche problem needs to be in the range of touchy to stubborn to be of concern (G3, K2), and still needs to be very triggerable or for human triggering to be possible. Two forecasters from Glacier also mentioned that adding a new PS problem is more likely when the danger rating is at least moderate.

The influence of other avalanche problem types on the decision to add a PS problem to the bulletin was conveyed in several interviews. Prior to adding a new PS problem to the bulletin some forecasters describe grouping a PS problem with other avalanche problem types. For example, a SS problem with clarifications in the comment section can be used to represent multiple problem types including PS problems during their first storm cycle (A3). Some forecasters use this practice of initially grouping the PS problem with another problem type to simplify communication with the public.

> From a public forecasting point of view, trying to communicate that much information to somebody initially I think is pretty cruxy. So, we stick just the storm slab problem that is failing on within the storm snow and in surface hoar in isolated areas for a few days, because the risk communication I think is a lot easier. And then as it develops and people almost kind of read about it for a few days the communication becomes a bit easier to say where the problem is and where the problem isn't. (K1)

Another use case for integrating a PS problem into a SS problem during its initial cycle is when there is a "huge storm over a known persistent weak layer". Even if the criteria for a PS avalanche problem are met, the main forecast message in this situation is to tell people to avoid avalanche terrain regardless of the persistent weak layer. In this case, adding a PS problem is perceived to "muddy the waters" (A2).

When a PS problem only has an isolated distribution or only a small percent of observed avalanche activity is on the associated persistent weak layer, forecasters may not list the PS as a problem and mention it somewhere else in the bulletin. A Kananaskis forecaster (K1), described a locally common situation where a WS problem failing on a persistent weak layer may be communicated as PS problem between forecasters but listed as a WS problem in the bulletin to avoid public confusion.

> Arguably a lot of our wind slabs are a persistent slab problem because they last quite a long time. They don't sort of develop and settle out in sort of the standard definition of a wind slab. You know, often our wind slabs here will last a long time because they are sort of these laminated one finger pencil wind slabs over top of a chunk of facets … But I think that people understand the wind slab problem here … like … if I call that a persistent wind problem in the alpine people get really confused. (K1)

Another situation where other avalanche problem types influence the initiation of a PS problem is to differentiate the problem from a new shallower SS or WS problem or to distinguish between multiple distinct failure planes.

3.2.1.2 Removing PS problems

The eleven interviews that discussed removing PS avalanche problems revealed some practices and considerations that exhibit consistency within forecasting agencies. On average these discussions generated 53 concepts. Forecasters from Kananaskis indicated that PS problems are only removed if they are not expected to come back. Some concept maps from Banff and AvCan also share this perspective indicating that it is rare to reactivate PS problems or that it will only be brought back if its removal turned out to be incorrect (i.e., they "blew the ending"). Other forecasters indicated that they would remove the problem and bring it back if it is expected to be gone for an extended period of time. For example, they will remove the problem if they expect it will be off for at least a week. In these circumstances, they might continue discussing the PS problem in the snowpack and avalanche summaries of the forecast to let the users know that the problem has not disappeared completely. These forecasters noted that they want to avoid message fatigue but also avoid confusing the public by adding and removing the problem in the short term. They also stated that there is more emphasis on the problem when it has been removed and then reactivated. The interviewed forecasters from Glacier National Park highlighted that they take a shorter-term perspective. Some primarily consider a single forecast period timeframe (if it is not a problem that day it would not be listed) and are willing to bring the problem back a day after it is removed. These forecasters cited maintaining credibility with backcountry users and avoiding diluting forecasting messages as a reason for their approach.

What I try to do in my header would be talk about the problems that we might see in the future, but not having a problem that day … as a rule of thumb … I don't want to keep problems in there that aren't a problem on that day, so I am okay taking something out and bringing it back." (G3)

Observations

Our analysis of the concept maps revealed that the most frequently considered observations for removing a PS avalanche problem across agencies are related to instability conditions, followed by snowpack observations, and very few weather or special and temporal observations (Figure 3.19).

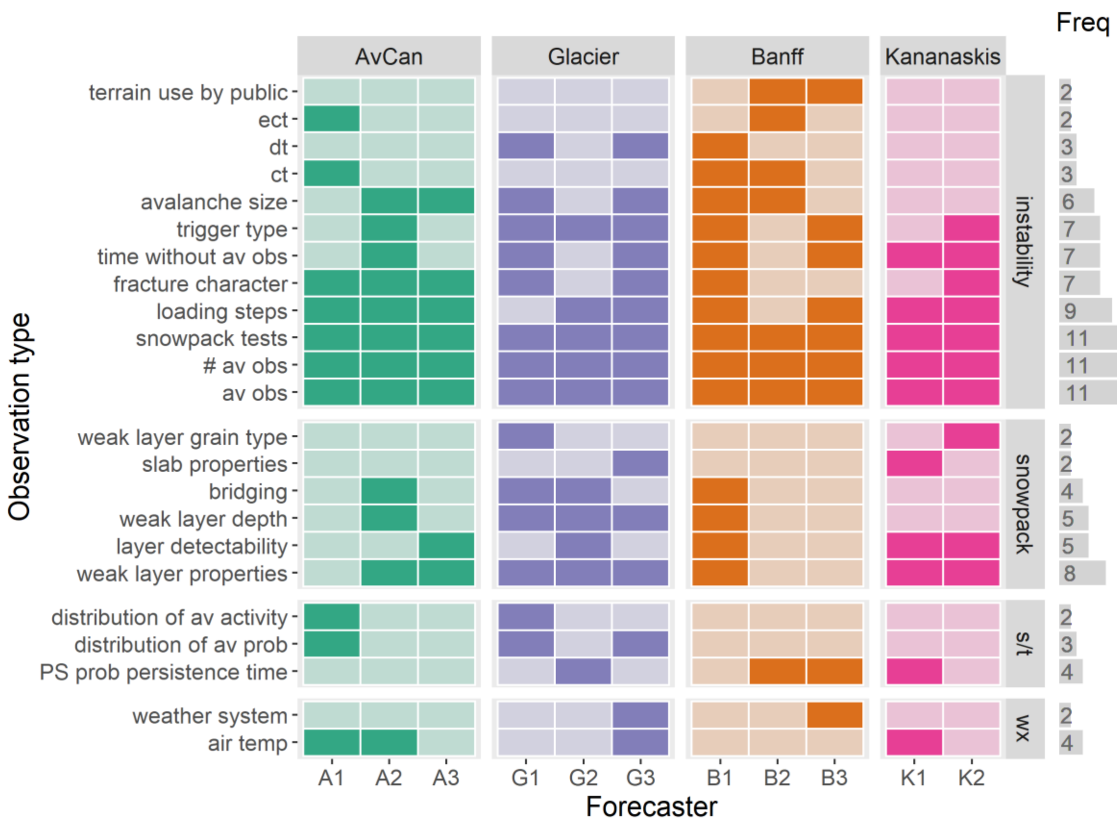

Figure 3.19 Observation types included by at least two forecasters as a consideration for removing PS avalanche problems. See caption of Figure 3.5 for detailed explaination of figure presentation.

Instability observations

When discussing considerations for removing PS problems, all eleven forecasters highlighted ***avalanche observations*** and ***snowpack tests*** to be important (Table 3.26). The ***number of avalanche observations*** (all interviews) was consistently considered.

Most forecasters indicated that they typically require no avalanche observations when removing the problem. Some also stated that a decreasing trend in the number of avalanche observations is important (A1, G1, B2, B3). Four forecasters (A2, A3, G1, B2) indicated a low level of activity can be acceptable when removing a PS problem. ***Trigger types*** (7 interviews; all agencies) were also relevant with forecasters focusing on no natural or skier triggered avalanches. Avalanches triggered by large loads (cornices, explosives, shallower avalanche cycles) were more likely to be acceptable to some forecasters while others indicated that they look for these triggers to test the PS problem with no results before removing. Typical values for ***time without observed activity*** (7 interviews; all agencies) ranged from no activity for three to five days up to at least two weeks (14 days). The range in values for time without activity was narrower between forecasters within the same agency. Both forecasters from Kananaskis indicated typical values of two weeks without activity (when the whole snowpack is steady and longer with a dynamic snowpack for K2). Two forecasters from Banff indicated typical values of at least 10 days (B1) or at least five to seven days before starting to consider the removal and then a few additional days to go through the process of actually removing the problem (B3). Only one AvCan (A2) and one Glacier (G3) forecaster provided explicit values for time without observed activity (two weeks and 3 to 5 days respectively). ***Avalanche size*** was a common consideration (6 interviews; AvCan, Glacier, Banff), but only one forecaster (A2) specified a value that indicated they would be less likely to remove the problem if sparse avalanche activity was larger than a destructive size 2. Another forecaster (B2) stated that the avalanche size is not a good indicator because it typically stays constant towards the end of a PS avalanche problem. Two Banff forecasters mentioned that broad ***terrain use by the public*** can contribute to validating their assessment as they consider removing the problem.

Snowpack tests were discussed in all interviews when considering removing a PS problem, but there was considerable disagreement on the value of snowpack test information for making this decision. One forecaster (A1) indicated that snowpack tests are more important because avoidance strategies limit avalanche observations, while others (A2, B3) indicated that snowpack tests are not a deciding factor due to the variable and anecdotal nature of test results. Relevant snowpack tests included deep tap tests, compression tests, and extended column tests. Forecasters generally agreed that an improving trend in test results is favourable for removal. Quantified values for ***loading***

steps primarily included no results or consistently hard results, with one forecaster (A1) indicating moderate to hard results. Desirable values for ***fracture character*** included non-sudden and/or non-planar results.

Table 3.26 Summary of instability observations, frequencies, and values for removing PS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
avalanche observations	11	●	●	●	●	considers *number, trigger, time without, size, and distribution of avalanche observations*	*n/a*
number of avalanche observations	11	●	●	●	●	most indicate typically no avalanche activity, four indicate some level of activity can exist, four indicate a decreasing trend	moderate
trigger type	7	◐	●	◐	◐	skier, natural, and large loads (explosives, cornices, shallower avalanches)	moderate
time without observed activity	7	◐	◐	◐	●	typical values range from at least 3 days to at least 14 days	weak
avalanche size	6	◐	◐	◐	○	typically stays constant; less likely to remove if sparse activity is larger than or equal to destructive size 3	moderate
terrain use by public	2	○	○	◐	○	includes 1000s of tracks and people skiing everywhere; validates assessment of “bottomed out” likelihood	moderate
snowpack tests	11	●	●	●	●	improving trend; commonly includes *deep tap tests, compression tests, extended column tests*	*n/a*
loading steps	9	●	◐	◐	●	no results (6) hard/consistently hard/already become hard (4) moderate to hard (1); trend of increasingly hard (2)	moderate
fracture character	7	●	◐	◐	◐	includes resistant, broken, progressive collapse, trend towards less planar/more resistant does not include sudden or planar	moderate

Snowpack observations

Weak layer properties were the most frequently described snowpack properties (Table 3.27) during conversations about the removal of PS avalanche problems. Typical

weak layer depth (5 interviews; AvCan, Glacier, Banff) values had a wide range including greater than 80 to 100 cm (G1), greater than 100 cm (G3), at least 130 cm (B1), at least 150 cm (A2), and at least 200 cm (G2). ***Detectability of the weak layer*** was also relevant (5 interviews; all agencies) where forecasters generally agreed that the layer is typically hard to find or no longer visible or identifiable in snow profiles, although one forecaster (G2) indicated that it can sometimes remain visible when the problem is removed. Related to weak layer detectability, a Kananaskis forecaster (K2) mentioned that they look for a change in ***weak layer grain type***. A Glacier forecaster (G1) also referred to grain type of the weak layer, but regarding the fact that they treat crusts and surface hoar layers differently.

Bridging leading to a lack of sensitivity to skier triggering was mentioned as a consideration by four forecasters (AvCan, Glacier, Banff), some of whom directly related this to their weak layer depth observation values. However, the overall snowpack and midpack structure and possibility of step downs were also highlighted as important factors when contemplating bridging by some (A2, G1). ***Slab properties*** were also brought up by two forecasters, but only one elaborated that they were interested in settlement and strengthening of the slab before removing the PS avalanche problem.

Table 3.27 Summary of snowpack observations, frequencies, and values for removing PS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
weak layer properties	8	◕	●	◔	●	considers *depth, detectability, and grain type of the weak layer*	*n/a*
weak layer depth	5	◔	●	◔	○	range from greater than 80 cm to greater than 200 cm	weak
layer detectability	5	◔	◔	◔	●	typically hard to find, no longer (visually) identifiable in snow profiles; sometimes still visible	moderate
weak layer grain type	2	○	◔	○	◐	typically has changed; crusts treated differently than surface hoar when considering removal	moderate
bridging	4	◔	◕	◔	○	no longer sensitive to skier triggering, can be trumped by step downs and overall snowpack and midpack structure	strong
slab properties	2	○	◔	○	◐	considers *settlement* and slab strengthening indicated by *slab density*	*indirect single value*

Weather observations

Only a few weather conditions (Table 3.28) were mentioned as important considerations for removing PS problems: air temperature (4 interviews; AvCan, Glacier, Kananaskis) and weather systems (2 interviews; Glacier, Banff). Relevant ***air temperature*** observations include when significant warming to greater than 0ºC tests the relevant weak layer and results in no avalanche activity (A2), and that removal happens faster when warmer temperatures exist (G3, K1). However, another forecaster (A1) stated that a cooling trend can be favorable for removal. Stable ***weather systems*** that promote healing of the problem were favorable conditions for removal, as opposed increased uncertainty leading to avoiding or debating removal when the forecast includes significant inputs that might test the layer (2 interviews; Glacier, Banff).

Table 3.28 Summary of weather observations, frequencies, and values for removing PS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
air temperature	4	◐	◐	○	◐	*favorable:* warm, cooling pattern *testing:* large warm up	weak
weather system	2	○	◐	◐	○	*favorable:* stable, typical weather that promotes healing *testing:* significant inputs forecast (wind, storm, warming events)	strong

Spatial and temporal observations

Our interviews revealed that some forecasters consider spatial and temporal conditions when thinking about removing PS problems (Table 3.29). Forecasters based in the Columbia Mountains (AvCan, Glacier) mentioned paying attention to the ***distribution*** of avalanche observations and not removing a PS problem when it is widespread, a source of overhead hazard in popular areas, or has the potential to surprise people. On the other hand, they are more likely to remove the problem when it is isolated, only present in extreme or non-traditional skiing terrain, and predictable. Typical ***PS problem persistence time*** (4 interviews; Glacier, Banff, Kananaskis) had a range of weeks to months with most values falling between 4 and 6 weeks.

Table 3.29 Summary of spatial and temporal observations, frequencies, and values for removing PS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
persistent slab problem persistence time	4	○	◐	◐	◐	typical range of weeks to months, most values between 4-6 weeks	moderate
distribution of avalanche problem	3	◐	◐	○	○	irrelevant non-traditional ski areas	strong
distribution of avalanche activity	2	◐	◐	○	○	not when widespread, activity that could hit people from above in valleys and drainages that are widely used, or when surprizing people; more likely when isolated, extreme terrain, and predictable	moderate

Additional considerations and practices

Beyond the physical conditions specified as important to the decision to remove PS problems described above, forecasters also indicated additional factors that contribute to the decision. Some of the interviewed forecasters included assessed components of the CMAH as part of their description for deciding whether to remove a PS problem. The avalanche hazard chart was noted to be relevant by two forecasters from Banff who described a process of watching the problem assessment gradually decrease toward the bottom of the likelihood on the avalanche hazard chart and remain there for a few days or a week (B3, B2) before they consider removing the problem. An AvCan forecaster (A1), who is also looking for a diminishing likelihood of avalanches, described monitoring the internal avalanche hazard charts and those of other operations within the region. However, this forecaster also highlighted that the charts typically include more uncertainty and are therefore less reliable during the problem removal phase compared to problem initiation. As a consequence, this forecaster put more weight on the language used in other operations' snowpack summaries and avalanche activity descriptions.

