FORMATION TO RECALIBRATION – HOW MENTAL MODELS ARE FORMED, UPDATED, AND SHARED IN AVALANCHE FORECASTING WORK.

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ABSTRACT: Avalanche forecasting represents complex cognitive work (McClung, 2002; Adams, 2005; Maguire & Percival, 2018), but much of the understanding of mechanisms used to carry out this work remains underspecified. Research suggests forecasters use mental models to apply their knowledge, along with currently available information, to reason about snowpack stability and the implications for their goals and objectives. This framing leads to the questions: How do forecasters' mental models form and recalibrate over time? How are faulty mental models identified? In addition, model updating is an inherently collaborative activity with the benefits of formal mentorship and networks of multiple, diverse perspectives being particularly valuable (Latosuo & Johnston-Bloom, 2018). Because of this, we ask: How does collaborative model updating work in practice? What strategies and practices aid in collaborative model updating? What role does mentorship play in model updating? This paper uses a literature review, secondary research, and focused discussions to examine the role of mental models, triggers for model updating, and collaborative model updating in avalanche forecasting work. In addition, it interprets these findings to propose recommendations that support and enhance knowledge sharing and learning within avalanche forecasting organizations.

KEYWORDS: mental models, mentorship, learning, team, knowledge sharing, updating

1. INTRODUCTION

Research has shown that avalanche forecasting is cognitively demanding work (McClung, 2002; Maguire & Percival, 2018). Accurate forecasting requires substantial knowledge of meteorology, snow science, terrain, regional variability, and hazard exposure to interpret risk and develop appropriate communication and mitigation measures. The mountain environments in which forecasting activity takes place are dynamic, with factors that make prediction challenging (Hoffman et al., 2017).

There is evidence to suggest that snow safety professionals rely on mental models (MM) to reason about stability implications and potential problems in the snowpack (Adams, 2005). Studies from other cognitively demanding work in complex, dynamic environments show that these MM are partial and incomplete (Woods et al., 2010; Feltovich et al., 1996). Acknowledging this raises questions about how MM are used—specifically, how practitioners recognize when they need updating.

In addition, because career progression through the avalanche profession is highly variable and underspecified, mentorship and collaborative sensemaking are common. Practitioners rely on peer-to-peer learning and mentorship to recalibrate.

This paper uses a literature review, secondary research, and a focused discussion of the role of MM, triggers for model updating, and collaborative model updating in avalanche forecasting work.

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2. MENTAL MODELS

Mental models have been described variously in the academic and trade literature as follows: “an internal representation of an external reality, based on learning and experience.” (Stepanov, 2018); “our cognitive assumptions about how the world works. They represent our beliefs about how things are related and what actions cause which results.” (Causeit, n.d.). The concept is not without critique (Hoffman & Klein, 2008). Still, empirical studies have shown it provides a helpful reference for studying ‘cognition in the wild’—that is, real people conducting real work in ambiguous, uncertain environments (Nowak et al., 2022).

Conversely, Cannon-Bowers & Salas (1991) note that “the mental model construct [describes] how humans organize observed information into patterns that reflect the relationships that exist between concepts and the features that define

them." The organization of information into a MM provides an efficient means to activate knowledge from memory that aids in comprehending meaning, drawing inferences, predicting future outcomes, and determining appropriate actions given the goals, priorities, opportunities, and constraints of a given environment. Content of the MM comes from formal education or structured learning experiences, or in unstructured or informal means such as reading, discussion, and through perception and experience of events in the world.

Utilizing MM in dynamic environments to understand dynamic processes necessarily requires them to change dynamically and in real time. Buckley (2000) states that model updating "is a dynamic, recursive process of learning by building mental models. It incorporates the formation, testing, and subsequent reinforcement, revision, or rejection of mental models of some phenomenon." (Fig. 1)

