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# The Elements of Applied Avalanche Forecasting Part I: The Human Issues

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**Abstract.** Avalanche forecasting has traditionally been defined from the perspective of a geophysical problem with respect to the state of stability of the snow cover. In this two-part treatise, avalanche forecasting is described in a broader sense by dividing it into seven inter-connected elements: I. definition; II. goal; III. human factors and perception; IV. reasoning process; V. information types and informational entropy; VI. scales in space and time; and VII. decision-making. Part I (this paper), contains the first four elements which are mostly about the human issues and Part II (the following paper) contains the last three elements, which are mostly about the physical issues, and some basic Rules of applied avalanche forecasting. A principal thesis is that all seven elements must be mastered for optimal avalanche forecasting. In addition to the seven elements, the connection to avalanche forecasting as an exercise in risk analysis is made. Inherent in the argument is that avalanche forecasting is a dynamic problem dealing with variations and interaction of a human (avalanche forecaster) and natural system (temporal and spatially varying state of instability of the snow cover). The primary result of the two papers is a first attempt to formally integrate human influences with a new interpretation of the geophysical problem. Since most avalanche accidents result from human errors, no description of avalanche forecasting is complete unless the human component is addressed.

**Key words:** snow avalanche forecasting, human biases, risk assessment, human perception

## 1. Introduction

Forecasting is a discipline concerned with prediction of current and future events. Familiar examples include weather forecasting, forecasting the state of the stock market or stream flows and river floods. In general, prediction is one of the most difficult activities that humans attempt. Weather forecasting, for example, after decades of research and considerable money spent is still not at the precision desired. It is convenient to classify forecasting problems into three rough categories: (1) problems involving primarily natural systems in which variations may or may not be random; weather forecasting is an example. (2) Problems involving primarily human systems in which variations are mostly not random; stock market forecasting is an example. (3) Problems with both human and natural systems interacting, characterized by random and non-random variations; avalanche forecasting is such a problem. It is not possible to exclude human influences from any type of forecasting so that forecasting for natural systems may include human influences.

In avalanche forecasting, human influences as well as the temporal and spatial variability of the snow cover must be dealt with. For example, human experience is important in avalanche forecasting not only to evaluate the state of the snow cover but also to aid decisions and to help avoid dangerous human biases and to make objective forecasts. Most fatal accidents today in North America and western Europe are caused by people triggering the avalanches themselves. This implies that the root cause of many such accidents is a failure in human perception: people thought the stability (or risk) was something other than it actually was. Similarly, accidents involving people in villages in Iceland, Turkey or India (McClung and Schaerer, 1993) may involve lack of proper forecasting and warnings which can imply poor perception. Therefore, the human element is crucial in avalanche forecasting and it deserves formal integration into the prediction and decision-making process. Since avalanche forecasting ultimately contains decisions involving the chance of death or losses, it is formally equivalent to a risk analysis.

The papers (Part I and Part II) constitute a first attempt to define the important elements of avalanche forecasting and to show linkages between them. The papers deal mostly with integration of the human (Part I) and physical (Part II) aspects of avalanche forecasting and the relation of the elements of avalanche forecasting to risk analysis. Therefore this treatise is not about how to forecast avalanches, rather it is an attempt to break avalanche forecasting into elements and to show how the elements are connected. The approach has far-reaching implications which allow estimates of the chance of success of models. Numerical and symbolic computing models as well as public warning scales (McClung, 2000) will have better chances of being useful if they are constructed with attention to the seven elements of avalanche forecasting. Part I and Part II deal mostly with applied avalanche forecasting in which the results of forecasts by field-based personnel (including back-country travellers) are directly applied to make decisions that affect people and facilities that may be threatened. Forecasting by office-based people resulting in large-scale bulletins which are passed to decision makers is mentioned but not strongly emphasized.

The applied avalanche forecasting (called avalanche forecasting hereafter) process implies decision-making following the prediction. This provides its formal link to risk analysis. Avalanche forecasting is not simply confined to estimates of instability, it is connected to decisions and the inherent risk associated with those decisions. Risk can be taken as the probability (or chance) of death or losses and, on reflection, an evaluation of risk is, indirectly, the end product of the avalanche forecasting process with decisions attached. Adams (1995) breaks risk analyses into two categories: (1) engineering analyses based on formal application of statistical principles such as for land-use planning in avalanche terrain (e.g., Keylock *et al.*, 1999) and (2) subjective, judgemental, dynamic, time dependent analyses mostly with inductive reasoning and an intuitive element which is difficult to reduce. Avalanche forecasting falls mostly within category 2, and the decisions which result flow from a category 2, analysis. The two classes of risk analysis are not separate. For example, a statistical computer analysis for avalanche prediction always requires judgemental use of the forecast combined with other factors and human influences.

