BASIC SCIENCE OF RAIN ON SNOW

Bruce McGurk[1], Randall Osterhuber[2], and Rick Kattelmann[3]

ABSTRACT

Rain on snow is a common event in the Sierra Nevada that occasionally generates floods, but has also generated coFnsiderable speculation and conjecture. This paper will summarize basic snowpack formation, structure, and response to melt and rain on its surface. Water transmission through snow is complex because the snowpack structure depends on the characteristics of the storms that created it, and no two years ever produce a snowpack with the same characteristics. The Sierran snowpack above 2100 m ranges from 2-5 m in depth at peak accumulation, and by spring, it is composed of 8-12 major layers that correspond to the prior major storm events. Melt and/or rain water transmission through snowpack is complex because the layers have varying temperature and densities, and the presence of crustal boundary layers that form during sunny, inter-storm periods. Rain on snow is transmitted both vertically and laterally along layers and interfaces, and steeper slope increases the horizontal speed and amount that may be delivered directly to stream channels. Vertical flow channels are often created that allow relatively rapid delivery of water to the soil surface. Rain can melt snow, particularly when lower or mid-elevations become snow-covered in cold storms and then are subsequently exposed to warm storms with high temperatures and winds. Contributions of that melted snowpack are typically small compared to the amount of rain that fell, some of which creates immediate runoff.

Rain-on-snow frequency and magnitude are increasing in the central Sierra Nevada, and the rain is reaching higher elevations more often (Osterhuber, 2019). Because runoff magnitude and timing are directly linked to the extent of the basin that receives rain as well as snowpack condition, this issue demands increased awareness and study of the snowpack as well as improved forecasting and verification of the rain-snow elevation of an incoming storm. (KEYWORDS: Rain on snow, flow fingers, snowpack, water transmission, snow layers, ice crusts)

INTRODUCTION

The snowpack in the Sierra Nevada develops as a result of multiple storms that occur as the winter season progresses from November through May. The storms are both due to atmospheric rivers (AR) that deliver multi-day storms that may deposit 1.5 – 2.5 meters of snow, or they may be frontal storms that come from either the west or the northwest. AR storms tend to be warmer and deposit snow at higher densities, while storms with a more northern source drop snow at low densities (6-8%) and snow layer temperatures that range from -8 to -4° C. Every year brings a different mix of storms, arriving in a varied sequence of magnitudes and sources.

In between the storms, the Maritime Province features variable length periods of clear skies and relatively warm temperature (Dickerson-Lange et al., 2016; Storck and Lettenmaier, 1999). Those periods produce an intra-storm surface layer at the top of the storm layer that is different than the layer below. The surface layer is characterized by coarse grains that result from repeated melt-freeze episodes due to radiation-driven melting and then nighttime freezing. The solar input causes both metamorphosis of the surface snow from crystals into rounded, sintered grains that freeze into a hard crust in the morning with varying degrees of bond strength that will support a person's weight. The process also releases liquid water that flows into the layers below.

By April, it is common to have a 2-4 m snowpack with 8 – 12 major layers or snow horizons. The layers range from 3 cm to 15 cm thick. The melt-freeze crusts, 1 – 3 cm in thickness, define the boundaries between the layers. The crusts can be loose and coarse metamorphosed grains or icy structures in the morning, but they are not vitreous plates of solid ice like that found on a water body. Within the storm horizons, snow temperature and grain size vary, and based on changes in storm temperature, grain size changes may form that act as additional liquid

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[1] Bruce McGurk, McGurk Hydrologic, Orinda, CA, brucemcgurk@comcast.net
[2] Randall Osterhuber, Donner Summit Avalanche Seminars, Tahoe Vista, CA, randall@donnersummitavalancheseminars.com
[3] Rick Kattelmann, Consultant, Mammoth Lakes, CA, rickkattelmann@gmail.com

water flow barriers. A Sierran snowpack is the absolute opposite of a homogeneous sand bed – it is a dynamic and structured snow mass with significant horizontal and vertical heterogeneity.

A common field technique is to apply a variety of dies mixed in liquid water and spray it on the surface of a snowpack to reveal the horizontal layers. The dye ponds up on the crusts and grain-size barriers within the pack, as shown in Figure 1.

