Changes in spatial patterns of snow stability through time

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Abstract. The spatial variability of snow stability presents a challenge to avalanche workers and scientists attempting to assess avalanche danger. Recent research has demonstrated, and attempted to explain, snowpack and snow stability variations over individual slopes. However, these studies have provided single snapshots of an exceedingly dynamic system instead of investigating stability variations over time. This research begins to address how spatial variability at the local slope scale changes through time and the some possible mechanisms for those changes. We performed ten Quantified Loaded Column Tests (QLCTs) in each of five snowpits within a 900 m^2 plot on a relatively uniform slope on three different days. We make a case that the behavior of the snow avalanche system is consistent with complex, nonlinear *Earth Surface Systems* (ESSs), and that research into ESS behavior in other fields might prove to be useful for examining changes in spatial variability through time. In particular, ESSs are typically characterized by sensitivity to initial conditions, which leads to increasing spatial variability through time. Our series of three QLCT trials exhibited changing stability patterns, suggesting that the spatial variability on a slope may increase through time in the absence of external forcing, but that variability may then decrease when additional load is added to the slope. This research provides some interesting initial insights into changes in spatial variability for practitioners and provides some baseline data for future scientific work in this area.

Keywords: spatial variability, snow stability, avalanche, avalanche forecasting.

1. Introduction

A goal of avalanche forecasting is to minimize the uncertainty about instability associated with the spatial and temporal variability of the snowcover (McClung, 2002). The spatially variable nature of the snowpack is well established, but it is still particularly troubling for avalanche workers trying to mitigate avalanche danger with explosives or attempting to assess the snowpack stability. Given the observed variability, a misplaced explosive, or a poorly located snowpit, might well mislead an observer about the current state of the snowpack. Further, the variability makes extrapolating stability test results difficult, even when that extrapolation is onto nearby terrain, let alone over the large areas covered by regional avalanche centers. Though some variability patterns have been associated with rock outcrops or wind drifting patterns, thus far no reliable method exists for determining where weaker and stronger parts of a slope might be located. As a result of these problems, there is a growing body of literature on the spatial variability of snow conditions on individual slopes, but this literature is limited to changes through space and does not specifically address how spatial patterns might change through time. However, the snowpack exists near its melting point, and its microstructural and mechanical properties can, and do, change extremely rapidly. Thus, the existing spatial variability literature simply provides a snapshot in time of an extremely dynamic and rapidly changing system. Our lack of knowledge of how patterns of snow stability change through time limits our understanding of the avalanche phenomena and leaves avalanche forecasters guessing how that variability might be evolving as snow stability changes. This research begins to address how spatial variability, at the scale of an individual slope, changes through time.

Most field-based spatial variability research has focused on individual slopes with areas between 10^2 and 10^4 m^2. A number of studies at this scale have demonstrated sizable spatial variations in snow stability and snowpack properties over short distances (i.e., Conway and Abrahamson, 1984; 1988; Föhn, 1988; Jamieson, 1995; Birkeland *et al*., 1995; Kronholm *et al*., 2001). Many of these studies attempted to explain the observed patterns of spatial variation based on wind drifting and/or substrate such as the presence of rocks, but none of them specifically address how those patterns might change through time. However, Conway and Abrahamson (1984) noted that relatively more stable slopes exhibited higher standard deviations and coefficients of variation, suggesting more spatially variable conditions on more stable slopes. More recently, Kronholm *et al*. (2001) also suggest that more stable conditions exist on more spatially variable slopes. These two studies hint that patterns of snow

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stability may change through time, becoming increasingly variable as the snow becomes more stable. However, neither study specifically addresses changes through time, nor do they suggest a mechanism for the hypothesized changes.

More recent work (Landry, 2002; Landry *et al*., 2002) has further complicated our understanding of spatial variations. Previous research assumed that observed spatial variations were inherently explainable due to factors such as snow depth, wind deposition, vegetation, and substrate like rocks outcrops. However, Landry (2002) investigated relatively uniform 900 m^2 slopes, with constant slope angles, consistent substrates, no wind drifting, and, in many cases, little variation in snow depth. In spite of this uniformity, these slopes exhibited remarkable spatial variability in shear strength and stability. Coefficients of variation ranged from around 10% to almost 50%, and nearly half of the pits (consisting of 10 Quantified Loaded Column Tests (Landry *et al*., 2001)) did not statistically represent their respective 900 m^2 plots. These results forced us to focus on the variability itself and how it might develop internally over time in the system, rather than trying to explain the variability based on terrain or other factors.

