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 hr) 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.
Introduction

At ski areas in North America that record failure layers, a majority of avalanches are estimated to fail in storm snow (Stethem and Perla, 1980; Williams and Armstrong, 1998; Bair, 2011). 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 sec^{-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 (Roch, 1966; Buser, 1983;
Buser et al., 1985; Davis et al., 1999; Gassner and Brabec, 2002; Purves et al., 2003; Heierli et al., 2004; McCollister, 2004) and physically based (Föhn, 1987; Jamieson and Johnston, 1993; Jamieson, 1995; Jamieson and Johnston, 1998; Conway and Wilbour, 1999; Bartelt and Lehning, 2002; Hayes et al., 2004; Zeidler, 2004; Casson, 2009; Gauthier et al., 2010) 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; Schirmer et al., 2009; Rousselout et al., 2010; Schirmer et al., 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 (Elder and Armstrong, 1987; Schweizer et al., 2003; Brown and Jamieson, 2008) and models (Durand et al., 1999; Schirmer et al., 2009; Rousselout et al., 2010; Schirmer et al., 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 and Koziol, 1953; Atwater, 1954): 1) old snow depth, 2) old snow surface, 3) new snow depth, 4) new snow type, 5) new snow density, 6) snowfall intensity, 7) precipitation intensity, 8) wind action, 9) air temperature, 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, changes in air temperature, did not.

With a few exceptions (i.e. Atwater and Koziol, 1953; Perla, 1970; Föhn et al., 1977; Stethem and Perla, 1980; Davis et al., 1999; McCollister et al., 2003; Rosenthal and Elder, 2003), 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 ºC, slightly lower than the average Coast base lodge temperature, –2.0 ºC, but higher than the average Intermountain base lodge air temperature, –6.0 ºC, and much higher than the average Rocky Mountain base lodge air temperature, –8.7 ºC (Mock and Birkeland, 2000). In one study (Mock and Birkeland, 2000), the mixture of Coast and Intermountain avalanche climate characteristics cause 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, Figure 1). “New” refers to 24-hr 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 3,700 avalanches with a bed surface estimate.

2.4 Avalanche activity

In addition to counting the number of avalanches, I also used the unweighted sum of relative class sizes (R-size, avalanche size relative to a path’s maximum). Other studies have used weighted size sums to account for nonlinearity in size classification (Salway, 1979; Schweizer et al., 1998; Mock and Birkeland, 2000; Zeidler, 2004; McClung, 2009). An absolute size classification (D-size, the avalanche size in terms of destructive force; see Greene et al., 2010) is preferable to compare results across different avalanche paths, but D-size has only recently been recorded at Mammoth Mountain. Since this study involves mostly small avalanches, unweighted sums of R-sizes were preferred because this metric emphasizes activity rather than size (Perla, 1970; Davis et al., 1999; Gauthier et al., 2010). Most small avalanches are classified as size R1, which is
similar D1 for most avalanche paths. Ski areas, at least in the US, devote considerable resources to preventing small avalanches from occurring while slopes are open, as they are a legal liability. For this reason, I included R1 avalanches in the following analysis rather than excluding them as in some studies (Davis et al., 1999; Birkeland and Landry, 2002).

I only examined records from 92 selected avalanche paths. Only avalanches triggered by explosives were counted. Naturally-triggered avalanches and those triggered by ski-cutting or artillery were excluded. Avalanches triggered by ski-cutting were excluded because they are consistently not recorded. Paths shot by artillery have been excluded since those paths are often shot blind and results are often not seen.

2.5 Explosive yield

Explosive yield was computed as the count of avalanches triggered by explosives divided by the sum of shots for the selected avalanche paths. As with R-size, avalanches triggered by artillery, by ski cutting, or triggered naturally were excluded.

