ON THE PREDICTABILITY OF SNOW AVALANCHES

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ABSTRACT: Snow avalanches are generally rare and occasionally extreme events. In the general context of prediction and predictably of extreme events, we will examine whether snow avalanches are predictable based on a few examples of forecasts at different scales. Clearly, avalanche predictability depends on scale. When the regional avalanche danger is High or Very High (Extreme), an avalanche is likely somewhere in the region. However, even at such high danger levels, the release probability in a single avalanche path is well below 50% (typically on the order of 1-10%). This means that a single avalanche is a rare event, which is not predictable even when higher danger levels prevail. At the lower danger levels – relevant for backcountry recreation – the release probability is significantly lower. The low release probability does not mean that the risk is low. Even with low occurrence probability the risk might be too high to be acceptable so that comprehensive preventive measures are required.

KEYWORDS: snow stability evaluation, avalanche forecasting, risk management

1. INTRODUCTION

Snow avalanche are rare events and large avalanches that cause damage or harm to people can be called extreme events. Jentsch et al. (2006) and Kantz et al. (2006) have described extreme events that can occur in natural, technical and societal environments. Based on their work, some characteristics of extreme events in respect to prediction and predictability are summarized below. Extreme events in nature such as hurricanes are generated by systems with complex dynamics. In the case of weather extremes the system is the atmosphere (coupled with the ocean etc.) and can in principle be described fully deterministically. However, the system may have a chaotic component, i.e. slight differences in the initial conditions might lead after some time to widely diverging outcomes. The system though is not random, and extreme events are typically not random events; it is not like throwing a dice.

Yet, the systems from which extreme events generate are usually too complex for a simple deterministic approach. A deterministic prediction implies that the current state is perfectly known, so that the future evolution can be calculated. However, as there are too many variables that should be known to characterize the current state, a deterministic prediction is usually not possible due to the lack of knowledge. In addition, a lack of knowledge about the underlying processes may further hinder a deterministic process.

Hence, a stochastic approach seems more suited and predictions of extreme events are usually probabilistic, i.e. an event of a given size is expected with a given probability at some specific time in the future. In other words, a probabilistic forecast means that it is not possible to precisely forecast the size, the location and the time of occurrence. Whereas less extreme and more frequent events are often prevented by countermeasures, it is too costly to try to mitigate extreme events. The only option is usually forecasting and based on it temporary protection measures such as preventive evacuation are taken.

Predicting extreme events requires that the underlying system has predictability. Predictability is a quality of the system and means that prediction is possible and holds on average (Haggett, 1994). What is a true prediction is not always easy to define: for example, if a rare event is predicted for today, but happens tomorrow. Predictability is a matter of debate, for example, for earthquakes (Main et al., 1999), and in general requires some sort of a precursor, or observational variable that announces the event. The lottery has no predictability since the system is completely random, whereas the next eclipse of the sun is perfectly predictable – provided you are familiar with astronomy and the movements of celestial bodies (Kantz et al, 2006). There are several types of predictions: interpolation, extrapolation etc. Typically a prediction is made about the occurrence of an event in the future, usually this is called a forecast.

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In the following, we will examine whether snow avalanches are predictable based on a few examples of forecasts at different scales. Predicting avalanches is usually called avalanche forecasting which McClung (2000) defined as predicting snowpack instability in space and time relative to a given triggering level.

2. PREDICTION OF SNOW AVALANCHES

Snow avalanche prediction (forecasting snowpack instability) can be made for various scales (McClung and Schaerer, 2006). We will focus on the regional scale (1000 km^2), the local scale (100 km^2) and the scale of an individual avalanche path (1 km^2). Typically, the prediction is about the danger level, the avalanche activity (or occurrence) and the probability of the single event for these three scales, respectively. Here we do not deal with scale issues related to the often found mismatch between the scale of the forecast and the scale of the underlying data (Hägeli and McClung, 2004).

Most natural snow avalanches occur due to snow loading, i.e. during or shortly after a snowfall or blowing snow event. Hence, at all scales the amount of new snow is considered as the key parameter when predicting large natural avalanches.

2.1 Regional scale

Figure 1 shows the new snow amount (3-d sum of new snow depth: *HN*3d) in relation to the danger level (5-degree European danger scale) for a 10-year dataset of new snow depth measurements from the Weissfluhjoch (Davos, Eastern Swiss Alps) and verified regional daily danger levels (Schweizer and Föhn, 1996). Whereas the avalanche danger clearly increases with increasing new snow depth, the spread at a given level is large, and vice versa for a class of new snow depth. Though, new snow depth is often used to provide rough guidance on assessing instability (Table 1) (e.g. Salm, 1982), the variation as shown in Figure 1 does in general not allow forecasting simply based on new snow depth. Obviously, other so-called contributory factors have to be considered, among those are wind, radiation/temperature, and snow stratigraphy (Schweizer et al., 2003).

