A NEW PERSPECTIVE ON COMPUTER-AIDED AVALANCHE FORECASTING: SCALE AND SCALE ISSUES

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ABSTRACT: This paper discusses the problems related to scale in avalanche forecasting models. The term 'scale' refers to a characteristic length or time of a process, observation or model. Following the ideas of Blöschl and Sivapalan (1995), it is shown that the scale characteristics of these three entities can be quite different depending on their individual properties. If these scales do not completely agree with each other, the information transfer between them involves inter- or extrapolation. This adjustment process between different scales is referred to as 'scaling' and the problems associated with it are scale issues. Ignoring these issues can have significant effects on the quality of the model prediction. The analysis of currently used avalanche forecasting methods and computer models reveals four main problems in this field: (a) the inability of weather monitoring networks to capture small scale phenomena such as snowdrift or surface hoar formation; (b) the insufficient spatial resolution of snow profile measurements with regard to their natural variability; (c) the poor resolution of stability measurements; and (d) the contradictions between input and output scales in avalanche forecasting models. Preliminary thoughts for the solution of these scale problems are presented in this paper.

KEYWORDS: Avalanche forecasting, Scale, Computer models

1. INTRODUCTION

The development of models in science traditionally follows a set pattern involving the following steps (O'Connell, 1991): (1) examining the phenomenon or process in question by collecting and analyzing data; (2) developing a conceptual model and translating it into a mathematical form; (3) calibrating the model to fit a part of the historical data set by adjusting the model coefficients; and (4) validating the model against the remaining historical data set. If the results are sufficiently close to the observations, the model is considered to be ready for use in a predictive mode. This process is in avalanche forecasting modeling no different than in any other science discipline. At the beginning of this process stands a phenomenon, which represents the truth and the ultimate goal of the modeling effort. Step (1) and (2) of the developing process can then be viewed as transformations from the truth to representations (Fig. 1). The real process is represented in measured data first, and then its characteristics are expressed in the model forecast. In each of these two transformations the information content is slightly changed and simplified. One aspect of this transformation is that the truth and the representations often have different scales. The term *'scale'* refers to a characteristic length or time of a process, observation or model (Blöschl and Sivapalan, 1995). If these scales do not completely agree with each other, the information transfer between them involves inter- or extrapolation. This adjustment process between different scales is referred to as *'scaling'*. The problems associated with it are *scale issues* (Blöschl and Sivapalan, 1995). In a good model either the individual scales match or the transformation between them is well known and incorporated into the model. Scale issues are

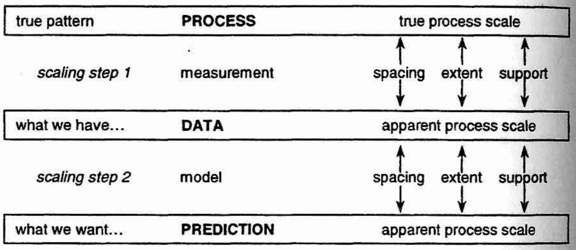

Figure 1: Relationship between scales of process, data, and prediction and related scaling issues (after Blöschl, 1999)

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important in a range of different disciplines. Examples are meteorology, geomorphology, hydrology, and even social sciences.

The scope of this paper is to present some ideas about the scale issues in computer-aided avalanche forecasting. For the main concepts about scale, we follow the ideas of Blöschl and Sivapalan (1995) and Blöschl (1999), who wrote reviews about the scale related problems in hydrology and snow hydrology. We will apply these ideas to the field of avalanche forecasting modeling and present how the performance of models could benefit from the inclusions of these aspects during their development. The issues presented in this paper are currently studied in our research group.

