WARM STORMS ASSOCIATED WITH AVALANCHE HAZARD IN THE SIERRA NEVADA

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ABSTRACT: Rain-on-snow events occasionally produce avalanches of varying magnitude depending on both snowpack properties and storm characteristics. Under rain-on-snow conditions in the Sierra Nevada, avalanche release appears to be most likely if new snow falls a couple days previous to the rain. In contrast, if the snowpack has already transmitted liquid water from the surface to the base, then even large amounts of rainfall rarely produce significant avalanches in the Sierra Nevada. Winter storms in this mountain range typically have rain/snow levels between 1200 and 2000 m. Warm storms with higher rain/snow levels of up to 2500 m occur a couple times in most winters and have the potential to generate rain-on-snow floods and wet-snow avalanches. This paper describes the characteristics of warm storms that had the potential to generate wet-snow avalanches. It also examines the frequency of rainfall following within three days of snowfall, which tends to be a hazardous combination.

A case study of a very warm storm at the beginning of 1997 describes snowpack response to rainfall at high elevations where such warm storms have rarely been observed. At the snow research station at 2930 m on Mammoth Mountain in the eastern Sierra Nevada, air temperatures exceeding 4° C and 220 mm of rainfall was recorded. Although few avalanches were observed during this storm, flooding was severe throughout much of the range.

KEYWORDS: avalanche, avalanche frequency, rain-on-snow, snow stability, wet-snow avalanche

1. INTRODUCTION

In a mountain range with a mostly maritime climate, the most important component for forecasting mid-winter avalanche activity is recent precipitation. In the Sierra Nevada mountains of California, widespread or destructive avalanche cycles not concurrent with precipitation events are rare. The largest storms to press upon the Sierra Nevada often precipitate rain at mid, and occasionally high elevations. When rain falls onto established snowpacks, avalanches can result. But not always. Preliminary evidence suggests that rain-induced avalanching is more apt if there has been snowfall a few days prior to the rain. This paper discusses the anatomy of warm, mid-winter storms and how they influence the snowpacks of the Sierra Nevada and avalanche activity.

2. WARM STORMS

Approximately 90 percent of California's precipitation falls between early November and late May. At elevations above 2000 m, most of that precipitation falls as snow. However, because of the Sierra Nevada's close proximity to the Pacific Ocean, the range tends to receive relatively warm mid-winter storms. Much of the snowfall at 2000 m elevation precipitates within a few degrees of 0° C. Hence, it is not unusual for rain to fall at Sierran mid-elevations during any month of the winter. Average monthly air temperature at the Central Sierra Snow Laboratory (CSSL, 2098 m elevation) near Donner Summit during December, January, and February—historically the three wettest months of the snow season—is approximately -2° C for each month. During the month of March, which historically receives 15 percent of the annual precipitation, the average monthly air temperature is only -1° C (Osterhuber 1997a).

Typical mid-winter flow at the 500-mb level over the Sierra Nevada incorporates air masses drawn eastward by both the polar and subtropical jet streams. Moist, unstable air masses can combine in any number of fashions, mixing cold air masses of the north with warmer southern air. With the subtropical jet drawn south, California receives predominantly cold, moist air pulled by the polar jet from the Gulf of Alaska. These cold fronts from the NNW deposit mostly snow in the mid and upper elevations of the Sierra Nevada. Rain/snow levels of 1600 m or lower are characteristic of these storms; precipitation totals are usually moderate, 35 - 50 mm. With high pressures positioned over the tip of Alaska's Aleutian Islands and northern

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Mexico, the polar and subtropical jet streams are forced south and north, respectively, converging in a strong west to east flow that hits the Sierra Nevada with maximum orographic uplift, resulting in high precipitation rates and totals. During these storms, precipitation intensities of more than 10 mm/hour have been observed at the CSSL for several hours. Storm totals often exceed 225 mm of precipitation and 2 m of snowfall. Rain/snow levels observed during these events are typically 1700 - 2100 m. It should be noted that the atmospheric dynamics of these events vary greatly. For example, warm, frontal air splitting and overlaying a colder retreating polar front has resulted in dramatically different rain/snow levels at differing latitudes. Rain/snow levels of 1200 m in the southern Cascades of northern California have been observed coincident with 2400 m rain/snow levels around Lake Tahoe (Pechner 1998).