Figure 1. After instrument ink is mixed with water and sprayed on a sloping snowpack, excavation reveals both the buried layers within the snow pack and the lateral travel of the water and dye within the layers. (Photo by R. Osterhuber)

WATER FLOW THROUGH SNOW AND MACROPORES

Water Flow through Snow

Water enters the snowpack from the surface due to melt (from solar insolation and/or advected heat) or rainfall. Each process produces a water flux of different magnitude, but rainfall can deliver the most water in the shortest period of time. Daytime melt can produce more than 2 cm of melt in late spring, and advected heat melt is generally only a few tenths of a centimeter.

The meltwater creates a non-uniform wetting front that moves downward through the grains in the snowpack, metamorphosing them from crystals to grains as it travels. The wetting front often concentrates into multiple preferential vertical flow channels, herein called a flow finger (McGurk & Marsh, 1995; Marsh, 1988). Water ponds up in the melt-freeze crust and concentrates into an area and moves vertically, metamorphosing the snow as it travels. Water moves vertically faster once it creates a flow finger because the grains in the finger become larger and the porosity increases. The flow finger can move water through the locally-warmed zone through a snow layer that is below 0° C without warming the whole layer.

The dye application process readily highlights the inter-storm crusts, but it takes a different technique to identify the flow fingers within a Sierran snowpack. A thick-section cutter was constructed by McGurk to allow vertical or horizontal sections of snow to be precisely cut from the snowpack. The sections could be 2.5 or 5 cm thick, and a backlighting and photographic techniques was employed to detect the layers and flow fingers so that no

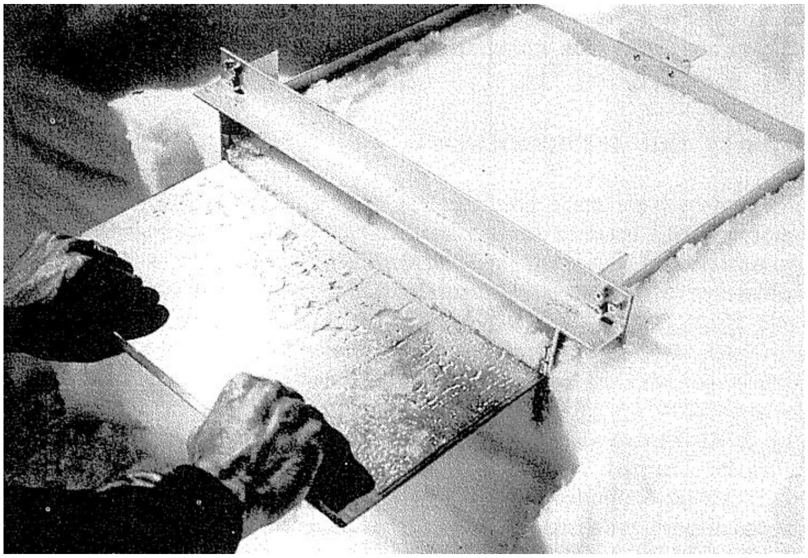

Figure 2. Stainless-steel blade being inserted to cut a horizontal thick-section of a snowpack that was then backlighted and photographed to reveal the flow finger pattern within the snowpack at sequential depths.

additional water was used which might adulterate the snowpack. Sharpened stainless-steel blades were used to cut the sections (Figure 2).

In vertical sections, the back-lighted sections revealed the melt-freeze crusts with their low-density, large grains of snow. Areas where liquid water concentrated also transmitted light through the destructive metamorphism that had occurred, as shown in Figure 3. Bright zones highlight thin, inter-storm layers as well as the fingers that were transferred the water from layer to layer.