The treatise is in two parts: I. the first four elements which are needed to illustrate the human issues of avalanche forecasting and in which human influences are formally introduced and II. the last three elements and the rules of applied avalanche forecasting (Appendix A; Part II) which are most closely related to physical issues. The connection between Part I and Part II is done from the perspective of the definitions of the seven elements.

## 2. The Seven Elements of Avalanche Forecasting

Avalanche forecasting has seven principal elements. Understanding and mastery of all seven elements are needed for accurate forecasting, elimination of human biases and construction of models. These seven elements are: those in *Part I*: I. definition; II. goal; III. human/factors and perception; IV. reasoning process; *Part II*: V. information: types and relation to informational entropy; VI. scale effects in space and time; and VII. decision-making. The elements have a character which makes them identifiably separate but they are all completely connected and interdependent in the forecasting process. The definitions and descriptions of the seven principal elements here are such that there is consistency in the relationships between elements. All seven elements implicitly include accounting for terrain. A complete discussion of terrain influences and general snow climate (e.g., McClung and Schaerer, 1993) is beyond the scope of the present paper but important links to terrain are mentioned in Part II.

### I. Definition

Avalanche forecasting is the prediction of current and future snow *instability* in space and time relative to a given triggering level. A major fundamental physical uncertainty in avalanche forecasting resides in the usually unknown temporal and spatial variations of instability in the snow cover including their links to terrain. The definition is in terms of instability rather than the more traditional one of stability (McClung, 2000) because the information sought by people in the process of making a forecast is that about instability. Information which reveals instability is the most highly prized type if it has low uncertainty [or informational entropy (LaChapelle, 1980)]. This aids human perception and reduce the uncertainty.

The triggering level for slab avalanches refers to the necessary deformation energy delivered to the snowpack to generate failures and fractures to release avalanches. In back-country accidents, fractures are often precipitated by dynamic deformation energy during skiing (McClung and Schweizer, 1999); in explosive control, high rate deformation energy generates the propagating fractures. Most slab avalanches release by loading due to new snowfall or blowing snow and, in such cases, loading activates imperfections which become self-propagating fractures (McClung, 1981). Therefore, the triggering level applied is a part of avalanche forecasting and it is part of the definition.

There is the possibility that some dry slab avalanches initiate without the need for an external trigger from added load, instead resulting from slab temperature changes (McClung, 1996) or slowly extending slip surfaces formed in weak layers by strain-softening to eventually produce propagating shear fractures (McClung, 1979). Such events are, from field observation and documented examples, very rare and very difficult to forecast.

The deformation energy needed to initiate slab avalanches depends on the size effects of imperfections in the snow cover and the details of load application (McClung, 1979; 1981; 1987; 1996). Since alpine snow is a highly rate sensitive with respect to shear failure strength and tangent modulus (Schweizer, 1998; McClung and Schweizer, 1999) and it is a strain-softening material (McClung, 1979) there will be macro-scopic size effects associated with failures (Bažant and Planas, 1998) when they become self-propagating fractures. These critical size effects will depend on the loading sequence (including energy and the rate at which it is applied) prior to achieving self-propagating catastrophic fracture (McClung and Schweizer, 1999). Since the location of critical imperfections is never completely known when avalanches are forecast there is always uncertainty, thus avalanche forecasting takes on a probabilistic, risk-based character. Element II (the goal) considers this type of uncertainty as well as other uncertainties in the analysis.

### II. Goal

The goal of avalanche forecasting is to minimize uncertainty about instability introduced by three principal sources of uncertainty: (1) the temporal and spatial variability of the snow cover (including terrain influences); (2) any incremental changes from snow and weather conditions; and (3) any human factors including variations in human perception and estimation. As stated, the goal introduces three primary sources of uncertainty and links them through risk and probability concepts.

From the human perspective, the goal may also be stated another way: that human perceptions about the distribution (temporal and spatial) of instability in the snow cover match reality as closely as possible. This is done by objective analysis using relevant data. Only data that are useful in the analysis (contribute to the goal) should be retained in the analysis. More information does not necessarily improve the accuracy of decisions; instead, more information can increase confidence that the decision will be correct (Makridakis,1990). Makridakis (1990) also argues from empirical findings that there is no relationship between how confident one is and the accuracy of decisions. The only entities that can truly reduce the uncertainty are more (new) information data of the right kind or actions that deal with resolution of variations in human perception. In statistical predictions [either numerical or probabilistic human inductive inferences (Makridakis, 1990)] redundant information will most likely reduce the accuracy of predictions.