A large high pressure cell over the Aleutians can effectively act as a blocking high, maintaining a more southerly flow of the polar jet stream. If this coincides with the subtropical jet stream oscillating north into California, air flow from warm, moist, low latitudes result. This pattern not only causes high rain/snow levels in the Sierra Nevada, but can deliver the mountain range's wettest events. Of the 20 wettest storms on record at the CSSL, 11 have *not* been associated with record snowfall. All eleven of these events have occurred either late autumn or mid-winter and fell as rain-on-snow (Osterhuber 1997b). The rain-on-snow storm of December 1964 dropped 858 mm of precipitation over 5 days; the rain storm of February 1986 precipitated more than 525 mm in the central Sierra Nevada over 8 days. The largest precipitation events in the central Sierra Nevada are the rain-on-snow events. Storms with rain/snow levels of approximately 2500 m occur a couple times during most winters, but rain has been observed falling at 3600 m in the southern Sierra Nevada during the spring on rare occasions (Kattelmann 1997).

During the past 47 years of record, the mean annual maximum rain-on-snow event at the CSSL is found to be 151 mm of precipitation—the majority of it rain—with a duration of about 4 days. This "average" rain-on-snow storm has a recurrence interval of approximately 2.6 years (Osterhuber 1997b). When the maximum annual rain-on-snow event precipitation totals are graphed as a time series, the slope of the plotted historic events increases by about 2 mm/year.

The rain-on-snow storms of the Sierra Nevada are of interest for several reasons. When warm, mid-winter rains fall onto the extensive snowpack of the range, high stream flows tend to result. Throughout history, the largest floods produced by the major river systems of California have occurred during rain-on-snow events (Kattelmann *et al* 1991). Much of the direct runoff produced is from the storm rainfall, but the presence of expansive snow cover greatly increases streamflow potential. In a maritime climate, such as that of the Cascade and Sierra Nevada mountain ranges, rain-on-snow has been found to produce greater runoff than either rainfall or snowmelt alone (Harr 1981).

The largest rain storms (and therefore the largest storms) tend to occur during mid-winter. At the CSSL, the mean date of commencement of each season's greatest rain-on-snow storm is January 25, with a standard deviation of 49 days. The largest rain storms are more likely to fall onto snow than not. Rarely does a rain-on-snow event precipitate only rain at mid-elevations in the Sierra Nevada. Rain/snow levels typically fluctuate with the advent and passing of large frontal systems. During rain storms, the 2000 - 2500 m elevations of the range commonly see a mix of rain and snow.

Because warm, maritime snowpacks tend to release at least small amounts of liquid water throughout the winter, underlying soils are more apt to be at or near saturation during winter and spring. When little soil moisture storage capacity is available, streamflow response to rainfall can be rapid. In the two weeks previous to January 6, 1997, the snowpack surrounding the CSSL (depth 173 cm, snow water equivalent 68 cm) had absorbed and outflowed more than 319 mm of rainfall. The pre- and post-storm snowpack water equivalents remained essentially equal. Underlying soils during this storm were considered to be at or near their water-holding capacity. Lowland and upland flooding throughout the Sierra Nevada was extensive during this event. If snowpacks are already producing melt due to solar radiation during clear weather, the pack may contain some appreciable amount of liquid (free) water that can be mobilized during a rain-on-snow event. In addition, melt caused by convection-condensation during warm storms can be significant, especially at the lower elevation, transient snow zone of the range (Kattelmann and McGurk 1989). All of these factors contribute to great streamflow and potential flooding during warm mid-winter storms.