2.6 Avalanche activity predictors

To determine which variables were important avalanche activity predictors, I analyzed the effect of eight weather variables, based on Atwater’s ten factors, over 737 storms using hazard probability $H$ defined by Perla (1970):
\[ H = \frac{\text{number of storms in interval with } S \geq t}{\text{total number of storms in interval}} \]  

where \( S \) is the sum of R-sizes for each storm and \( t \) is an arbitrary threshold, corresponding to 25\(^{th}\) (low) and 75\(^{th}\) (high) percentiles of R-sizes for all storms. Here, storms are defined as continuous days with new snow and include the following day after snowfall ends. Storms were placed into five evenly-spaced bins based on each weather variable. Variables examined were: maximum snow density change, maximum temperature change, mean wind speed, mean wind direction, total SWE, maximum SWE intensity, mean SWE intensity, and total snow. To limit storms to dry snow avalanches, only storms from December-April were included.

2.7 Extended Column Test

The Extended Column Test (ECT), developed by Simenhois and Birkeland (2006; 2009), is similar to the compression test developed by Canadian Park wardens in the 1970s (Jamieson, 1999), except that it employs a wider column, so that crack propagation is also observed. For details on how an ECT is performed, see Simenhois and Birkeland (2009). At least three ECTs were performed each day to ensure valid results. Although there were differences in the number of taps needed for propagation, all of the tests were consistent with regard to propagation; one any given day, all tests propagated on the same failure layer or none propagated.

Like other studies that evaluate the predictive accuracy of the ECT (Simenhois and Birkeland, 2009; Schweizer and Jamieson, 2010), I only
examined two cases: propagation and no propagation. When using the
propagation criterion alone, the ECT has been shown to be a more accurate
stability test than Compression Tests, Propagation Saw Tests, or Rutschblock
Tests (Simenhois and Birkeland, 2009; Schweizer and Jamieson, 2010).

2.8 Hypothesis test

Probabilities in the results are based on the Kruskal-Wallis (1952) test, which
assumes that populations have the same, not necessarily normal, distribution
and that all observations are independent. The null hypothesis is that the two
groups come from the same population. I used a threshold p value for
significance at $p \leq 0.05$ below which the null hypothesis is rejected and the two
groups are significantly different.

2.9 Classification trees

To determine threshold values for snow and SWE associated with ECT
propagation, I constructed classification trees. Classification trees are a method
of supervised learning where values are placed into classes that minimize a
chosen measure of impurity. In this study, there are two classes: “propagation”
(N=10) and “no propagation” (N=24). The measure of impurity minimized is Gini's
diversity index (Breiman et al., 1984).
3 Results

3.1 MMSP avalanche database

Most of the avalanches at Mammoth Mountain are small (Figure 2). This agrees with previous studies of avalanches at Mammoth Mountain (Rosenthal and Elder, 2003; Bair et al., 2008) and ski areas (Birkeland and Landry, 2002; Louchet et al., 2002; Faillettaz et al., 2004) that show there are many small avalanches and few large ones. About 56% of avalanches were estimated to have failed in a storm layer. Another 31% were estimated to have failed on the interface at the top of the old snow layer.

Seven crown face profiles of avalanches that failed on (storm/old) interfaces at Mammoth show that none of them contained persistent crystals; all contained nonpersistent crystals in the slab and the substrate (Bair, 2011). Also, a majority (20/23) of crown face profiles contained failure layers of storm snow. Thus, we assume that interface failures at Mammoth usually involve only storm snow.

Together, interface failures and failures in storm layers comprise 87% of avalanches at Mammoth. The proportion of storm snow avalanches decreases with R-size, but there are still three (27%) interface failures and five (45%) storm failures out of eight total R-size 5 avalanches in the database.

3.2 Weather variables important to avalanche hazard

Of the eight weather variables analyzed (Figure 3), only the precipitation variables (Figure 3e-h) had positive relationships with avalanche activity or “first order” (Perla, 1970) effects. Changes in snow density or air temperature (Figure...
3a,b) and wind speed/direction (Figure 3c,d) oscillate near a mean value and thus do not affect hazard probability. The “upside down storm” (increasing temperature, Atwater, 1954) did not affect avalanche hazard at Mammoth Mountain.