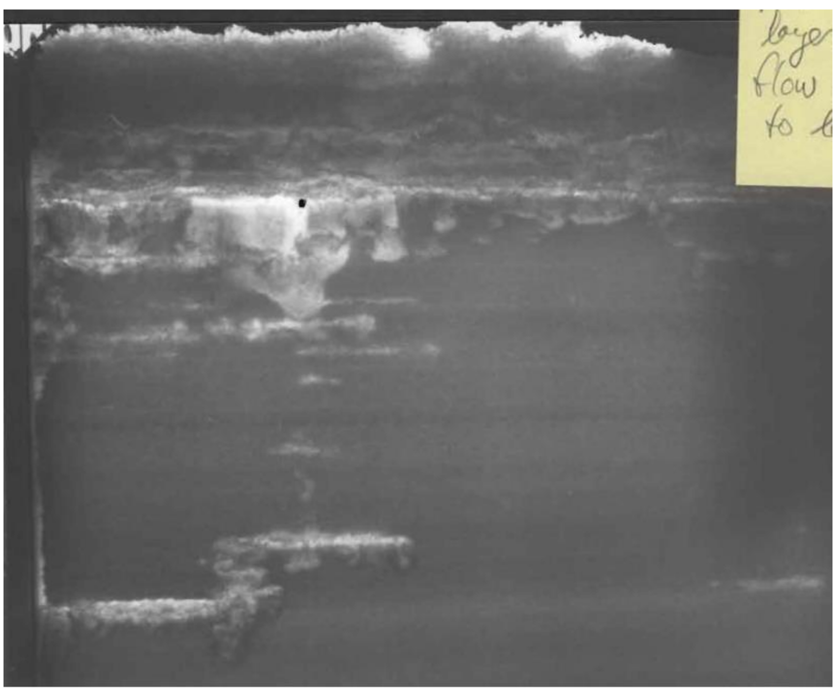

Figure 3. Bright zones highlight the lower-density horizontal layers in a vertical section cut by the thick-section cutter. Bulges downward show water accumulation zones, and small zones in lower layers illustrate the passage of water down to lower layers.

Horizontal slices in between melt-freeze crusts showed the areas that had been modified by water flow, producing higher porosity areas that transmitted the light more that the surrounding snow. Slices were taken in a series of aligned placements of the thick-section cutter to examine how the location, number, and size of the flow fingers varied both within a layer and between layers. Locations stayed mostly constant within layers (Figure 4), but changed completely between layers as the melt-freeze crust received and ponded up the liquid water before it found new locations to start a flow finger (McGurk & March, 1995).

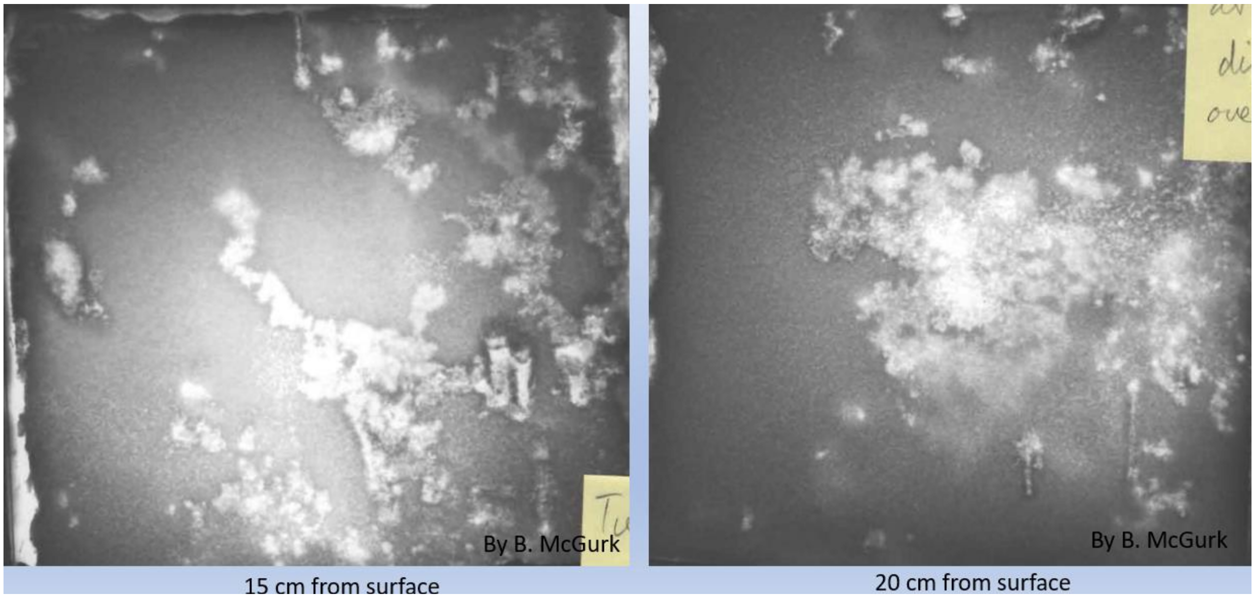

Figure 4. Two horizontal sections at 5 cm difference that show liquid water in similar locations within the snowpack.