Mid-winter rain-on-snow storms also tend to move soils. The ready recipe of high rates of rainfall onto snowpacks and soils with little (if any) ability to store additional liquid water, proves ideal for instigating the movement of large masses of soil. Landslides reek insidious havoc on residential and commercial structures and intermountain highways. Highway road cuts have proven to be especially vulnerable to rain-on-snow induced landslides: road cuts tend to be mostly free of soil-stabilizing vegetation, and often exist near the soils' maximum angle of repose.

Numerous landslides onto the highways surrounding the Tahoe Sierra have been observed during or immediately after mid-winter rain storms in 1982, 1983, 1984, 1986, 1995, and 1997. These debris flows have ranged in size from a few cubic meters to several hundreds of cubic meters. In the central and southern Sierra Nevada, 25 of 33 (76%) documented landmass failures during winters 1982 and 1983 were attributed to rain-on-snow (Bergman 1987). Researchers in western Oregon have associated 85 percent of observed landslides with rain-on-snow (Harr 1981). Wide-spread landslide activity during rain-on-snow is evidence that the snowpack is outflowing at least moderate—and often great—amounts of water.

Snow avalanche activity can also increase during rain-on-snow. Snowpack stability is influenced not only by storm characteristics, but also by features within the snowpack.

3. WATER MOVEMENT THROUGH SNOW AND SNOW STABILITY

The spatial and temporal distribution of liquid water movement through snow is complex. Deep snowpacks fashion a three-dimensional ice lattice with varying divisions of density, crystal and grain size and type, temperature, hardness, permeability and porosity. Snowpacks accumulate during the winter in a layer cake fashion. Each new layer of snow is unique to the atmospheric conditions during which it precipitated. Once on the snowpack surface (or ground), metamorphism of the new snow is further determined by the immediate atmosphere and surrounding snow layers. In warm mountain ranges like the Sierra Nevada, daytime air temperatures greater than 0° C are typical during clear weather between storms. This varies widely with time of year, elevation, aspect, and latitude, but slight surface melting is not unusual during clear days even in the dead of winter. Surface layers melting at day and refreezing at night develop crusts. These also vary in thickness, hardness, and permeability. Surface crusts are subsequently buried under the next snowfall. Some of these crusts may impede the vertical movement of water (Berg 1982), instead routing it laterally via capillary and gravitational forces. The extent and rate of this lateral movement is governed by the composition of the surrounding snow layers and slope angle. Various flow channels within the snowpack have been observed (*e.g.* Kattelmann 1985, McGurk and Kattelmann 1988) that act as efficient conduits for routing liquid water. Once formed, vertically oriented flow "fingers" within the pack have been known to hasten the water movement through the pack (Kattelmann 1985). The snowpack need not be either near isothermal (at 0° C) or at its water holding capacity to outflow water. Under rain-on-snow conditions, the rate at which water permeates through the entire pack is dependent not only on the snowpack makeup, but on the amount and rate of precipitation. At the CSSL, average rates of vertical water movement through a level snowpack have ranged from 3 to 88 cm/hour (Berg *et al 1991*) at the onset of rain-on-snow events.

Dry snow avalanches usually fail due to an increase in shear stress; wet snow tends to avalanche because of a decrease in shear strength. Unlike most mediums, snow exists naturally very close to its melt point. When liquid water is introduced into the ice lattice a general increase in temperature and decrease in mechanical strength results. At low amounts of liquid water, bonding between individual grains can increase slightly due to capillary forces. As water contents increase, these attractions weaken quickly. In the presence of water, snow has fewer small grains, fewer contacts, and therefore fewer bonds (Kattelmann 1984). For an inclined snowfield, resistance to sudden avalanching of one or more layers is a factor of those layers' combined strengths exceeding their combined stresses. When combined strengths equal combined stresses, avalanching occurs. Some observations suggest as slope angle increases, wetted volume and water holding capacity decrease (*e.g.* Kattelmann 1986). Rain falling onto an inclined snowfield reduces snowpack strength by reducing the number of bonds and the lubrication of layer interfaces. Increases in stress occur through the addition of added mass and increasing rate of creep. In the Sierra Nevada, avalanche cycles occur coincident with mid-winter rain storms often. Naturally occurring avalanches have been observed during numerous rain storms in the Sierra. The relatively recent events of 1986 (Wilson 1986), 1989[1], and 1995[1] were widespread and memorable. Not all rain storms, however, produce widespread or big avalanches. Avalanches have been observed at the initial onset of rain but decreased or ceased altogether even though rainfall continued.