2. SCALES OF AVALANCHE PHENOMENA AND CONTRIBUTING FACTORS

2.1 Scale definition

Characteristic time-scales of processes can be defined as: (a) the lifetime or duration for an intermittent process like a snowfall event; (b) the period for a periodic variable such as temperature; or (c) the correlation length for a stochastic process or variable, like shear strength. Similarly, space scales can be characterized either as (a) spatial extent, (b) period, or (c) integral scale. Frequently used methods for determining these scales are wavelets (Klees and Haagmans, 2000), spectral analysis, and autocorrelation (Stull, 1988) or variogram analysis (Blöschl, 1999). Some processes or variables have one or more preferred scales. They are called natural scales and appear as peaks in power spectra or autocorrelation graphs. In between these peaks is the so-called spectral gap. The spectrum of temperature, as an example, exhibits distinct peaks at one day and one year due to the rotation of the Earth and the tilt of the Earth's axis. In between, there is a less pronounced peak, which results from temperature changes associated to different air masses and fronts.

2.2 Analysis of contributing factors

The contributing factors, which lead to the formation of avalanches, are manifold and span several orders of magnitude in time and space. The individual factors have been described well in many textbooks, such as McClung and Schaerer (1993). They can basically be divided into two main classes.

The first class are made up of *external factors* like terrain and climate. These have very long time scales with respect to avalanches and hence influence their formation only in a static way. While climate has a large spatial scale as well, terrain varies on all scales and does not have dominant length scales.

The second group contains *internal factors,* which have shorter time scales than one season and affect avalanche formation dynamically. Weather as well as snowpack variables belong to this class. While weather variables have been studied extensively, there are only few studies that examine the variability and scales of the snowpack. Orlanski (1975) classifies atmospheric phenomena into three main categories: the macroscale, containing large phenomena like weather systems; the microscale, at the other end of the spectrum, including processes such as turbulence; and the mesoscale, covering processes in between. Although the spectrum is almost continuous, the fact that large processes have long time scales and smaller ones have shorter life spans allows individual phenomena to be separated and studied individually. This is very different for processes in the snow cover. There, small-scale processes with long time scales interact with larger scale processes with short time scales. Examples of the first process are snow metamorphism or thin weak layers, which persist for an entire season. Big snowfall events that last only a few hours, but affect entire mountain ranges are an example for the second process. Only few studies have been made about the variability of snowpack variables. Examples are the study of Birkeland et al. (1995) and a study currently being carried out at the Swiss Federal Institute of Snow and Avalanche Research (Schweizer et al., 2000). These studies help advancing the knowledge about avalanche initiation, but are on a scale too small from the point of view of forecast modeling. The only analysis that has covered a large study area was conducted by Birkeland (1998). This study looked at stability patterns of the Bridger Range in Montana, an area of about 90 km^2, in two single days, but did not find any spatial correlations. No studies have been made about the larger scale extent of avalanche related characteristics, such as the persistence of surface hoar layers.

2.3 Avalanche phenomena

The characteristics of the avalanching process itself are very similar to the characteristics of the contributing factors. The complex interaction of all the contributing factors at different scales makes it a *multi-scale phenomenon* in space and time. This makes it impossible to focus on individual processes and scales for the forecasting task, unlike in weather forecasting. This characteristic of avalanches makes the forecasting task very challenging. The avalanche initiation process has been studied intensively from the perspective of fracture mechanics over the last few decades (for an overview see Schweizer, 1999) and the dominant small-scale processes are well established. Currently only one forecasting model, the Swiss SNOWPACK, intends to include fracture mechanics into its stability evaluation scheme. We do not believe, though, that it will be possible to run this model at a scale, at which this process can be incorporated appropriately. This will be explain further in section 4.2. Therefore larger scale studies about avalanche activity seem to be more useful from the forecasting perspective. The only study of this kind has been done by Stoffel et al. (1998), who looked at the distribution of avalanche activity in the surroundings of the village of Zuoz (Switzerland). They were able to show the development of specific patterns, but could not explain them.

It is of primary importance for avalanche forecasting to explore the spatial as well as the temporal scales of the avalanche phenomenon and all the contributing factors in more detail. Such a study might lead to the definition of so-called *avalanche climate zones*, which are characterized by some homogeneity with respect to the avalanching process and the contributing factors. This might lead away from the 'operational' definition of forecasting model domains and also give insights about more appropriate monitoring networks for forecasting model-input parameters.

