Scale-invariant relationships for snow avalanches

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Abstract. Snow avalanches are the most common form of lethal mass wasting in the mountains of the western United States, resulting in more than 30 fatalities per winter. In this poster, which summarizes and builds on the work of Birkeland and Landry (2002), we investigate scale-invariant relationships associated with snow avalanches to better understand some of the complex interactions of the snow avalanche system. Our results reveal power-law relationships between avalanche frequency and size for several groups of avalanche paths, as well as a power-law between the response of the system and the binned frequency of those responses. Further, we also demonstrate a power law between avalanche frequency and the estimated fracture depth of the avalanches for groups of avalanche paths in several different snow climates. Interestingly, the relationships explored are valid both for datasets consisting largely of avalanches artificially triggered with explosives as well as for datasets consisting entirely of natural avalanches. Recent research demonstrates scale invariance in the fracture and fragmentation of ice [Weiss, 2001]. Our work suggests that scale invariance may also exist in the complicated fracture processes within seasonal snowpacks that result in the release of slab avalanches.

Introduction

Other natural hazards, such as earthquakes [*Gutenberg and Richter*, 1956], landslides [*Guzzetti et al.*, 2002] and forest fires [*Malamud et al.*, 1998] show robust power-law size/frequency distributions consistent with self-organized critical (SOC) behavior. Work on SOC often refers to "avalanches" through the system, and some papers have implied that these concepts might be applicable to "snow piles" and snow avalanches [*Bak and Chen*, 1991], even though the dynamics of the original sandpile models used to demonstrate SOC are quite different from the processes which release actual snow avalanches. Despite this difference, our investigations indicate that groups of snow avalanche paths exhibit power laws.

Large natural avalanche fracture line in Yule Creek, Colorado. Photo by Hal Hartman.

Data

We utilize the Westwide Avalanche Network (WAN) data for our analyses. The WAN was initiated and sustained by the U.S. Forest Service, and it includes data from all of the most avalanche-prone developed sites in the United States from the late-1960s until 1995. Most of the avalanches in the dataset were triggered by explosives. However, the Gothic, Colorado site is unique, with 21 seasons of observations (1974/75 through 1994/95) of over 3,000 natural dry-slab avalanches from 32 avalanche paths routinely observed by a single observer. In addition to the WAN data, our final dataset represents six winter seasons (1992/93 through 1997/98) in the lower Yule Creek valley of central Colorado and includes over 300 individual natural dry-slab avalanche events from 29 avalanche paths routinely monitored by a single observer. The Yule Creek dataset is unique in that it describes the "response" of the system in terms of the magnitude of an avalanche cycle.

Our datasets classify avalanche magnitudes according to the U.S. size scale, which utilizes five categories of avalanches from small relative to the avalanche path in question [*McClung and Schaerer*, 1993]. We considered only size 2 (small relative to the path) through size 5 (maximum) avalanches, since size 1 avalanches are often not recorded. Though this classification system yields somewhat subjective data, we propose that the U.S. classification system provides an approximate order-of-magnitude scale.

Results and discussion

Non-cumulative size/frequency relationships for Gothic show a strong log-linear relationship, with the slope of the best-fit line, α, equal to -0.74 (Figure 1). The dataset for Jackson Hole (Figure 2), consisting primarily of explosive triggered slides, shows a similar non-cumulative size/frequency log-linear relationship, surprisingly comparable to Gothic. Since a primary goal of avalanche hazard reduction is to pre-empt large avalanches by artificially triggering smaller ones, α should theoretically decrease (i.e., the best-fit line should be steeper) for datasets of triggered avalanches. We have analyzed 29 of the WAN sites and almost all demonstrate log-linear size/frequency relationships with a median α of -0.58 and a range from -0.34 to -0.89.

The Yule Creek dataset does not show the same clear size/frequency log-linear relationship as the other data we analyzed, perhaps because of its smaller size. However, a sequential graph of numbered storms and their associated avalanche cycle index scores for these data (n = 104 storms over six winter seasons) shows how some storms result in large system responses while others result in no response (Figure 3). Storms had to have at least 12 mm of snow water equivalent so the snowpack approached the critical *conditional stability* threshold, and we did not consider early season storms when the snowpack was too shallow to cover terrain anchors. It is noteworthy that the distribution of avalanche system responses to these storm perturbations results in another power-law (Figure 4).