4. AVALANCHE ACTIVITY

An investigation of the frequency of avalanche activity during rain storms was carried out at Alpine Meadows Ski Area in the late 1980s (Heywood 1988). Alpine Meadows, one of the most avalanche-active ski areas in the country, is a few

[1] Deep, wet slab avalanches occurred at several areas around Donner Pass either during or immediately after rainfall.

kilometers north of Lake Tahoe and receives rain-on-snow annually. 20 storms were analyzed that had adequate data on precipitation—both rainfall and snowfall—and avalanche activity. Of events with snowfall within three days previous of the rain, Heywood found positive correlations between avalanche activity and total rainfall, and between avalanche activity and rainfall intensity. There were only three storms that had no avalanche activity but that *did* have some snowfall within the three previous days. No unusual characteristics of these three events are evident. Heywood defined avalanche activity as "...widespread avalanche activity on most exposures, with either or both natural or artificially released slab avalanches." Avalanche size was not considered. Positive correlations were found between total rainfall and days since last new snow for both avalanche and non-avalanche days. For events with no snowfall within 4 days of the rainfall, no "avalanche days" existed.

We expanded this investigation by looking at data from an additional 55 (for a total of 75) mid-winter rain storms at Alpine Meadows. Rainstorms were identified from the records by notations entered in the daily weather logs. 24 hour precipitation and snowfall amounts were recorded; as were the number of days since last snowfall, and if any avalanche activity took place during the storm. Data records were mostly complete. Precipitation and snowfall data originated near the ski area's base at 2103 m. 24 hour precipitation values were generally totals from early morning to early morning. We recorded avalanche days as any day with any observed avalanche activity at all, natural or induced. Size of events and avalanche type were noted but not considered in the statistics. Total precipitation of the events varied widely, with a mean of 59 mm and standard deviation of 96 mm. New snow fell during 55 of the 75 events. Snowfall also varied widely: mean snowfall was 16 cm, standard deviation 33 cm. Data from the CSSL shows that the level snowpack there (21 km NW of Alpine Meadows) had drained some amount of liquid water previous to most of the rain storms (CSSL data was unavailable for 10 of the storms analyzed).

Of the 20 rain storms analyzed during which no new snow was recorded, 4 (20%) events produced avalanche activity. Of these events, 2 storms had snowfall one day previous to the rain. The other 2 events saw snowfall six and eight days (respectively) previous to rainfall. Avalanches observed during these two latter events included Class II explosive-induced slides and natural loose-snow avalanching. The mean rainfall amount for the avalanche-producing "rain-only" storms was 17 mm with a standard deviation of 16 mm. For the non-avalanche "rain-only" storms, the mean rainfall was 32 mm, standard deviation 62 mm. It should be noted that for the "rain-only" storm data set, the mean precipitation of the rainstorms producing no avalanches is greater than the storms that did produce snow slides. The "rain-only" storms of March 8, 1986 rained 166 mm, and December 11, 1995 rained 227 mm—neither of them resulting in avalanche activity.

For the remaining 55 storms examined for this study, some snowfall did accompany the rain. We divided these storms into two broad groups: storms with $i_o < 0.28$ and storms with $i_o \geq 0.28$, where i_o is a simple storm "density" index defined by

$$i_o = \text{total storm precipitation (mm)} / \text{total storm snowfall (mm)}.$$

When plotted against percentage of days with avalanche activity, the group of storms (n = 21) with $i_o \geq 0.28$ (low % snowfall) showed a weak correlation (statistically insignificant; $r^2 = .01$) between increasing days since last new snow and increased avalanche activity, independent of precipitation or snowfall amounts. For the $i_o < 0.28$ (higher % snowfall) data, the trend was strongly the opposite. As days since last new snow increased, percentage of days with avalanche activity decreased ($r^2 = .30$). There were 34 storms within the low i_o data set. Results of the analysis are compiled in Table 1.