3.3 ECTs

I performed ECTs on 37 days over two winters, 2010-11 and 2011-12. It was snowing or there was new snow on 34 of those days (92%). Tests on days without snowfall were all performed within one day of snowfall, at the end of a storm. For the selected avalanche paths, there were only six days (out of 967 or < 1%) with avalanches recorded more than one day after new snowfall, which suggested no need to perform ECTs more than one day after snowfall to predict avalanches inside the ski area. All ECTs took place at Lost Lake or Sesame West (Figure 1). Propagation occurred on 13 out of 37 days (35%).

All failures occurred on nonpersistent crystals, except for three sampling dates, 16 Feb, 17 Feb, and 16 Mar 2011, which were excluded from the analysis. Failures on nonpersistent crystals propagated on 10 of 34 days (29%). Whether or not an ECT propagated correlated with the amount of new SWE and snow (Figure 4). Results are given for both because new snow is more reliably measured than SWE. For new SWE, the median is 46 mm for propagation and 18 mm for no propagation ($p = 0.03$). For new snow, the median for propagation is 54 cm and 17 cm for no propagation ($p < 0.01$). Threshold values from
classification trees between “propagation” and “no propagation” are 25 mm SWE
(26% misclassification) and 29 cm snow (15% misclassification).

Days with propagation also have higher median snow storm totals (65 cm)
than days with no propagation (26 cm), but the difference is not significant ($p = 0.06$), suggesting that new snow and SWE have a greater impact on propagation.

Still, the $p$-value is close to 0.05, so there is some statistical evidence that days
with propagation have greater storm totals than days without propagation.

Days with propagation also have significantly greater R-size sums ($p < 0.01$).

The median R-size sum for propagation days is 49 vs. 0 for days without
propagation (Figure 5). Days without propagation do not have significantly
different explosive yields than days with propagation ($p = 0.27$).

3.4 Explosive yield

The total explosive yield for the 92 selected paths at Mammoth is 24%.

Explosive yield shows little relationship ($R^2 < 0.06$ or less) to precipitation
variables (i.e. new snow/SWE, storm snow, and new snow density), aggregated
over single days or multi-day storm periods. Although yield shows year-to-year
variation, from 0.15 to 0.35, linear regressions of the number of shots,
avenches, and yield per water year (Figure 6a-c) have slopes with 95%
confidence intervals that cross zero, which means there is no significant
statistical trend; the three variables are stationary. Explosive yield varies on a
path-by-path basis, from 0.03 to 0.61, with slight correlation to maximum start
zone angle ($R^2=0.15$, Figure 7).
3.5  Effect of performing avalanche control work after one day

To see the effect of performing control work more than 24-hr after snowfall, rather than while snowing or immediately after snowfall, I examined avalanche activity on the selected avalanche paths and grouped them based on how many days it had been since snowfall. There were 904 avalanche control days with snowfall in the past 24 hr, 28 avalanche control days without snowfall in the past 24 hr, 7 days without snowfall in the past 48 hr, 3 days without snowfall in the past 72 hr, and 2 days without snowfall in the past 96 hr. Because there were so few avalanche control days after 24-hr with no snowfall, I focused only on the first two groups (new snow and no new snow in the past 24 hr). Avalanche control days with new snow had significantly more avalanches, greater R-size sums, and greater explosives yields (all p-values < 0.01, Figure 8a-c). It is striking that the days without new snow had median values of zero for avalanches, R-size sums, and explosive yield, meaning that usually, explosives caused zero avalanches more than 24-hr since snowfall ended.

4  Discussion

4.1  Avalanche size and bed surface

Most avalanches at Mammoth were size R1 and failed in the storm layer. Most of the others failed at the storm/old snow interface. Thus, 87% of avalanches at Mammoth involved only storm snow. Although the proportion of avalanches that only involve storm snow decreases with R-size, even the majority (72%) of R5 avalanches involved only storm snow. Avalanche control
and ski compaction are the most straightforward explanations. Constant release of unstable storm snow by explosives and increased strength via compaction from the weight of thousands of skiers are effective measures to reduce avalanches on persistent weak layers.