Flow finger photographs at multiple depths within three layers were digitized and the number and diameter of the fingers were calculated. Layers with larger fingers had fewer fingers than layers with smaller fingers, most likely a response to snow grain size and layer temperature (Table 1; McGurk & Marsh, 1995).

Table 1 Flow finger diameter, spacing, and wetted area percentage for three photo series in a melting snowpack near Soda Springs, California.

Layer series	No. of	Diameter (mm):		Spacing (mm):		Percent
and depth (cm)	fingers	Mean	Std. dev.	Mean	Std. dev.	wetted
C - 2 - 172	19	20	8	47	32	6
C - 2 - 170	20	17	6	39	23	4
C - 2 - 167	16	22	8	52	34	6
Layer means	18	20	7	46	30	5
D - 3 - 158	37	13	6	22	20	6
D - 3 - 155	32	11	3	20	14	4
D - 3 - 152	33	14	6	20	12	6
D - 3 - 148	34	15	7	15	9	8
D - 3 - 144	42	9	4	16	11	6
D - 3 - 142	28	14	7	19	9	6
Layer means	34	13	6	19	13	6
D - 4 - 161	12	20	9	36	39	4
D - 4 - 158	13	19	10	37	36	4
D - 4 - 152	14	15	7	29	34	3
Layer means	13	18	9	34	36	4

The digitized images within one layer were overlaid to show the pattern, and the overlay showed that once a flow finger started pushing toward the soil surface, it varied slightly in its location, but stayed within a fairly confined area (Figure 5).

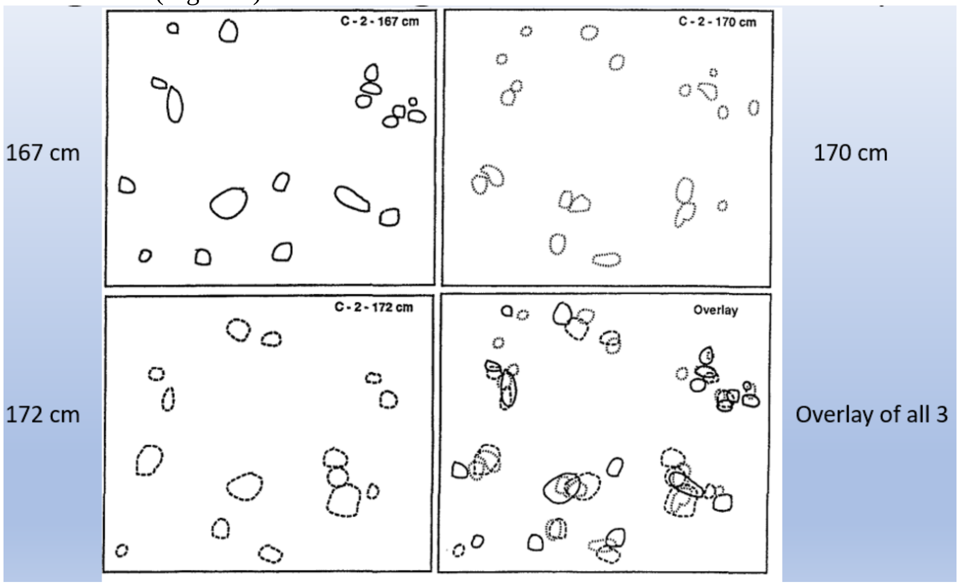

Figure 5. Flow finger outlines in three serial sections and the overlay of the sections, showing overlapping fingers from section to section, from a snow pit in April, 1990, near Soda Springs, CA, USA (McGurk & Marsh, 1995).