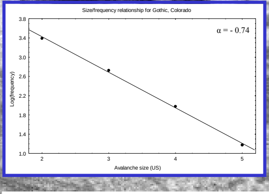

Fig 1: Non-cumulative size/frequency distribution for Gothic, Colorado (n = 3,093).

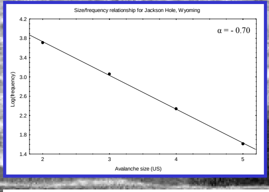

Fig 2: Non-cumulative size/frequency distribution for Jackson Hole, Wyoming (n = 7,009).

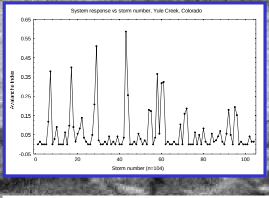

Fig 3: A sequential graph of 104 numbered storms in Yule Creek, Colorado versus storm avalanche index scores.

Results and discussion (cont.)

Two potential problems with the above analyses by Birkeland and Landry (2002) exist. First, we only have four points to evaluate for size classifications, making a robust statistical analysis of the observed relationships difficult. Second, we must assume the U.S. size classification is an order-of-magnitude scale. Rosenthal and Elder (2002) utilize the fracture depth of the avalanche to show scale invariance for one WAN site with primarily explosive triggered avalanches. Following their work, we investigate cumulative fracture depth/frequency relationships for all of our 29 WAN sites. All sites clearly demonstrate power-laws, with the slope of the best fit line, D, ranging from -2.44 to -4.44, with a median of -3.49; the slope for the relationship at Gothic for naturally occurring avalanches is -3.52 (Figure 5). Finally, we sum up all the avalanches from all of our sites to look at the cumulative fracture depth/frequency relationship. For nearly 50,000 avalanches with fracture depths ranging from 0.6 to 7.6 m, the slope of the least squares best fit line is -3.29 and the r-square for the relationship is 0.996 (Figure 6).

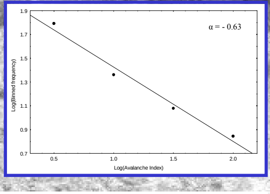

Fig 4: A power law exists between the storm avalanche index and the log of the binned frequency related to those avalanche indices in the Yule Creek system.

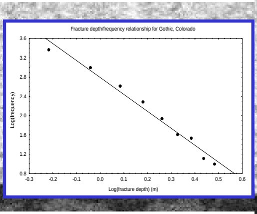

Fig 5: Cumulative fracture depth/frequency distribution for Gothic, Colorado (n = 3,093) for crown heights from 0.6 to 3 m (2 to 10 ft). The slope of the best fit line is -3.5.

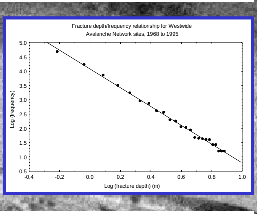

Fig 6: Cumulative fracture depth/frequency distribution for 29 different Westwide Avalanche Network sites (n = 48,991) for crown heights from 0.6 to 7.6 m (2 to 25 ft). The slope of the best fit line is -3.29 and the r-square for the linear regression is 0.996.

The flank of an avalanche in Jackson Hole's Cody Bowl. This slide was triggered by a 2 kg (5 lb) charge. Photo by Bob Comey

Avalanche at Jackson Hole below Tram Tower 5 triggered with a large buried charge. Photo by Warren Pratt.

Avalanche terrain in Gothic, Colorado. Photo by Chris Landry.

Summary

Our results may provide a new theoretical context for the study of snow avalanches. Despite the numerous complexities involved in snow avalanche formation and release, they show scale invariant, power-law size/frequency and fracture depth/frequency relationships consistent with self-organized critical behavior. In addition, at least one group of snow avalanche paths demonstrates another power-law associated with the response of the system to storm perturbations. We found no geographical trends in the spatial distribution of the slopes of the best fit lines for different sites based on climate. In fact, some sites which shared common ridgelines still had markedly different slopes. This suggests to us that the critical scale for the power law may be individual avalanche paths. Thus, contrary to popular opinion, the triggering mechanism may not control either the size/frequency or the fracture depth/frequency distribution. From a practical perspective, the distributions of small and medium sized avalanches may be useful for quantifying the risk of large snow avalanches within a group of avalanche paths.

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