LaChapelle (1980) introduced the primary idea that estimates of instability can be arrived at in several ways, particularly when high informational entropy data are used (informational entropy is discussed under element V in Part II; it is related to the relevance and ease of interpretation of data). In general, it is known in forecasting that an average of several estimates is better than one. Using several estimates is also the basis for improved weather forecasting using ensemble averages to deal with the inherent uncertainty in initial conditions as a hedge against chaos. In avalanche forecasting, several different estimates could be made by one person or several people making independent estimates particularly for assessing spatial variability of instability. Redundant information will not aid an avalanche forecast but several independent assessments might. Furthermore, if one piece of information revealing instability is found, one's perception may be altered regardless of the amount of information about stability previously collected. In the final analysis, information which reveals instability and reduces the uncertainty is most useful in achieving the goal.

## III. Human factors and perception

Of the three fundamental types of uncertainty introduced in the goal, the third type: human factors and variations in human perception and estimation has not received much attention in avalanche forecasting. The aim here is to produce a check list of the factors for the first time and show how they are related to avalanche forecasting. The factors considered in this section are derived from consideration of the patterns of human factors in accident case histories and the general principles about human issues in natural hazards. Fundamentally, since most deaths in western Europe and North America are caused by people triggering the avalanches themselves (McClung and Schaerer, 1993), the root cause of most of these accidents is failure in human perception: perception does not match reality. For such accidents, people thought the state of instability was something other than it actually was. Similarly, in some cases, the link to deaths and losses can sometimes be traced to failure in human perception at larger scales of human intervention: e.g., ineffective public policy to enact proper warning systems and restrictions. Recent examples of disasters in Turkey and India (McClung and Schaerer, 1993) involving people in villages may also be linked to failure in human perception at the local or national scale, such as ineffective public policy to provide proper forecasting-warning services.

Perception is equivalent to one or more people's picture of reality based on information processing derived from the senses. Perception and its variations are crucial in understanding human vulnerability to natural hazards (White, 1974) including avalanches. Perception is a filter preceding decision-making and it is important at several scales including individuals, groups, and levels of government.

In reality, all these human factors are connected in a complicated way within a person.

I divide human influences roughly into: (a) basic general (personality) traits and behaviour (termed risk propensity) and (b) the elements of *perception* commonly encountered in avalanche forecasting. In reality, there is no such easy division since the two groups of effects are related. However, in order to highlight the common elements of perception more directly related to avalanche forecasting, it is useful to undertake the division.

Following the classic work of White (1974) for natural hazards, the discussion is phrased in terms of variations in perception and estimation. According to White (1974) factors influencing variations include: risk-taking propensity, fate control and views of nature, recency and frequency of events. The discussion here contains White's factors as a subset and thus it is more comprehensive.

### (a) *Risk propensity: personality traits*

Risk taking propensity has a major influence on human activity (Adams, 1995). It is a complicated function of one's life experiences (which depend on age and are therefore time dependent), one's personality including views of nature, fate control, one's skill level, marital status and family details, cultural factors and perhaps others.

Risk propensity is included here as a human influence on decisions based on the totality of life experiences (not just experiences with avalanches) including basic personality factors, factors related to stage and situation in life and cultural factors. Since avalanche forecasting involves decision-making about risks (i.e., it is a risk analysis, McClung and Schweizer, 1999) which implies human action, risk taking propensity is a strong element in the process.

Following Adams (1995), I constructed a Risk-Decision Matrix (Figure 1) to display the relationship between risk propensity, perception (digesting data by the senses) and decision-making for back-country skiing. Correct decisions fall within two limits which define the lower and upper limits of acceptable risk for an individual. The area of correct decisions between these two limits is referred to as the Operational Risk Band (ORB). Errors are incurred when decisions lead to risk outside the ORB. The character of errors is described based on decisions and hypotheses about the state of instability of the snow cover. By analogy to errors in statistical hypothesis testing, (Lee, 1993), two types of errors are defined (Figure 1):

Type I: Reluctance to claim something is true unless hard proof is at hand;

In avalanche forecasting decisions, Type I most often (Appendix B; Part II) translates to reluctance to claim the snow-pack is unstable unless hard proof is at hand. An example of major importance occurs in back-country travel when the instability is conditional (Appendix A; Part II).