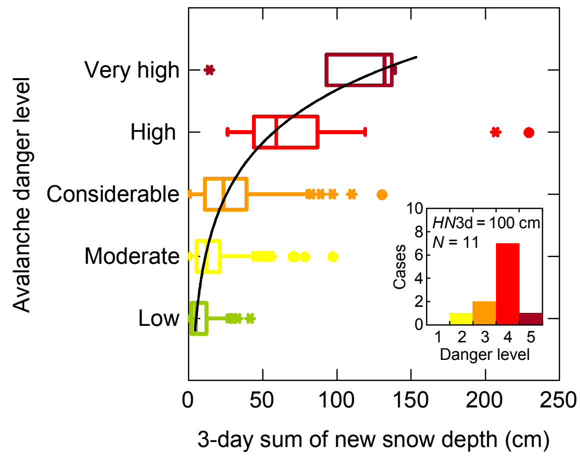

Figure 1: 3-day sum of new snow depth vs. verified regional danger level for Weissfluhjoch-Davos region (1985-1986 to 1994-1995) (adapted from Schweizer et al., 2003). Inset shows frequency of danger levels for a 3d-sum of new snow depth of about 100 cm.

On the other hand, for the case shown in Figure 1, for a given class of new snow depth, say 100 cm ($90 \text{ cm} < HN3\text{d} \leq 110 \text{ cm}$), the danger level is in fact usually best described as "High" (Figure 5, inset). So, prediction is possible. The new snow depth can be used as observable for predicting the danger level. However, if the cases with a 3-d sum of new snow depth of 20 cm ($15 \text{ cm} < HN3\text{d} \leq 25 \text{ cm}$) would be considered, there is no single danger level dominating, but the levels of "Low", "Moderate" and "Considerable" have similar frequencies. Prediction is not possible – yet we are not dealing with extreme events. In fact, rare and extreme events usually are better predictable than frequent events. The extreme events may have a prominent precursor-like structure, whereas for the frequent events the signal-to-noise ratio is often low which makes reliable predictions impossible (Kantz et al, 2006).

Of course, the new snow depth of 100 cm as used in the above example is a threshold value specific to this example. The threshold would be higher for regions with heavy precipitation (more maritime type of climate) and lower for regions with rather continental snow climate. Similarly, in backcountry forecasting the critical snow depth that indicates "considerable" danger (10-50 cm, depending on conditions) has been established as threshold value by Munter (2003).

Table 1: Assessing the danger of large natural avalanches: relation between new snow depth and avalanche activity (after Salm, 1982).

Sum of new snow depth	Consequences for infrastructure
< 30 cm	Almost no danger
30 - 50 cm	Occasionally, some isolated objects and exposed transportation lines might be endangered.
50 - 80 cm	A few large avalanches to the valley bottom are possible, some objects and transportation lines might be endangered.
80 - 120 cm	Several, large avalanches to the valley bottom have to be expected, some objects and transportation lines, as well as exposed parts of residential areas are endangered.
> 120 cm	Disastrous situation, even rarely or so far never observed avalanches to the valley bottom are possible, highest danger for exposed residential areas and transportation lines.

2.2 Local scale

If the forecasted danger level is "High" due to a new snow depth of about 100 cm, several large avalanches to the valley bottom may occur according to the definition of the danger level (Meister, 1995). What does that mean at the local scale where, for example, a safety service is responsible for a transportation corridor? By far not all potential avalanche paths in a given area (local scale) will produce an avalanche. An analysis by Schaer (1995) showed that even during major avalanche cycles only a minority of the potential starting zones did release. Even in February 1999, when the avalanche danger was "Very high" in many parts of the European Alps, only in about half of the potential avalanche paths in the region of Davos an avalanche did release, though in some several times (SLF, 2000). In other words, it is predictable that at a given danger level, say "High", some avalanches will occur – the local safety service has to take action. However, the location of these avalanches will be difficult to forecast. Certainly, due to terrain characteristics some avalanche paths will have a higher probability to produce an avalanche than others. These may serve as warning signals – or precursors.

Similarly, if the danger level just increased to "Considerable", chances are that at least one human-triggered avalanche will be reported.

2.3 Scale of an individual path

If we proceed to the smallest scale considered here, an individual avalanche path, uncertainty increases – and predictability decreases. As can be seen from the examples above, it is not uncommon that only about in 10% of the avalanche paths a release is recorded when the avalanche danger is "High" or even "Very high". The probability of an avalanche event in a given avalanche path is therefore in most cases lower than 10% – the individual event is not predictable.

Certainly, in some avalanche paths almost all the time when "High" or "Very high" danger prevails, an avalanche is observed – at least according to our perception. However, if we analyse the occurrence record for one of the most active avalanche path in the region of Davos, the Salezertobel path, for the last 50 years, it shows that the return period for a large avalanche is about 2 years (Schweizer et al., 2008). Given the frequency of the danger levels "High" and "Very high", about 1-2% of the days during winter time (about 150 days), the probability for a release, given a "High" or "Very high" danger level, is at best about 0.15 to 0.3. So even in this very active path the avalanche event is not predictable.