Less clear is why most avalanches at Mammoth fail within storm snow rather than at the storm/old snow interface. This finding suggests that snow directly above an interface is usually better bonded to older snow below than to newer snow above. One reason may be that most Sierra Nevada storms start with periods of low precipitation that increase gradually (Figure 9). Periods of low precipitation intensity allow storm snow to strengthen via compaction and sintering before additional weight causes enough stress to trigger an avalanche. Changing storm conditions, such as decreasing temperature and wind may also cause weaker snow to be deposited in the middle of the storm, rather than at the beginning. One might think that another reason for the prevalence of failures within storm snow is that skier traffic causes a ragged surface at the interface that inhibits fracture propagation. The distribution of 196 bed surfaces from avalanches on four avalanche paths that are permanently closed to skiing and only controlled with explosives shows a similar distribution to the ski area as a whole: ground (1 %), old (10 %), interface (31 %), and storm (58 %). Similar distributions between these paths and the whole ski area suggest that skier compaction and surface roughing do not affect bed surface distribution.
4.2 Factors that affect avalanche hazard

As with other studies focusing on ski areas have shown (Atwater, 1954; Föhn et al., 1977; Davis et al., 1999; Mock and Birkeland, 2000; McCollister et al., 2003), new precipitation is an important predictor of avalanche activity. The 29 cm of new snow threshold from the classification tree is very close to the 31 cm threshold originally given by Atwater (1954) in his 10 contributory factors. The upside down storm, commonly perceived by avalanche workers to increase avalanche activity, did not affect avalanche hazard. Similarly, Perla (1970) showed that the probability of low avalanche hazard was not affected by changing storm temperatures, although Perla found that the probability of high avalanche hazard increased with storms that increased in temperature. One explanation may be that storms with increasing temperature may be correlated with higher SWE amounts because of so called warm “Pineapple Express” storms that draw moisture from the southern Pacific. Thus, it may be high SWE amounts that increase hazard, not warming during a storm.

It’s unclear why wind speed and direction do not have more of a pronounced effect on avalanche hazard. For instance, an earlier study using classification trees on the Mammoth Mountain avalanche database (Davis et al., 1999) showed that a derived wind load parameter (24 hr SWE x 24 hr wind speed^4) was the most accurate factor for predicting the R-size sums. It is likely that wind speed and direction affect avalanche hazard at the individual path scale over short time frames. Yet, it may be that wind speed and direction do not have an effect over larger spatial and longer temporal scales. The narrow distribution of
speeds (3-7 m sec\(^{-1}\)) and directions (south to west) suggest that most storms have similar wind patterns at Mammoth. This lack of variability suggests that it is a poor predictor of avalanche hazard, which exhibits high variability between storms.

4.3 ECTs

Most days with new snow did not have ECT propagation. ECT propagation is an important predictor of avalanche activity. If an ECT does not propagate, there is almost no avalanche activity, but with propagation, there is high avalanche activity. The threshold for ECT propagation is very close to Atwater’s 0.30 m threshold for conditions favorable to avalanches. This threshold seems to be when new snow can sustain crack propagation. Low-density new snow is the weakest of all types (Roch, 1966), so it fractures easily, but those fractures often do not propagate far. At the slope scale, small failures are called sloughs. Sloughs are relatively harmless and are similar to ECTs that crumble in the new snow (ECTN or ECTX). When slabs are deeper or denser and therefore tougher, they can sustain a propagating collapse wave (Heierli et al., 2008) without slab fracture; that is without tensile fractures arresting fracture at the bed surface. These failures are similar to propagating ECTs (ECTP), usually with clean and planar fracture surfaces. Thus, the ECT can distinguish between new snow that is likely to slough and new snow that is likely to form a slab avalanche.

Although more explosives were thrown on days with propagation, explosives were still used on days without propagation and often did not produce any
avalanches. Median explosive yields for days without propagation were lower (0.19 vs. 0.37), but not significantly different ($p=0.27$), probably because of the small sample size. I suggest certain new snow stratigraphy conducive to avalanching caused high avalanche activity on propagation days, not increased use of explosives.