> We'll often see a little bit more uncertainty in the problem descriptions and bubbles and things like that and people having a hard time capturing their full ideas about a problem in the bubble … you kind of need to get into the words they use when they speak about it rather than the points on the chart that they use. So, I am looking for some of the intangibles about the language they are using. (A1)

The danger rating was mentioned as a relevant consideration by two forecasters but with differing values. One indicated that they require a low danger rating before removing a PS avalanche problem (B2), and the other indicating that the problem can be removed (with differing considerations) when the assessed danger rating is moderate, or in the considerable to high range (K2). Consequence was also noted by two forecasters (A3, K1) who indicated that higher consequences lead to problems being listed longer.

Other avalanche problems came up as a relevant consideration for removing PS problems in the context of balancing priorities of other avalanche problems. For example, in situations when there are more than three problems, a shallower avalanche problem that might be more reactive can be a higher priority for the forecaster when it is more likely to be encountered by the public and cause harm. Removing the PS problem but describing its potential in the discussion of a shallower problem is one approach to balancing problem types in these circumstances.

Forecasters generally highlighted that higher levels of uncertainty are associated with removing PS problems compared to adding them to the bulletin. The quality and availability of information was mentioned as a relevant factor for the removal decision by several forecasters. This included conversations about data sparse regions or data sparse times (stormy periods with limited observations or when people are not out skiing) requiring a more conservative approach to PS problem removal. Conversely, forecasters based in Glacier National Park indicated that the large amount of data available in that region can increase confidence. Group discussions and input from other forecasters were described as valuable approaches for increasing confidence in the decision to remove a PS avalanche problem.

3.2.1.3 Reactivating PS problems

The scenario for reactivating PS problems explicitly emerged in three forecaster interviews (A2, G2, B1). Two of these scenarios indicate that reactivating a DPS problem is more common or more likely than reactivating a PS problem, and one concept map indicates the reverse (that it is less likely that a DPS problem will be reactivated than a PS problem). On average this scenario was made up of 32 concepts.

> I think that is more of a definite decision with a deep persistent slab avalanche problem. I can see brining a persistent slab avalanche problem in back in again. (G2)

Observations that at least two of three forecasters agreed on as relevant for reactivating PS problem included major weather inputs and avalanche observations. All three forecasters agreed that ***loading*** is a factor. Loading values that could reactivate a PS problem included rapid loading (for example 60 mm of precipitation in 48 to 72 hours; G2), ***new snow*** accumulation of greater than 20 to 25 cm at treeline (B1) or 30 cm of storm snow (A2). Loading from shallower avalanche activity and wind were also noted. Forecasters (2 interviews; AvCan, Banff) also agreed that warming ***air temperatures*** are a factor including above 0ºC (A2) and especially the first warm up (A2). ***Avalanche activity*** (2 interviews; AvCan, Banff) included activity resulting from a big weather input (A2) or sometimes a single avalanche and almost always with several avalanches (B2).

3.2.2. Deep persistent slab avalanche problems

Interviews focused on decisions around DPS problems included discussions around considerations for adding, removing, and reactivating DPS problems in the bulletin. These discussions generated a total of 1222 concepts, 839 linking phrases, and 2168 connections.

3.2.2.1 Adding DPS problems

The considerations related to adding new DPS problems were discussed in all eleven interviews that focused on PS and DPS avalanche problems. The average size of this scenario was 56 concepts. The interviews revealed that DPS problems are typically added to the public bulletin by transitioning an existing PS problem into a DPS problem. However, some AvCan and Banff forecasters (A2, B2, B3) also described conditions or sub-scenarios that lead them to make the decision to directly forecast DPS problems, including one forecaster (B3) who indicated that DPS problems are more often directly forecasted.

Some of the rationales for directly forecasting a DPS problem included high confidence in the anticipated persistence of the problem, the desire to have the public be aware and think about the DPS problem sooner, and wanting to avoid user confusion between PS and DPS problem types because “a DPS problem is a different beast that is not just based on where it is in the snowpack.” Arguments for not directly adding a DPS to the bulletin and transitioning it through a PS problem first included avoiding confusion about calling it a DPS problem when the snowpack is shallow (less than one meter) or when the consequences of associated avalanches are not expected to be huge. One forecaster also mentioned that if the consequences and sensitivities are already described well in the bulletin as a PS problem, the transition to a DPS problem can be less urgent.

Observations

Frequently cited observation types for adding DPS problems included instability conditions, snowpack properties, and weather conditions (Figure 3.20). Our analysis of the concept maps revealed that the most considered observations for adding a DPS problem were the properties of the weak layer, snowpack tests and avalanche observations.

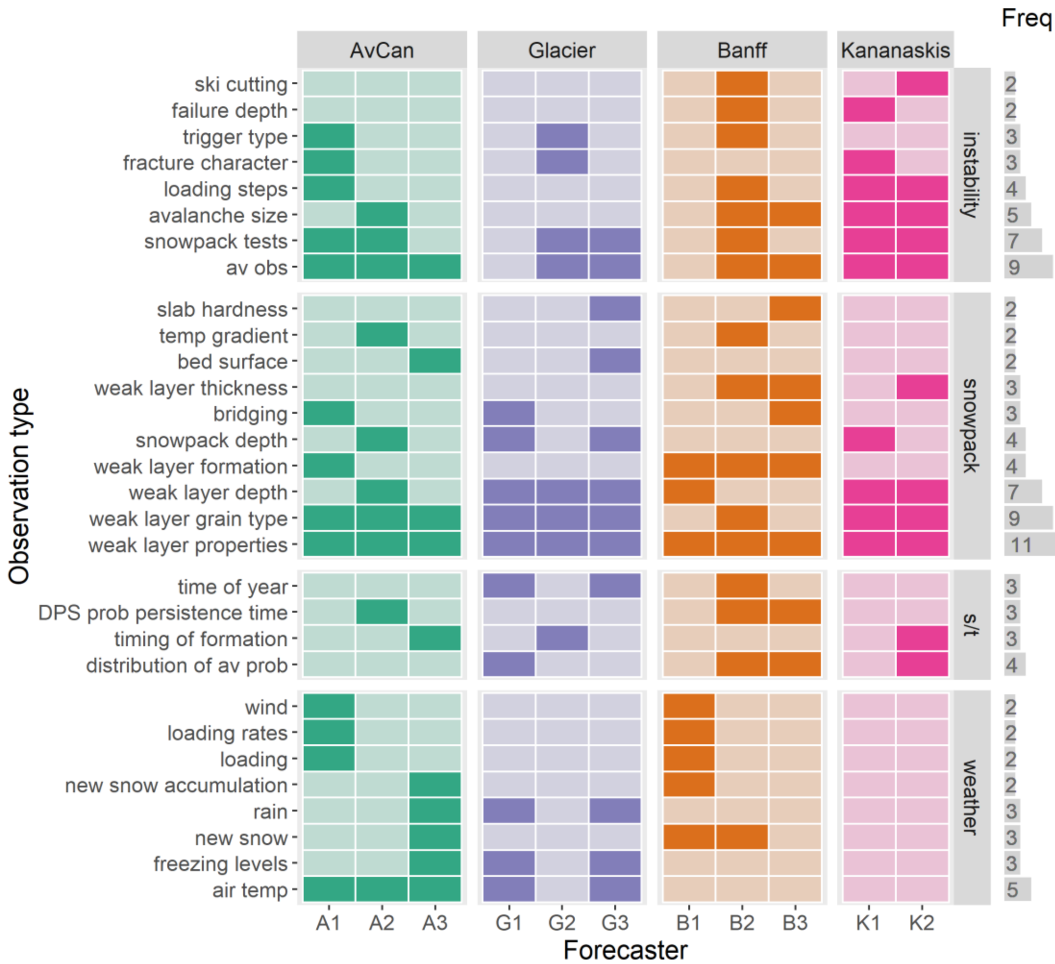

Figure 3.20 Observation types included by at least two forecasters as a consideration for adding DPS avalanche problems. See caption of Figure 3.5 for detailed explaination of figure presentation.

Snowpack observations

Among the snowpack properties considered (Table 3.30), ***weak layer characteristics*** were the primary consideration. Grain type was the most mentioned weak layer observation (9 interviews; all agencies) followed by weak layer depth (7 interviews; all agencies). While forecasters were very consistent in the ***grain types*** they associate with DPS (depth hoar, facets, crusts, facet-crust combinations, facets on glacial ice), there was more variability in the in the ***weak layer depth*** observations. Most of the forecasters who mentioned weak layer depth in their interview indicated that they associate DPS problems with a weak layer at or near the bottom of the snowpack. However, others mention that the weak layer should be in the bottom half or third of the snowpack;

quantified the depths as typically deeper than 40 to 100 cm (G3), 50 cm (A2), 100 cm (G2); or that it should be deeper than what is typically reached by human triggers. All forecasters in Banff and one AvCan forecaster highlighted ***weak layer formation*** as a relevant factor. All stated that weak layers associated with DPS form below the surface through metamorphism within the snowpack and are not deposited directly on the snow surface. Three forecasters from continental Banff and Kananaskis forecast regions also mentioned ***weak layer thickness*** as a relevant observation, but the provided observation values were less consistent. ***Bed surface characteristics*** including crusts and glacial ice were brought up as relevant observations by two forecasters (A3, G3).

Snowpack depth was a consideration for four forecasters (AvCan, Glacier, Kananaskis), but its application varied. One forecaster noted that DPS problems are more common in shallower snowpacks (A2), while another stated that they are less likely to add a DPS problem when the snowpack is less than a meter deep (K1). ***Bridging*** (3 interviews; AvCan, Glacier, Banff) was linked to snowpack depth by one forecasters (G1), while two others describe an absence of a bridging layer or slab as a consideration. ***Slab hardness***, and strong ***temperature gradients*** in the snowpack were also mentioned as important indicators by two forecasters each.

Table 3.30 Summary of snowpack observations, frequencies, and values for adding DPS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
weak layer properties	11	●	●	●	●	considers *grain type, depth, formation, thickness, anticipated persistence time, and hardness of the weak layer*	*n/a*
weak layer grain type	9	●	●	◔	●	depth hoar, facets, crusts, facet-crust combinations, and facets over glacial ice	strong
weak layer formation	4	◔	○	●	○	below surface formation	strong
weak layer depth	7	◔	●	◔	●	most indicate basal or near basal; other values include the bottom half or third of snowpack; numeric thresholds ranging from ≥ 40 cm to > 1 m; and a functional descriptor of > human triggering	moderate
weak layer thickness	3	○	○	◕	◐	often growing or decomposing, beginning at ≤ 1cm decomposing to 3-5 cm, ≥ 40 cm for depth hoar	moderate
bed surface	2	◔	◔	○	○	crusts, glacial ice	strong
snowpack depth	4	◔	◕	○	◐	more common in shallower snowpacks; less likely when < 1 m	weak
bridging	3	◔	◔	◔	○	absence of a bridging layer or slab	strong
slab hardness	2	○	◔	◔	○	typically hard, thick to thin slabs that are influenced by the wind (Banff)	*single value*
temperature gradient	2	◔	○	◔	○	strong temperature gradient	strong

Instability observations

Pertinent instability conditions for adding a DPS avalanche problem (Table 3.31) include both avalanche observations (9 interviews; all agencies) and snowpack tests. Among the relevant ***avalanche observations***, five forecasters (AvCan, Banff, Kananaskis) mentioned destructive ***avalanche size***, but there was some variation in the provided observation values. Typical size values included larger or equal to size 2, larger than size 3, but also sometimes smaller if it is earlier in the season or failing deep in isolated terrain features. A variety of different ***triggers*** were mentioned as relevant by three forecasters (A1, G2, B2) including skier, natural, explosive, cornices, large triggers, and remote triggers. Seven of the eleven interviewed forecasters mentioned ***snowpack***

tests as a relevant indicator for deciding whether to add a DPS problem to the avalanche bulletin. While the expected ***loading steps*** ranged from easy to hard results, the three forecasters who mentioned ***fracture character*** as an important observation all agreed that they look for sudden fractures.

Table 3.31 Summary of instability observations, frequencies, and values for adding DPS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
avalanche observations	9	●	◕	◕	●	considers *size, failure depth and characteristics, triggers of avalanche observations*	*n/a*
avalanche size	5	◔	○	◕	●	typical size values range from ≥ size 2 to > size 3; sometimes smaller early season or in isolated features failing deep	moderate
trigger type	3	◔	◔	◔	○	skier, naturals, explosives, cornices, remote triggers, and large triggers	weak
snowpack tests	7	◕	◕	◔	●	include *compression tests, extended column tests, and ski cutting*	*n/a*
loading steps	4	◔	○	◔	●	range from easy to hard results	weak
fracture character	3	◔	◔	○	◑	sudden	strong
ski cutting	2	○	○	◔	◑	considered for directly adding (Banff); not intentionally seeking but anticipating no results (Kananaskis)	weak
failure depth	2	○	○	◔	◑	low in the snowpack or at ground including rocks poking out (includes snowpack tests and avalanche observations)	moderate

Weather observations

While our interviews showed that weather observations (Table 3.32) are considered to a lesser extent for deciding whether to add a DPS problem to the bulletin, some avalanche forecasters consider big weather events that stress the snowpack and have the potential to activate a DPS problem. All AvCan and two of the three Glacier forecasters mentioned ***air temperature*** including big warming events, high ***freezing levels,*** or rapid cooling as relevant observations. In addition, some of the forecasters from these agencies also mentioned massive or weak layer penetrating ***rain*** events as critical observations. Some forecasters from AvCan and Banff highlighted ***new snow*** accumulation as an additional relevant observation, but the provided threshold values were much higher for AvCan (50 to 100 cm of HST) than Banff (at least 20 to 25 cm HST). Two forecasters (A1, B1) also described ***wind*** loading and ***loading*** generally, including rapid or sudden loading rates. Kananaskis was the only agency where weather observations were not mentioned during our conversations on adding a DPS problem to the bulletin.

Table 3.32 Summary of weather observations, frequencies, and values for adding DPS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
air temperature	5	●	◐	○	○	*initiating problem:* big warming events and high freezing levels or rapid cooling *during problem development:* cold air temperatures	moderate
freezing levels	3	◐	◐	○	○	high and sustained, above mountain top	strong
new snow	3	◐	○	◐	○	considers new snow accumulation, new snow density, snow water equivalent	weak
new snow accumulation	2	◐	○	◐	○	50-100 cm HST (AvCan); typically ≥ 20-25 cm HST at treeline (Banff)	weak
rain	3	◐	◐	○	○	massive or weak layer penetrating rain events; amount and rate values range with snowpack properties and time of year.	moderate
wind	2	◐	○	◐	○	rapid relative changes	*single value*
loading (general)	2	◐	○	◐	○	considers *new snow, wind*, *loading rates* significant loading and step downs from other avalanche problems	moderate
loading rates	2	◐	○	◐	○	sudden, rapid relative changes	strong

Spatial and temporal observations

Spatial and temporal factors were only rarely mentioned as relevant considerations by the interviewed forecasts (Table 3.33). Four forecasters (Glacier, Banff, Kananaskis) indicated the ***distribution of the problem*** was relevant. While the three forecasters working in a continental snowpack indicated that the problem is typically widespread across aspects, elevation bands, or regionally, a Glacier forecaster indicated that the problem is typically confined to a handful of paths. Forecasters who consider the anticipated ***persistence time*** of the DPS problem agreed that it is typically a consideration for longer than PS problems or for months to most or the remainder of the season. While forecasters also agreed that the ***timing of weak layer formation*** typically occurs early in the season, the typical ***time of year*** which the problem is added ranged from early in the season to in the spring.