Of the 75 storms examined, 39 events produced avalanches, 36 did not. A review of the avalanche days reveals that 29 of the 39 (avalanche) days

		mm							
	n	mean precipt	std dev precipt	mean snowfall	std dev snowfall	avalanche days	% avalanche days	mean days since last snow	std dev days since last snow
"rain-only" storms	20	30	57	0	0	4	20	7	5
$i_o < 0.28$ storms	34	39	27	203	135	23	68	3	3
$i_o \geq 0.28$ storms	21	111	154	259	528	14	67	4	4
all storms	75	59	96	160	330	39	52	5	5
avalanche days	39	81	118	260	420	39	100	3	4
non-avalanche days	36	36	56	50	110	0	0	7	6

Table 1. Number of days with avalanche activity, precipitation totals, snowfall amounts, and days since last snowfall for 75 rain-on-snow storms, Alpine Meadows Ski Area, California.

(74%) had snowfall mixed with the rain. In contrast, little more than half (54%) of the non-avalanche producing storms had some snowfall. The most significant difference between the two comes from examining their mean characteristics. On average, more than twice the amount of precipitation fell during the events that produced avalanches than those that did not; snowfall was better than five times as much. This strongly suggests that new snowfall is still the overriding factor in producing avalanche activity, even during rain-on-snow events. It should be pointed out that the 20 rain storms that did not have any snowfall had the lowest mean storm precipitation: 30 mm. Both the high and low i_o data sets reveal similar amounts of mean snowfall (26 cm vs 20 cm, respectively), but the standard deviation of the data sets varies considerably more (53 cm vs 14 cm). Figure 1 represents all 75 rain-on-snow storms categorized by number of days since the last snowfall. These data are plotted against days of avalanche activity.

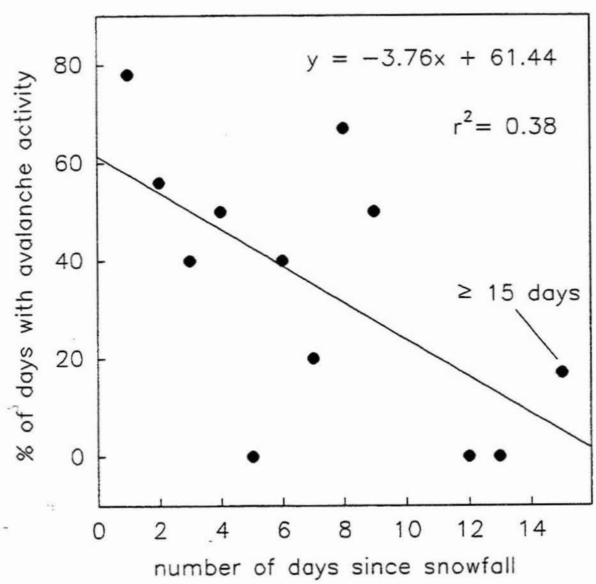

Figure 1. 75 rain-on-snow storms at Alpine Meadows Ski Area, California.

Heywood's research suggests that avalanche release is more likely when snow falls within three to four days previous of rain. We found after three or four days since snowfall, avalanche activity occurred during less than or equal to 50 percent of the events. The mean number of days since last snowfall for the avalanche producing storms was 3 days; for the non-avalanche storms, 7 days. Of the 75 warm storms, 42 had snowfall within 3 days of the rain. Avalanche activity was observed during 29 (69%) of these days. Of the remaining 33 storms, 14 (42%) released avalanches.

5. NEW YEAR'S STORM 1997, SOME OBSERVATIONS

Although rain-on-snow events in the Sierra Nevada usually affect only starting zones below 2500 m, rare storms with very warm temperatures can deliver rain above timberline. On occasion, rain has been observed at great elevations in the higher, southern part of the range.