It should be noted that the stability tests in this study suffer from limitations of study plots (Jamieson et al., 2007). Mainly, the new snow and stratigraphy at the study plot may not represent those in the avalanche starting zones. Spatial variation issues are inherent when using study plots to predict stability across a large area. To address issues with spatial variation in stability, ski areas use many explosives, even during times of moderate stability, to cover their avalanche terrain.

4.4 **Explosive yield**

The number of shots, avalanches, and yield are stationary over the past three decades. This result suggests that the avalanche threat did not change, nor did the effectiveness of avalanche control work at Mammoth Mountain. This result emphasizes the quality of the avalanche database, since long-term stationary databases are desirable for analysis.

The variation in explosive yield of an order of magnitude between paths is interesting and explains some of the path names. For instance, “Old Faithful” (Figure 10a) implies frequent avalanching and has an explosive yield of 45% (73 avalanches over 164 shots), while “Climax” (Figure 10b) implies accumulation
and infrequent avalanching and has an explosive yield of only 7% (70 avalanches over 1067 shots). Aside from Climax being a much larger path, the two have similar steep starting zones and aspect; 60° maximum slope and NE aspect for Climax; 65° maximum slope and E aspect for Old Faithful. One reason for the vastly different yields might be wind exposure. Old Faithful is considerably more wind-protected by trees than Climax, which is entirely above the tree-line. As a result of its wind exposure, Climax accumulates vast amounts of wind-loaded snow, which form permanent snowfields. Wind-slabs can be very strong and can thus accumulate to dangerous depths before failing. Since Old Faithful accumulates less wind-loaded snow, its new snow load is probably weaker and subject to more frequent avalanching than Climax.

4.5 Effect of waiting one day to perform avalanche control work

Avalanche control days with no new snow recorded in the past 24-hr had significantly fewer avalanches, lower R-size sums, and lower explosive yields. This is probably because new snow strengthens significantly in the first 24 hr via viscous compaction and sintering. Waiting one day to perform control work was the only significant factor that decreased explosive yield. Thus, waiting is a potential cost-saving measure in terms of labor, explosives, and risk of post-control avalanches. Yet, waiting a day or longer is often not a realistic option. Ski area managers must weigh costs with the financial benefits of opening terrain within 24 hr of snowfall, since new snow is popular with resort guests. The tradeoff is that processes that increase strength (e.g. viscous compaction and sintering) decrease the quality of powder skiing. Also, explosives are used to test
slopes, as well as to trigger avalanches, so low explosive yields after waiting a day may not undesirable, but rather an affirmation of a forecast for low avalanche activity.

4.6 Applying results to other ski areas

Explosive yields of 20-30% for Swiss ski areas reported by Gubler (1977) suggest little difference between yields in this study and those in Switzerland. Similarly, Perla and Everts (1983) report a yield of 24% over 12 years of helibombing missions for the Sunshine Ski Area Road, Alberta, Canada; although they excluded size D1 events.

It would be interesting to analyze a similar database from a continental ski area. I suspect that one would find similar results, but a higher prevalence of buried persistent weak layers and lower air temperatures might increase the waiting time needed to reduce avalanche activity. Likewise, the threshold new snow and SWE values would probably be different. Because these results are only based on measurements from one ski area, the specific thresholds are probably not broadly applicable.

5 Conclusion

This study examined explosively-triggered avalanches at Mammoth Mountain, where the great majority of avalanches only involve storm snow. Two datasets were examined. One dataset contains thousands of avalanches on selected paths over three decades. This dataset was used to find factors that affected avalanche activity. The findings were that avalanche activity increased with all
measures of precipitation, while changes in temperature and snow density did not affect avalanche activity. There was also not a specific wind speed or direction that increased avalanche activity. Explosive yield was about one avalanche per four shots, similar to yields reported in other studies. Waiting one day after snowfall ended to perform control work resulted in significantly fewer avalanches and lower R-size sums, and it is the only significant factor that decreased explosive yield.