Surface Evidence of Flow Fingers and Vertical Flow Tubes

On relatively flat terrain, melt or rainfall travels little horizontally, but the liquid water ponds up in melt-freeze crusts, finds a low spot, and water starts to metamorphose the crystals into larger grain with associated higher porosity around the grains, and the flow finger develops and transmits water vertically from the surface to the bottom of the pack. With subsequent warming of the surrounding snowpack, the porous frozen grains in the fingers partially melt and lose cohesion, and create small depressions. Alternate conditions can produce bumps on the snow where the finger structure was sufficiently frozen that the surrounding snow warmed, settled, and produce the bumps shown in Figure 6A. Rain on snow (ROS) can produce depressions and troughs where water has traveled laterally and the warming snow has collapsed into the low-density channels (Figure 6B).

a

b

Figure 6. Photo A shows the bumps can develop when the flow fingers remain consolidated and the snow around them settles due to melt and warming. Photo B shows a snowpack that had received 100 hours of rain at CSSL which produced dimples and dendritic patterns due to lateral water flow (Osterhuber, 2013; Photos by R. Osterhuber).

Basal Macropores

Horizontal delivery of water that has percolated through the snowpack to stream channels is aided by the formation of open channels near the soil surface (Kattelmann & Dozier, 1999; Kattelmann, 1985). Although presumably present at the base of the snowpack after sufficient water has flowed through the snow to saturate the snow just above soil surface, they are typically visible to human observers only after the upper portions of the snowpack have melted away for a couple of before they disappear. Most basal macropores are 1-2 cm in diameter, and in this case they are round. However, the largest observed reached 8 cm. When the size passes about 3 cm, they become oval – wider than taller (Figure 7). They tend to be found at the base of the snowpack, especially if there is a basal ice layer on top of the soil. They are formed by the water flow eroding the saturated grains and washing them away in the flow. They allow rapid open-channel flow into the stream network.

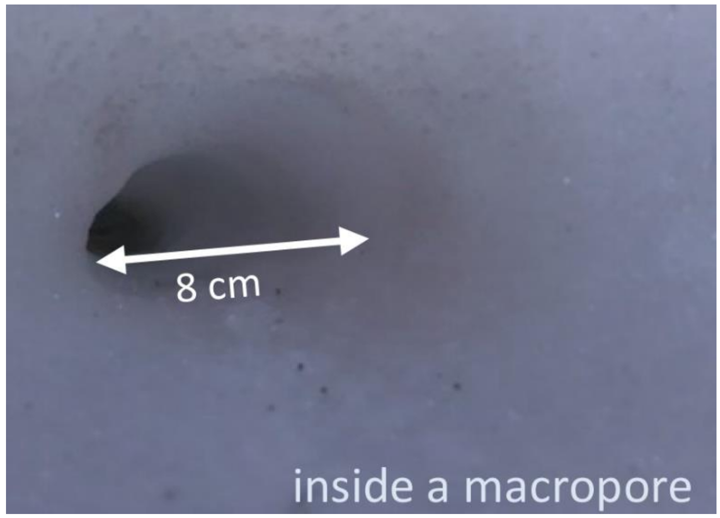

Figure 7. The left panel shows small, circular basal macropores, and the figure above shows a larger, oval macropore. Photos by R. Osterhuber.

ELEVATION, STORM ORIGIN, AND COLD CONTENT

At the Central Sierra Snow Laboratory, Sierra Nevada storms can be typical Maritime Province storms and be “warm” and deposit snow during air temperatures from -3 to +2° C, typically from the west or south-west. Many of them are due to Atmospheric rivers, and these special storms deliver more than half of the typical winter’s snow. However, the Sierra also gets storms with cold polar air, and these deliver snow with air temperatures in the -10 to -5° C range. The layer that is produced reflects the origin and temperature of the storm. While the Snow Lab is at 2,098 m (~6,900 ft), higher elevations get colder snowpacks due to the lapse rates associated with air masses crossing higher elevations.

Cold content, Q_{cc}, is a measure of how cold a snowpack is, and how much heat would be required to bring the snow to an isothermal state of being near 0° C. The cold content of an entire snowpack, or more accurately, a snow horizon, is calculated base on the heat capacity of ice, the average temperature of the snowpack or layer, the melting point of ice, the density of water, and the layer thickness. The colder the snowpack, the more heat is required to bring it to isothermal at 0° C. While heat inputs come from many sources, solar insolation dominates as a warming mechanism.

A widespread and persistent assumption has been that cold content must be zero before liquid water can be released from the snowpack. However, with the formation of flow fingers, water can be transported to the soil from the surface, even through a layer with a negative Q_{cc}. The liquid water can release heat when freezing and metamorphosing the snow in the flow finger, and that warms snow in the finger to have larger grains and become more porous, hence transporting water in a rapid manner. Of course, by about April 1, the snowpack will have warmed and the Q_{cc} is typically zero, and the snowpack is termed "ripe."