Table 3.33 Summary of spatial and temporal observations, frequencies, and values for adding DPS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
distribution of avalanche problem	4	○	◔	◕	◑	most indicate widespread distribution related to aspects, elevations, and region. one value of indicates typically limited to a handful of paths	moderate
deep persistent slab problem persistence time	3	◔	○	◕	○	anticipated to be months to most of or remainder of season, longer than PS problems	strong
timing of weak layer formation	3	◔	◔	○	◑	early season	strong
time of year	3	○	◕	◔	○	values range from early in the season to spring	weak

Additional considerations and practices

In addition to observations about the physical conditions, forecasters also described additional factors that are taken into consideration when making the decision to add a DPS problem to the public avalanche bulletin.

Other elements that forecasters assess which were included as relevant considerations by more than one forecaster included the consequence and likelihood of the problem. Five forecasters (all agencies) consistently described high or huge consequences as being a crucial factor. Two forecasters indicated likelihood values typically being in the possible to unlikely range (AvCan) or very unlikely (Glacier). Sensitivity was also more specifically mentioned by four forecasters although values showed some variability with one forecaster indicating the problem is typically reactive (B2), another specifically mentioned both skier and machine triggering (A1), while the remaining two agreed the problem is typically harder for a skier to trigger but reactive to larger loads (K1, K2).

Other avalanche problems are noted to play a role in making the decision to add a DPS problem to the public bulletin. Before a DPS problem is initiated as its own problem some forecasters will typically mention the problem within the discussion of a different problem. A transition to a DPS problem may also occur to differentiate it from newer emerging PS problem. PS problems that become deep in the snowpack may be grouped or combined with existing DPS problems. One forecaster described the potential benefit of grouping PS and DPS problems to simplify public communication given concerns about users' ability to grasp differences in terrain selection between these problem types. When there are no problems a more isolated DPS problem that would otherwise be excluded from the problem list in the bulletin might be included.

3.2.2.2 Removing DPS problems

Considerations for the removing DPS problem scenario discussed by all eleven forecasters revealed a variety of perspectives on relevant observations, values, and additional considerations. The average size of this scenario was 39 concepts. Forecasters expressed a range of opinions on whether DPS problems should be maintained or removed from the public bulletin through periods dormancy. At one side of this range is the perspective that once a DPS problem is in the bulletin it is in for the season and should only be removed once per year when a collective decision that the avalanche season is over has been made. At the other end of the spectrum is the perspective of only including the problem during the relatively short periods of acute instability. The majority of forecasters fall somewhere in between indicating a wide range of timeframes of how long a problem should be dormant before it should be removed.

Some of the rationales for DPS problems being removed and reactivated included considerations of message fatigue when the DPS problem is listed all season and getting more emphasis when the problem is removed and reinitiated.

Having a problem disappear and then come back I think is more impactful for people sometimes, than if it just sits there in the forecast for the entire season and then maybe you have a big event like a big warm up and try to bring people's attention back to that problem, but it never disappeared. If you take it out and bring it back for a big weather event, I think it lands in people's minds a bit better. But that being said I wouldn't be comfortable taking it out to just make a point later. (A2)

Alternatively, considerations supporting maintaining the problem in the bulletin longer included that if there is the potential for DPS avalanches that should affect decision making, the default is to maintain the problem unless there is a compelling reason to remove it.

Observations

The observation types that were most frequently considered for removing DPS problems were related to instability conditions (Table 3.34). Weather conditions (Table 3.36) and spatial or temporal conditions (Table 3.37) were also considered but to a much lesser degree. There were no observation types related to snowpack conditions mentioned by two or more forecasters as a consideration for removing DPS problems from the bulletin (Figure 3.21).

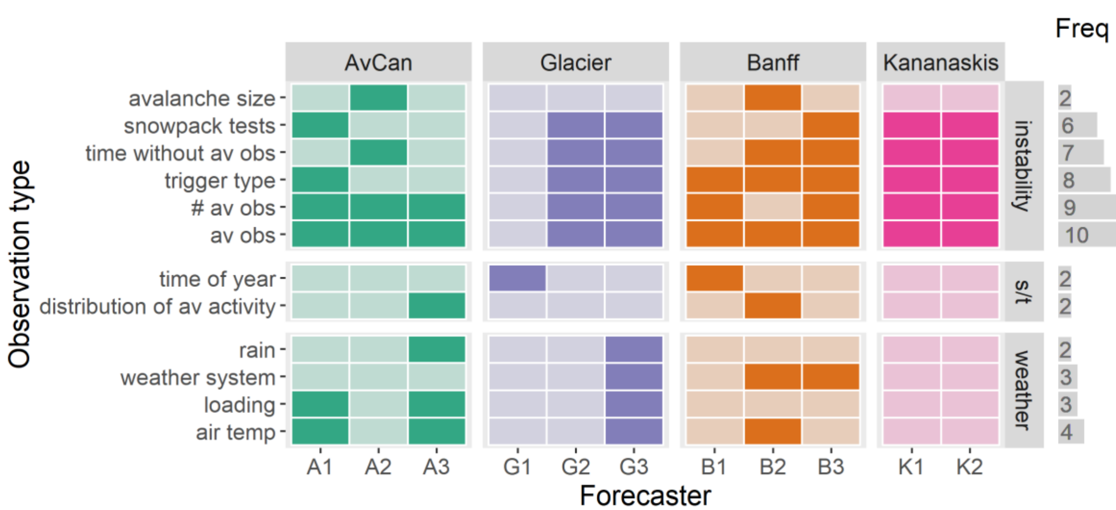

Figure 3.21 **Observation types included by at least two forecasters as a consideration for removing DPS avalanche problems. See caption of Figure 3.5 for detailed explaination of figure presentation.**

Instability observations

Our analysis of the concept maps revealed that the most commonly considered observation types for removing DPS avalanche problems were related to ***avalanche observations*** (10 interviews; all agencies). These observations included the ***number of avalanche observations*** (9 interviews; all agencies), ***trigger type*** (8 interviews; all agencies), and amount of ***time without observed activity*** (7 interviews; all agencies). The majority of forecasters (all agencies) agreed that they typically require associated avalanche activity to completely cease before considering removing a DPS problem. This included one forecaster (B2) who also indicated that a single avalanche on the layer in a neighboring region can be enough to keep the problem listed. Three forecasters (A1, A2, K1) stated that sparse or anomalous activity can sometimes be acceptable. ***Trigger types*** of interest consistently included explosive, natural, and skier triggered avalanches. Some forecasters specifically noted looking for the problem to be tested by large loads such as explosives, large cornices, and shallower avalanche cycles without results.

Table 3.34 Summary of instability observations, frequencies, and values for removing DPS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
avalanche observations	10	●	◐	●	●	considers *number, trigger, time without, distribution, and size of avalanche observations*	*n/a*
number of avalanche observations	9	●	◐	◐	●	most forecasters indicate no avalanche activity, three indicate that there can be sparse activity or an anomalous result	moderate
trigger type	8	◐	◐	●	●	explosive, natural, skier, cornice; tests by large loads (explosives, large cornices, shallower avalanche cycles without step downs)	strong
time without observed activity	7	◐	◐	◐	●	where directly quantified ranges from > 7 to > 21 days. More specific examples include a wider range (refer to Table 3.35).	weak
avalanche size	2	◐	○	◐	○	typically very large destructive size that stays constant	moderate
snowpack tests	6	◐	◐	◐	●	trend of increasing hardness to consistent no results	strong

Values provided for the required length of ***time without observed activity*** before a DPS problem is removed from the bulletin (Table 3.35) were less consistent. Forecasters often simply indicated that the required time was longer than for PS problems. Where explicitly provided, typical values ranged from greater than seven days to greater than 21 days. However, some more specific examples values for the removal of DPS avalanche problems ranged from as little as one day to up to the end of the season. ***Snowpack tests*** (6 interviews; all agencies) included no results. A trend for the snowpack tests was also noted in some cases including consistently no results, a steady increase in hardness of results, and typically two to four weeks with no results. Destructive ***avalanche size*** was also noted by two forecasters (A2, B2), but was not a valuable observation for the removal of a DPS avalanche problem since the size is maintained and typically very large.

Table 3.35 Amount of time without activity values (grey italics indicates values have been implied from other observation types).

Agency		Amount of time without activity values
AvCan	*A1*	*- requires longer period of more confidence inspiring results than with other problems*
	A2	- longer than for PS - typically > 3 weeks (21 days)
	A3	*- 24-48 hrs (1-2 days) following period of instability due to rapid change in temperature* *- > 2 days following period of instability due to sudden increase in load (snow)*
Glacier	*G1*	*- entire season*
	G2	(included as observation type, but with no values provided)

	G3	- significant amount of time, for example:
		    - approximately 1 week (7 days) with stable weather
		    - less than 1 week (7 days) with a shift to cold weather
		- typically longer than PS problems because they are more unpredictable

Banff	B2	- at least 7 days - typically ≥ 10 days
	B3	- long dormant periods where there is nothing going on to begin considering removing and then the process for considering removing the problem takes additional time - longer time frame compared to PS *- timeframe given for PS was ≥ 5-7 days to reach bottom of likelihood plus a few additional days to consider removing*
Kananaskis	K1	- start considering at 2 weeks (14 days) - typically removed ≥ 2 weeks (14 days)
	K2	- typically maintained in the forecast while dormant for a longer period prior to removal relative to PS problems *- PS timeframe of "a while" for example a couple of weeks with a steady snowpack and longer with dynamic snowpack*

Weather observations

When considering weather conditions (Table 3.36) forecasters discussed looking for favorable weather conditions for removing the problem, and/or weather conditions that are likely to initiate or test the problem. ***Air temperature*** (4 interviews; AvCan, Glacier, Banff) was the most frequently indicated weather observation for removing DPS problems. Three forecasters (AvCan, Banff, Glacier) indicated cool, cold (-25ºC) or cold snaps (change form above freezing to less than -10ºC) as favorable for removal. Alternatively, one forecaster (A3) indicated that prolonged warming or a rapid change in temperature can be informative for the decision to remove a DPS problem since it provides a stress test of the layer. More broadly considering the general ***weather system***, two forecasters (Banff) indicated that they are more likely to remove the problem during a long clear spell and not when a storm or significant wind events are in the weather forecast. One forecaster (G3) indicated that high-pressure systems that lead to diurnal freeze thaw cycles are favorable for removal. ***Loading*** generally (3 interviews) including loading from ***rain*** (2 interviews) and new snow (1 interview) were considered relevant observations by forecasters based in the Columbia mountain range (AvCan, Glacier). While a lack of loading or lack of rain was consistently indicated as favorable conditions for removal, a test with a significant amount of rain in 24 hours with no avalanche observations can confirm that a problem is dormant and increase confidence for removal (A3). Similarly to the adding DPS problem scenario, Kananaskis was the only agency where weather observations were not mentioned during conversations about removing a DPS problem from the bulletin.

Table 3.36 Summary of weather observations, frequencies, and values for removing DPS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
air temperature	4	◕	◔	◔	○	*favorable*: range from cold to moderate *testing:* prolonged warming and rapid changes	moderate
weather system	3	○	◔	◕	○	*favorable:* long clear spells, no storm coming, diurnal high-pressure systems that lead to freeze thaw cycles, and long stagnant periods *testing:* significant inputs (wind events and storms)	moderate
loading (general)	3	◕	◔	○	○	includes both *rain and new snow* *favorable:* lack of loading *testing*: sudden increases in load	moderate
rain	2	◔	◔	○	○	*favorable*: lack of rain *testing:* rain in combination with a lack of avalanche activity to either increase confidence (5-20 mm in 24hrs) or consider the problem dormant (>30-50 mm in 24 hours)	moderate

Spatial and temporal observations

Spatial and temporal factors were not frequently mentioned as relevant observation for removing DPS avalanche problems (Table 3.37). ***Time of year*** was noted in two interviews (B1, G1) with the problem typically remaining a concern until the end of March or into May. The ***distribution of avalanche activity*** was also stated by two forecasters (A3, B2) one of whom indicated the distribution should not be widespread or "sporadic".

Table 3.37 Summary of spatial and temporal observations, frequencies, and values for removing DPS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (11)	A (3)	G (3)	B (3)	K (2)	Values	Value Consistency
distribution of avalanche activity	2	◔	○	◔	○	not when widespread or sporadic	*single value*
time of year	2	○	◔	◔	○	typically remains a concern until the end of march or into may	strong

Additional considerations and practices

Besides the physical conditions indicated by the observation types and values discussed above, forecasters also mentioned several additional factors that are taken into account when making the decision to remove a DPS problem from the public avalanche bulletin. Two forecasters from Banff indicated that they look for the likelihood assessment in the hazard chart to gradually decrease toward the bottom and remain there for a period of time before considering removing the problem. Forecasters indicated that the high consequence associated with DPS problems make them particularly challenging to remove especially for newer forecasters. In addition to the residual uncertainty and "shockingness" of avalanche observations and snowpack tests, forecasters cite a feeling of personal responsibility making DPS avalanche problems a big deal or more significant to remove than other problems. Some relate this to personal comfort levels and risk tolerance that can be influenced by feeling responsible for other people's decisions following previous incidents or not wanting to be the forecaster to remove the problem and then have a large event on it. One forecaster described not feeling the same pressure when adding and removing problems from InfoEx.

> The first 48 hours after I remove that problem it haunts me. Like I just think to myself, I just basically cross my fingers and oh god I hope nobody triggers a large deep avalanche in the next 48 hours, and then I feel better after that. (B2)

> I would say a newer forecaster … is much more hesitant to pull it out because they see the potential consequence in owning that. And that could be, you know you write a bulletin, and somebody dies on it. Like I can tell you every single bulletin I have ever written that somebody has died on. It can be harder for that I think because there is a mental piece to this adding and removing a problem specific to a public avalanche bulletin, within the InfoEx it can be different, you know. (K1)

> We’ve had incidents in the past where people have felt quite responsible when they went back and looked at their bulletin. And they go ‘I wish we would have kept it in’, right. So, it does weigh on a person, there is like, there is a bit of pressure there. There is more skin in the game when you pull it. It’s actually, there is a little more risk for you right. Or you can feel that way, and so it is easier to leave it in. And that is a factor, I think some people may deny that, but I think, I have felt that. (B3)

> Sometimes they stay in for almost a whole season; honestly, they are really hard to take out. I think part of that is a human factor because they are so destructive that you don’t want to be the forecaster that was working and decide to take that problem out and then there is a big avalanche. So I think that sometimes with that stuff it is probably less scientific than we would like to think and a little bit more fear based that you yeah don’t want to be the one to remove that and then have a big event happen on it. (A2)

Other avalanche problems were also noted to play a role in making the decision to remove a DPS problem. Since other problems can act as a potential trigger type for the deeper the DPS problem, some forecasters indicated that the coexistence of shallower avalanche problems can be a factor for maintaining a DPS problem in the bulletin for longer. For example, one forecaster (K2) indicated that they require a strong midpack with no PS problem and typically no other weak layers of concern to remove a DPS. On the other side, other forecasters mentioned that the coexistence of shallower avalanche problems can be a contributing factor for removing the DPS problem if forecasters conclude that the shallower problems are more relevant for bulletin users.

3.2.2.3 Reactivating DPS problems

Perspectives on reactivating DPS problems varied considerably between forecasters. Explicit concept maps for the reactivating DPS problem scenario were developed with eight of the eleven forecasters discussing PS and DPS problems, on average this scenario includes 23 concepts. Of the remaining three forecasters one forecaster (A3) stated that there is a fifty-fifty chance that the problem may be reactivated depending on the particular weather factors. Another forecaster (A1) indicated that they are less likely to remove a DPS problem if they are expecting it to come back, and the final forecaster without a reactivating DPS scenario (G1) indicated DPS problems are not removed until the season is over. Of the forecasters who included a separate scenario for reactivation, two (AvCan, Banff) indicated that that reactivating a DPS problem is more common or more likely than reactivating PS problem and one (Glacier) indicated the reverse.

Forecasters who discussed the reactivation of DPS problems as a distinct scenario consistently highlighted the importance of weather observations (Figure 3.22). Avalanche observations and time of year were the only other observation types that were considered by more than one forecaster.