Knowledge about nonlinear, dynamical *Earth Surface Systems* (ESSs) provide insights into our observations of variability on relatively uniform slopes and help in developing hypotheses for changes in variability through time. Phillips (1999) defines ESSs as complex, interacting systems, using soils and landforms as his primary examples. We believe that snow avalanches also constitute an ESS. For example, Phillips (1999) states that the characteristics of ESSs reflect complex interactions between the four major spheres. This clearly applies to snow avalanches, since they result from interactions between terrain (lithosphere), weather (atmosphere), and snowpack (hydrosphere/cryosphere), with trees, other vegetation and even human-triggers (biosphere) also playing a role.

Other credible evidence exists to support the idea that snow avalanches constitute an ESS. For example, a central principle of ESSs is that both order and disorder are simultaneously present and discernible, according to the scale of observation. Phillips' (1999) primary examples focus around soils, which are also quite spatially variable over short distances. However, at broader spatial scales a certain amount of order emerges. This broader scale is evident to the experienced soil scientist and is why reasonably accurate soil survey maps can be developed despite recognized small-scale variability. This is analogous to the snow avalanche system. In contrast to the often-confounding variability observed at the scale of individual avalanche slopes or study plots, a degree of order emerges at larger spatial scales. For example, an avalanche cycle in a specific mountain range may only occur on north through east aspects in areas exposed to wind loading. Birkeland (2001) statistically demonstrated this larger scale order for one small mountain range, but little other work has rigorously addressed this scale. As added evidence of some broad scale order for avalanche phenomena, veteran avalanche forecasters are capable of accurately predicting large scale patterns of snow stability despite the amount of variability existing at the slope scale, much like a soil scientist creating a soil survey map. The evidence of larger scale order in a system exhibiting considerable disorder at smaller spatial scales reinforces our contention that snow avalanches constitute an ESS.

A critical characteristic of ESSs, from the point of this paper, is that they are sensitive to initial conditions. Phillips (1999) calls systems with such initial sensitivity *deterministically complex*, though others have also termed such systems *deterministically chaotic* or simply *chaotic* (Lorenz, 1993). Some recent research suggests that snow avalanches constitute complex systems that may exhibit characteristics of chaos, self-organized criticality (Bak, 1996), or both (Birkeland and Landry, 2002; Louchet *et al*., in press; Dendievel *et al*., 2002; Faillettaz *et al*., 2002a; Faillettaz *et al*., 2002b; Rosenthal and Elder, 2002). In addition, the characteristics of deterministic complexity appear to describe at least some of the important processes at work within seasonal snowpacks. For example, Akitaya's (1974) classic research on depth hoar formation demonstrates the importance of initial conditions. Snow with a density less than 260 kg/m^2 weakens under a temperature gradient, while snow denser than 260 kg/m^2 becomes weaker, stronger, or does not change, depending on the temperature gradient. A more recent investigation that modeled the non-linear dynamics governing snowpack metamorphism has shown how interactions between in-snow temperature gradients, water vapor pressure gradients, and snow density are susceptible to abrupt, situation-specific transitions between snowpack-strengthening and snowpack-weakening regimes (Miller, 2002). Thus, snowpack properties at a given location can be highly dynamic through time and are likely sensitive to initial conditions.

Accepting that snow avalanches constitute ESSs sensitive to initial conditions has important implications for changes in spatial variability through time. In such systems, small and essentially unmeasurable (and perhaps unknowable) differences between adjacent parts of a slope might diverge through time, resulting in increasing spatial variability. This spatial divergence through time has been observed in several other systems, such as soils (Phillips, 1999). Clearly, the soil system is different than the snow avalanche system, with the most obvious difference being how quickly the system changes through time. Soils are quasi-stationary from the temporal perspective of a human lifetime, while snow may change dramatically at the temporal scale of a single day or less. Nevertheless, we suggest that sensitivity to initial conditions may help explain the sizable spatial variations observed by Landry (2002) on seemingly uniform slopes.

Given our field observations and the above literature review regarding ESSs, we present the following hypotheses for this research. First, we hypothesize that spatial variability, at the slope scale, increases (or *diverges*) through time. Second, we hypothesize that, in the presence of some sort of forcing, like a significant precipitation event, spatial variability decreases (or *converges*) through time. The reader is cautioned that our data are limited, and therefore our results should be viewed with appropriate skepticism. Still, these are the best data we have available for our analyses, and our results provide an encouraging baseline for future work.