3. SCALES OF FORECAST INPUT PARAMETERS

3.1 Scale definition

Blöschl and Sivapalan (1995) suggest that the measurement scale consists of a scale triplet: spacing, extent, and support (Fig. 2). 'Spacing' or resolution refers to the distance between samples; 'extent' refers to the overall coverage of the data; and 'support' refers to the integration volume or area of the samples. We will use a slightly different definition. While originally related to instrument properties such as response time and source area, we will interpret support as the area or time span of which the specific measurement is representative. All three components of the scale triplet are needed to uniquely specify the space dimensions of measurements. This triplet can also be applied in the time domain.

In order to capture processes appropriately, they should be observed according to their natural scales. Processes that are larger than the coverage appear as trends in the data, whereas processes of a much smaller scale than the coverage appear as noise. It is, however, not always possible to monitor at the appropriate scales. In order to bridge this gap, the scaling effect of the mismatch must be well understood and taken into account during further data analysis.

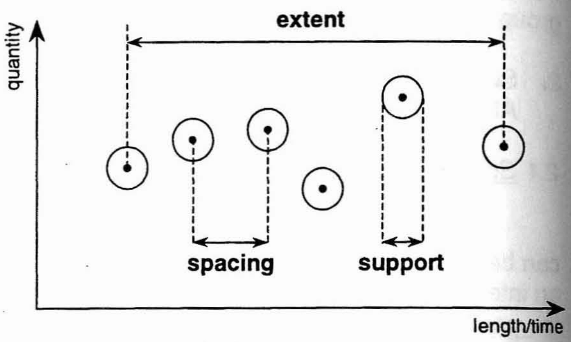

Figure 2: Definition of the measurement and model scale. The scale triplet can be applied to measurements and models (after Blöschl and Sivapalan, 1995).

3.2 Analysis of input parameters

McClung and Schaerer (1993) have classified the information that is used for avalanche forecasting into three classes according their informational entropy, the relevance and ease of interpretation for predicting avalanche occurrence. The three classes are: *Class III: snow and weather data* provide indirect evidence about current and future snow stability and weaknesses. These data are generally collected at or above the snow surface. *Class II: snowpack factors* give evidence about presence, strength and loading of weak layers. This information is sought from within the snow cover. *Class I: stability factors* deal with the direct relationship between loads and weak layers. Data include stability tests or observed avalanche occurrence, which give direct information about past and present avalanche activity. The individual variables are described in great detail in McClung and Schaerer (1993). In general, the lower the number of the class, the lower the informational entropy (uncertainty) with respect to the actual avalanche process and therefore to the prediction.

The *extent* is very similar for all data classes. In most operations, measurements are generally taken continuously throughout the entire winter and the temporal extent covers the entire season. The spatial extent, however, varies between different types of operations. While national forecast services can maintain large monitoring networks, small operators have often only one or two study plots.

We suspect that the *support*, in space and time, decreases from class III to class I data. While weather variables can be characteristic for a significant part of a mountain range, snowpack characteristics seems to be more local and only representative for a smaller area. No study has explicitly examined this aspect of snow profile data in detail yet. It is currently one of the focuses of our research. Class I data, actual avalanche occurrence and stability tests, have only very small spatial and temporal support. Studies such as Föhn (1988) or Jamieson (1995) clearly reveal this characteristic.

In order to monitor a phenomenon entirely it is necessary that the *spacing* is in correspondence with the support; a small support needs a higher resolution and vice versa. Typically, the space resolution is much poorer then time resolution. For class III data the time resolution is generally of the order of hours up to one day for main weather sites. These sites are often part of the monitoring system of national weather forecast services, which are designed for monitoring weather changes related to synoptic systems and work well on that scale. With this network, however, it is not possible to monitor many smaller scale phenomena, which are crucial to the formation of avalanches. An example is drifting snow. Nevertheless, the monitored variables, in this example wind speed and direction, can give enough conclusive evidence about its existence. Empirical approaches like the one of Purves et al. (1998) for drifting snow are very promising for solving this scale problem. More remote weather sites, which are only visited on occasion, can improve the spatial resolution of the data on those particular days, but their time series are in most cases too coarse for any kind of analysis.