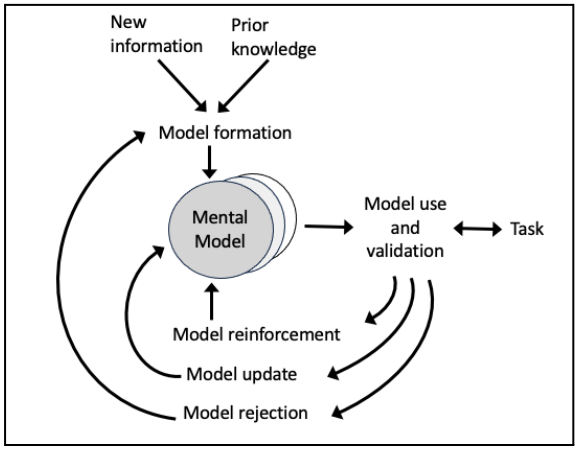

Figure 1. Mental model learning framework, adapted from Buckley (2000)

But, as Woods et al. (2010) point out, "mental models can contain inaccurate, incomplete, or flawed understandings. This is especially true with advanced knowledge acquisition of difficult material in ill-structured domains (Spiro et al., 1992). Jones, Ross, Lyman, Perez & Leitch (2011) note that "conceptualizing cognitive representations as dynamic, inaccurate models of complex systems acknowledges the limitations in peoples' ability to conceive such complex systems." Because of this, one might assume studying MM has limited utility, but as Klein & Hoffman (2008) point out, "these compact accounts permit them to track causal structures and get the gist of key relations without getting swamped by details. Thus, mental models can be thought of as lean cognitive representations rather than cracks in the veneer of rationality."

It's worth stating more plainly that having a miscalibrated MM in avalanche forecasting is not a sign of incompetence but rather of the continuously changing and complex domain in which forecasting takes place.

So how do forecasters recognize when their MM are wrong or incomplete, and what do they do to correct it?

3. MODEL UPDATING & RECALIBRATION

Given that mental models are partial and incomplete, three key guidelines emerge: 1) continuous updating is a needed and ongoing function of practice, 2) there are many triggers for model updating and recognizing these can improve personal and team model calibration, 3) having opportunities for sharing MM with others is critical.

3.1 Updating in practice

The knowledge requirements are high with such a complex phenomenon as snow stability. Coupled with a relatively short training period, most practitioners recognize the need for continuous updating or on-the-job learning. However, not all work environments have the same opportunities for continuous updating.

In addition to a general need for ongoing knowledge acquisition to elaborate one's MM, the underlying knowledge needs to be calibrated or fine tuned if it is inaccurate or incomplete. The opportunity for updating in this way is directly related to specific problems encountered or experiences in everyday work. This means updating happens in an ad hoc or opportunistic way and that incomplete or inaccurate understandings can persist unnoticed for long periods of time in one's career.

Lastly, there is a multi-layered time component to ongoing model updating. The need exists in the moment-to-moment, day-to-day, over the season, and across a career. In moment-to-moment updating, new information about *current* conditions is critical for real time sensemaking - integrating new information helps answer questions, "Is this terrain safe enough for us to keep for the public today?" Day-to-day updating helps with anticipation and planning to address needs, such as when a helicopter operation is determining how to safely manage terrain for multiple groups when there is an incoming storm cycle. Over the season, model updating could be deciding if a language choice in a public forecast created message fatigue or understanding that a crust formed in November became the layer of concern for the shed cycle in April. In addition, models are refined over a career where new experiences and data are

seen as patterns that are integrated into a more abstract understanding. For example, an experienced practitioner can recognize signs when a coastal climate may behave more like a continental climate to make better inferences about the patterns of avalanches likely to occur.

3.2 Opportunities for sharing mental models

Given that mental models are inherently partial, incomplete, and faulty in some way) and are expressed in environments with high spatial and temporal variability (Schweizer et al., 2008), the forecasting domain requires *collaborative* model updating.

Specifically, the concept of collaborative cross-checking for correctness (Patterson et al., 2007) is useful. Collaborative cross-checking is defined as "a strategy where at least two individuals or groups with different perspectives examine the others' assumptions and/or actions to assess validity or accuracy." It has been shown to provide benefits such as revealing hidden assumptions or incorrect beliefs about a situation; identifying information gaps, unintended side effects of a decision or action, and boundary conditions or contingencies.

It's worth noting that while model updating is a critical and generally accepted requirement of forecasting work, opportunities to do so can be constrained by operational realities (time pressure), a lack of available resources (peers are too busy, not experienced, or not reachable), culture (a lack of knowledge sharing, high competition, etc.), personal beliefs (being worried about being seen as incompetent).

