Outline

• Snowpack structure, source of layers, temperature changes during storms, melt/freeze crusts
• Water flow, flow fingers, dimples, dendritic patterns, macropores, runoff efficiency
• Cold content, elevation effects on cold content
• Rain & temperature effect on snow, rain-induced melt
• Characteristics of ROS at Central Sierra Snow Lab, seasonality, trends, avalanche
Metamorphism, change from crystals to sintered grains.
Snowpack development, layers, crusts

• Multiple storms through the season, intra-storm temperature changes, cold vs. warm storms, sunny periods between storms
• By spring, 2-4 m snowpack, 8-12 major layers or horizons
• Melt/freeze crusts, 1-3 cm, between layers, sunny weather intervals
• Crusts may be loose, coarse metamorphosed grains late in the day
• Will support your weight in morning, but are not vitreous planes
• Within horizons, temperature and grain size varies
• Grain size changes may act as flow barriers
• Snowpack is opposite of “homogeneous sand bed”
Dye application highlights layers

By R. Osterhuber
Flow through snow, fingers, dimples, patterns, macropores, & runoff efficiency

- Liquid water is from snowpack surface, from melt or ROS
- Wetting front precedes uniform wetting, which develops preferential flow channels, here called flow fingers, which move water efficiently
- Can travel through layers that are below 0° without warming the whole layer
- Dyed sections easily photographed because dyed water ponds up
- Section cutter uses backlighting and no water/dye to reveal wetted, larger grain zones corresponding to layers and flow fingers
Thick section cutter, horizontal slice

By B. McGurk
Dyed and back-lit layers and fingers - vertical

By MW Williams, CO

By B. McGurk
Horizontal slices at sequential depths

15 cm from surface

20 cm from surface
Flow fingers within 3 layers - variation

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

<table>
<thead>
<tr>
<th>Layer series and depth (cm)</th>
<th>No. of fingers</th>
<th>Diameter (mm):</th>
<th>Spacing (mm):</th>
<th>Percent wetted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Std. dev.</td>
<td>Mean</td>
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<tr>
<td>C - 2 - 172</td>
<td>19</td>
<td>20</td>
<td>8</td>
<td>47</td>
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<tr>
<td>C - 2 - 170</td>
<td>20</td>
<td>17</td>
<td>6</td>
<td>39</td>
</tr>
<tr>
<td>C - 2 - 167</td>
<td>16</td>
<td>22</td>
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<td>52</td>
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<tr>
<td>Layer means</td>
<td>18</td>
<td>20</td>
<td>7</td>
<td>46</td>
</tr>
<tr>
<td>D - 3 - 158</td>
<td>37</td>
<td>13</td>
<td>6</td>
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</tr>
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<tr>
<td>Layer means</td>
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<td>Layer means</td>
<td>13</td>
<td>18</td>
<td>9</td>
<td>34</td>
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</tbody>
</table>
Flow finger vertical alignment – within layer

Fig. 2 Flow finger outlines in three serial sections and the overlay of sections, showing overlapping fingers from section to section, from a snow pit in April, 1990, near Soda Springs, California, USA.
Surface evidence of flow fingers and flow tubes
Vertical versus horizontal flow, dendritic patterns

• On fairly flat terrain, melt or ROS travels little horizontally, but fingers deliver water vertically from the surface to the bottom of the pack.

• With subsequent pack warming, the porous, frozen grains in the finger partially melt and become smaller, and the wetted area contracts and creates a depression.

• On steeper slopes, horizontal travel along layer boundaries also occurs, melting and eroding the snow, creating a porous flow path that is not hollow.