The time resolution of class II data is of the order of one or two weeks, which seems appropriate for most slow evolving processes in the snowpack. Faster processes, such as the formation of surface hoar or big snowfall events, should be deducible from class III data. Numerical models, such as the surface hoar model by Föhn (2000) can be used to solve this scale problem. The spatial density of class II data is very similar to the one of class III data. Most operations have one or two study plots where snow profiles are analyzed in regular intervals. Due to the smaller support of this data class, we infer that this resolution is too coarse to represent the natural variability of the snowpack accurately. It is, however, operationally often not feasible to maintain a denser monitoring system. Numerical models like the Swiss SNOWPACK (Lehning et al., 1999) are a possible solution for this scale problem. The high cost for the installation of the necessary weather station make this method too expensive for many operations. We propose another approach for solving this issue. Starting from a central snow profile, the surrounding area is divided up into zones, which show some homogeneity with regard to terrain and current weather conditions. Examples of such zones are forested areas, lee and windward slopes, or areas with temperatures above the freezing level. These zones have to be defined dynamically since they change constantly with weather conditions. The idea is to extrapolate the main snow profile characteristics from this one central location to these zones according to the current weather conditions and dominating processes. Expert rules seem to be the most appropriate method for this task. Most of the important processes that are related to avalanche formation have been the subjects of intensive research projects and ski guides do this extrapolation every day while guiding. Therefore we believe that enough knowledge is available for the formulation of these expert rules.

Similar arguments as for class II data apply to class I data. While it has been shown that stability test in a study plot are very useful for avalanche forecasting (Schweizer et al., 1998), it is currently not possible to monitor snow stability at the temporal and spatial resolution that would reflect its variability correctly. The extrapolation approach mentioned above might be able to help slightly increase the spatial resolution, but there will always be a scale issue here. The only method to overcome this issue is to treat stability as a probabilistic variable.

4. SCALES OF FORECAST MODELS

4.1 Scale definition

Model scales are very similar to measurement scales. They also consist of the same scale triplet (see Fig. 1 and 2), but are related to the spatial and temporal properties of the model. *Extent* can be associated with the model domain; *resolution* and *support* are related to the grid size in most models. Since avalanche forecasting models are generally not run on grids, this interpretation has to be slightly modified.

4.2 Analysis of different forecast model types

The purpose of computer aided avalanche forecasting is to give practitioners an additional tool which helps them deal with the available data and to use them in a consistent way. McClung (2000) has classified avalanche predictions into three main categories according to measurements available and uncertainty in the data.

All of the following forecasting methods and models are run at least once a day, which is in agreement with the scales of the measurements as well as the forecasting objective.

Type A is generally used for national forecast bulletins. It is a true forecast that is based on forecasted class III data. Due to the characteristics of the data, this forecast is representative for entire mountain ranges, but can only predict vague estimates of the actual stability situation. The French model chain SAFRAN – CROCUS – MÉPRA (Durand et al., 1999) is an example of a Type A forecast. The entire model domain, which covers the French Alps and the Pyrenees, is divided into 38 individual massifs (approx. 500km^2 each). Based on weather forecast results and available observations, characteristic snow profiles are calculated for different aspects, slopes, and altitude intervals. Afterwards, the expected avalanche activity is determined for each of these individual sectors and expressed on the French 7-step danger scale. The calculated snow profiles as well as the predicted danger scale should be interpreted very carefully, since no information at the appropriate scale was included into the calculations. A more general danger scale level forecast for entire massifs would seem to be more appropriate for the scale of the input parameters. It has, however, never been explained in detail how these massifs were defined.