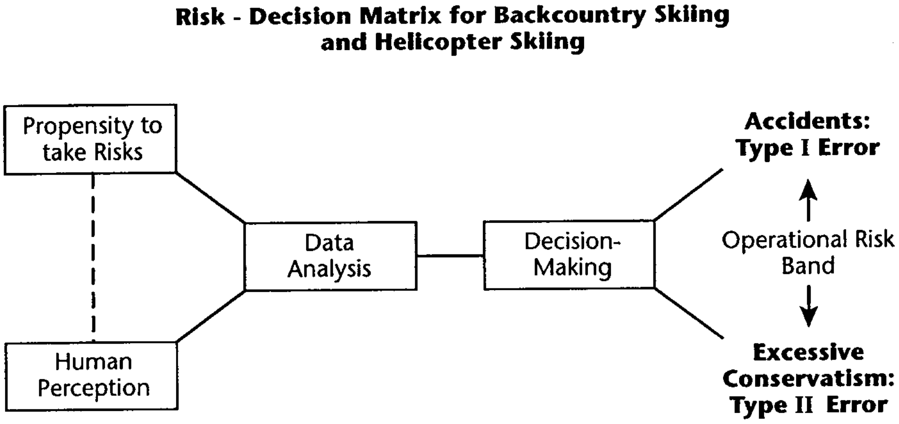

*Figure 1.* Schematic showing integration of human factors into decision making with error free decisions in the Operational Risk Band (ORB). Correct decisions fall within the ORB.

Type II: Excessive conservatism resulting in a failure to act (such as removal of avalanche warnings) when it is necessary.

In avalanche forecasting decisions, Type II most often (Appendix B; Part II) translates to excessive conservatism resulting in lack of action. Examples include: not opening ski terrain, not opening transportation corridors, not removing avalanche warnings when the snow-pack is mostly stable. Type II mistakes are strongly related to the credibility of warnings. The upper limit of the ORB is near the maximum risk people are willing to accept (the region where rewards or benefits are generally greatest). Wilde (1994) argues that people constantly try to achieve an optimal value of risk called Target Risk which optimizes the difference between potential gains and losses during human activity. For example, people constantly try to achieve Target Risk by modifying their actions (related to risk propensity). Bruns (1997) discussed Target Risk in relation to guiding in avalanche terrain. Target Risk is near the upper limit of the ORB.

The lower limit of the ORB represents the lower bound of acceptable risk for an individual associated with excessive conservatism: a limit that people avoid through decision-making. Going below the lower limit often represents lack of action where opportunities are missed such as exhilarating skiing. When decision-making is added as a formal element of avalanche forecasting, the process becomes an action oriented risk analysis so that people operate within the ORB with a focus on being close to the upper limit of the ORB where the greatest benefits accrue since rewards usually increase with risk.

One advantage of the Risk-Decision Matrix is that it can be used to outline the goal of an industrial skiing operation such as helicopter skiing when considering avalanche hazards. The goal of a helicopter skiing operation (from the avalanche perspective) is to maintain risk in the ORB: to provide more exciting skiing than a fixed lift ski area but to keep risk below one which provides excessive danger to clients. Thus, the goal of a such a skiing operation, in relation to avalanche forecasting, does not coincide with the goal of avalanche forecasting (minimizing uncertainty) in the operation. Similar logic about the ORB applies to forecasting for transportation routes, fixed-lift ski areas, and warnings for villages or back-country warnings produced by mountain weather forecasters.

All proper human decisions about risk that concern avalanches, including operations which practice avalanche forecasting, keep the risk within the ORB (the risk limits between errors) by estimating the costs. The costs for exceeding the upper limit of the ORB are death, injury and destruction. For this reason, people focus mostly on staying below the upper limit. Typical costs for operating below the lower limit of the ORB are loss of freedom, individuality and perhaps a bruised ego or regret for missing an opportunity. In avalanche forecasting, the costs of going below the lower risk limit can have important economic implications including excessive delays in opening roads, railways and ski runs and loss of credibility in forecasted warnings. Appendix B, Part II of this treatise contains a discussion of decision-making with general definitions of errors in forecasting.

### (b) *Common elements affecting human perception about instability in avalanche forecasting*

*Positive elements: targeted education and experience combined* The fundamental elements which shape human perception (excluding risk propensity factors) in a *positive* (beneficial) direction in avalanche forecasting are:

1. Targeted education, specifically about avalanches, includes an appreciation for uncertainty and data sampling and results from scientific investigations and models can have an important influence to improve perception. Targeted education may arise from formal courses, informal instruction and self-teaching. According to White (1974), general education and level are not related to improved perception about hazards.
2. Experience including objective, dynamic analysis of data and information is essential for optimal perception if it is combined with targeted education. Makridakis (1990) cites evidence that, in many repetitive routine decisions, experience and/or expertise do *not* contribute more value to forecasting decisions. Wilde (1994) argues that education alone does not have an effect on people's propensity for seeking Target Risk. However, experience *combined* with targeted education and objective reasoning is very effective for influencing correct decisions in avalanche forecasting and improving human perception.