2. Methods

2.1 Study area and sampling conditions

We utilized a slope in the Lionhead area, located about 15 km west of West Yellowstone, Montana, for this study (Figure 1). The slope is northeast facing, generally planar, and protected from ridgetop winds. At the time of sampling, it did not show any signs of disturbance by skiers or snowmobilers. The slope had room for three 900 m^2 plots (30 by 30 m). Located within 100 m of each other, these plots varied only slightly in slope angle and aspect characteristics and provided reasonably similar conditions (Table 1). Clearly, given the spatial variability documented on relatively uniform slopes (Landry, 2002; Landry *et al.*, 2002), it is quite possible that conditions between our plots varied, perhaps considerably. However, since our sampling scheme is destructive, we cannot sample the same locations twice. In order to proceed with this work we must assume that conditions within each of these three plots is reasonably similar, and that the evolution of stability patterns within each plot is also similar.

A layer of 15 to 20 mm surface hoar formed on the slope from December 21st to 26th, 2001 (Figure 2). This layer was buried on December 27th, and we sampled plots on the slope on January 9th, 15th, and 26th. Dangerous avalanche conditions on the slope above the sampling site between the 15th and the 26th prevented a regular sampling interval. We did not have remote instrumentation available at this site, but we roughly reconstructed the meteorological evolution of the weak

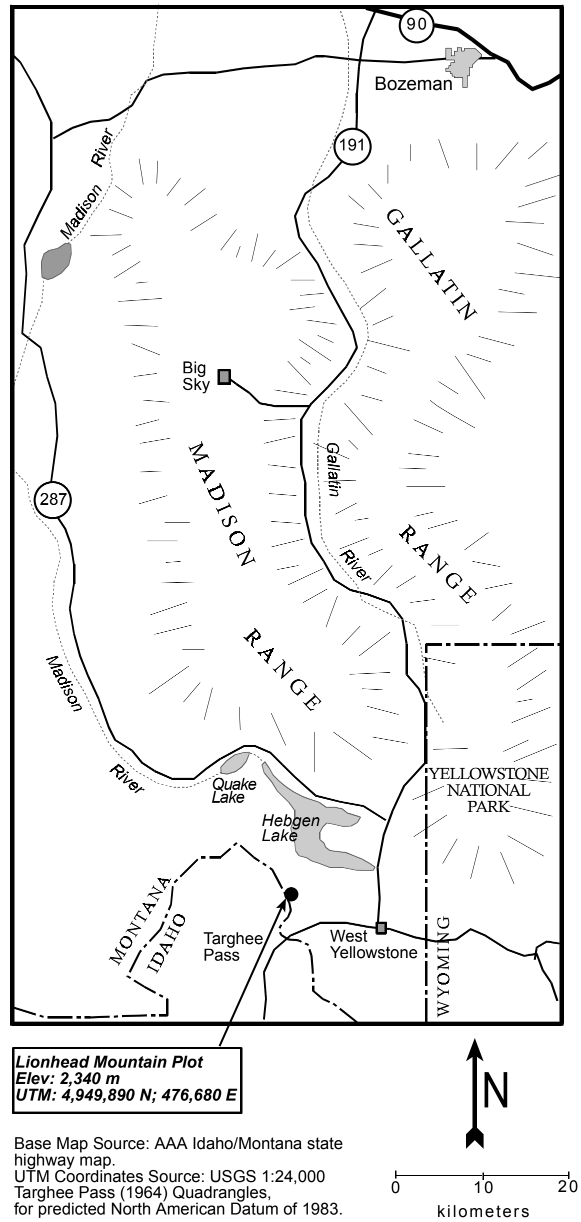

Figure 1: Location of the Lionhead study plots.

layer and slab. After the surface hoar was deposited, it was buried under a relatively thin slab (28 cm) before the January 9th sampling day. Between the 9th and the 15th, little new snow fell. Snowfall began in earnest after the 15th, with significant accumulations both before, and during, the January 26th sampling day.

2.2 Measuring and calculating stability within plots

To assess changes in spatial variability through time on the slope, we collected data from the three 900 m^2 plots (30 m by 30 m) over the course of about three

Table 1: Aspect and slope angles associated with the plots for each of the sampling trials.