The second dataset is smaller and contains two seasons of ECT results at Mammoth Mountain. These ECT results were compared with results from avalanche control work using explosives and with new precipitation amounts. The ECT was a powerful predictor of avalanche activity; days with ECTs that propagated had significantly greater numbers of avalanches and R-size sums than days without ECT propagation. Days with ECT propagation also had significantly greater snowfall, with the threshold between propagation (ECTP) and no propagation (ECTN/X) being 29 cm of new snow, very close to Atwater’s threshold value of 31 cm. That new precipitation above a threshold causes increased avalanche activity is not a new finding; the new finding is that ECT propagation also has a similar threshold. Thus, I suggest that ECT propagation is an important tool to predict explosively-triggered avalanches in storm snow.

6 Acknowledgments

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Figure captions

Figure 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.

Figure 2 Class size and bed surface estimates in MMSP occurrence records

Vertical axis is avalanche count, the horizontal axis is class size, relative to the path (Greene et al., 2010). Colors are bed surface estimates. Sample size $N = 3,743$.

Figure 3 Avalanche hazard probabilities for selected paths and weather variables

The vertical axes are avalanche hazard probabilities, the horizontal axes are bin centers for different weather measurements. The colored lines represent thresholds for R-size sums, based on percentiles for all storms; low hazard (gray) exceed the 25th percentile and high hazard (orange) exceed the 75th percentile.

These graphs can be compared with those in Perla (1970). The number of storms analyzed $N=737$. 
Figure 4 New SWE and snow grouped by ECT propagation, storm snow failures only

Left (a) shows new SWE for days with and without ECT propagation. Right (b) shows the same for new snow. $N = 10$ days with propagation and 24 days without propagation. Line at center is the median, boxes are 25th and 75th percentiles, whiskers are non-outlier ranges, and crosses are outliers. Outliers are points larger than $p_{75} + 1.5(p_{75} - p_{25})$ or smaller than $p_{25} - 1.5(p_{75} - p_{25})$, where $p_{75}$ and $p_{25}$ are 75th and 25th percentiles. Non-overlapping notches indicate statistical significance at $p=0.05$, based on the Kruskal-Wallis test.

Figure 5 Sum of R-sizes grouped by ECT propagation, storm snow avalanches on selected paths

$N = 10$ days with propagation and 24 days with no propagation.

Figure 6 Number of shots, avalanches, and explosives yield by water year

For the selected avalanche paths, the total number of shots (a), avalanches (b), and explosive yield (c) are plotted by water year.

Figure 7 Explosive yield vs. maximum start zone slope

Maximum starting zone slope for selected avalanche paths, derived using a high resolution (0.3 m$^2$) digital elevation model. Gray line is a least-squares linear
regression. The slope is 0.0051 (95% confidence interval is 0.002 to 0.008), $R^2=0.15$.

Figure 8 Effect of new snow on avalanche activity and explosive yield for selected avalanche paths

Box plots for: (a) number of avalanches, (b) sum of R-sizes, and (c) explosive yield (b) grouped by snow in the past day. The “no new snow” group had no new snow in the last 24 hr, but snow prior. The “new snow group” had snow within the last 24 hr. $N = 132$ days for “no new snow” and $N = 904$ days for “new snow”.

Figure 9 Study Plot hourly water equivalent vs. elapsed time since precipitation began

Vertical axis is median hourly water equivalent from a precipitation can at the Study Plot (Figure 1). Horizontal axis is elapsed time since precipitation began. $N = 110$ storms.

Figure 10 Satellite images of two avalanche paths

Old Faithful (a) is on the left, Climax (b) is on the right. Labeled contours are elevations in m.
References


Figure 2

Avalanches

R-size

ground
old
interface
storm
Figure 3
Figure 4
Figure 6
Figure 8

(a) [Box plot showing avalanches versus new snow and no new snow]

(b) [Box plot showing R-size sum versus new snow and no new snow]

(c) [Box plot showing explosive yield versus new snow and no new snow]
Figure 9

Elapsed time, hr

Hourly water equivalent, mm
Figure 10

(a) Old Faithful

(b) Climax