4. IDENTIFYING PATTERNS OF MODEL UPDATING

To identify patterns of model updating in avalanche forecasting, we first conducted a literature review to frame the problem in the wider body of research into complex work in dynamic operational environments.

In the spirit of this conference—merging theory with practice—we conducted a series of focused discussions between the authors to facilitate a reciprocal knowledge elicitation and generative analysis. Early discussions were led by the research engineer and focused on the findings from the literature review. Relevant theoretical topics were presented to the group to shape discussion and inform the application of theory to the avalanche domain. From these discussions, we developed a series of 30 keywords and conceptual frames to search the secondary data.

The secondary research consisted of interview data from prominent mentors (Latosuo & Johnston-Bloom, 2018). The keyword searches were used to look for evidence on MM recalibration emerging from mentorship relationships, often referenced as crucial pathways for knowledge exchange and professional development in the avalanche industry. The secondary analysis was completed by looking for thematic material that relates to MM building and calibration using both qualitative data analysis software (NVivo 14.23.0, 2023) and open coding. The 30 codes about MM upgrading were then organized into the seven emergent categories of Sharing, Asking/Not Knowing, Mistakes, Uncertainty, Changes, Career Path, and Surprise.

The discussions on the secondary research findings were led by the avalanche professionals. These discussions moved through varying levels of abstraction - from the general (theoretical foundations) to the particular (specific examples) - to connect broader patterns of MM to avalanche-specific contexts. The team reviewed the data from a specific keyword search, analyzed its implications in the broader conceptual framework, and then grounded it by eliciting examples and experiences from the field. This is in alignment with Cassirer (1954), "It is.. the fundamental principle of cognition that the universal can be perceived only in the particular, while the particular can be thought of only in reference to the universal."

5. RESULTS & DISCUSSION OF PATTERNS

Several patterns emerged through the analytical process as being important to collaborative model updating. These correlate to the categories from the secondary research coding with several overlapping in different patterns.

The first relates to the nature of the work and industry driving the need for continuous updating. The second relates to triggers or moments of recognizing that there was a need for changing or examining one's MM. The third was opportunities for sharing and model updating.

5.1 Dynamic knowledge acquisition - the need for model updating

Categories of changes, sharing, and career paths formed the first pattern, which represents systemic factors that contribute to a need for ongoing updates to one's MM.

In half of the interviews, participants touched on the idea of 'not knowing everything' and needing to have humility in what one can actually know. The realization that mental models are both incomplete and that the knowledge in the field

remains one of discovery, was captured by a participant who said,

"*You can't know everything, and that's not a reasonable thing to even set your mind toward."*

This points to a fundamental truth about the need to continually be learning and revising one's MM. Other participants echoed this:

"I'd ask different people what they thought about this, that, or the other thing, and a lot of times people would say, 'Well, I'm not sure,' or, 'We don't know.' "

"The more that people share, especially people that have been through really big avalanche cycles or really unusual conditions… It helps you to take another little step backward to realize some of the things that you don't know. And there's a lot we don't know."

The seasoned professionals have a more realistic understanding of the limits of their knowledge about the complex and dynamic avalanche risk environment. This attitude can be related to recognition of the bounds of their current MM and of the motivation to recalibrate faulty or spotty models.

"I learn on a regular basis… An expression we use at [operations] *a lot is 'lesson delivered.' The context of that is it's quite incorrect to say 'lesson learned' because 'lesson learned' would indicate that you're not gonna make the same mistake again. 'Lesson delivered' is an expression for the lessons that we get frequently for the mistakes that we make repeatedly."*

This statement speaks to the nature of knowledge and applying that knowledge in dynamic environments. There are important nuances of how knowledge and practice can be applied, and practitioners must be flexible and alert to the need for model updating.

5.2 Model formation and career progression

What also underscores the incompleteness of mental models is the career path of the industry itself, as the training requirements are relatively low given the complexity of the avalanche phenomenon and how the knowledge acquisition path is underspecified.

One participant described it as such:

"...Our training is too short. You look at becoming a professional lineman or an electrician or a plumber; you're looking at a 4,000-hour apprenticeship. And throughout that, you have formal classes, you have examinations, you have a lot of on-the-job training, and then you become a journeyman, and then you have another 4,000 hours to get to the master process. For better or worse, we're looking at a profession with 13 days of formal training from start to finish."