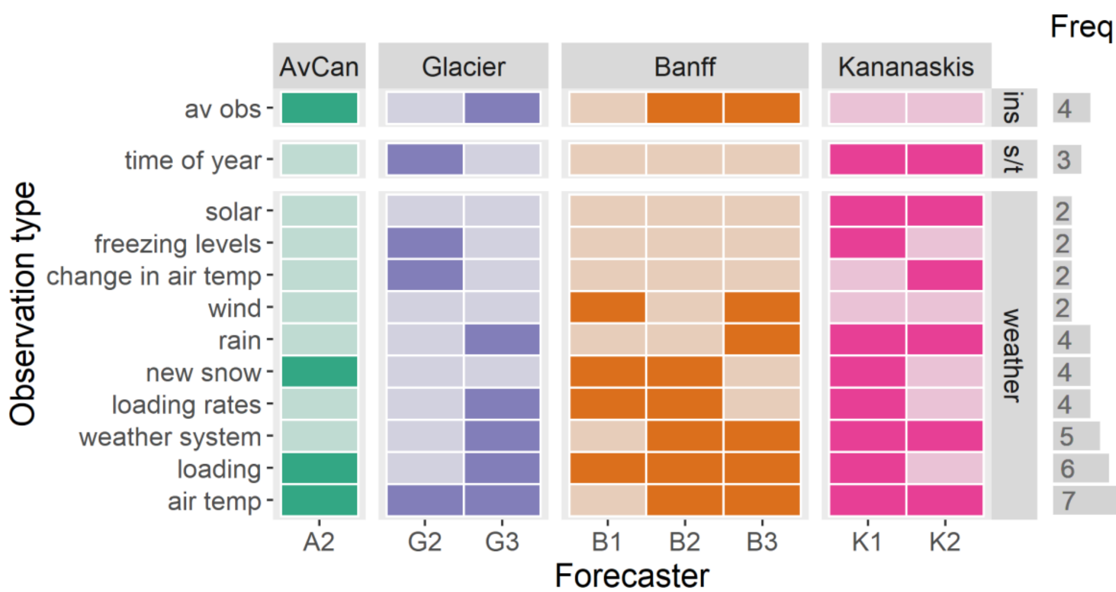

Figure 3.22 Observation types included by at least two forecasters as a consideration for reactivating DPS avalanche problems. See caption of Figure 3.5 for detailed explaination of figure presentation.

Most commonly forecasters described DPS avalanche problems to be reactivated by major weather events involving warming or loading (Table 3.38). When observation values were provided, they generally agreed or were non-conflicting. Warming events included rapid or prolonged warming, ***air temperatures*** above 0ºC (AvCan, Glacier, Banff), without overnight refreezes and high elevation ***freezing levels***, and special attention is given to the first big warm up of the season (A2). One forecaster from Glacier (G3) quantified a big warm up as 10ºC valley temperatures for at least three days or multiple days of 5 to 10ºC in start zones and tracks without overnight refreeze. Forecasters from Kananaskis indicated rapid ***solar*** events as a factor. Three forecasters agreed that the ***time of year*** is typically in the spring (G2, K1, K2) and occasionally midseason (K2).

Six of eight forecasters (all agencies) mentioned ***loading*** from new snow, wind, rain, and/or shallower avalanche problems as a significant consideration for reactivating DPS avalanche problems. ***Loading rates*** were indicated by most to include sudden or rapid loading, only one forecaster (Banff) indicated incremental loading as sometimes a consideration. ***Rain*** events were included by four forecasters (Banff, Glacier, Kananaskis) but the amount was only quantified by one forecaster (G3) who indicated at least 40 to 60 mm of rain. ***New snow*** was quantified by four forecasters as at least 20 to 25 cm at treeline (B1), 30 to 50 cm (B2), at least 30 cm (A2), and greater than 50 cm (K1). ***Wind*** loading was also noted as a consideration by forecasters from Banff, but no specific values were provided.

Table 3.38 Summary of weather observations, frequencies, and values for reactivating DPS avalanche problems. See caption of Table 3.1 for detailed explaination of table presentation.

Observation Type	Frequencies All (8)	A (1)	G (2)	B (3)	K (2)	Values	Value Consistency
air temperature	7	●	●	◕	●	> 0ºC, no overnight refreeze, big warm ups and especially the first warm up	strong
change in air temperature	2	○	◐	○	◐	Rapid warming, prolonged warming	strong
freezing levels	2	○	◐	○	◐	high elevation freezing levels for example maintained at > 2000 m overnight	strong
solar	2	○	○	○	●	rapid warming, rapid influx of solar radiation	strong
loading	6	●	◐	●	◐	includes values for *new snow, wind, rain, and other avalanche problems*	*n/a*
loading rates	4	○	◐	◕	◐	rapid or sudden loading; 3 mm/hr for extended periods or 1 mm/hr for 40 hours; sometimes incremental	moderate
rain	4	○	◐	◔	●	≥ 40-60 mm	*single value*
new snow	4	●	○	◕	◐	ranges from ≥ 20 to > 50 cm	moderate
wind	2	○	○	◕	○		*no values*
weather system	5	○	◐	◕	●	major weather events including huge/very large/high QPF storms, pineapples, really strong exceptionally warm prolonged chinooks	strong

While observations for reactivating DPS problems were primarily related to weather, three forecasters (Glacier, Banff) also mentioned that ***avalanche observations*** can play a role in their decision to reactivate the problem in the bulletin. Generally, these forecasters indicated that an increase in deep releases would be a factor. The forecaster from Glacier indicated that typically more than one avalanche observation would be required (e.g., a couple of avalanches in combination with significant weather inputs) whereas one of the forecasters from Banff indicated that a single big surprising avalanche (e.g., an anomalous size 3.5) could be enough to reactivate the problem. Forecasters from both Banff and Glacier indicated that cornice failures are also consideration.

3.2.3. General additional considerations and practices for persistent slab and deep persistent slab problems

The presence of high levels of uncertainty and the resulting approaches for dealing with this uncertainty was a recurring theme on the conversations about PS and DPS problem decisions. Forecasters indicated a relatively higher degree of uncertainty when making decisions about changing the status of DPS slab problems compared to PS problems or other problems in the public bulletin. More uncertainty was also associated with removing problems than with adding them. The following strategies for dealing with uncertainty have primarily been discussed in the context of DPS avalanche problems, but some are also more generally applicable to PS and potentially other problem types when evidence is limited.

One factor that was frequently mentioned to contribute to the increased uncertainty for DPS problems was the relatively lower availability of information about the problem. Forecasters mentioned that it is harder to accumulate good quality information due to the high consequences associated with the problem type, and observations were noted to be scarcer due to large-scale avoidance strategies of professionals and the public heading the advice in the forecast. The precise timing of DPS cycles was described as short and hard to predict with avalanche observations that might only be received by the forecaster after the cycle has already ended. Another forecaster pointed out that when the problem is reactivated it can sometimes be more reactive than a true forecast due to not having sufficient observations to be able to reliably predict the onset of a DPS cycle.

> It is hard to predict when [DPS problems] are going to become reactive, and then by the time we start reading about it we are already a day

> behind. So, we are reading yesterday's information today to write tomorrow's forecast … so we are two days behind already when we actually get the information. (A3)

Getting input from other forecasters both internal to the organization or from the wider community is one approach for dealing with uncertainty that was mentioned by forecasters from all operations to varying degrees. Forecasters based in the Rocky Mountains (Banff, Kananaskis) described rules about building consensus between a certain number of forecasters or for a minimum number of forecast meetings before removing DPS problems from the bulletin. In Kananaskis, this was described as requiring a minimum of two subsequent meetings between at least two or three forecasters before removing a DPS problem. In Banff, one forecaster described a more general practice of not adding or removing PS or DPS problems without consensus from at least three forecasters. While forecasters in the Columbia Mountains (AvCan, Glacier) did not articulate specific rules about building consensus, they did describe the value of group discussions with other forecasters internally. The lower frequency of occurrence of DPS problems in the Columbia regions was also noted to increase the value of information from peers and mentors. Office-based AvCan forecasters similarly highlighted a value of observations and assessments from field teams and local professionals for removing DPS problems.

Another tactic that forecasters described for addressing high levels of uncertainty associated with removing DPS problems is the continued communication about the problem through other channels after it has been removed from the problem list. Alternate communication methods included continuing to discuss the problem elsewhere in the bulletin (discussion, snowpack summary, or headline), on social media, or at fireside chats.

> It's the only problem that we pull out and also say "don't forget about it". I can't think of any other problems that we say, "hey this isn't a problem anymore– but it might be." (K1)

Forecasters also highlighted the importance of these alternate public communication platforms for addressing challenges in the public's understanding of low probability high consequence situations and communicating differences in terrain choices between PS and DPS.

3.3. Additional considerations applicable to all problem types

Several additional considerations that forecasters described as being influential for their decisions to add, transition, remove or reactivate an avalanche problem consistently emerged across the discussed scenarios. The following subsections describe these general considerations that are broadly applicable across many problem types in more detail.

3.3.1. Number of problems

The influence of other avalanche problem types was a consistent consideration throughout all interviews on both topics. At least one forecaster included this consideration in every major scenario for all problem types.

The prospect of having no problems listed in the bulletin was an influencing factor articulated by some forecasters. In the case of adding problems, some forecasters mentioned that it lowers their thresholds for inclusion. This means that they would list problems with lower consequences (e.g., destructive avalanche size 1) (A5) or more isolated distributions (G3) than they normally would. Another forecaster suggested that problems might also be added earlier because they feel the need to have some problem in the bulletin in anticipation of a storm when there is not much else going on even if it is uncertain whether the problem will actually materialize during the current forecast period (G4). Specific problem types including DL, cornice, and WS problems were suggested to come up more often when there are no other problems to talk about (G5, B2).

> The simple fact that we call it a problem and we try to list them that is our dominant sort of workflow means we're going to look for them. So, I think it is hard for forecasters to let go of that and say there is no problem. So sometimes I think some of the problems hang around a long time even when they might not really be problems … And for us a lot, like it happens all the time we just, there has got to be something wrong with the snowpack you know, and I just think you can always chuck a wind slab on there. People do it all the time, I probably do too. You know it snows ten we get a bit of wind we're generally pretty stable but yeah you might see a few wind slabs here and there so yeah, we'll pop it on there. Without much extra thought to be honest with you, it's almost like a default to have a wind slab on there. (B2)

A potential lack of problems can also lead to existing problems being removed more slowly. One forecaster explained the reasoning behind this practice with the perception that removing all problems from a bulletin is sending a strong risk communication message to bulletin users that could be misinterpreted as there being no hazards that need to be managed (A5). Another forecaster suggested that the level of confidence in the conditions required to move to no problems is higher than to remove a problem in general. This required level of confidence to go to no problems was indicated to be less achievable at the spatial extent of a public forecast region compared to applications with smaller regions, like heli-ski tenures or ski resorts, where it is more attainable to build a personal grasp of the conditions from touching and skiing (B6).

In contrast to the effects of few or no problem situations on forecasting practices around avalanche problems, our interviews also revealed practices related too many problems. Public forecasts at all agencies are limited to a maximum of three problems that can be simultaneously listed. Additionally, some forecasters expressed a preference for minimizing the number of problems communicated to less than three when possible (B1, A4). Another forecaster described a preference of only communicating one surface problem type and one deep (PS or DPS) problem type at a time (B2). The motivation for these practices includes forecasters' perception that fewer problems keeps communication simple (A6) and more likely within bulletin users' attention span (A5). Another forecaster also noted that typically three problems is enough, and that the public might not be able to handle more because the travel advice would be so overlapping (B5). Either due to personal preference for fewer problems or the functional limitation of the bulletin system, forecasters in both the SS/WS and PS/DPS topic interviews shared practices for combining multiple problem types under a single problem label. When combining problems, forecasters often suggested that the unlisted problem types would be mentioned somewhere else in the bulletin text. Conversely to the no problems scenario, one forecaster indicated when more problems exist a SS problem might be removed sooner to avoid watering down other avalanche problems (A5).

> I think that is the biggest [difference] doing the public versus the private or the guiding scenario … is in the guiding world you can sort of assume that, or maybe it is not an assumption, everybody is trained to be looking for these residual problems and so you may not have to mention it. And here you have a lot of uncertainty of who the user group is and how they are going to take the information and roll with it so, we have to try and hedge our bets a little bit more. (B4)

> It is maybe a little bit of a triage thing knowing that your reader has a limited attention span and perhaps is only willing to consider a limited amount of information. (A5)

Considerations for deciding which problems to combine and which to list individually included which problems are anticipated to be most relevant to skiers and climbers (B5), the consequence of the problems (A5), and the distribution of the problems that can be used to describe more than one problem (A6).

3.3.2. Character limits

Parks Canada forecast operations using AvalX (Banff, Glacier) have a limitation on the number of characters that can be used to describe an avalanche problem. The limitation was mentioned by six forecasters (B5, B6, G3, G4, G5, G6) throughout their interviews. One of the highlighted approaches for getting around the character limit was to use more problems to help distinguish and describe differences in more detail. In other cases, however, forecasters mentioned the character limits as a reason for not including less relevant problems because there would not be sufficient room to explain them. Other forecasters noted having to oversimplify problem descriptions and attributes. For example, indicating wind slabs on opposite aspects of the prevailing wind direction when channeling of local winds is more important (B6).

> Yeah that is critical yeah, that happens quite a bit, [the character limit] influences our communication far more than you would think. … It strikes me as I would read an Avalanche Canada forecast, or even one that the Kananaskis guys produce next door to us, it strikes me how much freedom they have to communicate, versus how little we really have. And as things get more and more complex, like if we are going to distinguish between a storm slab and wind slab or include a wind slab within a storm slab in our description you start knocking out characters pretty quickly there and it becomes very muddled. (B6)

3.3.3. Goals and objectives

During our interviews, forecasters made several statements about what goals or objectives they are trying to achieve with the public forecast generally and more specifically the problems list. Accuracy of forecasts and communication goals were both commonly mentioned, and most forecasters described needing to balance these two objectives. However, which goal generally carries more weight varied between forecasters. Some indicated that effective communication to the public is more important than technical precision, and conversely others stated that communication considerations are always trumped by the conditions.

> We are almost more of a communications shop than we are a forecasting shop… or maybe it is fifty-fifty, and so I think that we look at … every problem and every situation as a communication problem. (A3)
>
> I also think there is another thing that goes in here, I, and this isn't test results or anything, but I think it is how responsible you feel for the bulletin. What you think your job is … do you feel like you are making decisions for people or do you think you are just giving information. I think the way that you write the bulletin and feel responsible for other people's decisions will affect whether, and when, or if you actually pull these things, or want to. (B3)
>
> I really want the forecast to be accurate and … true to the Conceptual Model as opposed to trying to like shape behavior by tweaking these things in a way that looks worse than it is or something. (A4)
>
> I guess again it is sort of like this balance between being always perfectly technically accurate with your bulletins versus trying to accomplish our primary goal which is efficiently affecting decision making in avalanche terrain and risk behavior. And so, it could be there is scenarios where my bulletin would be more technically accurate to include that … problem, because it is a problem … but I may choose not to do that for fear of losing the reader's attention because … he or she has one more thing to read and consider and I really want that person to be focused on those other two problems. (A5)

Some forecasters also mentioned focusing more strongly on giving users actionable information to assist with decision making, managing risk, and deciding where to go.

3.3.4. User context

Concerns about over-forecasting, crying wolf, and message fatigue also consistently came up throughout all interviews. The prevailing sentiment was that it is a challenge to achieve an appropriate balance, which is illustrated by the range of tendencies that were expressed related to whether it is best to be more conservative and list problems more readily or not.

