WATER IN SNOW LIKES TO GO WITH THE FLOW: DYNAMICS OF LIQUID WATER IN SNOW AND ITS IMPACT ON STABILITY

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ABSTRACT: Rain-on-snow, rapid warming, and snowmelt events can cause significant changes in slope stability. Liquid water causes dry snow to rapidly change, increasing the densification rate by several orders of magnitude and changing microstructure. The rapid shock to the snowpack can cause initial widespread avalanching, and delayed avalanches can occur after the water has followed a complicated path to a failure layer, while the longer term effect of drainage increases stability. The flow path of water through snow is complex and poorly understood. It is highly variable over short spatial and temporal scales, and challenging to measure. The CryoGARS group has over the past 4 years developed an intensively monitored snow study site within the Bogus Basin Ski Area in Idaho to study water flow in a layered alpine slope Automated continuous measurements are made on a slope with multiple radar systems, arrays of lysimeters, time-lapse cameras, soil moisture pits, and ultrasound depth sensors, in addition to a full energy balance weather station and an additional lysimeter array on a broad ridge above. Weekly observations include detailed manual snow profiles, stable isotope profiles, LWC with dielectric probes, penetrometer measurements, slope-scale resistivity surveys, and spatial radar profiles using an aerial tramway. This multi-sensor multi-disciplinary study provides a new view of liquid water flow in snow and the importance of lateral flow caused by stratigraphy.

KEYWORDS: liquid water content, rain on snow, snowmelt, unsaturated flow, wet snow avalanches

1. INTRODUCTION

Rapid snowmelt and rain-on-snow events can cause a rapid change in snowpack stability, leading to widespread avalanching (Conway and Raymond, 1993; Conway, 1998). Wet slab avalanches can release when the additional liquid water reaches the weak layer, and in the case of rain-on-snow events, when the weight of the additional mass causes the shear stress to exceed the weak layer strength (e.g. Conway and Wilbour, 1999). Prior to either of these conditions being met, widespread avalanching is often observed immediately after the onset of rain (Conway and Raymond, 1993), but the mechanism of release is not yet well understood.

Wet snow avalanches are often difficult to artificially control, due to the large attenuation of the pressure waves from explosives in wet snow. Evaluating the impact on stability of rapid snowmelt and rain-on-snow events requires understanding of the dynamics of water movement in unsaturated snow. In addition to causing wet snow avalanches, these events are also responsible for major flooding that is currently poorly understood and underestimated by snow hydrology models. The dynamics of liquid water flow in snow is also important for estimates of surface mass balance and the travel-time of meltwater traveling from polar ice caps and glaciers to the ocean, for predicting time scales of sea level rise (ILLANGASEKARE et al., 1990; Pfeffer

Fig. 1. Runnels are surface expressions of preferential flow of liquid water in unsaturated snow, where water is concentrated in parallel channels oriented downslope. Photo: Patrick Melvin.

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Fig. 2. Dye experiments indicate water can move hundreds of meters downslope along layer boundaries on time scales of hours, often with vertical melt pathways occurring between multiple saturated layer boundaries. Snow between vertical melt channels is typically close to dry, while channels have high liquid water content. Right photo: Adam Brown.

and Humphrey, 1996). With global temperatures rising, the shift from snow to rain at some elevations will likely cause increased rain-on-snow occurrence at elevations where historically only snowfall events occurred [Mote et al., 2005]. The already widespread occurrence of rain-on-snow, coupled with the likely increase in regions experiencing midwinter rain due to climate change, indicates the need for a thorough understanding of the dynamics of water movement in unsaturated snow during spring snowmelt and rain-on-snow events.

2. PREVIOUS UNSATURATED FLOW IN SNOW STUDIES

The flow of water within unsaturated snow is a complicated and poorly understood phenomenon, with permeability boundaries that cause slope-parallel lateral flow over large distances, and cylindrical, vertical melt pathways, which cause large spatial variability at the slope scale (e.g. Williams et al., 1999). Dye tracers have been used to delineate the hydrologic pathways in snow (W., 1954, 1949; P. and Woo, 1984; Schneebeli, 1995; PA et al., 2004). W. (1954) used fuchsine dye to delineate water paths within a snowpack that exhibited dendritic patterns, highlighting both vertical and lateral flow paths through the pack, caused by spatial variation in snowpack characteristics.

Strata within the snowpack may have differing permeability that can vary due to differences in pore size distributions (Colbeck, 1975). The stratification may consist of layers of ice, but also changes in grain size and liquid water content can be important. This stratification can impede the vertical infiltration of water and route water parallel to stratigraphy (Colbeck, 1975). Most slope-scale hydrology studies in snowmelt-dominated areas assume that all snowmelt moves vertically into the land surface at every point (Carey and Woo, 1999; Stadler et al., 1997), and even the most complex physically based snowpack models rarely allow for slope-parallel movement of water within the snowpack.