Snow Zones and Storm Temperature

The western flank of the Sierra Nevada can be divided into zones in terms of what falls when storms sweep through. The lower elevations are the rain zone, and above that is a transition zone of 1500 – 1800 m (5000 – 7000 ft) where both rain and snow occur. Above that are the elevations where a seasonal snowpack forms and rain is/was less common. Climate change is changing the defining elevations and the frequency of rain events, and will be explored in more detail below.

Cold storms routinely deposit 2-15 cm of snow in the transition zone. As time passes and sunny skies occur, the snowpack warms, and if a warm storm arrives, it may bring rain to the transition zone snowpack. The rain may fall at 1 – 2° C, thereby adding sensible heat to the already ripe snowpack and adding 4 – 8 J of heat per gram of rain. However, melting a gram of snow/ice requires 333 J, so that rain itself does not melt much snow.

However, humid and windy conditions associated with warm storms can melt a significant amount of snow because of condensation of water vapor onto the snow surface. Energy exchange from convection-condensation processes is far greater than the small amount of heat conducted by the rain. For example, at high temperature (10°C) and high wind speed (10 m/s), a warm storm can generate 80 mm of melt in a day (Kattelmann et al., 1998). However, only long-duration storms can melt much snow. Rain also causes rapid metamorphosis and densification of a snowpack, so the snowpack after a warm storm is often shallow compared to before the storm. Warm storms do cause snowmelt, but often the perceived "melt" is actually densification.

RAIN ON SNOW AT CSSL

The Central Sierra Snow Lab is near Donner Pass in the Yuba River basin, and has detailed climate data since 1978 and detailed snow data since 1890's. It has multiple precipitation gauges, had two 18 m^2 lysimeters, and stage height measurements in Castle Creek, with a 1300-ha watershed that rises to 2,775 m elevation. Winter rainfall has become a regular occurrence, and the Lab averages 1.5 m of precipitation and 11 m of snow. The core winter months are December – March, and ~17% of storms are rain in December and March, and about ~8% of storms are rain in the colder months of January and February (Osterhuber, 2019).

ROS statistics have changed between 1978 and 2018 as climate has changed. At the start of the period, 3-4 winter storms delivered rain, but in 1986 there were nine rain storms between December and March. Six years still had zero rainstorms. 2017 had several unusually large rainstorms. Today, the mean rainstorm is 65 mm in depth, lasts 43 hours, and the intensity is 1.8 mm/hr. Twenty years ago, the mean rain was 57 mm, the storm lasted 32 hours, and the intensity was 1.6 mm/hr (Osterhuber, 2019).

The fraction of rain for the whole water year (WY) versus just the winter months (Dec – Mar) from 1978 to 2018 is plotted in Figure 8 (Osterhuber, 2019). While the R-squared values are not high due to the scatter, the trend of rising fraction of rain is strongly suggested.

EFFECTS OF RAIN ON SNOW

The increasing fraction of storms that are rain instead of snow has implications beyond the loss of snowpack augmentation. Rain up to higher elevations increases the basin area that receives rain, thereby changing streamflow response from negligible to potentially significant. During very warm storms, effective contributing area of rainfall-runoff may be several times greater than during colder storms that deposit snow over most of the basin (Kattelmann, 1997). Rain on snow is already associated with many of the largest floods that California has experienced (Kattelmann, 1999; Kattelmann et al., 1991), but higher fractions of rain and higher rain-snow elevations will exacerbate the flood risk. While recreational use of stream channels in winter is much lower than during spring or summer months, there is always risk of higher flows that arrive quickly and with little warning.