> We understand the ideology of crying wolf you know maybe either leaving your hazard too high for too long or vice versa and then the idea of having a … problem that you virtually never change. However, … you are trying to assist people in making decisions and if [the problems are] still there in some fashion, we often feel like the default is it is better to leave it there. (K3)

> There'll always be some uncertainty and residual hazard and our job is to highlight the parts that are unique or the big risks … if you are going to go ski a couloir with a cornice at the top of it and it is a bit of a breezy day, then forecasting for that particular thing is going to be quite different from the general forecast of … 35 degree open slopes, and … the user has to just accept some of that risk as well. … If we always cry wolf then when it becomes a problem on a big scale then our bulletin doesn't look any different and it is hard to differentiate. (B4)

> The nature of the beast is trying to in some ways average your perceived risk over a large region. … Try to not to cry wolf, you know, by being hyper conservative with every forecast, because then you lose credibility. So, this balance between wanting to communicate the appropriate amount of caution without … people feeling like you are their finger wagging mother all the time. I do think about that often. (A5)

The attributes of the users that are being considered were also diverse. For example, one forecaster from Banff (B5) described trying to include what a person coming from a different region or continent would need to know to manage their avalanche risk in the park. In contrast, other forecasters (A5, G1, G3, G4) were concerned about losing credibility with frequent local users.

> You get people out here that are skiing five to six days a week all winter, if they're paying attention to the bulletin and you are consistently over calling it again and again and again, they're not going to tune in. They're going to think of it as garbage. So, you really do have to try and nail it. (G4)

One Banff forecaster (B1) also mentioned that ideally the behavior of recreationists should reflect which forecast region they are in as well as the avalanche bulletin. This was related to the underlying baseline conditions characteristic of different regions and snow climates harboring different challenges, for example basal instabilities in the continental climates. It was indicated that these differing baseline conditions can potentially result in public bulletins reflecting the same broad hazard information (e.g., danger ratings or problems) in different regions that are not directly comparable because they should be interpreted in the context of these underlying conditions.

The range of different levels of user sophistication was another attribute factored into problem selections. An AvCan forecaster stated that as a rule they write their bulletin considering a user with an avalanche skills training course, but also have an awareness of more and less experienced users (A4). A forecaster from Kananaskis described experimenting with the use of different problem types to try and improve communication but also noted that it is hard to get evidence to support whether user understanding was improved (K3). A Glacier forecaster (G1) shared that maintaining a PS problem during periods of dormancy can allow more experienced users to connect the dots with their own observations.

Forecasters also mentioned considering a variety of user activities, behaviors, ability to manage certain problems, and their terrain use when making decisions about avalanche problems throughout the interviews. Frequently skiers were mentioned, and relevant distribution of problems was sometimes considered with respect to ski terrain. Snowmobilers, ice climbers, and snowshoers were also described although less frequently. When selecting avalanche problems, some forecasters integrate specific terrain use considerations such as typical or high use areas, where people are likely to be throughout the day (G4), access of more extreme terrain as common terrain gets skied out (K1) or at lower hazard ratings (G3), and spring ski traversers (G1).

3.4. Ordering problems

Towards the end of the interviews, all 22 forecasters were queried about their practices around how they select the order of avalanche problems in the bulletin. Frequently, forecasters indicated that the problem which they list first is viewed as the most hazardous or most dangerous to users. All forecasters described placing weight on the likelihood and/or consequence component of avalanche hazard to decide the order of avalanche problems. Some forecasters described their approach as focusing on the "top right" corner of the avalanche hazard chart used in the CMAH.

Most forecasters agreed that the most hazardous or most important problem should be listed first. However, some situations exist where it is unclear whether one problem is more hazardous than another. A good example of this is a situation with a higher consequence lower likelihood problem and a lower consequence higher likelihood problem. Presented with this situation, 14 of the 22 interviewed forecasters expressed that they are more likely to weight likelihood as the more important consideration over consequence. Notably, this includes nine of the ten forecasters situated in continental snow climates, eight of whom used an example of typically ordering a more likely WS problem ahead of a less likely but higher consequence DPS problem to demonstrate this perspective. However, forecasters also listed a few situations where this order might be reversed including the anticipation of a period of heightened likelihood of the DPS problem due warm up, if a DPS problem running full path has become “fairly common”; and during periods of stable weather. Forecasters’ rationale for focusing more on likelihood was often centered around wanting to communicate with users what they are most likely to encounter. One forecaster (A6) pointed out that having backcountry recreationist actually see the evidence of the problem that is listed first helps maintain credibility with them. For some of the forecasters, the idea that shallower problems with higher likelihood can also trigger deeper higher consequence lower likelihood problems was also part of the reason for focusing on higher likelihood problem.

> If you had the number one problem as something that you very rarely see like an unlikely problem and then buried down in problem three you had something that when you are out there you are going to see all the time. I think you would probably lose a little bit of confidence from the public. (A6)

Although not the primary factor for ordering problems for most forecasters, consequence was frequently discussed. Among the forecasters who indicated weighting likelihood more heavily, there was often a minimum avalanche size threshold before the problem was considered. For example, a problem that produces avalanches typically not large enough to injure or kill a person (i.e., less than destructive avalanche size 2) would be listed lower despite being more likely. Three forecasters working in transitional snow climates (G3, A1, A4) also expressed that consequence can carry more weight. The common example used to demonstrate this was ordering more consequential PS problems over more likely SS problems. Five forecasters did not differentiate between the relative weights between likelihood and consequence.

Beyond likelihood and consequence, some forecasters described other factors they consider when ordering problems. The trickiness or manageability of problems was remarked on by five forecasters (A3, A4, G5, B4, B6). With the easier problems to manage (e.g., cornice or DL problems), being ranked lower and problems that are more likely to surprise someone or that are more challenging to manage are typically ranked higher.

> A low probability high consequence avalanche problem like a persistent layer that is in that stage, I am always going to put it at the top. Because it is the hardest thing for people to comprehend. (A3)

> Anytime that I think that folks are going to go out there and get surprised I really want to convey that. So sometimes I will intentionally put a persistent slab first and hopefully get people to scratch their head about it, those who get deep enough into the forecast to read it there. (A4)

> Very often what ends up being on the bottom there is the low likelihood high consequence. Which very often is what scares the heck out of me the most as a forecaster … in that I can go out and sense surface slabs and superficial problems and very easily steer around them in the terrain. The deep persistent slab problem is the one that I can't get around very easily, and I can't deal with very well, nobody has the great tools for predicting when it is going to go. I don't know, I think if I had my way, I guess what I am saying I'd put the deep persistent slab problem maybe as the first problem quite a bit of the time. (B6)

Three forecasters (B4, G1, A2) described ordering problems with respect to how they are situated in the snowpack from top to bottom. Some of them noted that this order typically aligns with the likelihood of the problems, and it provides an objective criterion for ordering when the order is otherwise unclear. One forecaster (A1) remarked that the novelty of a problem can be a secondary consideration with newer problems being ordered higher.

Bulletin users were mentioned throughout the discussions on ordering problems. Some forecasters mentioned that the activity types of bulletin users can play a role in decisions about ordering problems. Skiers were referred to most commonly, but forecasters in the Rocky Mountains also mentioned ice climbers, snowmobilers came up in one interview with an AvCan forecaster (A4), and snowshoers were also mentioned by two forecasters (K3, A4). One forecaster described how the ranking of DPS and SS or WS problems might be different depending on whether one considers snowshoers or skiers.

> You know if we are speaking to the snowshoe crowd, and we are talking about triggering a wind slab in the alpine or treeline that then might step down, probably for them the most important thing is the deep persistent. But the skiing and climbing crowd what is probably more important is the surface slab they are going to kick out. (K3)

Another forecaster (B4) described how knowledge about how users' activities within the forecast region changes at certain times of the year might influence how problems are ranked. For example, ice climbers might be the primary target audience early in the season, and then skiers may become a bigger consideration as the snowpack develops in the region.

> Right now for example, in Yoho National Park there is almost no ski access there because it is a bit lower … but there is an awful lot of ice climbing going on in the area … so we might change the order to try and target the group that we think is going to be using that zone the most. And then the same thing, as the snowpack develops in the main bulletin area, we will probably move a little bit more towards the skier focus and highlight the problems that could affect the skiers. And that often ends up being the deep persistent, or the persistent slabs, and things like that versus the cornices and the loose dry sloughing and gully issues. (B4)

Terrain use of recreationists was another consideration, including whether a problem is anticipated to be relevant outside of extreme terrain or to focus on terrain that is most likely to be used given the weather conditions.

In interviews where the topic of how readily a forecaster is willing to switch the order between problems arose, forecasters consistently indicated this to be a day-to-day decision rather than a longer-term decision. This practice was noted by some to help emphasize a problem when conditions change.

Chapter 4.

Discussion

This study seeks to contribute insights into the operational link between observations and assessed avalanche problems by understanding how the fundamental definitions of the CMAH are being applied and what other factors influence these decisions. Below, we examine the operational application of avalanche problems in public forecasting with respect to existing guidance and literature. Building on these results, we then discuss practical implications for improving consistency in the application of avalanche problems types. Finally, pertinent limitations of our research approach are articulated.

4.1. Operational use of avalanche problems

Interviews with forecasters revealed some general trends that relate to all scenarios. The results also show a diversity of perspectives and varying levels of uniformity related to both relevant physical observations and additional considerations.

4.1.1. General trends

At the broadest level the average number of concepts which represent forecasters considerations for each of the assessment scenarios can be compared. The number of concepts contained in a concept map is a simple metric for the extent of knowledge about the topic at hand that has been used in educational applications of concept mapping (de Ries et al., 2021). If we consider the relative differences in the average number of concepts included as a rough indicator of the richness of knowledge that forecasters hold for each scenario there are a few notable trends.

Scenarios related to adding a particular avalanche problem type on average contain more concepts than their removal counterparts. This could suggest that forecasters have a wider knowledge base to draw on related to identifying the initiation of an avalanche problem than they do for deciding to remove the same type of problem. Furthermore, it could reflect the higher degree of uncertainty which forecasters expressed when removing problems compared to adding them. This aligns with the asymmetry in the higher strength of positive information associated with instability compared to the lower strength and residual uncertainty associated with indicators of stability (e.g. avalanche observations carry more weight about instability than a lack of avalanche observations does about stability) (Fredston & Fesler, 1999; McClung, 2011). A similar interpretation can be made about the adding and removing scenarios for DPS problems; these exhibited the smallest average number of concepts compared to the corresponding adding and removing scenarios for other problem types. Commonly, DPS problems are associated with a higher degree of uncertainty compared to shallower avalanche problem types due to the relatively less and more-challenging-to-interpret information (Conlan, 2015). Unlike shallower problems, for which forecasters can more readily draw on field tests and that generally have a higher frequency and distribution of avalanche observations, DPS problems release more rarely, more spontaneously, and with more limited data due to avoidance by professionals (Conlan, 2015). While these general trends in concept map size appear to align with reasonable explanations, the relatively smaller sizes of the removal scenarios and DPS topics might also be associated with the fact that these topics were generally discussed later in the interviews.

Scenarios associated with avalanche problems that occur rarely in an interviewee's forecast region also tended to have fewer observation types. This was evident for the SS scenarios with Kananaskis forecasters who reported rarely using that problem type, and for the adding and removing DPS problem scenarios of Glacier forecasters. An explanation for this could be that forecasters do not develop a rich domain knowledge structure for avalanche problems which they rarely encounter in their forecast region. Similarly, the avalanche problem types that frequently occur within a snow climate region were reflected in the examples that forecasters used to describe how they order avalanche problems. Nearly all forecasters from Banff and Kananaskis described WS and DPS problems to reflect their perspectives on ordering problems, whereas SS and PS problems were much more commonly used by Glacier and AvCan forecasters. This aligns well with the higher prevalence of DPS problem situations in the Rocky Mountains and PS problem situations in the Columbia Mountains documented by Shandro and Haegeli (2018).

4.1.2. Consideration of the physical properties

Generalizations between scenarios can also be made by taking a closer look at the content of the concept maps, specifically the information classes of the relevant observation types. Operational avalanche forecasting is informed by three classes of information that range from most direct and easy to interpret to more indirect and more challenging to interpret. These data classes are instability factors (class I), snowpack factors (class II), and meteorological factors (class III) (LaChapelle, 1980). Forecasters indicated that all these information classes are relevant to their avalanche problem assessments, however particular information classes appear to be more important for certain types of scenarios. Our results show a higher proportion of observation types related to weather and snowpack information were associated with scenarios where an avalanche problem is added than when it is removed. Furthermore, when adding a problem, weather observations were the most common for surface problem types (SS and WS) and snowpack information for the PS and DPS problem types. This nicely reflects that the formation of SS and WS problems are directly associated with weather events, while the formation of PS and DPS problems are defined by weak layers within the snowpack. Weather observations were also the most commonly mentioned observation types in the reactivating PS and reactivating DPS scenarios where forecasters are aiming to anticipate the reemergence of a dormant avalanche problems based on forecasted weather events.

The forecasters interviewed in this study frequently mentioned that instability observations play an important role in their decision whether to add or remove avalanche problems. Instability observations make up the largest proportion of relevant observation types in scenarios when forecasters were considering removing a problem from the bulletin. Relevant instability observation types which came up in multiple scenarios include avalanche observations (10 scenarios) including the trigger type, avalanche size (destructive), number of avalanche observations, and time without observed avalanche activity; and snowpack tests (9 scenarios) including fracture character and loading steps. The use of instability observations for adding different types of avalanche problems highlights that in addition to identifying the avalanche problem type (e.g., PS versus SS), they can also provide important insight into whether the given set of characteristics actually constitute a significant enough problem to include in the bulletin.

4.1.2.1 Alignment with of the Conceptual Model of Avalanche Hazard

In general, the physical observation types and values that forecasters identified as important for adding and removing avalanche problems align well with the avalanche problem definition table included in the CMAH (Table 4 in Statham, Haegeli, et al., 2018). However, our interviews also highlighted a few interesting discrepancies.

Relevant observation types which can be linked to those provided by the CMAH were more commonly found in the adding a problem scenario compared to its corresponding removal scenario. For example, the scenario for adding DPS problems included observation types related to weak layer grain type, location, and formation; slab hardness; typical persistence time; and avalanche size, which can all be found in the CMAH definition tables. In the scenario for removing DPS problems, however, avalanche size (included by two forecasters) is the only observation type from the definition table that emerged as a relevant consideration. This is likely a reflection of the iterative process of avalanche forecasting where the previous day's forecast is used as a starting point. Once an avalanche problem has been identified and established in the list of current concerns forecasters do not have to continuously re-establish the problem type and the decision to remove a problem is a distinctly different question.

Even though the decisions to remove avalanche problems are more heavily guided by class I data that is not included in the CMAH definition tables, most of the removal scenario descriptions of our interviewees still included some CMAH observation types. For example, the removing WS scenario includes observation values indicating the loss of cohesion in the slab due to faceting (three forecasters), and the removing PS scenario includes observation values indicating that weak layer grain type has changed or has become difficult to detect (four of five forecasters that included weak layer detectability). Although these observation types were not the most frequently indicated within their scenarios, they highlight that the conditions defined in the CMAH still provide some relevant criteria for deciding when SS, WS, and PS are no longer a problem. An interesting special case is the removing of DPS problems where avalanche size was the only CMAH observation type mentioned by our interviewees. However, their explanations highlighted that avalanche size is unlikely to change when they are considering removing the problem. This suggests that the CMAH definitions do not provide any practicable guidance for removing a DPS problem.

While the physical observations mentioned by our interviewees generally align well with the observation values included in the CMAH definition tables (Statham, Haegeli, et al., 2018), there were also a few exceptions. Most prominently, the mentioned observation values with grain type of the weak layer show considerable deviation from the CMAH definitions for the surface problem scenarios. The CMAH defines the typical weak layer type for both SS and WS problems as decomposing and fragmented particles and precipitation particles (Statham, Haegeli, et al., 2018). Additionally, the CMAH states that SS problems involve instability within the storm snow or at the old snow interface and WS problems are explicitly identified as "overlying a non-persistent weak layer" (Statham, Haegeli, et al., 2018). All but one forecaster indicated grain type of the weak layer or underlying surface as a consideration for adding a SS problem[3]. However, observation values consistently described persistent grain types including surface hoar, facets, and/or crusts as a positive indicator for adding the problem. In some cases, the presence of a persistent grain type was also noted to lower other thresholds for the problem such as new snow accumulation. While this result contradicts the definition of the conceptual model, there is strong agreement among forecasters about this practice, and it is one of the most consistent observation types across all scenarios. The most prevalent explanation for this result comes from the additional considerations where forecasters commonly described the practice of transitioning through a SS problem before forecasting a PS problem, a practice also described by Klassen (2014). For office-based forecasters, another possible explanation for this practice is the challenge of identifying whether an unstable storm snow interface has developed within the storm snow based on weather data alone. Being aware of a persistent grain type at the interface can give office-based forecasters more confidence that the new storm snow will develop into a slab avalanche problem.