*Negative Elements: Common biases in avalanche forecasting and their resolution* Human biases account for significant variations in perception and estimation in forecasting. A bias may be defined simply as an irrational preference or prejudice which exerts a *negative* (undesired) influence and interferes with objective reasoning. One important use of computerized forecasting is to provide estimates as free as possible from human bias. A disadvantage is that any computer or mathematical model is only a partial representation of reality.

Lee (1993) lists four classes of bias: (1) incorrect inference about cause and effect; (2) biases of perceiving evidence (related to data sampling in avalanche forecasting); (3) biases introduced by social interactions; (4) biases affecting organizations rather than individuals. Class 4 biases may arise from adherence to organizational purposes at the expense of good decisions arising from forecasting principles. Class 4 is important because it implies that human perception must sometimes be dealt with at varying scales ranging from personal or groups to local, national and even international. Examples of class 4 could be management overriding decisions of avalanche forecasters for organizational benefit, adherence to a group objective on a ski tour to the exclusion of objective forecasting analysis or government decisions not to deploy forecasting and warning systems.

In Appendix A, some common biases in forecasting provided by Makridakis (1990) and my own experiences and their resolution are discussed according to the elements of avalanche forecasting. Such biases also include human factors in using computer techniques (Appendix A). Biases of all four types are encountered in avalanche forecasting but most of those listed in Appendix A are found in the first three classes.

Biases have important effects on human perception and estimation but the state of instability likely determines their influence. In cases approaching Absolute Instability (widespread natural avalanching), biases probably have small influence since data sampling and observations provide a fairly good match of perception and reality. However, in the much larger and more important category of Conditional Instability (requiring a finite external trigger for avalanching), biases can forge a gap between perception and reality which is dangerous because the state of instability is not obvious. Part II, Appendix A contains more information about Absolute and Conditional Instability. Any serious framework for avalanche forecasting must encompass resolution of biases as shown in the examples in Appendix A, Part I.

### *Positive or negative elements: Data sampling and relation to expected variations in human perception*

In addition to targeted education and experience (positive influences), and biases (negative influences) perception is also influenced by data sampling and the relationship to the current (or future) distribution of instability. Information from data sampling may be positive or negative with respect to linking perception about instability with reality. If ample information is revealed about instability, perception may be good. However, if instability is present and not revealed by sampling, perception may be poor. Data sampling forms a very important link with perception, experience and risk and the influence of data sampling is related to the temporal/spatial patterns of instability in back-country travel.

*Table I.* Approximate qualitative scale for danger linked to perception and variations combined with data sampling for back-country travel for people with experience

| Qualitative danger | Public danger scale | Typical instability | Perception and variations |
|---|---|---|---|
| LOW | HIGH or EXTREME | ABSOLUTE: Low triggering level | GOOD: Small variations |
| MODERATE | LOW or MODERATE | CONDITIONAL: High triggering level and/or highly localized instability | POOR: Small variations |
| HIGH | MODERATE or CONSIDERABLE | CONDITIONAL: Moderate triggering level and/or localized instability | FAIR: Large variations |

### *Example of perception and variations related to public warnings*

According to Lee (1993) improper data sampling is related to bias but it is of such importance in avalanche forecasting that a separate discussion of it is included here. Data sampling forms much of the basis of the International Danger Scale for public warnings (McClung, 2000). To illustrate the concepts, the discussion here is framed around the Danger Scale (the scale used in Canada is in Appendix B but it is similar to those in other countries). The discussion below (summarized in Table I) indicates that the International Danger Scale does not take into account human perception and its variations (McClung, 2000).

For Absolute Instability (widespread natural avalanching: see Part II: Appendix A) or when natural avalanches are expected and avalanches are easy to trigger, there is usually very good perception for *experienced* people and the danger from the human perception portion of the risk is expected to be LOW (High or Extreme on the Danger Scale; see Table I). For this situation, there is ample evidence about instability and experienced people will generally agree, resulting in small variations in perception.

On the other extreme, where instability is located in only isolated locations or the triggering level may be high, perception is generally poor and the human perception portion of the risk may be MODERATE (Low or Moderate on the Danger Scale; see Table I) for experienced people. In this case, the chance of intersecting the instability is low (high triggering level or instability only in isolated locations) but perception about instability may be poor. In this situation, even most experienced people will agree that there is fairly good stability and variations in perception are likely to be small: most people will believe the snowpack is stable.

The intermediate case for which a moderate triggering level will initiate avalanches, natural avalanches are not available, and/or instability is found in more than widely isolated locations, will likely have large variations in human perception, high uncertainty and the qualitative danger from perception is expected to be HIGH (Moderate or Considerable on the Danger Scale; see Table I). The material in Table I is consistent with the concepts for other hazards discussed by White (1974). He argues that the greatest variations in hazard perception and estimation are associated with recency and frequency of personal interaction, with hazards of intermediate frequency being responsible for greatest variations in perception.

