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Forecasting artificially-triggered avalanches in storm snow at a large ski area

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ABSTRACT

At ski areas, a majority of avalanches fail in storm snow. Using thousands of observations from avalanche control work at Mammoth Mountain, CA, USA, a large coastal ski area, I analyzed important predictors of avalanche activity. New (24 h) precipitation increased avalanche activity, while changing temperatures and different wind patterns had no effect. If slopes remained undisturbed for one day after snowfall, the number and size of avalanches as well as the explosive yield (avalanches per shot) were all significantly reduced. I also examined a smaller dataset of Extended Column Test (ECT) results and their relation to avalanche activity. ECT propagation was a powerful predictor; days with ECTs that propagated had significantly more avalanches and larger sizes. Days with propagating ECTs also had significantly greater new snow amounts, with a threshold value of 0.29 m of new snow, very close to the 0.31 m threshold from Atwater's 10 factors. That new precipitation above a threshold causes greater avalanche activity is not a new finding; the new finding is that ECT propagation (versus non-propagation) also has a similar new snow threshold. Thus, I suggest that ECT propagation is an important tool to predict explosively-triggered avalanches in storm snow.

1. Introduction

At ski areas in North America that record failure layers, a majority of avalanches are estimated to fail in storm snow (Bair, 2011; Stethem and Perla, 1980; Williams and Armstrong, 1998). Storm snow crystals are called *nonpersistent* because they metamorphose into rounded or faceted forms within a few days (Jamieson, 1995). Older faceted crystals are called *persistent* because, once buried, they can remain in the snowpack for weeks or months. Because they are often deeper and more destructive, avalanches that fail on persistent crystals have received significant study, while those on nonpersistent crystals have received little study. Despite the lack of research, avalanches that involve only storm snow are a significant hazard. For instance, the worst avalanche accident at a North American ski area was caused by an avalanche that only involved storm snow. The accident occurred on 31 Mar 1982 and killed seven people at Alpine Meadows, CA (Heywood, 1992). The storm snow accumulation at the time of the accident was 2.2 m on top of a well bonded melt-freeze crust. Crown heights were 2–3 m (Penniman, 1986). Strong winds, averaging up to 39 m s^{-1}, easily account for the added wind load.

1.1. Avalanche forecasting

Conventional avalanche forecasting has been performed by experienced avalanche professionals using a variety of measurements and information sources to guide decisions, which are largely based on empiricism and intuition (LaChapelle, 1980). Various attempts at statistical (Buser, 1983; Buser et al., 1985; Davis et al., 1999; Gassner and Brabec, 2002; Heierli et al., 2004; McCollister, 2004; Purves et al., 2003; Roch, 1966) and physically based (Bartelt and Lehning, 2002; Casson, 2009; Conway and Wilbour, 1999; Föhn, 1987; Gauthier et al., 2010; Hayes et al., 2004; Jamieson, 1995; Jamieson and Johnston, 1993, 1998; Zeidler, 2004) stability models have been made, but have not gained widespread acceptance in the avalanche community. With increased computing power, spatially explicit (Durand et al., 1999; Hirashima et al., 2008; Pozdnoukhov et al., 2008; Rousselout et al., 2010; Schirmer et al., 2009, 2010) models have emerged, but have not proven capable of providing better guidance than conventional forecasting methods. Further, verification is difficult since avalanche activity is often not observed or reported and depends on triggering factors such as skier traffic. Avalanche hazard forecasts (Brown and Jamieson, 2008; Elder and Armstrong, 1987; Schweizer et al., 2003) and models (Durand et al., 1999; Rousselout et al., 2010; Schirmer et al., 2009, 2010) have been verified with *a posteriori* hazard estimates, snow pit data and stability tests, or a limited number of avalanche occurrences. Avalanche hazard forecasting largely depends on scale and type of area. For example, for the same absolute hazard level, a backcountry area will have far fewer avalanche occurrences than a ski area with extensive avalanche control measures. Many stability models were developed for backcountry forecast areas, so their accuracy cannot be directly compared to models specifically developed for ski areas or other areas with extensive avalanche control measures.

At many ski areas, one will find snow safety professionals still implicitly using Atwater's 10 contributory factors (Atwater, 1954; Atwater and Koziol, 1953): 1) old snow depth, 2) old snow surface,

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3) new snow depth, 4) new snow type, 5) new snow density, 6) snowfall intensity, 7) precipitation intensity, 8) wind action, 9) air temperature, and 10) snow settlement. Perla (1970) examined the impact of the 10 contributory factors on avalanche hazard over 107 storms at Alta, UT. He found that all measures of precipitation (e.g. Atwater's factors 3, 6, and 7) show clear positive relationships with avalanche hazard. Other factors, such as wind speed and changes in air temperature, did not.

With a few exceptions (i.e. Atwater and Koziol, 1953; Davis et al., 1999; Föhn et al., 1977; McCollister et al., 2003; Perla, 1970; Rosenthal and Elder, 2003; Stethem and Perla, 1980), much of the avalanche forecasting literature focuses on backcountry areas. Since there are few studies that focus on ski areas or on avalanches that fail in storm snow, the aim of this study is to describe a few simple variables that have proven successful for predicting avalanches at a large ski area.