4.1.2.2 Observation consistency

Similarities and differences demonstrated within the observation types and associated values described by forecasters provide insights into where practices exist that might lead to diverging avalanche problem assessments. Very few observation types were considered consistently by all forecasters. There were only three major scenarios where all eleven forecasters agreed on more than one observation type being relevant. These

[3] Some forecasters provided similar explanations for adding a WS problem with and without new snow.

included wind, new snow, and air temperature for adding new SS problems; weak layer properties, specifically weak layer grain type, and avalanche observations for adding PS problems; and snowpack tests, avalanche observations and specifically the number of avalanche observations for removing PS problems. The only relevant observation that all forecasters indicated for the adding WS scenarios (both with and without new snow) was wind, and all forecasters also indicated that weak layer properties were relevant for adding DPS problems. The number of observations which at least half of the forecasters mentioned in a scenario ranged between four observation types (removing WS and reactivating PS scenarios) and thirteen observation types (adding PS scenario).

While there does not appear to be a strong consensus between forecasters of which observation types they use to add or remove avalanche problems in the discussed scenarios, this does not necessarily equate to problem types being used inconsistently. It is important to remember that forecasters were asked open-ended questions as opposed to being presented with a list of potentially relevant observation types. Thus, the omission of an observation type does not necessarily mean that the forecaster explicitly discounted it. However, we assume that the most important observation types to the range of forecasters for each scenario is captured within this dataset. It is also possible that forecasters come to the same avalanche problem assessment using differing observation types. A similar result was observed by Armstrong et al. (1974) where only one observation type (wind) of 31 relevant observation types was shared by four forecasters who recorded contributing factors of their individual daily forecasting procedures over a winter season in the same region of Colorado. Despite considering different factors as important, these four forecasters demonstrated similar accuracies in their stability forecasts over the investigation period (R. L. Armstrong et al., 1974). LaChapelle (1980) explains this phenomenon with the redundancy in data allowing for different ways to reach the same forecasting conclusion.

Shifting focus from discrepancies in observation types to examining differences in observation values offers more direct insight about possible sources of misalignment between forecasters. There are a few observation types where forecasters very much agree on the relevant observation values. An example for this is all eleven forecasters concurring that the weak layer grain types associated with adding PS problems typically include surface hoar, facets and/or crusts. However, most observation types are associated with a range of observation values. When adding a WS problem in the presence of new snow, for example, new snow accumulation values shared by eight forecasters included typical values that ranged from less than 10 cm to less than 20 cm, while other forecasters indicated that it could be potentially any amount of snow, sometimes more than 20 cm in combination with a SS problem, or up to 15 cm with winds in the strong to extreme range. In other instances, the range of values is substantial or potentially contradictory, which could result in diverging decisions about adding or removing an avalanche problem. When adding a SS, for example, all eleven forecasters included wind as a consideration, but values covered the entire range of possible wind speeds with some forecasters directly contradicting each other over whether wind capable of snow transport can be present when a SS avalanche problem is added.

Some of the observed variability within observation types and values seems reasonable given the different contexts of forecasters who participated in this study. Some of this variability can likely be explained by actual differences between forecast contexts such as differences in snow climate, forecast region size, or characteristics of the terrain in the region. For example, the scenario for adding SS problems reflected regional differences in wind speed values with typical values spanning from light to strong for Glacier; light to moderate for Banff, and calm to light in Kananaskis. The minimum end of typical values was expressed to be lower by all forecasters situated in continental snow climate compared to those in the transitional snow climate at Glacier National Park. Given that critical wind speed thresholds for transporting snow increase with temperature and humidity (Schmidt, 1980), the colder average temperatures and less dense snowfall events in continental snow climates relative to transitional snow climates (R. L. Armstrong & Armstrong, 1987) provide a potential explanation for the lower wind thresholds in the continental snow climate regions where lower wind speeds could favour WS over SS problem development. Wind transport is also highly dependent on local topography (McClung & Schaerer, 2006) and some forecasters located in the Rocky Mountains described their forecast regions as being particularly susceptible wind slab development due large amounts of alpine terrain. Another example, where regional differences are observed is related to the typical amount of time since a weak layer is buried before a PS problem is added. In this case AvCan and Glacier forecasters reported shorter typical timeframes between 36 hours and four days, whereas forecasters from Banff and Kananaskis reported longer typical times in the range of seven to 14 days. These discrepancies in typical timeframes could be related to the climatic conditions which influence problem development. For example, the lower temperatures and less intense snowfall characteristic of continental snow climates (R. L. Armstrong & Armstrong, 1987) may require longer time periods to develop a consequential slab. Additionally, while forecasters from all regions generally agreed on the weak layer grain types capable of constituting a PS problem, forecasters from continental regions indicated facets as occurring more commonly compared to forecasters in transitional snow climates who indicated more commonly dealing with surface hoar. Differences in typical grain types associated with PS problems could be a contributing factor reflected in the differing typical development and persistence timeframes of PS problems between regions. Jamieson (2006) for example found facets overlying a curst to be prone to releasing avalanches for longer than surface hoar layers overlying a crust.

While variability due to actual physical differences is reasonable and can explain some instances, additional sources of variability also appear to exist. These less desirable discrepancies contributing to forecaster variability are related to additional considerations such as differing risk communication practices, approaches to dealing with uncertainty and system constraints are discussed in Section 4.1.3.

4.1.2.3 Comparison to data-driven approach

A recent study by Towell (2019) used a data-driven statistical approach to explore the link between modeled weather and snowpack data and the avalanche problem types in the public avalanche bulletins for Glacier National Park. Results from the varied approaches taken by Towell (2019) and the present study provide a complementary view on the factors that influence avalanche problem selection for public bulletins. In general, the variables that emerged as significant predictors in the analysis of Towell (2019) were often also mentioned by forecasters in the present study, which is reassuring for the validity of both studies.

The strongest similarities were observed in the scenarios related to adding surface problems (adding SS, adding WS with new snow, adding WS without new snow) where the most frequent observation types were related to weather and snowpack information classes. The adding WS scenarios appear to provide a particularly good match with the relevant statistical splits in Towell's (2019) conditional inference trees having a strong relationship with the most frequently cited observation types (wind, air temperature, distribution (elevation band), and new snow) in addition to additional considerations which confirm the strong relationship between SS and WS problems. The adding SS scenario similarly shared relevant observations for weather variables including new snow and wind, snowpack properties related to slab density, and additional considerations related to SS WS relationship. However, a couple of the most frequent observation types cited by forecasters as relevant for this scenario in our interviews (air temperature: all forecasters; grain type of the weak layer or underlying layer: ten of eleven forecasters) did not emerge as significant predictors in Towell's (2019) analysis even though the simulated dataset included them.

We see a bit more variation in the most frequently cited and most significant observation types between the two studies when it comes to the persistent problem types and removing problem scenarios. While we continue to see agreement in the use of snowpack observation variables for adding DPS and PS problems, the increasing importance of instability factors such as avalanche observations and snowpack tests seen in our concept maps was not observed by Towell (2019). This is because the Towell (2019) dataset did not include instability information such as avalanche observations and snowpack test results. This provides an explanation for why no significant predictors for removing DPS and PS problems (problem types combined) were discovered. However, the relatively smaller number of concepts for removing problem scenarios in our results also confirm the general observation of Towell (2019) that the forecasters generally use fewer predictors for removing avalanche problems than adding new problems. This strengthens the notion that a less rich knowledge base exists for problem removal scenarios, which is consistent with forecasters highlighting that the removal scenarios are more challenging.

4.1.3. Additional considerations and practices

In addition to the insight on the physically based observation types and values that drive avalanche problem assessments, our results bring to light a variety of additional considerations that influence forecasters' decisions about avalanche problem types. On average, these factors made up 17% of the concepts that forecasters described when discussing a scenario. The additional considerations mentioned by interviewees that carry potential implications for consistency can roughly be categorized into the following topics: a) risk communication objectives or preferences of forecasters; b) forecasters' approaches to dealing with uncertainty; and c) effects of the forecast system that the avalanche problems are assessed within and communicated from. The following discussion provides insights about how these additional factors might explain some of the observed differences in the physical observation types and values discussed above, and how they likely affect the selection of avalanche problems in public avalanche bulletins more broadly.

4.1.3.1 Risk communication

The primary objective of the public avalanche bulletin in Canada is to provide relevant risk information to backcountry recreationists (Statham & Jones, 2006). Consistent with this objective, it follows that forecasters' decisions about the content of the bulletin is informed by their views on how to best communicate avalanche conditions to the public. However, the influence of forecasters' individual risk communication preferences and strategies are less transparent and likely one of the main sources of inconsistencies.

One unique challenge that public forecasters are faced with is related to the balance of public risk communication objectives with the technical aspects of avalanche hazard assessment. The CMAH (Statham, Haegeli, et al., 2018) is explicitly intended to be a hazard assessment process that does not consider the exposure and vulnerability of the element-at-risk. However, there appear to be situations where the risk communication objectives of the public bulletin are at odds with a purely hazard assessment perspective on avalanche problems. While forecasting software such as AvalX aims to assist forecasters to "separate out the technical analysis methods of forecasters from public communication strategies" (Statham et al., 2012), our results suggest that the underlying problem selection can still be influenced by forecasters perspectives on how to best communicate with the bulletin user.

Some forecasters articulated an explicit hierarchy between objectives with regard to communication or technical accuracy to the conditions. However, there was some disagreement over whether communication goals should outweigh a desire to be technically correct or vice versa. Unlike some other natural hazard domains where expertise and associated objectives of technical scientific accuracy and public communication are separated into different roles such as weather or hurricane forecasters and broadcast meteorologists (Bostrom et al., 2016; Demuth et al., 2012) public avalanche forecasters balance both of these goals internally, potentially blurring the line between technical hazard assessment and risk communication. As one forecaster put it, they “consider every problem and every situation as a communication problem" (A3). A reflection of these potentially opposing views about public risk communication and hazard assessment is also illustrated by forecasters who noted differences in how they use avalanche problem types when communicating with other professionals compared to how they are implemented in the bulletin. Disparate perspectives on when public communication goals should outweigh what a forecaster perceives as the most accurate representation of existing conditions, and which tactics are the most effective to communicate are likely sources of inconsistency.

Grouping of avalanche problems

Most of the time, avalanche conditions are characterized by the coexistence of multiple avalanche problems. A number of operational practices were expressed related to the relationships between particular problem types. Some of these problem interactions include ways that problems are either grouped together under a single label or simultaneously listed together to convey a message.

Forecasters shared a widespread desire to keep problem information simple and easy for bulletin users to understand. Given this intention, forecasters expressed a preference of using fewer avalanche problems when possible. To achieve this, avalanche problems with similar or overlapping risk mitigation strategies are commonly grouped together under a single problem label. For example, SS problems were frequently referred to as being used to represent additional avalanche problem types such as WS and developing PS problems. Similarly, some forecasters mentioned merging PS and DPS problems into a single problem because for example they prefer to only communicate one surface problem and one deeper (PS or DPS) problem at a time. The relevance of making the distinction between PS and DPS avalanche problem types was weighed against questions about users’ ability to properly differentiate appropriate risk mitigation actions. Additionally, multiple coexisting instances of the same problem type (e.g., multiple persistent weak layers for PS problems or multiple generations of wind slabs for WS problems) are also frequently included in the bulletin under a single label. Forecasters may also be forced to group problems due to system constraints as is described in Section 4.1.3.3.

While grouping problems together is a common practice, there are also instances when forecasters purposely list these problems separately to highlight important differences. Examples of such situations include transitioning a PS problem that was previously grouped into a SS problem to it distinguish from newly emerging SS or WS problems, or to distinguish between variation in problem distributions at different elevation bands for SS and WS problems that might otherwise be grouped.

While many forecasters group problems sometimes and explicitly distinguish between similar problems at other times, our interviews revealed considerable differences in how this general practice is implemented by individual forecasters or forecasting agencies. For example, we saw varying strengths of opinion on whether SS and WS problems should ever be simultaneously listed. An organizational difference was also evident with how SS and WS problems are typically grouped together with Kananaskis being the only agency who indicated including SS problems under the label of a WS problem while all others typically group WS problems under a SS problem label. Hence, differences in individual practices for grouping avalanche problems may be a substantial source for inconsistencies in avalanche problem information presented in avalanche bulletins.

Evidence of grouping SS and WS problems impacting avalanche problems published in public avalanche bulletins has also emerged in other studies examining public forecast data including Shandro and Haegeli (2018), Statham, Holeczi et al. (2018) and Towell (2019). Additionally, Statham, Holeczi, et al. (2018) found significant differences in the proportion of forecasts that simultaneously list SS and WS problem types and PS and DPS problem types among three neighbouring forecast regions in the Canadian Rocky Mountains (Kananaskis Country, Banff National Park, Jasper National Park). Their results clearly confirm how differing risk communication practices around grouping problems may influence forecast consistency.

Avalanche problem progression

Practices around combining avalanche problem types also influence the communication of an avalanche problem's progression. Interviews reveal two general approaches to communicating the initial progression of a problem: Either directly forecasting a problem or transitioning through another problem type as the problem develops. Forecasters described a number of possible progressions with WS problems (either SS to WS or directly forecasting WS), PS problems (SS to PS, WS to PS, or directly to PS), and DPS problems (PS to DPS or directly to DPS problem). The physical conditions of how a particular problem develops can relate to how the progression will be communicated. For example, it makes a difference whether a PS problem develops slowly through incremental loading or more suddenly subsequent to larger storm events. However, communication preferences also appear to play a role. A gradient of opinions was expressed about whether a forecaster would ever, sometimes, or rarely directly initiate certain problems. Most forecasters justified their personal approach based on what they perceived to be easier for the user to understand. However, these perspectives do not seem to align very well. For example, we saw conflicting views about whether it is more confusing to add a DPS problem when it is relatively shallow in the snowpack or to change the label of a problem from one to the other. We therefore conclude that differences in the communication of the initial progression of avalanche problems are a potential source of inconsistency for avalanche problem information published in avalanche bulletins.

The expressed range of perspectives about communicating problem progressions also seem to provide an explanation for the observed differences in observation values in some scenarios. For example, forecasters who described directly forecasting DPS problems either did not include weak layer depth as a consideration for the scenario or quantified one of the lower threshold values. In the adding PS problem scenario, differences in opinions on these progressions are potentially responsible for the diverging avalanche observation values, which included the presence, absence, continuing trend, or declining trend of avalanche observations. An additional example is the transition from SS to WS scenario, which most forecasters described as a product of initially grouping these problem types together but eventually needing to communicate the WS problem on its own because it persists for longer than the SS problem. However, the same progression of avalanche problems could also be associated with a WS problem that truly develops after the initial storm due to a subsequent wind event. These different progressions likely account for the discrepancy in wind values mentioned by forecasters for the transitioning SS to WS problems, which included contradictory wind duration values of no substantial new wind or required ongoing steady wind since the initial storm.

Relation to other bulletin messages

Forecasters mentioned that some forecast conditions send a particularly strong risk communication message to bulletin users. Among these is the no problem scenario, where forecasters are concerned that the bulletin might give users a sense that they do not have anything to worry about. As a result, some forecasters change their threshold for including or removing problems under these circumstances. For example, a problem with an otherwise negligible distribution, a smaller destructive size, or an anticipated arrival beyond the forecast period might be included if it is the only potential problem. This suggests that the assessment of what constitutes an avalanche problem can be a relative assessment in relation to other problems as opposed to a fixed set of absolute criteria that does not change over time.