Type B forecasts use actual weather observations and sometimes snow profile and stability test results are included as well. It is therefore more an evaluation than an actual forecast. Almost all early morning forecasts in ski resorts or highway operations are of this type. The vast majority of avalanche forecasting models is designed for this task, especially tailored towards the needs and resources of an operation. The first models employed statistical methods. Examples are the nearest neighbor method of Buser et al. (1987) and the model of McClung and Tweedy (1994), which combines cluster techniques and parametric discriminant analysis. For the numerical parts, their input consists mainly of class III data form one or two weather stations and some class II data. The forecast consists or two parts: a probability for avalanching for the entire model domain and a list of avalanche paths, which have run under similar conditions. The probability forecast is thought to be representative of the entire domain. This means that the resolution is zero and the support is equal to the extent of the model. The list of historic avalanches increases the resolution slightly. This most general model output agrees with the scale of the input parameters used. Nevertheless, the model domains have always been dictated by the specific operation and it has never been shown that this size is good for a forecasting model domain. Maybe, it might be possible to forecast avalanches with the same input parameters and with a similar accuracy for an even bigger area or, the performance could be increased by dividing the model domain into smaller sectors.

More recent models have tried to forecast more specifically and calculate probabilities for certain aspects and altitude ranges. For this purpose more detailed class II data were included into the analysis. To do so, new computing techniques had to be employed, which led to the development of expert systems, neural networks, and hybrid systems for avalanche forecasting. Examples of these efforts are the forecasting models DAVOS and MODULE by Schweizer and Föhn (1996) or the hybrid system ALUDES (Schweizer et al., 1994) that combines a neural network with an expert system. Although the resolution of the output of these models is increased, the resolution of the input variables is unchanged. The data are still monitored at one or two central locations in the model domain. While the incorporation of more snowpack data seems correct, it has not been taken into account that the support of this data class is probably smaller than the one of class III data. This might be one reason for the only moderate increase of forecast performance by these models.

Type C forecasts are typically made in helicopter skiing or backcountry traveling after avalanche occurrences have been scanned for and stability tests have been performed (class I data). Here, the focus lies on the stability evaluation of individual terrain features, such as rolls or gullies. The forecasting tool NX-LOG (Bolognesi and Buser, 1995) calculates avalanching probabilities for individual gullies. The model combines the nearest neighbor method with an expert system. Input parameters are similar to the systems mentioned above and therefore it is expected that the resulting forecasts have the same shortcomings.

A completely different approach is pursued with the SNOWPACK model of Lehning et al. (1999). This model uses high quality meteorological input data to calculate the snowpack characteristics at specific locations. Each location is equipped with an automatic weather station which consists of a wind station on a mountain crest and a snow study plot nearby. The ultimate goal of this system is to predict avalanches with the help of a rupture criterion calculated on the basis of the snow properties modeled. Although correct from the scale perspective, we suspect that the output of this model is just one point sample with only insufficient support to give adequate evidence about the stability situation in its larger surroundings.

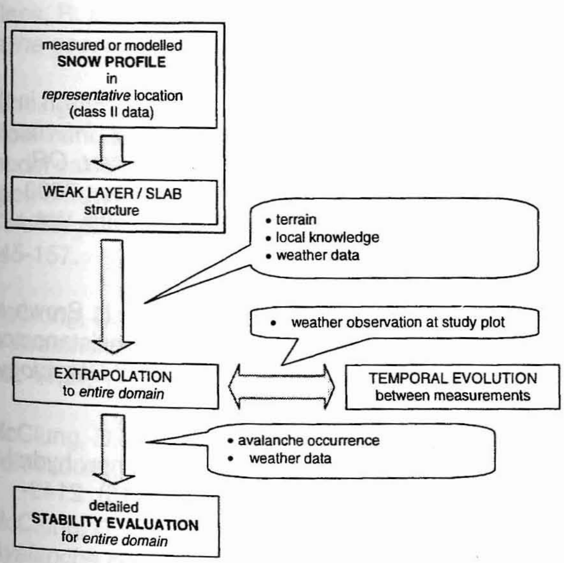

Figure 3: Flow diagram of proposed model approach for stability forecast at a higher spatial resolution.