This sentiment was elaborated on by another experienced practitioner:

"For some people, the avalanche industry's a little frustrating. They'll want to get into the avalanche industry, but there's not a really simple path all the time… There's a lot of different paths to get there."

In essence, there is a recognition that the 'scaffolding' of one's initial MM—established largely through participants' own experience and a brief formal training—is lightweight. Indeed, one of the authors recognized the degree to which their first job following training - an internship - influenced the early formation and updating of their own MM, stating, *"The forecasters had very different approaches to forecasting, and each delivered guidance and feedback in ways that were equally valuable. The contrast of being told to* ***feel*** *the snow under the skis and [also] pressed to clearly* ***explain*** *the science of rounding facets provided a foundation in developing intuition and articulating fundamental processes."* [emphasis added]

A second participant recognized that *"having mentors that were willing to share their experiences allowed me to develop my sense and my knowledge at a more rapid rate than if I had just cast out on my own and started blindly going into this field."*

While it is clear that model updating is a necessary and required part of operating in the avalanche world, there remains an unclear progression.

Further, having access to those who can help support model updating through on-the-job training or mentorship, while crucially important, is highly variable in its content and quality and not guaranteed.

5.3 Triggers for model updating

Recognizing the need for model updating was evidenced by examples of asking questions and 'not knowing,' mistakes, and sharing. There were a number of ways in which knowledge sharing and collaborative model updating was triggered in the professional forecasting context, some self-identified, others externally driven. Consider the following example:

"There was a day when I did a control route and walked across a slope feeling nervous about it. Then, the next day, coming back with a different approach and triggering a very large avalanche. I talked to [mentor] *about that that evening. His*

basic question for me was, 'How do you feel about walking across that thing yesterday? Was that a good idea?' I tried to make a lot of excuses for why I knew exactly what I was doing. I think he mostly just laughed at me.

It was a really good lesson in understanding the risk that we were taking and the importance of looking back at your decisions and reexamining them... That was something where I adjusted my risk tolerance."

It is clear the participant recognized some uncertainty in their choice, as did their mentor. However, when (gently) pressed, they discounted the mentor's observation. Only after reflection were they able to revise their assessment of the conditions.

This example is indicative of several overlapping triggers for a model update.

The research showed four distinct triggers for model updates:

Identifying a knowledge gap: when lacking specific knowledge, local context, or understanding of dynamics.

"*I was probably pretty annoying as a ski patroller ... with a lot of the older ski patrollers. Cause you get on the ski lift with them, and I'd always be playing the 'what if' game with them. I'd say, 'Well, what do you think would happen now if it snowed another foot of snow? Or what do you think would happen now if we had clear weather and then it snowed? Or what do you think would happen now if this happened or that happened?' I was always asking questions."*

Identifying a knowledge gap can also be perceived by, or initiated from, working collaboratively. Traditionally in mentoring relationships, a more experienced practitioner notices and highlights a more junior practitioner's knowledge gap. However, the exchange itself can be a catalyst for self-identification.

"A mentee would ask a simple question, and you think you have the answer to it, but then once you start really discussing it, you realize, there's a lot of gaps in my knowledge, and I need to go back and make sure what I thought about all this time is accurate. Or if it's not accurate, maybe it's impossible to be accurate."

Receiving or providing a critique: when one party has more knowledge or context than another, and they are engaged specifically to critique the interpretation and sensemaking of another.

In describing the importance of the feedback loop, one participant underscored the need for *"...somebody to have those conversations with that can take the time to not necessarily come up with answers, but just sort of sharpen the pencil on if we're actually doing a good job out there or not."*

Engaging in a collaborative model update: when both parties have deep expertise, but the nature of the problem or conducting the forecast is complex and ambiguous, and a high degree of uncertainty exists.

"*It's been a big thing for me, looking and having dialog and understanding how different people are seeing the same thing, whether it be having similar or different opinions on it."*

Experiencing a surprising or unexpected event: when one party or group experiences an event that caught them off guard.

"The whole process of trying to figure out why a certain path avalanched and why it didn't do that anywhere else is where all the learning comes from."