Our interview data also suggests that avalanche problems are sometimes considered relative to the typical conditions within a region. For example, one forecaster indicated that bulletin users' behavior should ideally reflect not only the conditions described in the bulletin but also which region they are situated in. This perspective is closely related to concerns about message fatigue and a desire to ensure that the public bulletin within a region looks substantially different when unusual or particularly challenging conditions exist, as is discussed in more detail in the subsection below. While using avalanche problems that are relative to the baseline conditions for a region might have benefits for local users, there might be considerable downsides for bulletin users who travel between regions who may be caught off guard if the same problem type is used substantially differently such that different mitigation measures are required.

Assumptions about bulletin users

The avalanche forecasters interviewed in this study continuously expressed that they consider bulletin users' attributes, needs and behavior when choosing whether to include an avalanche problem in the bulletin or not. Relevant user attributes that forecasters mentioned included residence (local or visiting), level of training, bulletin literacy, attention span, and activity types. While bulletin users are diverse (St. Clair, 2019), differences in who forecasters are considering when they assess avalanche problems can have a considerable impact on their choices. For example, a forecaster who described trying to maintain credibility with skilled local users indicated being more willing to add and remove problems, whereas a forecaster who described writing their bulletin for someone who is coming in from a different region expressed being more likely to hold onto a problem. Some forecasters also mentioned that assumptions about recreationists' behavior and terrain use play a role in their assessment. When removing a WS problem, for example, some forecasters expressed higher confidence in recreationists ability to recognize this particular hazard and therefore felt more comfortable removing the problem despite residual risk still existing. Some forecasters expressed that their avalanche problem choices are influenced by whether they affect skiable terrain and/or widely used areas. These assumptions about user attributes and behavior can also be a consideration for forecasters when ordering the avalanche problems. For example, a forecaster mentioned how weather conditions impact terrain use (e.g., white-out conditions compelling recreationists to stay at treeline or below) or the predominant activity type at a certain time of year (e.g., more ice climbers exposed in the early season before the snowpack builds up in popular ski terrain) might shift how problems are prioritized.

Diverging views about whether problems should be removed and reactivated or maintained are also related to differences in perspectives on what constitutes an avalanche problem that warrants being communicated in the public bulletin. While the CMAH differentiates between avalanche problem types, it does not offer any suggestions for what makes an avalanche problem substantial enough to be considered a “problem” since that depends on the specific avalanche safety context. This question was relevant to both adding and removing avalanche problems, but forecasters indicated that removing problems was more challenging than adding them. Some forecasters appear to adopt a shorter-term risk-based perspective that considers whether bulletin users are likely to interact with the problem to inform this decision. Others maintain a longer-term hazard-based perspective opting to communicate the avalanche problems that exist in a manner less influenced by whether bulletin users are likely to see the problem during the current forecast period. This is particularly evident with PS and DPS avalanche problem types which can experience periods of dormancy. There was a substantial division between some forecasters on whether dormant avalanche problems should continue to be communicated within the public bulletin or if they should be removed and later reactivated. WS avalanche problems were also expressed by some forecasters as challenging to remove as wind slabs can also continue to exist to some extent when they are considering removing the problem.

Furthermore, several forecasters mentioned that concerns about message fatigue or losing credibility with users affect how readily they will add and remove avalanche problems. However, how these concerns were not acted on uniformly across forecasters, which could lead to differences in how avalanche problem types are handled. In addition to impacting the addition and removal or maintenance of dormant PS and DPS problems, a similar but shorter-term dynamic also exists with the addition and removal of WS problems. In this case, some forecasters prefer to remove an old lingering WS problem in anticipation of giving emphasis to new incoming WS problem, whereas others describe maintaining communication about the existing lingering WS problem until the incoming WS arrives. Several forecasters also suggested that they use the order of avalanche problems to further emphasise their message, which leads them to readily reorder problem types on a day-to-day basis as conditions change. Differences in forecasters' willingness to make frequent changes to the order of avalanche problems is reflected in the problem order fluctuations observed by Statham, Holeczi, et al. (2018) and provides additional explanation to what the authors correlated to shift changes of forecasters.

4.1.3.2 Dealing with uncertainty

Uncertainty is inherent in all forecasting, and avalanche forecasting is no exception. Several sources contribute to uncertainty in avalanche hazard assessment including uncertainty in weather forecasts, uncertainty about the spatial variability of the terrain and the overlying snowpack, as well as uncertainty associated with the behaviour of people (Canadian Avalanche Association, 2016). The forecasters interviewed in the present study highlighted the following forecast situations to be particularly challenging due to high levels of uncertainty: situations with PS and particularly DPS avalanche problems; and removing problems more than adding problems. Forecasters shared a variety of approaches for dealing with uncertainty that influence what information is presented in the bulletin and when problems emerge and recede.

"Be conservative" has been proposed as a Golden Rule of Forecasting which is particularly applicable to complex situations in uncertain environments (J. S. Armstrong et al., 2015). In the case of uncertainty around how a particular avalanche problem will likely develop, forecasters described tactics for avoiding "getting burnt". For example, the common practice of using a SS problem to represent a developing PS problem gives forecasters more time to gather additional information and reduce their uncertainty around whether the problem is likely to persist. Transitioning between avalanche problem types was also viewed as a buffer for dealing with the uncertainty around the removal of a problem. For example, transitioning a SS problem into a WS problem is described as easier than directly removing it. Another example comes from a forecaster who describes that when they are uncertain of which avalanche problem type will develop with an incoming storm, they are more likely to forecast a SS problem over a dry loose problem, which they view as less severe. Similarly, other forecasters indicated taking a less conservative approach to removing lower consequence surface problems such as SS problems and being increasingly conservative as the consequence of the problem increases (e.g., PS or DPS).

While the interviewed forecasters generally agreed with the relative increase in conservatism proportional to the consequence of the problem to be removed, the personal threshold values for removing PS and DPS problems mentioned in our interviews showed some striking differences. For example, when considering removing DPS problems the required amount of time without observed avalanche activity ranged from 24 hours up to the remainder of the season. Interestingly, an expert opinion survey by Conlan (2015) including 31 avalanche professionals found a significantly smaller range of values for the number of days of predictive relevance of recent deep slab avalanche observations in a region (1 to 7 days with 60% of values between 1 and 3 days). While assessing the predictive value of DPS avalanches is not the same as the decision to remove an DPS avalanche problem from the bulletin, the substantial difference in these time ranges is still noteworthy. The time without observed activity for the relatively lower consequence PS problem showed a narrower, although still sizable, range of three to fourteen days. As described above, one likely reason for the broad ranges is personal communication preferences for whether these problem types should be removed during periods of dormancy and then reactivated as necessary or if they should be maintained. Another mechanism for dealing with uncertainty when removing these types of problems involves the continued communication about problems outside of the problems list after removal by either mentioning it elsewhere in the bulletin or using alternate platforms such as social media or fireside chats.

Forecasters also described placing an increasing value of information coming from peers during situations of high uncertainty including discussions with other forecasters or information from field teams and local professionals. The rare occurrence of DPS problems in the Columbia Mountains was highlighted as a situation when forecasters from Avalanche Canada and Glacier National Park place high value on knowledge from peers and mentors. Both forecasting agencies located in the Rocky Mountains cited having rules about building consensus with a certain number of forecasters or for a certain number of meetings before they will remove a DPS problem. Aggregating perspectives of multiple forecasters moderates the effects of divergent perspectives of individuals within forecast teams and likely results in a more consistent line of messaging when comparing day to day forecasts of the same agency. However, if decisions are deliberated within forecast teams group polarization (Myers & Lamm, 1976) could potentially also amplify perspectives and result in a higher degree of variability between forecast regions.

Several forecasters recognized during interviews that their personal characteristics also likely play a role in how conservative a forecaster might be when removing problems. This was again particularly relevant to the low likelihood high consequence removing DPS problem scenario. Individual forecasters' risk tolerance and feelings of personal responsibly should an incident occur after they remove a DPS problem were cited as considerations. This feeling of responsibility was also sometimes associated with specific previous experiences involving incidents or fatalities on days that a forecaster issued the forecast, potentially leading to more conservative decisions in the future. Some forecasters also described contemplating what their own risk management strategies for the given situation would be to inform whether a problem should continue to be listed. Long-term public forecasters mentioned that higher levels of experience as a public forecaster allows them to remove avalanche problems more readily and confidently.

4.1.3.3 System constraints

Constraints placed on forecasters by the systems which they work in can also impact how avalanche problem types are selected. This includes the larger organizational framework, their roles, the information that is available to them, and the forecasting software and tools which are used.

Available information sources

Differences in available information sources also exist between agencies which provides another explanation for the observed differences in relevant observation types and values for adding or removing avalanche problems. There are fundamental differences between office-based (AvCan) and field-based (Banff, Glacier, and Kananaskis) avalanche forecasting programs that affect what information is available and how it is used for adding or removing avalanche problems. The ability for field-based forecasters to base their decisions on their "gut feeling" from being out in the conditions puts them in a very different position than a office-based forecaster who must wait to glean this type of information from qualitative language communicated in field reports. While Avalanche Canada addresses this shortcoming with having dedicated field teams in regions that would otherwise be data-sparse, the location and size of their forecast regions still prevents their forecasters to “personally feel the snow” in their forecast regions. Some observation types also emerged as unique to certain operations, for example ram penetration was mentioned as a consideration for assessing snow available for transport in the adding a WS without new snow scenario for all Glacier forecasters but at no other operations.

Furthermore, the value placed on observation types may vary due to information quality or personal forecaster preferences even where similar information sources exist. For example, forecasters in the Columbia Mountains expressed higher confidence in basing their SS and WS problem decisions on weather forecasts with a higher level of trust in precipitation values and a lower level of trust in wind predictions. Forecasters in the Rocky Mountains, on the other side, expressed less confidence in weather forecast values (especially precipitation values) and therefore rely more heavily on weather stations or field observations before adding SS problems. Timing and availability of data associated with avalanche observations is another example of where information sources vary. For example, some Glacier forecasters noted the value of access to immediate information from avalanche detection networks used by their highway program that can provide data with exact timing even during low visibility periods. In contrast, an AvCan forecaster noted the two-day delay on avalanche observation data from when it is observed in the field to receiving it and making use of the information for the upcoming forecast period. Despite avalanche observations being relevant to both situations, the delay in information could foreseeably result in different avalanche problem forecasts in some cases even if the actual conditions were similar.

Software constraints

The structured workflow that Canadian forecasters use in their daily assessment process is supported by software platforms such as AvalX (Statham et al., 2012) and AvID (K. Klassen, personal communication, 2022). Both of these platforms provide forecasters with an interface to complete hazard assessments following the CMAH and publish select components of the more detailed assessment into the public bulletin that recreationists see. AvalX was developed by Parks Canada (Statham et al., 2012) and has been in operational use by Parks Canada and Avalanche Canada since the winter of 2011/12. AvID is currently being developed by Avalanche Canada (K. Klassen, personal communication, 2022), and Avalanche Canada has been using the system to produce their avalanche bulletins since the 2019/20 winter. Parks Canada plans to switch to AvID in the winter of 2022/23 (G. Statham, personal communication, 2022).

One of the most prevalent system constraints discussed across all interviews is the maximum limit of three problems that can be simultaneously listed within the public bulletin. While this constraint aligns with forecasters' desire to keep communication simple and easy to comprehend for users, it can force the grouping of problems in some situations. This highlights how system constraints can shift the criteria typically used to identify problems even within the same region due to the number of other problems that simultaneously exist. For example, if more than three problems exist a forecaster may need to combine several problems that would otherwise be discussed separately. On the other side, one forecaster noted that because the avalanche problem assessment is a key component of their workflow, they could be looking for problems even when there might not be one.

Another system constraint with repercussions for avalanche problem selection is the character limits in AvalX which restrict the length of descriptive text that Parks Canada forecasters (Banff and Glacier) can use in their forecasts. Forecasters wanting to explain the avalanche problem situation more comprehensively mentioned that using more problems can be a workaround as it increases the overall available space to describe conditions that they would otherwise not be able to elaborate on.

Other system constraints

The time when forecasts are issued was less frequently discussed as a system constraint. However, an interesting example of how publishing time can impact which problems are forecast comes from Glacier National Park forecasters, who issue forecasts in the morning whereas other agencies publish their forecasts in the afternoon. It was mentioned that SS problems not anticipated to arrive until subsequent forecast periods might be added early to provide users with more information when planning the evening before.

4.2. Practical implications

The present exploration of the operational application of avalanche problems in public avalanche bulletins in Canada has revealed diverse perspectives on avalanche problem assessment and communication. While previous studies have primarily documented existing inconsistencies (Clark, 2019; Haegeli et al., 2012; Lazar et al., 2016; Schweizer et al., 2020; Statham, Holeczi, et al., 2018; Techel et al., 2018), the more comprehensive descriptions of the considerations underlying decisions about adding and removing avalanche problems presented in this study aim to provide depth to the existing explanation for the observed variability in avalanche hazard assessments. While it is challenging to properly separate actual variability that comes from differences in conditions (which should be reflected in bulletins) from variability that originates in operational or conceptual differences, the studies mentioned above provide mounting evidence of inconsistency in public avalanche bulletins beyond what would be expected due to actual differences in conditions alone. Our results show potential sources of spurious variability in hazard assessments between regions, agencies, and individual forecasters, which can be used as a starting point for exploring possible interventions for improving consistency in avalanche problem assessments. Areas that present potentially worthwhile prospects discussed below include context specific training and guidance that integrates a public communication perspective; decision aids or guidelines that can be integrated into forecast systems at the scenario based scale; and research to develop an improved understanding of specific bulletin user needs.

4.2.1. Training and guidance for the public forecasting context

Formal guidance and training specifically tailored to public forecasting currently does not exist within the Canadian avalanche industry training program framework. While avalanche forecasters typically come into their roles with technical training and experience in avalanche hazard assessment and mitigation through both industry training programs and practical experience in other avalanche safety contexts (14 of 22 interviewed forecasters disclosed a background in guiding), prescribed public risk communication training is not standardized throughout the industry. This leaves individual forecasters and forecast agencies to develop their own risk communication practices which are not necessarily transparent to other forecasters or agencies. Our interviews have highlighted several apparent challenges within the public communication paradigm that potentially could be addressed through training or general guidance.

Although individual forecast agencies and forecast regions carry differing contexts, some challenges associated with operationalizing avalanche problems in a risk communication context appear to be more universal. For that reason, transparent public forecast community wide guidance on the general topics could be valuable to help forecasters answer questions such as:

- Is the primary objective when selecting avalanche problems to provide the most accurate reflection of the hazard conditions or should risk communication objectives be weighted more heavily if they conflict?
- What constitutes an avalanche problem that should be listed in the public forecast? Is a dormant problem still a problem?
- Should avalanche problems in a region be relative to baseline conditions within the region or consistent across all regions?
- Should avalanche problem inclusion criteria shift over time within the same region, for example with respect to the existence or lack of other problems?
- What criteria should be used to order avalanche problems in the bulletin?
- Who are the bulletin users that should be targeted when assessing avalanche problems and which communication tactics are most appropriate to meet their needs?

While these questions might not have straightforward answers, the development of transparent guidance or interagency training opportunities for public forecasters to share their practices and perspectives about these kinds of topics could alleviate some inconsistent views that emerged in the present research.

4.2.2. Decision aids and guidelines

To address inconsistencies at a more granular level, more involved interventions are likely required. Approaches to reducing noise and bias in subjective human judgements can include improving decision hygiene by structuring complex decisions, aggregating independent judgements, or developing formal judgement guidelines (Kahneman et al., 2021). The use of rules or algorithms is another method that can eliminate noise associated with human judgment, although in some cases can still be at risk of perpetuating biases (Kahneman et al., 2021). In addition to fostering consistency between existing forecasters, the preservation of scenario specific expertise in guidelines tailored to forecast regions has the potential to support both the development of new forecasters and the recalibration to local conditions for experienced forecasters who move between regions. Localized knowledge elicited through concept mapping has been demonstrated as useful for this purpose in the closely related field of weather forecasting (Hoffman et al., 2017).