4.3 Proposed new model approach

From the analysis of currently used avalanche forecasting models we conclude that there is a *spectral gap in forecasting resolution* between the probabilistic forecast for entire domains and the point forecasts of numerical models. In order to close this gap, we propose a new model approach for avalanche forecasting (Fig. 3). The model can be divided into three modules: (a) an extrapolation module for snow profile characteristics; (b) a module that calculates the temporal evolution of the extrapolated snow profiles; and (c) a module that analyzes the computed profiles for the final stability evaluation.

As described in section 3.2, the entire model domain is divided up into homogeneous zones. The characteristics of the snowpack in these individual zones are deduced from a central snow profile, the current weather situation, and local knowledge about terrain and predominate processes.

Since snow profiles are only recorded once every week or two, it is necessary to calculate the evolution of the snowpack characteristics between measurements. The inclusion of daily or hourly weather measurements as well as local knowledge into the analysis justifies this resolution increase.

Together with observed avalanche activity and stability tests, the modeled snowpack characteristics of individual zones can now be used for a detailed stability evaluation of the entire model domain. The snow profile assistant (McClung, 1995) will be used as a starting point for this module.

An expert system in combination with a GIS seems suited best for the implementation of this model. These are preliminary thoughts about a possible model approach that includes all available data properly according to their scale characteristics.

5. CONCLUSIONS

The main focus of this paper is the examination of scale related issues in avalanche forecasting models. From a theoretical point of view, it is shown that processes, measurements and model predictions have different types of *scales*. While processes are characterized by their natural scales, measurements and models are described by the scale triplet extent – spacing – support. Many of the process and measurement scales have not been analyzed in detail yet. It is one of our main focuses to determine these scales from the perspective of avalanche forecasting. The rich databases of Canadian Mountain Holidays and the Canadian Avalanche Association are very suitable for such an analysis. They contain 5 to 10 years of detailed information about weather, snowpack characteristics, and avalanche activity covering big parts of the Columbia Mountains and the Province of British Columbia. This study might result in the definition of *avalanche climate zones*, which could give useful insights about more appropriate monitoring networks and lead away from the 'operational' definition of avalanche forecasting domains. An in-depth analysis of currently used avalanche forecasting models should reveal more detail about the forecast scales, and might uncover some of their shortcomings and increase their performance.

The fact that the measurement and the model scale hardly ever coincide with the process scale creates *scale issues*. Scale issues are associated with the inter- or extrapolation of information between process, data, and forecast. Four main scale issues are pointed out in this paper: (a) the inability of weather monitoring networks to capture smaller scale phenomena such as snowdrift or surface hoar formation; (b) the insufficient spatial resolution of snow profile measurements with regard to their natural variability; (c) the poor resolution of stability test measurement; and (d) the contradictions between input and output scales in avalanche forecasting models.

Problems (a) to (c) could be solved with a tremendous increase in monitoring resolution. This is, however, not feasible for operational use. More practical are *parameterizations*, which infer smaller scale characteristics based on data measured at a larger scale and local knowledge. An example for a possible solution of problem (a) is the model approach of Purves, et al. (1998). Numerical models might be an answer to problem (b), but the small support of these calculations limits their use for generalizations about the conditions in the immediate surrounding. We propose an expert system approach for extrapolating the main characteristics of the central profile to the adjacent areas on the basis of terrain, current weather conditions, and local knowledge. It is hoped that this approach is able to catch processes like the formation of wind slabs on lee slopes, the development of surface hoar forest openings, and crust formation. Since stability test results are highly variable even within slopes, the only feasible solution for scale issue (c) seems to be the probabilistic treatment of this data class. Our arguments about problem (d) should receive more attention during the development of forecasting models. It is generally not possible to increase the resolution of the prediction without an increase of the input parameter resolution. We believe that our model presented in section 4.3 is a feasible approach for the incorporation of information from all data classes according to their scales.

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