Sampling date	Aspect	Slope angle	
		Mean (n=5)	Range
9 January 2002	38º	26.8º	25º-28º
15 January 2002	46º	26.8º	26º-27º
26 January 2002	46º	26.4º	25º-28º

weeks. Within each plot we used a systematic sampling design, distributing five snowpits in a regular pattern across the plot (for a diagram of the pit layout, see Landry *et al*., 2001). Shear strength data for our targeted surface hoar layer was collected using the quantified loaded column stability test (QLCT) method (Landry *et al*., 2001). Ten QLCT were performed in each of the five snowpits, using two rows of five, 50 cm

Figure 2: Backlit photograph of the surface hoar layer tested in this study, with a hand holding a pencil for scale. Photo taken on 1/1/02 approximately 200 m uphill from where the plots were sampled. Photo by Doug Chabot.

wide test cells, with the front of the second row of five cells 1 meter uphill of the front of the first row. We size-adjusted QLCT results to a sample size of 'infinite' area, according to the area of the weak layer actually tested. QLCT calculations yielded shear strength τ_∞ in units of N/m^2. We also measured slab water content (height in m, measured normal to slope) above the weak layer once at each pit in order to calculate the shear stress τ_{Slab} (N/m^2) acting upon the weak layer at that pit location:

$$\tau_{Slab} = \rho\, g h \, Sin\Psi \qquad (1)$$

where h represents the height of the slab measured normal to the slope (in m), ρ is the density of the slab (in kg/m^3), g is the acceleration due to gravity (9.8 m/s^2), and ψ is slope angle. A stability ratio was calculated:

$$S_{QLCT} = \tau_\infty / \tau_{Slab} \qquad (2)$$

Mean strength and mean stability values were calculated, pit-wise and plot-wise.

2.3 Conservative t-test analyses of "no difference" in strength and stability

For each pit in a given plot, two-sample *t*-test analyses were adapted to conservatively evaluate the hypotheses of "no difference" between a single pit's mean strength $\bar{\tau}_\infty$ and its plot's mean strength $\bar{\tau}_{\infty(Plot)}$, and between a single pit's mean stability $\bar{S}_{QLCT}$ and its plot's mean stability $\bar{S}_{QLCT(Plot)}$. This adaptation of the two-sample *t*-test evaluated whether the mean strength $\bar{\tau}_\infty$ and/or mean stability $\bar{S}_{QLCT}$ in any single snowpit within a plot reliably represented mean plot strength $\bar{\tau}_{\infty(Plot)}$ and/or mean plot stability $\bar{S}_{QLCT(Plot)}$ and, therefore, whether that study plot represented a single "strength (or stability) population".

In our application of the two-sample *t*-test, the assumption that samples be drawn from two separate populations was relaxed. Instead, we pooled results from a single snowpit with the remaining four snowpits at a plot to obtain mean study plot stability $\bar{S}_{QLCT(Plot)}$ or mean plot shear strength $\bar{\tau}_{\infty(Plot)}$. If a particularly strong/weak or stable/unstable pit were not pooled with the remaining four pits, plot-wide variability in strength or stability would have been understated and made to appear more consistent than was actually measured.

2.4 Definitions and measures of variability

There are several possible ways to define spatial variability, and each depends on the scale of observation. For this paper, we define the *spatial variability of a pit* as the coefficient of variation of stability (of the general form $CV = s/\bar{x}$, where s is the standard deviation of the sample mean strength $\bar{x}$) for the 10 QLCTs from that pit. The coefficient of variation is the preferred method for quantifying spatial variability at the pit scale since it is less dependent on mean strength than the standard deviation, which increases with increasing strength for shear frame measurements (Jamieson and Johnston, 2001). We further define the *spatial variability of a plot* as how representative the stability of our individual pits are of the 900 m^2 plot mean stability. This representativeness is tested with the t-test described above (p-value < 0.05). Thus, if all five pits do not statistically differ from the plot mean, we consider the plot to be spatially uniform. By our definition, as more pits statistically differ from the plot mean, the spatial variability of the plot increases.

Both pit variability and plot variability have practical implications. When the pit variability is high but the plot variability is low, an observer may note differing side-by-side stability tests. However, each part of the slope would be reasonably representative of the rest of the slope, allowing the variable pit data to be effectively extrapolated across the slope. A more dangerous situation exists when plot variability is high. Then, individual pits may not effectively represent the slope, and pits dug in one location may give misleading information about the slope. Clearly with our definitions, we can have situations where the pit variability increases while the plot variability decreases, or vice versa. For this study we focus primarily on plot variability.