In the avalanche forecasting context, the CMAH took fundamental steps towards structuring forecasting judgments into four smaller components that characterize the type of avalanche problem, its location, likelihood, and size (Statham, Haegeli, et al., 2018). However, these smaller components in themselves remain complex judgments, as is demonstrated by variable and sometimes conflicting perspectives described in the present examination of how avalanche problems are identified. Guidelines which decompose judgements into smaller, easier-to-assess components can be an effective way to focus practitioners' decisions on the most relevant cues. Analogous to avalanche forecasting, clinical diagnoses by healthcare practitioners also leverage inductive reasoning (to match specific aspects of a case to a likely diagnosis), deductive reasoning (to provide scientific underpinnings of diagnosis), and abductive reasoning (to identify the best explanation given available information) and can also be prone to cognitive biases (Gilliam, 2019). The use of specific and simple-to-assess guidelines have proven successful at increasing consistency and accuracy in numerous medical diagnostic settings, however guidelines involving vague or ambiguous criteria such as those implemented for psychiatric diagnosis have been less successful (Kahneman et al., 2021). Simple assessment and decision aids developed and applied to more specific applications of avalanche risk management have also proven successful at promoting greater objectivity and consistency. For example, the assessment of destructive avalanche size in Canada is defined primarily based on a subjective assessment of harm that an avalanche could potentially impart on various objects (people, vehicles, structures, etc.) and is supported with simple physical definitions of typical mass, length, and impact pressure (McClung & Schaerer, 1980). A small sample[4] of experienced Canadian forecasters were found by Moner et al. (2013) to be more consistent in both their avalanche size assessments and the importance placed on assessment parameters than European forecasters that were using less explicit and more

[4] sample later expanded as detailed in Jamieson et al. (2014)

ambiguous guidelines. Numerous other examples of targeted guidelines and decision aids in the avalanche risk management domain also exist, including for example the threshold sum decision support tool for assessing DPS avalanches by Conlan and Jamieson (2017) and the Guidelines for avalanche terrain land-use in Canada detailed in Canadian Avalanche Association (2016).

While guidelines and decision aids have the potential to increase consistency between forecast agencies, their development is challenged by the differing system constraints (e.g., available information sources) and actual differences (e.g., due to snow climate). Obviously, the development of consistent guidelines between forecast regions should not come at the expense of accuracy. Research in the weather forecast domain has shown that while lack of consistency (either over time from the same forecast source or between multiple simultaneous sources) can have a negative impact on user trust, it is dwarfed by the impact of inaccuracy (Burgeno & Joslyn, 2020; Su et al., 2021). Development of guidelines or decision support tools for forecasters must therefore find a balance of fostering consistency while remaining flexible enough to be applied in different public forecast contexts. Even where differences in the context of agencies necessitate different approaches to avalanche problem application, collaboration and transparency between forecast agencies during the development of such guidelines could foster consistency including with the broader international public forecast community. Examples of existing guideline documents for the use of avalanche problems in public avalanche bulletins include the avalanche problem type forecast criteria checklist included in the employee manual of the Colorado Avalanche Information Center (Colorado Avalanche Information Center, 2022) and the avalanche problem guidance documents of the United States Forest Service National Avalanche Center (USFS National Avalanche Center, n.d.).

Having active forecasters leading or closely involved the development of any guidelines or decision aids will be critical to operational success. While guidance could be developed for any or all avalanche problem scenarios, forecasters may find the highest value by focusing on more challenging scenarios that currently lack guidance. For example, the removing DPS problem scenario was described as one of the most challenging by forecasters due to the associated high degree of uncertainty and large consequences. Our observations also highlighted that the CMAH does not provide any practicable information for the removal of this problem type. The expansive degree of variability reflected in the amount of time that should elapse without observed avalanche activity also emphasizes the variety of perspectives about whether dormant DPS problems should be removed and reactivated. Furthermore, the personal responsibility and feelings of dread that some forecasters indicated when removing DPS problems could be somewhat alleviated by a tangible and transparent reference to help substantiate their decisions. All of these factors result in a scenario where guidance and a more structured approach to assessment has the potential to both provide value to the forecaster and substantially increase consistency.

The format of potential decision aids could be as simple as a lookup table or checklist including a refined selection of relevant observation types and values for a scenario. Alternately, a more complex system could be developed using algorithms that would allow for the leveraging of additional data sources such as numeric snowpack models. Two approaches that can be used to develop algorithms include data-driven models and expert systems. Recent studies exploring the development of forecasting algorithms have highlighted significant challenges with purely data-driven approaches relying on existing operational datasets that are hindered by noise and bias in human judgements (Clark, 2019; Towell, 2019; Widforss, 2021). The results of the present study, however, can offer valuable insight for how to better use the existing assessment data for these types of developments. For example, by identifying circumstances when the assessment data is more trustworthy and suitable for model development.

Expert systems developed from forecaster knowledge directly also offer a promising alternate approach for developing meaningful algorithms. While the present study aimed to elicit expert knowledge and rules-of-thumb that could be further refined for the application in such a system, the exploratory nature and large degree of variability and between forecasters observed in the present results limit their direct use for the development of expert systems. Nevertheless, the observation types and values relayed within our results can provide a meaningful starting point for the development of more robust expert rules. For example, the present values could be supplemented or confirmed using existing empirical or theoretical values or used to initiate the iterative development of internal forecasting thresholds. The integration of additional considerations such risk communication tactics could also provide more consistent guidance beyond the physical observations.

As relevant observation types and thresholds are being identified, refined, and implemented, tracking observation values of the specific cases where they are applied could also be useful in the development of a frame-of-reference to anchor future judgements against. This would potentially allow forecasters to take an “outside-view” where judgements and their confidence can be calibrated against the statistics of similar occurrences which can temper variability caused by fixating on the narrative that has been developed around a unique case (Kahneman & Lovallo, 1993).

4.2.3. Further research on bulletin users

Forecasters expressed a wide variety of assumptions about users when making avalanche problem type assessments, in some cases leading to conflicting perspectives about how problems should be listed and in what order. Creating a shared understanding of the target user of the avalanche problem type assessments within a region could be an important step towards more consistency. However, the inherent diversity within the backcountry user community and the wide range of bulletin use practices make this a challenging task, although some considerations do exist to assist with this.

The tiered structure of the public avalanche bulletin is designed to accommodate different users (European Avalanche Warning Service, n.d.; Statham & Jones, 2006), and as such, the information within each tier of the bulletin does not need to be optimized to reach every potential user. Rather, each tier can be tailored to those who benefit most from the type of information it contains. The broad array of user considerations and sometimes contradictory targeted communication tactics described by forecasters during our interviews suggest that forecasters currently do not share a consistent perspective of who the intended target audience for the avalanche problem information really is.

Existing and future bulletin user research could assist forecasters in developing a shared understanding on how to approach user considerations most effectively when assessing avalanche problem types. The user typology identified by St. Clair (2019) takes an important step by identifying a class of bulletin users who are most reliant on avalanche problem information. These Type D bulletin users distinguish between different avalanche problem types and use the assessed characteristics of the problem including distribution, likelihood and avalanche size to make decisions (St. Clair, 2019). Additional insights about the link between training, age, and number of days in the backcountry per season with how bulletin information is being used has also been presented by Haegeli (2021). As the body of bulletin user research builds it will likely provide powerful insights for empirically testing and refining the most appropriate tactics for communicating avalanche problems. For example, broader population information about whether users relying on avalanche problems are likely to review the bulletin daily or only prior to each trip into the backcountry could help answer questions about how much of a concern message fatigue should be or if these users are likely to pick up on subtle changes how problems are listed day to day. In the meantime, developing shared guidance that makes user assumptions more transparent could promote consistency between forecasters. Additionally, this could integrate forecaster's local knowledge and assumptions about users in their region.

More targeted research could also provide insights about the utility of the current distinctions between avalanche problem types for recreationists. Practices around frequently grouping certain avalanche problem types together to improve communication raises questions of whether the existing granularity of the North American avalanche problem types provide value to the relevant bulletin users. For example, some forecasters questioned whether users have a sufficient understanding of differing terrain choices for PS and DPS problems. A useful perspective on the PS and DPS problem pair could potentially come from European forecasting agencies where they are communicated under the single problem type referred to as "persistent weak layers" or "old snow" problems (European Avalanche Warning Service, 2017). Simplifying the number of problem types for communication in the bulletin would also potentially reduce inconsistencies between forecaster assessments in the grey areas between problem types.

4.3. Limitations

The new perspective on avalanche problem assessments presented in this research should be considered within the context of the following limitations. The open-ended structure of the concept mapping interviews allowed for the exploration of forecasters' considerations without limiting them to preconceived factors identified by the research team. However, a consequence of the unrestricted interview approach is that beyond the primary focus questions and the scenarios identified in the starting concept maps, the content discussed within each of the scenarios is not uniform among forecasters. Hence, the quantitative frequencies of observation types should be interpreted with caution. Since forecasters were not directly queried about specific observation types, the omission of an observation type in an interview does not necessarily mean that the forecaster discounts a particular observation type.

While our interviews elicited domain knowledge and information on forecasting practices from individual forecasters, it is critical to understand that operational avalanche forecasting is often a distributed activity involving close colleagues within a forecasting team, other avalanche professionals and the wider professional community (Maguire & Percival, 2018). Accordingly, the role and support of peers was commonly cited as a consideration in our interviews. Although concept mapping can be conducted in group formats potentially reflecting the setting of operational forecasting more realistically, individual interviews were preferred to more aptly capture the range of perspectives that exist in this exploratory study. Group dynamics including social influences (Lorenz et al., 2011), and group polarization (Myers & Lamm, 1976) have the potential to amplify certain perspectives in operational settings beyond the values that were shared in individual interviews.

Recruitment of participants in this study focused on experienced forecasters who were more likely to have developed expertise that would lead to the effective elicitation of expert domain knowledge. On average forecasters in our study had 19 years of experience working in the avalanche industry and 11 in the role of a public forecaster. It is important to recognize that this level of experience is not representative of the full public forecasting population even within the forecasting agencies in western Canada. Given that many forecasters specifically highlighted the importance of their personal experience for their avalanche problem assessment practices, we anticipate that less experienced forecasters could have considerably different perspectives on important physical observations types and additional considerations. This means that the variance presented in this study likely underrepresents the true range of perspectives and practices in the public avalanche forecaster community.

Chapter 5.

Conclusion

Avalanche problems have become an integral element of avalanche hazard assessment and communication since the introduction of the CMAH (Statham, Haegeli, et al., 2018). However, without an explicit link defining the relationship between specific observations and avalanche problems, avalanche problem assessments are reliant on the subjective judgements of avalanche forecasters that are prone to noise and bias. Several recent studies including Clark (2019), Lazar et al. (2016), Statham, Holeczi, et al. (2018), Schweizer et al. (2020), Techel et al. (2018) have shown considerable inconsistencies between avalanche hazard assessments presented in public avalanche bulletins.

To address this challenge, this study aimed to develop a comprehensive understanding of the range of factors that public avalanche forecasters in Canada consider when adding or removing avalanche problems from the public avalanche bulletin. We interviewed twenty-two experienced forecasters from four different avalanche forecasting agencies (Avalanche Canada, Glacier National Park, Banff, Yoho and Kootenay National Parks, and Kananaskis Country) and used concept mapping to represent observations and other relevant considerations. Interviews either focused on storm slab (SS) and wind slab (WS) avalanche problems, or persistent slab (PS) and deep persistent slab (DPS) avalanche problems.

Our interviews revealed a wide range of physical observations and additional considerations that forecasters take into account when making decisions about avalanche problems. While some of the observed variability can be attributed to true physical differences between forecast regions related to terrain or snow climate, others originate from personal perspectives on risk communication objectives and tactics, approaches to dealing with uncertainty, and the attributes of the systems that forecasters operate within. Risk communication practices including grouping avalanche problems, communicating the progression of a problem, tactics to highlight key bulletin messages, and consideration of bulletin users were consistently mentioned by forecasters. However, forecasters' perspectives on how avalanche problems should be used in light of these considerations diverged considerably and were sometimes contradictory. Similarly, all interviewed forecasters expressed challenges with uncertainty in their forecasting judgments, but individual comfort levels and personal approaches for dealing with the uncertainty revealed discrepancies. System constraints, such as differences in available information, emerged as another source of variability in forecasting practices. Notably, this includes the necessary reliance on substantially different streams of information for field-based and office-based forecasting approaches. Other relevant system factors included software constraints such as the maximum of three avalanche problems that can be simultaneously listed or character limits on forecast text, both of which forecasters described a variety of workarounds in their problem selection to improve communication.

The operational forecasting practices described in this research highlight likely sources of the forecast inconsistencies that have been reflected in other studies but also offer a meaningful starting point for exploring avenues to address them. While physical differences in conditions and many system constraints related to the availability and quality of data are forecast operation specific and associated challenges need to be managed locally, practices related to how forecasters shape their risk communication messages and how they cope with uncertainty are more general issues that span agencies and forecasting operations.

One of the possible approaches for addressing the observed differences would be to increase the available guidance and training on the operational application of avalanche problems in public forecasting. For example, forecasters seemed to have diverging opinions on how to balance the objectives of using avalanche problems to provide the most accurate representation of hazard conditions versus prioritizing effective public risk communication. The information included might differ considerably based on the perspective of the forecaster who drafts the avalanche bulletin. Developing a common vision about these types of questions and designing supportive guidance or training to address them has great potential to create more consistency among public avalanche forecasters.

Our results also highlighted that removing problems is particularly difficult for forecasters, and the personal thresholds and approaches for making decisions under these circumstances vary considerably. This is particularly prevalent in the high uncertainty scenario for removing DPS problems where relatively few considerations were revealed and amongst them wide ranges of values and contradictory risk communication perspectives. We believe that public avalanche forecasts could benefit considerably from guidelines or decision aids specifically developed for decisions around the removal of avalanche problems. The observation types, values, and additional considerations identified in this study provide a meaningful starting point for exploring relevant considerations that could be included in such guidelines. Developments in this area could be further supported by research examining patterns in datasets that forecasters use as inputs. For example, an analysis of how much time typically elapses between the last avalanche observation associated with a problem reported in the InfoEx and when the problem is removed could provide valuable and complementary insights for developing forecasting guidelines.

In addition to contributing insights for the development of enhanced guidelines and training directly, the results of this research also provide critical contextual information for the data-driven design of new algorithms or decision aids based on datasets of past avalanche problem assessments. While past research in this area has been hampered by the inherent noise in human judgment data, the insights on operational practices presented in this research can help to better interpret the available information and explain discrepancies between physically based expectations and the problems included in the bulletin. While it is difficult to retroactively eliminate the non-physical operational influences on the dataset to a degree that would facilitate a fully data-driven development approach, the insight presented in this research will allow the operational data to be used more meaningfully for validating algorithms and decision aids that have been developed through other means.

Since the avalanche forecasters in this study expressed a wide range of different perspectives about their users, we strongly believe that continued research into bulletin users, including how they interpret and apply the avalanche problem information presented in the bulletin is critical for making avalanche bulletins more consistent and effective. Further insights in this area will clarify the characteristics and needs of the diverse avalanche bulletin audience allowing forecasters to optimize their communication tactics.

While our research and recommendations have focused on public avalanche forecasting and the communication of avalanche hazard to the public, similar operational challenges and inconsistencies in the application of the CMAH likely exist in other avalanche forecasting applications and potentially hamper the communication of avalanche hazard among avalanche professionals. Considerations around public communication observed in this study are clearly not applicable to other forecast applications, but these forecasters could be influenced by other contextual and organizational factors such as internal practices for tracking weak layers or operational practices that integrate the existence of specific problem types. A better understanding of how avalanche problems are used and the range of factors that influence assessments could assist avalanche professionals across applications to interpret the information shared on platforms like InfoEx more efficiently and effectively.

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