There is also increased risk associated with the increased potential for avalanches to occur after ROS. Osterhuber (2019) has documented an increased avalanche potential when ROS occurs within three days of a snowfall event. The newer the snow, the higher the potential that it can be triggered by ROS, likely because of the

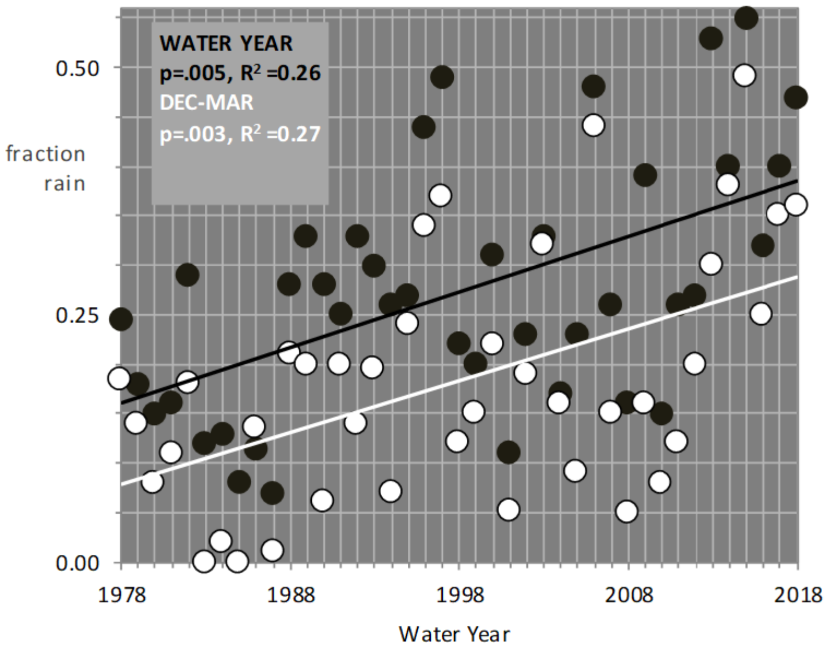

Figure 8. The dark dots are storms for the entire water year, and the white dots show storms during the colder winter months.

lack of settlement and consolidation that occurs during metamorphosis. Large avalanches have released within minutes of rain occurrence following new snowfall (Osterhuber, 2019), as shown in Figure 9. The opposite is the case when rain falls on a near-ripe or metamorphosed snowpack – it produces only minor instability. In this case, grains are likely sintered to each other and flow fingers have developed that allow the rainfall to be transported to the soil surface without significant delay. These observations support our understanding of wetting fronts, preferential flow fingers, lateral flow, and gain-scale metamorphism.


Figure 9. An avalanche that released on the west shore of Lake Tahoe after a rain-on-snow event in March, 2018. Photo by J. Cyzezewski.

Rain on snow occurrence is increasing per Figure 8, and more information is needed for water managers to respond in a timely manner and reduce flood risks via reservoir operations. A critical need is for forecasts of where will it rain in a watershed – by elevation and longitude, and by latitude. The second critical information that is needed is for radar and other remote or local sensor networks to detect where is it raining during a storm.

Finally, the response of the snowpack to ROS is strongly affected by the presence or absence of flow fingers in the snowpack in mid-to-upper elevations. The presence of flow fingers indicates a snowpack that is less likely to avalanche and can transmit ROS or surface melt in a predictable manner. Simply knowing that a snowpack has previously transmitted water would suggest that response to subsequent inputs of water will be relatively rapid.

CONCLUSIONS

Snowpacks in the Sierra Nevada develop from a procession of storms during a winter that deposit layers with varying temperatures and density. Clear weather between the storms produces melt-freeze crusts that separate the storm layers or horizons. Melt at the surface or rainfall causes flow fingers to develop and transmit the liquid water through the layers to the next lower crust, whereupon it is redistributed to create a new pattern of flow fingers in the next lower layer. Surface features such as dimples, bumps, and dendritic patterns can be produced by various weather patterns and freezing, melt, and collapse of water-modified snow features. Macropores near the soil surface transmit water laterally and speed the delivery of meltwater to streams. The Sierra Nevada has different elevation zones that are either rain zones, transition zones with rain or snow, and zones where snow is the predominant form of precipitation. In the transition zone, warm windy storms can produce accelerated snow melt. Rain on snow at the Central Sierra Snow Lab has become more intense, lasts longer, and the fraction of rain versus snow has increased between 1978 and 2018. Rain on snow at higher elevations increases midwinter streamflow and increases the potential for avalanche on slopes with recent snowfall. More information is needed about the forecasted and actual locations of rain on snow and the presence of flow fingers in the mid-to-upper elevation snowpacks.

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