Statistics on fatalities and accidents from the alpine countries of Europe are consistent with the human perception scale described in Table I (McClung, 2000): most accidents and fatalities are in the Moderate or Considerable Danger classes. Jamieson and Johnston (1992) showed that there has yet to be a fatal accident for guided parties in helicopter skiing in Canada for instabilities in new snow. New snow instabilities are usually near the surface so that smaller avalanches form and new snow instabilities are often easy to detect through skiing and stability tests resulting in good perception, particularly for experienced people.

Often to verify mathematical models, random sampling is conducted. However, randomness is not usually desirable in a sampling process for avalanche forecasting. What is suggested here is that sampling should not be random in order to have the best chance of successfully detecting instability. In order to achieve this, priority should be given to extrapolation to worst case scenarios and searching (mentally and/or physically) for the instability (Fredston and Fesler, 1994). This might be called ‘targeted sampling’. Studies of stability test results collected at regular sampling intervals along slopes [e.g., Föhn (1989)] have shown that such techniques are likely to be very inconclusive.

## IV. Reasoning process

Reasoning in avalanche forecasting involves both inductive and deductive processes with inductive reasoning fitting the character of the activity most closely. Below, I describe how these processes fit together for most forecasting applications.

### (I) *Inductive reasoning*

The fundamental reasoning process in avalanche forecasting is a dynamic, (mostly) *inductive* integrative process which is probabilistic in character with an intuitive component which is very difficult to reduce (LaChapelle, 1980). Avalanche forecasting is not an event, it is an evolutionary process arising from information about the state of instability in the snow cover assembled cumulatively in time (McClung, 2000) even if computer assisted forecasting techniques are employed as part of the process. Some aspects of avalanche forecasting have much in common with real-world probabilistic inference: a widespread, mostly undocumented human activity based primarily on narrative data in non-quantitative form. However, there are important differences. Since avalanche forecasting is concerned with prediction of a physical phenomenon (probable avalanche release), it is not equivalent to forecasting for typical scenarios in business applications for which the laws of physics do not apply.

The dynamic process of integrating information about instability using inductive reasoning is somewhat analogous to Bayesian revision (Pearl, 1988) using updated information as time proceeds. A characteristic of inductive reasoning is that one datum can completely change an opinion about the outcome and this is true for avalanche forecasting; particularly when a low entropy datum is found to reveal instability (such as avalanche occurrence) though no similar data was previously found.

Ideally, each avalanche forecast, for any path, at any time, begins with the first snowfall of the winter. Subsequently, this forecast is revised to a new forecast as more information is collected. Bayes Theorem (e.g., Press, 1989) provides one of several possible probability concepts to link data: Posterior Probability $\propto$ Likelihood $\times$ Prior Probability. The Bayesian prior in this process is analogous to the old forecast with the Posterior being sought. The reason forecasters are hesitant about forecasts made after long absences from their areas (LaChapelle, 1980) is their mistrust of using only the Prior in the forecast without current Likelihood conditions properly integrated. Snow instability can be highly time dependent making prior information worthless. For example, prior information is worthless about new snow instability if collected previous to the snowfall. The likely reason Bayesian techniques have been successful in computer avalanche forecasting applications (McClung and Tweedy, 1994; McClung, 1995) is that they mimic the human reasoning process, fitting naturally into the dynamic, inductive process. Also, they allow judgemental information to be combined with numerical results or data because numerical data alone must necessarily provide an incomplete picture (Schweizer and Föhn, 1996).

### (ii) *Deductive reasoning*

Even though avalanche forecasting is mostly an inductive process, proper forecasting should include results from deductive reasoning during the dynamic, evolutionary process. Deductive reasoning, including results from deterministic models, contains essential information about avalanche formation, physical laws and optimal rules such as Bayes Theorem (e.g., Press, 1989) which are not accessible exclusively through experience.

Results from deductive reasoning come from targeted education including models (both deterministic and probabilistic). Results from deterministic models and deductive processes are preferably simple rules which can be integrated into the dynamic process as opposed to direct real-time use of a formal model. Typical results applicable from deterministic models which cannot be derived from experience include the importance of imperfections in avalanche release (McClung, 1987; Bader and Salm, 1990; McClung and Schweizer, 1999) and the role of snow temperatures in dry slab avalanche release (McClung, 1996).