Two other terms we use in discussing changes in variability at both the pit and plot scales are *spatial divergence* and *spatial convergence*. In the context of this paper, spatial divergence is simply increasing spatial variability through time. In other words, adjacent parts of the slope are diverging from one another and becoming increasingly different. At the pit scale this divergence is measured by an increase in the coefficient of variation through time, while we would measure this at the plot scale by an increasing number of pits that are not representative of the plot. Conversely, spatial convergence is simply decreasing spatial variability through time as adjacent parts of the slope become more similar. This would be shown through a decrease in the coefficient of variation at the pit scale or an increase in the number of pits that statistically represent the plot.

3. Results and discussion

The three sampling days exhibited different results (Table 2), and differing patterns of stability (Figure 3). Examining the observed patterns shows that several pits on 1/9/02 had relatively small ranges, especially pits 1, 2 and 4. By 1/26/02 the variability about the mean is much greater, while the plot from 1/15/02 is intermediate between the other two days. Visually exploring the data in these plots appears to show that variability is increasing through time at the pit scale. However, it is difficult to discern changes in spatial variability at the plot scale. Thus, we rely on statistical tests to objectively analyze the observed patterns.

Table 2: Stability-sampling trials summary, Lionhead (Std Dev = sample standard deviation, CV = coefficient of variation).

Date	Plot mean strength (N/m^2)	Plot mean shear stress (N/m^2)	Stability			Pits statistically representative of plot stability	Pits statistically unrepresentative of plot stability
			Plot mean	Std Dev	CV		
1/9/02	375	148	2.53	0.26	10.2%	5	0
1/15/02	523	170	3.08	0.33	10.6%	3	2
1/26/02	1,084	452	2.43	0.39	16.2%	4	1

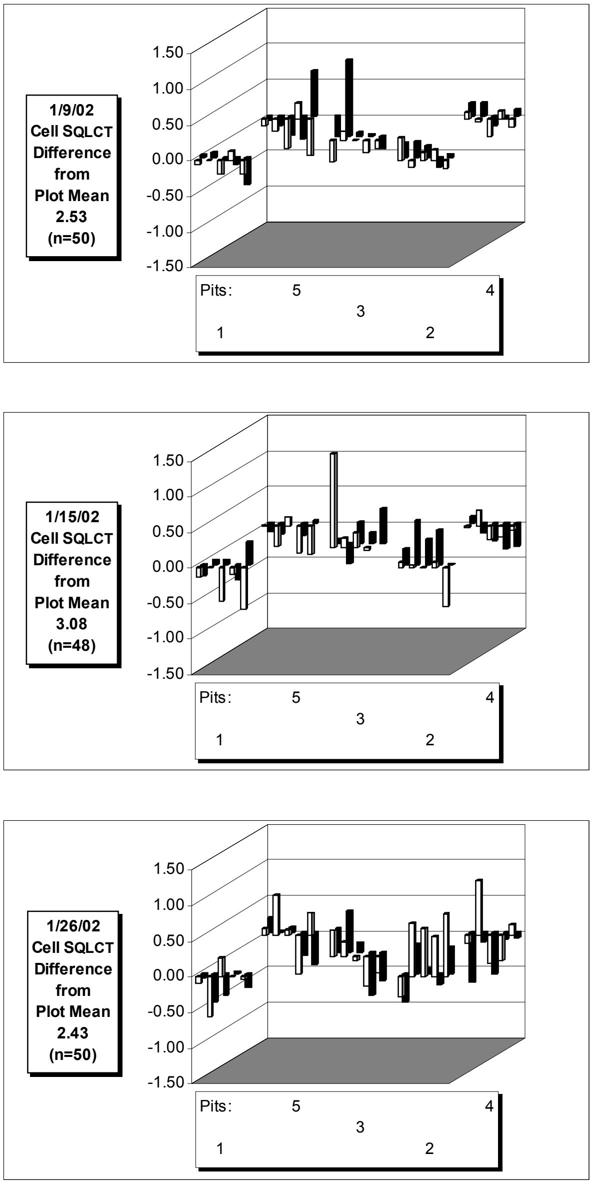

Figure 3: Results of each QLCT test for the three sampling days. Bars represent the deviation from the mean S_{QLCT} for the plot.