The analysis of triggers for model updating clearly indicated that, while it may not have initially been a joint activity, the efforts to 'fill the gap' most certainly were.

5.4 Knowledge sharing

There was a consistent overlapping pattern relating to knowledge sharing and collaborative model updating in all categories- Sharing, Asking/Not Knowing, Mistakes, Uncertainty, Changes, Career Path, and Surprise.

For example, all the interviewees (n=11) mentioned the importance of sharing experiences with other professionals as they develop their own competencies in the workplace. Their reflections included language about sharing information, observations, or experiences and explanations about phenomena in mixed geospatial scales. Having dialogue with people with varied perspectives made knowledge accumulation faster and helped target the focus of learning. This dialogue was particularly beneficial when there was a high level of diversity amongst the parties involved —including professionals from other operations and even different snow climates as they provided valuable ways to look at the conditions. This sharing aligns with the function of revising and updating the current MM by comparing and contrasting the information from self and others. One participant described this as:

"It was seldom that he would give a simple answer to a question. He more often challenged me to reason my way through it, more valuable than just coming up with the answer or getting the answer spoon-fed to you."

Maintaining long-term connections and distinct communities of sharing professional knowledge is deemed beneficial, especially when the conditions reveal something unusual or unexpected, as shown in the following quote:

"Having those career-long connections with other people to share information and talking to people who live in different snow climates and different operations and have these different perspectives… I think it's really advantageous to talk to people who are dealing with different sets of problems."

Model recalibration can be around the technical knowledge itself or in applying that knowledge to what 'good practice' may be. For example, a participant described an experience where a colleague had reframed an action he was about to take relative to their long-term objectives.

"It was probably graupeling at three to four inches [7-10 cm] an hour; it was a pretty intense storm. I was trying to go down a route that I'd done before that was definitely ripe for avalanching.

I was picking my way through it as a heli-ski guide where you can work from this point to this point, 'We can ski cut here, and everything seems ripe enough that we can easily mitigate our way down.' [He] pulled me back and said, 'You know you could probably pull this off, but what message does that send to our students when they see similar conditions where it's snowing at three to four inches [7-10 cm] an hour? Is this the behavior that you want them to do?' "

All the interviewees referred to the value of identifying and openly discussing mistakes that had happened in the workplace. The humility about being wrong can assist in developing a culture of continuous learning without blame or unconstructive critique and lead to improved updating of shared mental models.

6. STRATEGIES FOR COLLABORATIVE MODEL UPDATING

Latosuo & Johnston-Bloom (2018) noted that organically formed knowledge sharing was the norm in the avalanche industry. Therefore, we have compiled some practices from this research to give forecasters lightweight methods to integrate into their everyday work.

6.1 Individual strategies for model updating & calibration

Practicing metacognitive strategies such as focused reflection, identifying knowledge gaps, recognizing triggers in oneself and others, and continually eliciting feedback is advised. In early career development, model updating should focus on both knowledge content and the dynamic relationship between concepts. Playing the 'what if' game described by the 'annoying' novice example is highly valuable for learning as it focuses on content and relationships, allowing one's MM to become richer and more accurate. Specifically, one can be opportunistic about things like informal locker room debriefs or happy hour "shop talk" to practice articulating one's MM in detail. Using language like "Here's what I knew…" or "It wasn't clear to me how…" and explicitly noticing the boundaries of one's MM can encourage others to recognize their own boundaries and/or to help 'fill the gaps' for the individual sharing.

In addition, seeking out (and providing) rich descriptions of complex cases, accompanied by descriptions of the reasoning (even if it turned out to be wrong), helps develop greater levels of correctness, completeness, and complexity in knowledge organization. Both the practices of reading cases, as well as writing them, offer a chance to identify knowledge gaps and update faulty or incomplete MM.

6.2 Team strategies for model updating & calibration

Reciprocal aiding of collaborative mental models comes from recognizing trigger patterns and actively engaging in collaborative model updating. Using prompts like "Walk me through how you think about X…" or "I've realized my understanding of Y is fuzzier than I'd like it to be. Can we discuss it further?" can allow for broader discussions than more targeted questioning may. Given the prevalence of the fear of looking incompetent, it can be helpful to create conditions for learning when more experienced forecasters make their MM explicit to allow others to recognize gaps in their own MM that they may have difficulties identifying.