(iii) *Evolutionary character of the reasoning process and data flow: example for back-country skiing*

The evolutionary character of avalanche forecasting is a property which makes a clear distinction between two major branches of back-country skiing: ordinary back-country skiing by the public and helicopter skiing as practised extensively in Canada. For helicopter skiing, the forecast process begins with the first snowfall and the cumulative, integrative process lasts through the winter. The informational data base is huge with information collected from snow profiles, avalanche observations, snow-pack observations, past experience with terrain features, and skiing through the entire winter over an area of more than 2000 km$^2$. In ordinary back-country skiing, the data-base is much smaller and much of the information about the current situation (called singular information: see description in Part II) must be accumulated on the day (or few days) the skiing is done. The knowledge in the data base about instability is far less in ordinary back-country skiing requiring much more on-site testing and analysis on a per-day basis to approach the same level of forecasting accuracy as in a skiing operation.

## 3. Summary

Avalanche forecasting consists of seven separately identifiable but connected elements. A mastery of all seven elements is needed for optimal forecasting. The linkages between the elements, including the human factors and physical factors, are extensive. These complex linkages do not allow a chain of events for avalanche forecasting to be prescribed in an element by element sense as might be possible for a purely physical problem.

No system of avalanche forecasting is complete unless the human factors and perception are included. The human factors are the root cause of many back-country accidents involving human triggering and they may be linked to other catastrophes as well. The general framework for the human factors, provided here for the first time, is based on an explanation of patterns in accidents and the framework is meant to provide a checklist to explain accidents involving human errors for most, if not all, accidents involving human errors.

The Operational Risk Band (ORB) is related to goals in operations or back-country travel in regard to avalanche hazards to which avalanche forecasting contributes. The goals of operations involve making decisions to fall inside the ORB to avoid errors which may include actions which are too risky or too conservative. The goals of operations regarding avalanche matters are not the same as the goal of avalanche forecasting which is concerned with minimizing uncertainty from three sources: temporal and spatial variations of instability, incremental changes from snow and weather and the human factors including risk propensity, perception and its variations.

Avalanche forecasting with decision-making included is similar to a dynamic risk assessment with an information flow through time by mostly inductive reasoning with an ever present residual risk. Part II of this treatise contains more information on decision making.

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## Appendix A: Some Common Biases in Avalanche Forecasting

In this appendix, a list of some common biases in avalanche forecasting and their resolution is provided. A complete system for avalanche forecasting should include provision for resolution of biases.

Bias 1. Search for supportive evidence: Willingness to gather facts which lead to certain conclusions (e.g., stability) and to disregard other facts which threaten them (e.g., instability). Resolution: Search for any information which reveals instability and its likelihood and account for sampling and its influence on human perception.

Bias 2. Inconsistency: Inability to apply the same decision criteria in similar situations. Resolution: Formalize the analysis and decision-making process (see Part II).

Bias 3. Conservatism: Failure to change (or changing slowly) one's own mind in the light of new information/evidence. Resolution: Monitor changes in the snow cover and its instability and build procedures to take action when important changes or effects are identified. The Prior in the dynamic, integrative Bayesian process must be updated due to the dynamic character of snow instability assessment (see Part II for discussion of the Bayesian process). Resolution of this bias is particularly important to avoid excessive conservatism in opening ski terrain or highways after instability passes. Buser *et al.*, 1987, showed that computer assisted avalanche forecasts can sometimes result in faster changes from instability to stability than forecasts by conventional methods. However, the Buser *et al.*, 1987, computer assisted technique may induce another false bias since it is based mostly only on new snow and weather data which may not provide enough information to reliably make the change.

Bias 4. Recency: The most recent events (or data) dominate those in the less recent past, which are downgraded or ignored. Resolution: Consider both the fundamental features of the current situation (singular data) as well as events from the past (distributional data) in an objective manner. Extrapolate to the worst case. This bias is very important for situations in which instability persists for long periods.

Bias 5. Frequency: The most frequent events dominate those which are less frequent (not seen for a long time). In general, smaller events are more frequent whereas larger events occur less frequently and may not be within human experience. Resolution: Same as Bias 4.

Bias 6. Availability: Reliance upon specific events easily recalled from memory, to the exclusion of other relevant information. This can refer to the 'Red Herring' in which an unusual event occurs and is imprinted indelibly in memory. Such an event is treated then as a general, common event (instead of an exception) and it may dominate the specifics of the case at hand. Computer assisted forecasts which recall 'Nearest Neighbours' (Buser *et al.*, 1987) can help resolve this bias. Resolution: Same as Bias 4.

Bias 7. Illusory Correlations: Belief that patterns are evident and/or two variables are causally related when they are not. Resolution: Deductive reasoning, models and mathematical and careful analysis of data are required, experience alone will usually not resolve this bias. Improperly formulated computer assisted models for which variables are added on an ad hoc basis without correlations accounted for (e.g., Buser *et al.*, 1987) may contain this bias.