Mean strength rose though the sampling period, increasing 40% between the first two sampling days and an additional 107% between days two and three (Table 2). Mean shear stress from the slab also increased. Between the first two days shear stress increased 15%, while between the last two days it increased nearly 170%. The net result of these changes was that the stability ratio (S_{QLCT}) increased from 2.53 to 3.08 between the first two days when only a minimal new load was added. By the third day, despite the observed increases in strength, the stability ratio dropped to 2.43 in response to significant loading between the two days.

The coefficient of variation, used to quantify the pit scale spatial variability, was relatively constant between the first two sampling days (Table 2). Thus both the plot mean, and its standard deviation, increased at the same proportion between the two days. The coefficient of variation for the final day increased to more than 16%, demonstrating increasing spatial variability at the scale of the individual pits.

Though the spatial variability of the individual pits increased through time, this paper concentrates on spatial variability at the *plot* scale since that gives a better indication of how well data can be extrapolated from one part of the slope to another. On the first day, all five pits were statistically representative of the plot mean, indicating the snow stability was relatively uniform across the plot (Table 2). This is not surprising given the young age of the weak layer and the fact that the slope had been recently loaded. The second sampling day provides an interesting comparison. Little additional load, or shear stress, was added to the slope by the second day (on average only 22 N/m^2), and the coefficient of variation was similar to the first day. However, at the plot scale, two of the five pits statistically differed from the plot mean. Thus we observed an increase in the spatial variability of the slab/weak layer system at the plot scale: spatial divergence through time.

Data from the third sampling day provides additional interesting information. At the plot scale only one pit was not representative of the plot mean stability (Table 2). Thus, the slope that initially diverged appears to have begun converging. Clearly, this spatial convergence does not mean that the slope became more uniform at all scales. At the scale of individual pits, variability increased. However, more pits were representative of the entire plot, which is evidence of convergence at the plot scale. These observations differ from other more temporally constant ESSs like the soil system. Our data reflect an interesting capacity for snow to reverse the process of spatial divergence when subjected to a sufficient disturbance, and to become more spatially uniform at the plot scale through time. The unique and dynamic nature of snow as a material, which exists in nature near its triple point, helps to explain these changes.

Between the first and second sampling days, little additional shear stress, in the form of new snow load, was added to the snowpack (about 3.7 N/m^2 per day). However, initial conditions undoubtedly varied somewhat across the slope. Since the system is likely sensitive to initial conditions, the variability amplified through time, resulting in increasing spatial variability at the slope scale. Shear stress increased significantly between the second and third sampling days, averaging

25.6 N/m^2 per day over the 11 days, with peak accumulations probably much higher. In fact, the load was increasing dramatically on the final sampling day, with snowfall rates of 2 to 4 cm/hr. We hypothesize that the increased load and shear stress served to increase and accelerate creep rates. Accelerating creep rates may have mobilized the slab, in effect increasing the connectivity between different parts of the slope. This, in turn, produced the spatial convergence of stability at the plot scale. If this theory holds, then the cessation of loading, and deceleration of creep to a steady rate, would be expected to produce renewed spatial divergence. Unfortunately, we were unable to perform a fourth sampling trial at this location to test that hypothesis.

4. Conclusions

This research developed hypotheses about changes in spatial variability through time using research on *Earth Surface Systems* (ESSs) (Phillips, 1999), and tested those hypotheses using data from a slope in the Lionhead area near West Yellowstone, Montana. We measured the stability of a prominent surface hoar layer. Results showed the strength of the weak layer increased through time (Table 2), a finding verified previously by other researchers for surface hoar (i.e., Chalmers and Jamieson, 2001). Stability on the slope first increased, but later decreased in response to rapid snow loading. Spatial variability at the pit scale, quantified by the coefficient of variation, remained similar between the first two days, but increased markedly by the third day. Spatial variability at the plot scale, which was the primary focus of this paper, increased between the first two days and then decreased between the second and third sampling days, possibly due to the large-scale mobilization of the slab under accelerating creep rates.

Our results should be viewed with appropriate scientific skepticism. First, we measured three different parts of the same slope. Even though our plots had reasonably similar conditions in terms of their slope angle, aspect, and exposure to wind (Table 1), we cannot be sure that each of the three plots started with the same spatial variability at the plot scale, or that the variability of each plot changed through time in a similar manner. However, we could not avoid this problem because of the destructive nature of our sampling technique. Our second problem is that our results are based on limited data. Clearly, a stronger case could be made for our conclusions with a larger dataset, but even this small dataset was difficult to collect. Despite the above, these are the best available data for our analyses, and we feel our results are an encouraging baseline for future work on changes in spatial variability through time.