3. DISCUSSION

In summary, if we consider the three scales, predictability decreases with decreasing scale. Whereas, the avalanche danger at the regional scale, as well as the occurrence of some large natural avalanches at the local scale can be predicted on average, the single event in a given avalanche path is not predictable. This predictability is only given for large or even extreme events. Small events, those typically triggered by backcountry travellers, are even less predictable. For the large events at least the location where avalanches might occur is predictable. It is rare that large avalanches release from unknown starting zones. For example, in February 1999 in the Swiss Alps, the very large majority of the large avalanches descended along well known avalanche tracks and ran out in the run-out zones as indicated in the danger maps. Based on this spatial predictability it is possible at all to plan and carry out avalanche protection works.

If, for example, the probability for an avalanche to hit a road at even “High” or “Very high” danger is relatively low, say 10-20% – which means strictly speaking the event is unpredictable, what does this mean for the local safety service. Needs the road to be closed? If so, this would mean that only in 1 out of 7 times the road is reached by an avalanche when it is closed. With this rather high number of false alarms the warning service might become unpopular soon. However, depending on the traffic volume and the avalanche characteristics, the risk is in the order of 0.02 death per day of “High” or “Very high” danger for a single avalanche path reaching the road which is not negligible. From an economical point of view protection measures are justified and the cheapest option is usually a forecasting program (temporary preventive closures) possibly combined with explosive control (Wilhelm, 1999).

In fact, the proportion of events to non-events for road closures is typically in the range of 2-10, depending on the terrain and the number of avalanche paths that affect the road stretch that is closed. The relatively high number of false alarms is the direct consequence of the uncertainty, i.e. the low predictability of an individual avalanche event.

At the lower danger levels, the triggering of an avalanche by a backcountry traveller is described as “possible” in the definition of the danger levels (Meister, 1995). For 10 years of Swiss avalanche death statistics, McClung (2000) has shown that the likelihood of death at a given danger level is proportional to about 0.86 for “Moderate” and 1.98 for “Considerable” danger. These values were calculated for the whole area of the Swiss Alps. Assuming that the Swiss Alps can be subdivided in about 50 regions and that about 1 out of 20 avalanches results in a fatality, the probability that in a given region at a given danger level (“Moderate” or “Considerable”) an avalanche is triggered by a backcountry traveller, is proportional to about 0.34 to 0.79, respectively. Depending on the number of backcountry travellers and the number of potential avalanche slopes they cross, the probability for a backcountry traveller to trigger an avalanche on a given slope on a given day when “Moderate” or “Considerable” danger prevails is very, very small – probably on the order of 10^{-5}. Due this low probability the triggering is the exception not the rule so that the recreationists that have not triggered an avalanche do not realize that they have taken an elevated risk.

The quality of snow avalanche forecasts is typically rather poor, i.e. the skill score in a statistical sense is low. However, this does not mean that the forecasts are useless – quite in contrary. If the economic value is considered, even a forecast with a low level of predictability can be very useful, i.e. can help to prevent death or injury. In fact, it has become apparent in recent years that the skill score as used in meteorology to rate weather forecasts is not the only perspective on the problem of how to define predictability (Palmer, 2006).

4. CONCLUSIONS

We examined the predictability of snow avalanches in the context of the prediction of extreme events. The predictability of snow avalanches depends on the scale under consideration, the forecast variable and the size of the event (equivalent to the danger level). The uncertainty increases with decreasing scale and size of the event. Whereas at “High” or “Very high” danger it is predictable that some large natural avalanches will occur, i.e. the probability that at least one avalanche will occur in a given region is >50%, the single event in a given avalanche path is not predictable since the probability of occurrence is typically on the order of 1-10%. At the lower danger levels, the occurrence probability for avalanches in the backcountry are far lower. However, even if it is strictly speaking not predictable whether an avalanche, for example, will hit the road when the danger level is “High”, the risk is usually too high for occurrence probabilities on the order of 1-10%. In other words, the low level of predictability does not mean that no preventive measures (e.g. temporary road closures) are required since the economic value of the forecast needs to be considered. Low probability forecasts can be useful if large values are at stake.

Though snow avalanches as other meteorological hazards can theoretically be predicted from the mainly deterministic system that describes the atmosphere, the uncertainty in the description of the actual state and the model formulation leads to a low level of predictability. Prediction is particularly difficult since we do not have a comprehensive theory of avalanche formation. The avalanche release process is complex in the sense that it is very sensitive to small variations in the initial conditions (which is typical to failure processes in materials with high disorder). Furthermore, we do not have an observable that is closely linked to the failure process, and that could be used as reliable precursor. Even with a better understanding of the processes involved in avalanche formation, the approach to prediction will remain a probabilistic one. The pessimistic view, expressed for the earthquake prediction problem (Main et al., 1999), is that the better understanding will show why prediction is difficult rather than improve predictability.

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