At the snow research station (2930 m) on Mammoth Mountain in the eastern Sierra Nevada, documented rain events include: January 1980 when rain was recorded for five days (Davis and Marks 1980); and April 1982, when a storm that delivered rain up to 3000 m—soon after a major snow storm—initiated a wet avalanche cycle in the Sierra Nevada. Since then, mid-winter rainfall at this site has been rare. A few millimeters of rainfall were observed at this site during both the 1995 and 1996 winters, and 70-80 mm of rain fell there during May 1996 (Kattelmann 1997). The New Year's 1997 storm—a severe storm with intense precipitation and unusually warm temperatures—deposited more than 200 mm of rainfall at elevations above 3000 m but did not produce a major avalanche cycle. The high rain/snow levels provided an opportunity to observe snowpack response to rainfall at high elevations where such warm mid-winter temperatures have rarely been observed.

At Mammoth Mountain, the season's snowpack began to accumulate with a storm on November 21-22, 1996 that deposited more than 90 cm of snow at the study site. Three storms during December each deposited more than a meter of snow at this site. Precipitation during December 1996 was more than twice the average for the month at almost all recording sites in the Sierra Nevada. Direct-action avalanches were common because of the intense snowfall.

The series of storms that became progressively warmer began on December 26 with fluctuating rain/snow levels averaging around 2000 m. Warmer air began entering the Sierra Nevada on December 29, and rain climbed to higher altitudes. Temperatures continued to rise, and precipitation intensified over the following four days. On January 1 and 2, 1997, air temperatures ranged from +2 to +4° C at the Mammoth Mountain study plot. These high temperature measurements suggest that rain was falling above 3000 m for at least 36 hours and up to 3500 m for perhaps 12 hours.

At the study site, steady rain began shortly after midnight on January 1. There may have been minor amounts of rain mixed with the predominantly solid precipitation as much as six hours earlier. Rainfall intensities varied between 1 and 6 mm/hour on January 1 and increased on

January 2 with a few periods of more than 10 mm/hour. About 220 mm of rainfall was measured during the storm. Windspeeds averaged over 15-minute intervals varied from 4 to 13 m/s. Before the rain started, the snowpack was about 2.5 m deep with an average density of about 300 kg/m^3 and temperatures of -1 to -5° C. The first water that percolated through the snowpack took about 9 hours to reach one of nine snowmelt lysimeters at the site (Kattelmann 1997). Snowpits were excavated at several sites on and near Mammoth Mountain following the storm. The rainfall produced a very complex layer structure in the top 30 cm at all sites. In this near-surface region, wet zones alternated with ice lenses and dry zones. Thickness of the different zones varied across pit profiles and between pits. Some of the wet zones and ice lenses appeared to be only a millimeter or two in thickness. Other ice lenses and complexes of ice lenses were up to 50 mm thick. On flat ground, the intricate stratigraphy continued throughout the profiles to the soil surface. However, there were a few dry zones of up to 12 cm thick. Snow temperatures were 0° C on level ground. Below the near-surface region, snowpits examined on sloping ground differed markedly with their level counterparts. Evidence of water flow below the top 30 cm was either lacking altogether or present in bands of 5-10 cm thickness at the presumed interfaces between snow layers deposited by different storms. A few irregular ice blobs were found in the otherwise dry layers. Temperatures of these layers remained below -3° C. Although these snowpits provide only a very limited sample of snowpack response to rain during this one event, they suggest that water bypassed much of the deeper snowpack on sloping terrain as it flowed down slope in the near-surface region. Most slopes in the region were covered with surface expressions of a trellis-pattern rill network after the storm (Kattelmann 1997). These complex drainage networks may have routed enough of the percolating rain water through the snowpack, minimizing structural instability during this event.

6. CONCLUSIONS

Warm mid-winter rain storms strike the Sierra Nevada a couple times a year. Historically, many season's greatest storms have been warm, rain-on-snow events. Several of these storms have caused landslides, extensive flooding, and widespread avalanche activity throughout the range. Observations from 75 rain-on-snow storms at a ski area in the central Sierra Nevada suggest that avalanche activity is more imminent when rainfall is accompanied with snowfall, especially if new snow falls within a couple days before the rain. For 55 rain storms that had accompanying snowfall, avalanche activity seemed to be independent of amount of new snow, even though the storms with a low percentage snowfall had a mean storm precipitation value far exceeding those with more concurrent snowfall (111 mm vs 39 mm). Avalanche activity was more pronounced during events with mixed rain and snow than those with just rainfall, but the "rain-only" storms had less precipitation overall.