Much more research and data are necessary to fully explore changes in spatial variability through time. Future research might address a number of important questions: 1) How quickly, and under what conditions, will a slope spatially diverge? 2) How much new snow load, and at what rate, is necessary to cause spatial convergence?, 3) Can warming temperatures also produce creep acceleration sufficient to mobilize the slab and cause convergence?, and 4) What are the range of possible mechanisms for spatial convergence and divergence?

The results of this research, though preliminary, have practical implications for avalanche workers. At the scale of individual snowpits, our results suggest that we might expect increasing spatial variability with increasing load. Thus, side-by-side snowpits are more likely to have different results. We note, however, that more extensive data collected on surface hoar layers in Canada do not always show a clear relationship between load and increasing coefficients of variation within a pit (i.e., Chalmers and Jamieson, 2001). At the scale of a larger plot, our results suggest that the representativeness of a snowpit on a slope may decrease through time due to spatial divergence, in the absence of a significant forcing mechanism. When a new snow load is applied, the slope may converge, with any group of stability tests located within a pit more likely to represent the plot. From a practical perspective, the most dangerous conditions are when the spatial variability at the pit scale is low, but the spatial variability at the plot scale is high. Such a situation existed on our second Lionhead sampling day, and in a number of other single day trials conducted by Landry (2002). In these cases, side-by-side stability tests are likely to be similar, which increases the confidence of the observer about the test results. Nevertheless, those results may not accurately represent what is happening on the rest of the slope. Since our understanding of these changes is undeniably incomplete, our results further reinforce the notion that targeted sampling continues to be the optimal technique for avalanche workers searching for instability (McClung, 2002). In the end, a better understanding of changes in spatial variability at a variety of scales may help avalanche workers reduce uncertainty when interpreting and extrapolating stability tests.

Finally, our work supports the idea that the *avalanche system* is an example of an ESS. It has many of the characteristics of classic examples of ESSs, such as being composed of many interacting, nonlinear, and dynamic sub-systems, and simultaneously displaying both order and disorder, depending on the scale of observation. We also believe it is sensitive to initial conditions, and that this may be the reason for our observations of sizable spatial variability on relatively uniform slopes (Landry, 2002; Landry *et al*., 2002), as well as helping to explain changes in spatial variability through time. Phillips (1999) advocates a systems-based approach to the study of ESSs to complement deterministic research into these systems. Several investigators have performed systems-based analyses at the scale of a group of avalanche paths, such as cumulative avalanche activity in response to a perturbation (some examples include Perla, 1970; Armstrong, 1977; Birkeland and Landry, 2002; McCollister *et al*., 2002). We believe a number of other topics in our discipline may benefit from this approach, such as studies of the spatial and temporal scales of a variety of avalanche processes.

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References

Akitaya, E. 1974. Studies on depth hoar. *Contributions from the Institute of Low Temperature Science*, Hokkaido University, Ser. A, No. 26, 74 pp.

Armstrong, R.L. 1977. Continuous monitoring of metamorphic changes of internal snow structure as a tool in avalanche studies. *J. Glaciology*, 19(81), 325-334.

Bak, P. 1996. *How nature works: The science of self-organized criticality*. Copernicus, Springer-Verlag, New York, 212 pp.

Birkeland, K.W. 2001. Spatial patterns of snow stability throughout a small mountain range. *J. Glaciology,* 47(157), 176-186.

Birkeland, K.W. and C.C. Landry. 2002. Power laws and snow avalanches. *Geophysical Research Letters*, 29(11), 10.1029/2001GL014623.

Birkeland, K.W., K.J. Hansen, and R.L. Brown. 1995. The spatial variability of snow resistance on potential avalanche slopes. *J. Glaciology*, 41(137), 183- 190.

Chalmers, T.S. and J.B. Jamieson. 2001. Extrapolating the skier stability of buried surface hoar layers from study plot measurements. *Cold Regions Science and Technology*, 33(2-3), 163-178.

Conway, H. and J. Abrahamson. 1984. Snow stability index. *J. Glaciology*, 30(106), 321-327.