• Subsequent melt causes the porous, low-density tube to settle, creating dendritic patterns on the hillside, like a river network.
Extended ROS also causes divots and branched patterns

- Dimples and dendritic patterns after 100 hours of rain at CSSL
Basal macropores

• Horizontal delivery is aided by formation of open channels near the soil surface (Kattelmann, 1985; Colbeck, 1978)

• Only visible for 1-2 days in last 0.5 m at base of pack, and they then disappear – most are 1-2 cm diameter, but can reach 8 cm

• When 1-2 cm, pores are round. Over 3 cm, become oval - wider

• Largest channels are found at the base, above the basal ice layer

• Form by flow eroding saturated grains and washing away the grains

• Macropores lead to the stream network and increase delivery rate
Basal Macropores

inside a macropore

By R. Osterhuber
Elevation, storm origin, and cold content

• Sierra Nevadan storms can be “warm” and deposit snow with air temperatures from -3° to +3° C, typically from west or south-west, now known as Atmospheric Rivers

• Storms with cold, polar air also occur, with snow from -10° to -2° C

• Due to the lapse rate associated with air masses moving to higher altitudes, higher elevations generally have packs with colder snow.

• $Q_{cc}$ is calculated based on heat capacity of ice, average temperature of the snowpack or layer, melting point of ice (0°C), density of water, and layer thickness.

• Energy input comes from many sources, but solar insolation dominates.

• Water release occurs even when snowpack $Q_{cc}$ is negative, but by spring the snowpack $Q_{cc}$ is zero, and the snowpack is termed “ripe”
Snow zones, storm temperature, advected heat, melt vs densification

- Low elevations are the rain zone, above it is a transition zone of 1500-1800 m (5000-7000 ft) where both rain and snow occur, above that are higher elevations where a seasonal snowpack forms and rain is less common.
- Cold storms routinely deposit 2-15 cm of snow in the transition zone.
- Time passes and that snow warms, and then a warm storm may arrive with rain in the transition zone.
- The rain could be 1°-2° C, adding sensible heat to the already ripe pack, adding 4-8 J of heat per gram of rain. Melting a gram of ice requires **333 J**.
- Humid, windy storms can also melt snow due to condensation, at a rate 600 times larger per gram, but only long-duration storms melt much snow.
- Rain causes rapid metamorphosis and densification, leading to perceived “melting” of the snowpack due to rain.
ROS at CSSL: frequency, occurrence, magnitude

- Lab is at 2098 m (6900 ft) near Donner Pass, detailed data since 1978, including precip gauges, two 18 m$^2$ lysimeters, and stage height in Castle Creek which drains 1300-ha watershed with 2775 m elevation
- Winter rainfall is a regular occurrence, 1.5 m of precip, 11 m of snow
- Core winter months are Dec-Mar, ~17% of storms are rain in Dec and Mar, and ~8% are rain in the colder Jan and Feb.
- On average, 3-4 winter rain storms, but 1986 had nine, six years had 0
- Today, mean storm rains 65 mm, lasts 43 hrs, intensity is 1.8 mm/hr
- 20 years ago, mean storm was 57 mm, lasts 32 hrs, at 1.6 mm/hr
Fraction of rain for WY and winter months, 1978-2018
Effects of ROS

By R. Osterhuber
L. Tahoe, west shore after ROS, March, 2018

By J. Cyzezewski
Avalanche Response to ROS

• Increased potential with ROS occurring within 3 days of snowfall, and the newer the snow, the higher the potential

• Large avalanches have released within minutes of rain occurrence following new snowfall

• Rain on “old” snow typically produces only minor instability

• These observations support our understanding of wetting fronts, preferential “finger” flow, lateral flow, and grain-scale metamorphism
Information needed

• Where will it rain – elevation and latitude, maybe longitude
• Where is it raining NOW during a storm – radar?
• Instrumentation for widespread cold content measurement
• Cold content distribution, esp. in March, by elevation/slope/aspect
• Frequency and magnitude of increase of rainstorms, by latitude
• Presence or absence of flow channels in mid-to-upper elevation snowpacks
Outline - review

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• THAT’S ALL, FOLKS! THANKS, QUESTIONS?
References