Bias 8. Selective perception: People tend to see problems in terms of their own background and experience. Resolution: Combine both targeted education and experience in the process objectively. Seek collective opinions and especially from people with different perspectives (backgrounds).

Bias 9. Making a decision based on the 'authority' or 'ego' of a person: People with more experience or theoretical knowledge tend to be perceived as experts and they can dominate group decision-making. A person with either theoretical knowledge or experience alone is not an expert. Resolution: Formalize the decision-making process and use all data in an objective, collective manner. Galileo's prescription about authority applies: 'The authority of a thousand is not worth the humble reasoning of a single individual'. André Roch's prescription related to ego applies as well: "No avalanche knows you are an expert".

Bias 10. Underestimating uncertainty: Excessive optimism, illusory correlation, and the need to reduce anxiety result in underestimating uncertainty. Resolution: Estimate uncertainty objectively. Consider both distributional (data about past occurrences) and singular data (data about the situation at hand) and estimate their worth (informational entropy and use as relevant samples) in giving a picture of the instability based on proper sampling. Reduce human uncertainty by elimination of biases through formal decision-making processes and well formulated computer assisted models (Haegeli and McClung, 2001).

Bias 11. Optimism, wishful thinking: People's preferences for future outcomes affect their forecasts. Resolution: Be objective and seek a collective decision. Pay attention to the forecast of a disinterested third party if possible. No avalanche cares about your preferences! This is particularly important for expedition mountaineering parties with major objectives.

Bias 12. Anchoring: Predictions are unduly influenced by initial information which is given more weight in the forecasting process. Resolution: Always start with objective information (a forecast) and continually revise that forecast as more relevant information becomes available. Consider the importance of changes and discuss them with others and integrate the information into a revised forecast. Continual revision is essential for good avalanche forecasting. Avalanche forecasting must be viewed as a highly dynamic, integrative process due to the dynamic character of the instability.

Anchoring can also result by accumulating information which does not indicate instability in one location (or a set of similar locations) and subsequently using that information to extrapolate to a location where the instability conditions may be unrelated. In this process, one's confidence can be falsely boosted about stability by using data which are not relevant at the location in question. This shows that biases are not separate entities; they can be combined with the other biases or the effects of data sampling to produce errors.

Bias 13. Use of rules of thumb: The forecasting process is reduced to use of independent rules of thumb which oversimplify the problem. Rules can come from experience or deterministic models and they usually require an assumption which begins with: "All other things being equal, ..." which is either forgotten or unrealistic in real-time applications. Resolution: Experience combined with targeted education has to be used to integrate information together in a dynamic process. Rules of thumb can constitute a basis for integrating singular and distributional information but they cannot be used separately. Rules of thumb are static; avalanche forecasting is dynamic and multi-faceted. Rules of thumb may appear in computer models and bias the results.

Bias 14. Guide-client relationship and peer pressure: Guides must deal with their own biases, those of their clients and the interaction between the two. An expert in avalanche forecasting must have ample amounts of targeted education *and* experience. It must be assumed that a client has much less of each than a guide and, therefore, the assumption must be made that a client has little input into a decision-making process about avalanche hazards. Resolution: Similar to bias 11. If a client, without the targeted education and experience to make an objective analysis, expresses preference for action, the ambition of a client must not be allowed to over-ride objective decision-making. Be objective and seek a collective decision among fellow guides if possible. Formalize the decision-making process and adhere to it.

The same bias might apply to managers of highway operations or railways. A manager without experience *and* targeted education in avalanche forecasting should not interfere with the objective analysis of an expert.

## Appendix B: International Danger Scale As Used in Canada

The International Danger Scale is used for public avalanche warnings in regard to back-country travel in avalanche terrain. The version now used in Canada according to Dennis and Moore, 1997 is listed in Table II.

*Table II.* Danger scale for public warnings in Canada

| Level | Description | Action |
|---|---|---|
| LOW | Natural avalanches very unlikely. Human triggered avalanches *unlikely.* | Travel is generally safe. Normal advised. |
| MODERATE | Natural avalanches very unlikely. Human triggered avalanches *possible.* | Use caution in steeper terrain (defined in accompanying statement.) |
| CONSIDERABLE | Natural avalanches possible. Human triggered avalanches *probable.* | Be increasingly cautious in steeper terrain. |
| HIGH | Natural and human triggered avalanches *likely.* | Travel in avalanche terrain is not recommended. |
| EXTREME | Widespread natural or human triggered avalanches *certain.* | Travel in avalanche terrain should be avoided and travel should be confined to low angle terrain well away from avalanche path runouts. |

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