Conway, H. and J. Abrahamson. 1988. Snow-slope stability – A probabilistic approach. *J. Glaciology,* 34(117), 170-177.

Dendievel, R., J. Faillettaz, D. Daudon and F. Louchet. 2002. Snow avalanche release, scale invariance and criticality. Paper presented at the 27th General Assembly of the European Geophysical Society, Nice, France, March 2002.

Faillettaz, J., D. Daudon, F. Louchet, R. Dendievel and J-R. Grasso. 2002a. Snow avalanche release: from fracture mechanics to physics of complex systems? Paper to be presented at the Int. Conf. on Structural Integrity and Fracture, Perth (Australia), 25-28 September, 2002.

Faillettaz, J., F. Louchet, J-R. Grasso, D. Daudon and R. Dendievel. 2002b. Scale invariance of snow triggering mechanisms. *Proceedings of the 2002 International Snow Science Workshop*, Penticton, British Columbia, Canada, September 2002.

Föhn, P.M.B. 1988. Snow cover stability tests and the areal variability of snow strength. *Proceedings of the 1988 International Snow Science Worshop*, Whistler, Canada, 262-273.

Jamieson, J.B. 1995. Avalanche prediction for persistent snow slabs. Ph.D. dissertation, Department of Civil Engineering, University of Calgary, Calgary, Alberta. 258 pp.

Jamieson, J.B. and C.D. Johnston. 2001. Evaluation of the shear frame test for weak snowpack layers. *Annals of Glaciology*, 32, 59-69.

Kronholm, K., J. Schweizer, M. Schneebeli and C. Pielmeier. 2001. Spatial variability of snowpack stability on small slopes studied with the Stuffblock test. To be published in the proceedings of the *II International Conference "Avalanches and Related Subjects"* Kirovsk, Murmansk, Russia, September 3 - 7, 2001.

Landry, C.C. 2002. Spatial variation in snow stability on uniform slopes: implications for extrapolation to surrounding terrain. M.S. Thesis, Department of Earth Sciences, Montana State University, Bozeman, Montana, USA, 248 pp. http://www.fsavalanche.org/NAC/techPages/theses/landry.pdf

Landry, C., K. Birkeland, K. Hansen, J. Borkowski, R. Brown, and R. Aspinall. 2002. Snow stability on uniform slopes: implications for avalanche forecasting. *Proceedings of the 2002 International Snow Science Workshop*, Penticton, British Columbia, Canada, September, 2002.

Landry, C.C., J. Borkowski, and R.L. Brown. 2001. Quantified loaded column stability test: mechanics, procedure, sample-size selection, and trials. *Cold Regions Science and Technology*, 33(2-3), 103-121.

Lorenz, E.N. 1993. *The essence of chaos*. University of Washington Press, Seattle, Washington, 227 pp.

Louchet, F., J. Faillettaz, D. Daudon, N. Bedouin, E. Collet, J. Lhuissier, and A-M. Portal. In press. Possible deviations from Griffith's criterion, and consequences on slab avalanche release. To be published in: *Natural Hazards and Earth System Sciences*. Paper presented at the 26th General Assembly of the European Geophysical Society, Nice, France, 25-30 March 2001.

McClung, D.M. 2002. The elements of applied avalanche forecasting. Part I: The human issues. *Natural Hazards*, 25, 111-129.

McCollister, C., K. Birkeland, K. Hansen, R. Aspinall, R. Comey. 2002. A probabilistic technique for exploring multi-scale spatial patterns in historical avalanche data by combining GIS and meteorological nearest neighbors with an example from the Jackson Hole Ski Area, Wyoming. *Proceedings of the 2002 International Snow Science Workshop*, Penticton, BC, Canada.

Miller, D.A. 2002. An integrated microstructural study of dry snow metamorphism under generalized thermal conditions. Ph.D. Dissertation, Department of Civil Engineering, Montana State University, Bozeman, Montana. 257 pp. http://www.fsavalanche.org/NAC/techPages/theses/miller.pdf

Perla, R.I. 1970. On the contributory factors in avalanche hazard evaluation. *Canadian Geotechnical Journal,* 7, 414-419.

Phillips, J.D. 1999. *Earth Surface Systems*. Blackwell, Malden, Massachusetts, 180 pp.

Rosenthal, W. and K. Elder. 2002. Evidence of chaos in slab avalanching. *Proceedings of the 2002 International Snow Science Workshop*, Penticton, British Columbia, Canada, September 2002.