2. Location, data, and methods

2.1. Mammoth Mountain

Mammoth Mountain is a silica dome cluster (Hildreth, 2004) with a base elevation of 2424 m and a summit at 3369 m. LaChapelle's (1966) avalanche climate classifications would place it in the Coastal Transition Zone. Like other Pacific Coast areas, Mammoth Mountain receives heavy winter precipitation, accumulating an average of 890 mm of snow water equivalent (SWE) and 719 cm of snow depth from December through March. Mammoth's Main Lodge elevation, 2712 m, is higher than most Pacific Coast ski areas and is similar to Intermountain areas, which have an average base elevation of 2605 m (Armstrong and Armstrong, 1987). Mammoth's higher elevation leads to colder temperatures and infrequent mid-winter rain, uncommon characteristics for Coast areas. The average Main Lodge December to March daily temperature is −2.4 °C, slightly lower than the average Coast base lodge temperature, –2.0 °C, but higher than the average Intermountain base lodge air temperature, –6.0 °C, and much higher than the average Rocky Mountain base lodge air temperature, –8.7 °C (Mock and Birkeland, 2000). In one study (Mock and Birkeland, 2000), the mixture of Coast and Intermountain avalanche climate characteristics causes Mammoth to be classified as a Coast area in half the years and an Intermountain area in the other half.

2.2. Mammoth Mountain ski patrol (MMSP) daily weather observations

At Mammoth, trained observers have taken daily morning weather observations and measurements on over 6000 days since 1982. Total depth, new snow, new snow density, new SWE, temperatures, relative humidity, visibility, and several other measurements are taken every day between 5:00 and 8:00 am during the winter season (November–April) at the patrol snow study site (Study Plot, Fig. 1). “New” refers to 24-h accumulations (Fierz et al., 2009). Often, new snow is manually weighed to determine SWE.

2.3. MMSP avalanche database

The avalanche control records are stored in a database with over 15,000 avalanches and over 40,000 total records (includes non-avalanches, avalanches, and unseen results due to visibility) from 1982–2012. Only 1% of avalanches were naturally triggered; 99% were artificially triggered, in decreasing order by: explosives, artillery, and ski cuts. Records are estimates of avalanche properties that can be easily observed, such as: relative class size, crown height, slab width, and total length (Greene et al., 2010). Bed surface has only been recorded in the database since 2006, so there are only about 3700 avalanches with a bed surface estimate.

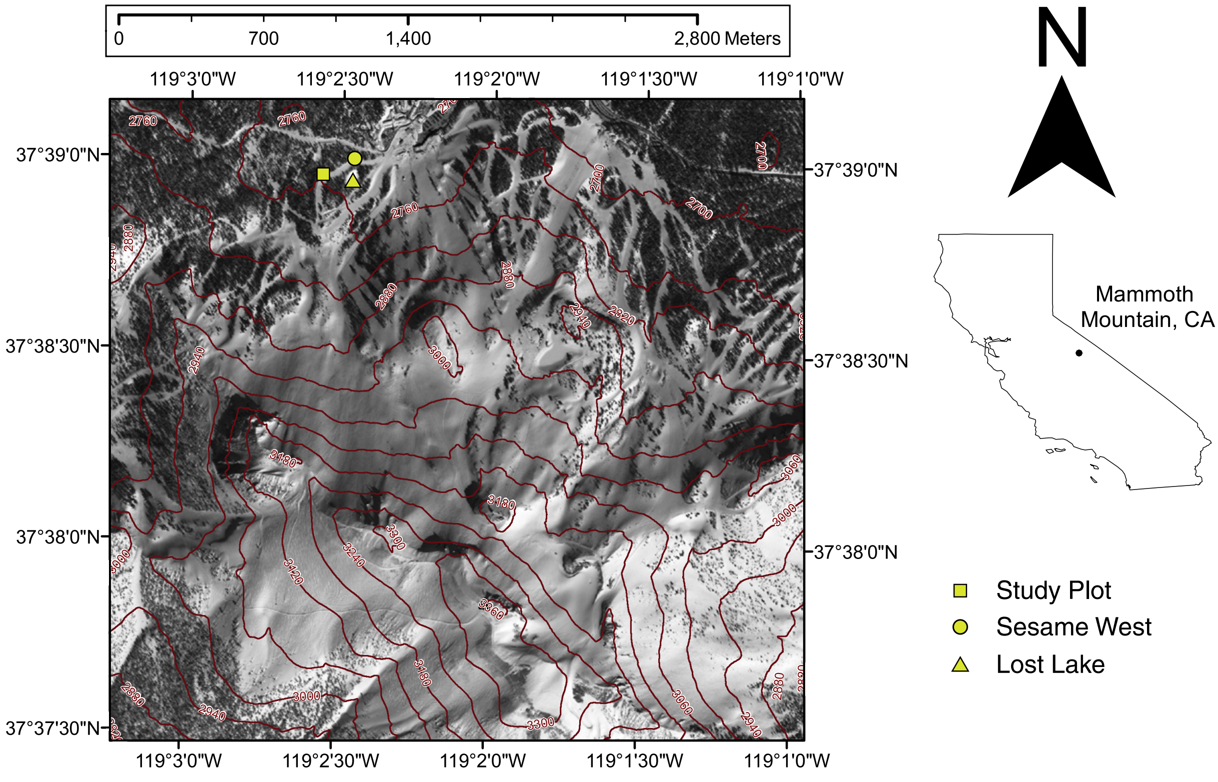

Fig. 1. Map of Mammoth Mountain ski area. Study Plot is where precipitation is measured. Sesame West and Lost Lake are nearby sites where stability tests were made.