Changes in the water content of a layer within the snowpack can also cause water movement within snow. Saturation within zones in the snowpack allow for rapid metamorphism (Marshall et al., 1999) and subsequent grain size growth. This rapid grain growth is commonly observed in the field, and was investigated in the laboratory setting by Wakahama (1967). This increase in grain size and saturation leads to an increase in hydraulic conductivity within that layer (Colbeck, 1975). It follows that this increase in conductivity could route vertically infiltrating meltwater in the lateral direction down slope, following this higher conductivity flow path.

Layers of ice within a snowpack were shown to have permeability 5-10 times lower than permeability values determined in the surrounding snowpack (Albert and Perron, 2000), and therefore could cause significant ponding of water and lead to slope parallel flow. The most common process through which these ice layers form is not through melt occurring and freezing at the surface, but rather meltwater generated at the surface infiltrating to some depth and ponding at a layer boundary. Water is retained in the pores, and subsequently re-freezes, creating a quasi-continuous ice horizon within the snowpack (Colbeck, 1975). H and Benedict (1994) showed through experiments involvinig thermistor grids that in snowpacks containing multiple ice layers, the vertical flow from a natural rain-on-snow event was impeded vertically and routed laterally. Ice layers have also been found to be responsible for lateral redistributions of flow even on gently sloping topography (P. and Woo, 1985).

Most snow hydrology studies on unsaturated flow have focused on experiments at flat sites, where discontinuities are seen to slow the wetting front. Colbeck (1975) attempted to account for discontinuous ice layers by using an anisotropic hydraulic conductivity, which predicted the ice layers would impede flow and slow the transit time of meltwater through the snowpack. In contrast, other studies (P. and Woo, 1985; Furbish, 1988; Jordan, 1983) have found that ice layers are discontinuous, and route water laterally for short distances which tends to concentrate meltwater into vertical channels at the discontinuities. The lateral flow along ice layers was observed to be short, and the increased liquid

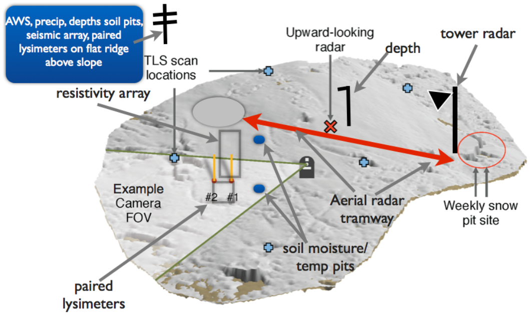

Fig. 3. Overview of Bogus Basin Snow Site, showing instrumentation on slope for monitoring liquid water storage and movement in snow and soil.

Fig. 4. GPR profiles from an aerial tramway were performed weekly to monitor major stratigraphy, SWE, and depth.

water content in the concentrated vertical channels caused hydraulic conductivities much higher than the average unsaturated snowpack, leading to a much faster wetting front than in a homogeneous snowpack.

Models have been developed to account for snowpack layering and vertical flow channels (e.g. ILLANGASEKARE et al., 1990; P. and Woo, 1985), however they require information about the snowpack stratigraphy and spatial density and size of vertical preferential pathways, which is difficult to measure. Accurate estimates of liquid water content are difficult since water in snow can cause phase changes and increase densification rates, and measuring this important quantity has been stated as one of the biggest challenges in comparing models and observations (Jordan, 1983).

Recently accurate laboratory experiments of different snow samples were performed to determine the water saturation curve, and calculate model parameters necessary for applying unsaturated flow models from soil hydrology (Katsushima et al., 2009; Hirashima et al., 2010).

3. MONITORING LIQUID WATER FLOW ON A SLOPE WITH MULTIPLE TECHNIQUES

Previous experiments on unsaturated flow in snow have primarily focused on low angle study sites, where gravity acts nearly perpendicular to the snow stratigraphy. Due to the importance of this process on wet snow avalanche release, we focused our studies on a 25-35 degree south-east facing slope, which develops significant stratigraphy due to midwinter surface melt and wind. The Bogus Basin Snow Site (hereafter B.S.), is located within the boundary of a small ski area 15 miles from Boise, ID. This site has an approximately planar slope with minimal ground surface roughness, is wind loaded and develops a 1-2 meter snowpack by April 1.

We installed a full energy balance meteorological station on the flat ridge above the slope, which measures incoming and outgoing shortwave and long wave radiation, shielded precipitation, multiple snow depth, soil moisture, and soil temperature sensors, wind direction and speed, air temperature, and relative humidity. A upward-looking GPR (e.g. Heilig et al., 2010; Mitterer et al., 2011) is installed in a large buried enclosure, and moves up and down along a linear actuator during hourly observations to allow classification of signals caused by instrument noise. This radar system has run successfully for multiple snow seasons, and is used to monitor bulk snowpack liquid water content (Bradford, 2009) with a co-located ultrasonic depth sensor, as well as SWE and major stratigraphic layers (e.g. Marshall and Koh, 2008). Weekly manual GPR measurements were made for 2 winter seasons from an aerial tramway which crossed near the upGPR. A tower mounted GPR monitors depth, stratigraphy, and SWE from above the snowpack.