Though some natural avalanche activity was observed during the 75 storms investigated, we determined avalanche release during or immediately after rain-on-snow storms mainly by the snowpack's positive response to explosive charges. Other than naturally occurring avalanches, no evidence is available to determine if the snowpack would have avalanched otherwise. Ski areas have almost constant observers, and since naturally occurring avalanches are relatively rare (compared with the avalanche activity that's explosive-induced within a ski area), real-time observation of a snowpack's behavior with respect to stability remains somewhat limited to within-bounds.

Warm, wet snowpacks behave more like a fluid compared to their colder, drier counterparts that exhibit brittle tendencies. Consequently, older near-isothermal snowpacks respond poorly to explosive-induced avalanche release (Heywood 1988). Using explosives as a yardstick by which to measure the stability of snowpacks under rainfall is therefore limiting. Though somewhat rare, deep-slab instability in wet Sierran snowpacks does occur (*e.g.* 1989, 1995), most commonly during spring melt and rain-on-snow. Explosives may be an ineffective gauge of stability for deep, wet packs. Analysis of the 75 storms is therefore biased toward the avalanching of storms with new snow. Of course, deep, wet slab releases within a ski area's boundary—explosive-induced or not—would most certainly have been noted. Since the forecasting of avalanches is of greatest concern wherever (and whenever) they cross paths with people or their property—namely ski areas, highways, and structures—using in-bounds avalanche control as a meter of snow stability remains valid—and in fact necessary. More qualitative analysis is needed to determine how susceptible any particular snowfield is to rain-induced avalanching—or not. Additional research is needed to link snowpack pre-storm and post-storm stratigraphy with avalanche response to rain-on-snow, both for natural and mechanically altered (ski area) snowpacks.

Snowpit observations within level snowpacks on and around Mammoth Mountain in the eastern Sierra Nevada following a rain-on-snow storm in early January 1997 reveal evidence of rain water movement through the entire snowpack. After the same storm, inclined snowpacks exhibited wetting of primarily the near-surface snow layers. With water movement mostly confined to the near surface layers, free water-induced weaknesses may have been restricted to the upper layers of the pack. Though widespread and/or destructive avalanches were not observed during this storm, precipitation was intense, rain/snow levels were high, and flooding was severe and extensive throughout the range.

The majority of avalanche activity in the Sierra Nevada is due to significant amounts of snowfall. Rain-on-snow storms that produce avalanches are more prone to do so when snowfall is mixed with rainfall. But because some rain storms do not cause avalanching—even with new snow—one could infer that for these events the rain is not introducing enough of a decrease in shear strength to cause instability. Since large amounts of water introduced into a parcel of snow decreases its mechanical integrity, the deeper layers of the snowpack during non-avalanche producing rain storms must be directing liquid water away from shear planes. Conversely, rain storms that do produce avalanches may be routing liquid water laterally over impenetrable layers acting as shear planes for overlaying snow slabs. Of the 20 "rain-only" storms analyzed, the events producing no avalanches had (on average) greater precipitation than those that did cause slides. Lesser amounts of percolating water unable to penetrate hard snowpack layers—while still weakening interfaces—may be one explanation for this. The presence of flow fingers or other conduits to efficiently move water through the pack are an indicator that the pack has previously transferred some amount of free water. These snowpacks would be less inclined to route water over ice lenses, hard layers, crusts, or other potential shear planes. Establishing whether a snowpack has developed subsurface flow channels and/or has transmitted appreciable amounts of liquid water could be an important component when forecasting snow stability during rain-on-snow.

ACKNOWLEDGMENTS

Larry Heywood made available much of the rain-on-snow data. Mike Pechner supplied 500-mb level circulation maps.

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