Bigger picture strategies of maintaining a well-calibrated MM included maintaining a diverse set of relationships over a long-term basis. This occurs in formal mentorship arrangements and simply maintaining connections by making ongoing networking and relationship management a part of one's professional practice.

6.3 Organizational supports to aid model updating & calibration

Most avalanche operations have regular meetings to discuss snowpack conditions and

forecasting challenges. Formats may differ, but the emphasis on sharing knowledge is universal. These varied daily meetings support information exchange between forecasters, guides, and educators and utilize industry-wide frameworks to organize the information, such as the Conceptual Model of Avalanche Hazard (CMAH) (Statham et al., 2018). An integral part of risk management protocols, morning (AM) and evening (PM) meetings are usually mandatory for all staff.

These meetings often use digital platforms that make sharing visual representations possible - or artifacts- of information, decisions, plans, or actual terrain choices or snow conditions, such as photos, Google Earth imagery, and GPS tracking.

Several strategies can aid in collaborative model updating related to a) the structure of the meeting, b) the ways in which information and materials are presented, and c) encouraging ad hoc and emergent exchanges in addition to the meeting.

The structure of the meeting

Structuring the meetings to begin at the level of new forecasters and build up to more sophisticated levels of knowledge is an established practice within many safety-critical operations. Other high knowledge domains—such as with medical rounds—start with the junior colleague establishing the baseline for the discussion, and then added nuance and complexity are built from there. This practice tries to avoid 'leaving anyone behind.' A similar example from the industry is that new staff members are encouraged to arrive at the meeting with an opinion and to speak up. In a conversation about a forecaster meeting, one staff member commented that it was not uncommon to show up thinking one thing to start the meeting and leave, coming to a completely different conclusion. (personal communications, B. Lazar and J. Konigsberg August 23, 2023)

The presentation of information

Information artifacts play an important role in creating more consistent shared mental maps of operational knowledge and procedures as they create an external shared frame of reference for all parties. A physical artifact makes explicit underlying assumptions, beliefs, and knowledge. They are tangible and concrete instantiations of ideas, decisions, and actions that provide an external reference. They can also be referred to at later points in time, aiding memory and recall, and are especially helpful in passing information between more experienced professionals and newer guides.

The images and maps can be annotated to add more details or to target focus. Visual sharing is especially helpful for mechanized guiding companies that have limited opportunities for staff training, short seasons, and high-performance pressure (personal communications, H. Munter, August 23, 2023).

6.4 Industry considerations

Opportunities for cross-boundary exchanges

In Southcentral Alaska, since 2015, the Chugach Avalanche Center has been hosting weekly stability meetings during the winter months, where local avalanche professionals from Alyeska Resort, the Alaska Department of Transportation, Alaska Railroad, Chugach Electric Association, Chugach Powder Guides, and other guiding and educational services get together to share information. It provides a venue for questions, observations from a range of operations, and a mixing of generations of avalanche professionals with unique perspectives.

We have described the value of case studies (as presentations or journal articles) and recommend a stronger emphasis on sharing lessons learned—even from early career practitioners. Increasing the availability of forums for more diverse groups of professionals to share observations and operational lessons from unusual seasons, big events, and complicated forecasting problems can help others recognize similar patterns and key into heads-up situations. Similarly, reading past season summaries, looking at accident reports, and talking to more experienced professionals can illustrate the potential in terrain where one's personal tenure has been more benign. It may be useful to offer training on how to write up and/or present cases to encourage more professionals to do so.

7. CONCLUSION

This analysis used multiple overlapping methods to show the importance of collaborative model updating—particularly in early model formation. In addition, several triggers for updating were noted. Triggers were shown to be a function of metacognitive efforts, interactions between peers, and as a result of surprising or unexpected events. Mentorship was seen to be an important aspect of model updating—for the ability to elicit information and critique directly but also because of the need to make one's thinking explicit to others. A variety of practices—drawn from other complex domains and examples given in the literature—were provided to aid readers with lightweight, practical

suggestions for integrating this research into their everyday work. Future research into the content and timing of collaborative model updating provides a rich opportunity to further explore skill and knowledge acquisition in professional avalanche forecasting.

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