If lateral flow of water in snow is significant, downslope gradients in soil moisture would be expected to develop prior to the wetting front reaching the ground and the snowpack becoming saturated. A semi-permanent seventy-two node 3-D Electrical Resistivity Tomography (ERT) array monitors soil moisture on the upper half of the slope on a weekly basis, and in-situ soil moisture and temperature sensors have been installed at 4 depths between 0.1m and 1m in each of two soil pits on the B.S. slope.

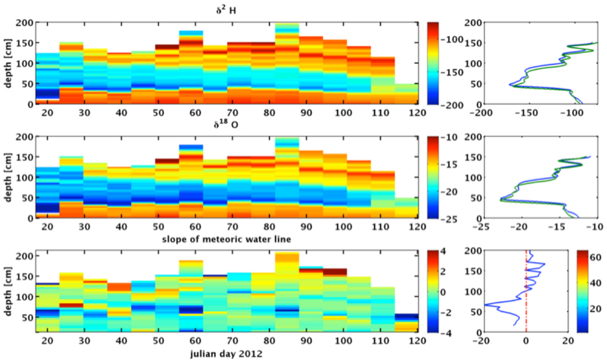

Fig. 5. Stable isotopes measured at 5cm vertical resolution in weekly snowpits. Upper panels show oxygen and deuterium isotopes, and bottom panel shows the deviation of these isotopes from the local meteoric waterline. Far right panels show results from two side-by-side profiles, demonstrating repeatability.

High vertical resolution (5 cm) profiles of stable isotopes were measured weekly for the past 3 winters. Significant variations is isotopic composition form due to differences in atmospheric conditions during storms, and are expected to disappear when the wetting front moves water through the snowpack. Isotopic signature persists for more than a month after first significant melt, as the majority of liquid water moved downslope along upper layer boundaries, with the lower half of the snowpack remaining dry-moist for this period. Fig. 5 shows the evolution of the profiles of excess deuterium and oxygen ratios, relative to mean sea water, on the top and middle panels on the left. The top and middle panels on the right show two typical profiles on a given day, illustrating the repeatability and small variability at the meter scale. The bottom panel shows the deviation from the local meteoric waterline, indicating possible locations of significant phase changes (melt/sublimation).

Four individual lysimeters were installed on the slope and have recorded outflow for 4 seasons. The lysimeters have a collection area of 4 square meters, and all are blocked on the downhill edge. Two of the lysimeters are also blocked on the uphill side, so that total outflow should equal the SWE deposited directly above the lysimeter, less any sublimation. Isotopic analysis and measured temperature gradients indicate sublimation is not signficant at this site. The two lysimeters that are only blocked on the downhill side can receive water inputs from upslope. Two time-lapse cameras were installed and recorded high resolution photographs every 15 minutes throughout the winter. Calibrated markers within the field of view are used to estimate changes in snow depth.

High resolution digital surface models were produced from snow-free and snow-covered TLS surveys. Weekly manual snow profiles were performed, in addition to snow characterization with Near-InfraRed photography, SnowMicroPenetrometer profiles, and in-situ dielectric wetness profiles. An active source seismic survey was performed to determine the soil/bedrock geometry, to improve soil moisture inversion results.

4. RESULTS/CONCLUSIONS

We show that lateral flow is a significant process at this site during the period between initial wetting of the surface snow, until the wetting front penetrates to the ground. Upward looking radar observations are used to track the depth of the wetting front, and isotopic signatures are used to independently infer the depth of major water penetration. Soil moisture patterns show a downslope soil moisture gradient which increases until the wetting front reaches the soil, at which point the gradient decreases until the soil moisture on the slope becomes approximately uniform as the soil becomes saturated everywhere. The lysimeter experiment shows both significantly more outflow from the lysymeters that are unblocked on the uphill side, and the timing of outflow due to diurnal variations in surface melt between the two lysimeter types is consistently offset, as would be expected if lateral flow was an important routing mechanism. Energy balance modeling and unsaturated flow modeling are compared with the many independent observations supporting the significance of lateral flow.

CONFLICT OF INTEREST

The creation of this document was not supported financially or materially by Bogus Basin Ski Area, nor any manufacturer of scientific equipment. It is an unfortunate coincidence that the study site name could be misinterpreted as a description of the quality of the scientific data from this location, which is anything but *bogus*. The reader also asked not to infer anything about the validity of the results from the study site, based on other common meanings of the site acronym (B.S.).

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