VARIABILITY OF LIQUID WATER CONTENT IN AN ALPINE SNOWPACK

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ABSTRACT

During the early stages of snowmelt runoff, snowpack liquid water content was sampled at five sites in an alpine basin in the southern Sierra Nevada. Typical values ranged from 1 to 3 percent by volume with some values from 5 to 8 percent. The high variability of the measured liquid water content suggests that objectives and sampling design must be carefully considered when attempting to monitor snowpack liquid water content.

INTRODUCTION

Liquid water content of snow is widely regarded as an important property of snow cover. The amount of liquid water in snow directly influences metamorphism of snow grains and the rate of water flow through the snowpack (Colbeck, 1978). Therefore, knowledge of liquid water content may be useful in forecasting snowmelt runoff, assessing snowpack response to rainfall, predicting timing of wet snow avalanches, evaluating changes in snowpack chemistry, and interpreting snowpack remote sensing data.

Because of the assumed importance of liquid water in the snowpack, there has been a proliferation of techniques to measure its amount. At least 50 papers in the scientific literature describe or compare methods of measuring liquid water in snow (e.g.,Colbeck, 1978; Boyne and Fisk, 1987). However, there has been little reporting of data about liquid water content or efforts to make use of these techniques. This situation may result from an inability to take advantage of liquid water information in operational forecasting and difficulties in obtaining such information routinely (Colbeck, 1978). Furthermore, the variability of liquid water content over time, across snowfields, and within a snowpack profile make monitoring and synthesis of the liquid water regime of snow cover difficult.

The lack of information obtained from field measurements led to this pilot study in the southern Sierra Nevada. This study was conducted as part of a comprehensive investigation of the hydrology of an alpine lake basin with respect to precipitation chemistry (Dozier, *et al.*, 1989). The objectives of this study regarding liquid water in snow were to observe the initial wetting of the snowpack during the transition from winter to spring conditions, determine some typical values of liquid water content and their variability, and evaluate the requirements for a sampling scheme to obtain liquid water information.

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STUDY APPROACH

All measurements were made in the Emerald Lake basin, a 1.2 km^2 headwater catchment in Sequoia National Park, California. This basin has an elevation range of 2800 to 3400 m and a generally-northern exposure. In this basin, seasonal snowpacks may accumulate 0.5 to 2 m of snow water equivalence and remain below freezing until spring (Dozier, *et al.*, 1989).

Liquid water measurements were made from mid-March until mid-April in 1988 as the snowpack began to melt. Measurements were made as other projects allowed so scheduling was not ideal. Liquid water content was measured in successive snowpits excavated at five sites in the higher-elevation part of the basin. Measurements were made between 1200 and 1600 PST in an attempt to document the higher water contents during active melting and percolation. This sampling period avoided the effects of the night-freeze crust that was often up to 20 cm deep. A few measurements were made before the night-freeze crust thawed to assess the residual or irreducible water content in the deeper layers.

All liquid water measurements were made with a dielectric moisture meter purchased from the Department of Physics, University of Innsbruck (Denoth and Wilhelmy, 1988; Denoth, 1989). This electronic device consists of a 12 x 15 cm flat sensor, which is inserted into a snowpit wall, and a tuning and display unit. This instrument takes advantage of the large difference in the dielectric constant (ratio of the flux density of an electric field through a material to that in a vacuum) of ice and water at high (MHz) frequencies. The measured dielectric constant of the ice-air-water mixture that comprises wet snow can be used to calculate the liquid water content where the snow density is also known. The probe is sensitive to liquid water in a volume within 1.5 cm of both sides of the sensor. Corresponding snow densities were obtained with a wedge-shaped cutter of 1 liter volume manufactured by Snowmetrics. A slight outward slope to the pit wall and vertical orientation of the sensor allow the sensor to remain in place without holding it and also avoids the ponding that results if the sensor were inserted horizontally.

The primary advantage of the dielectric moisture meter is its simple and rapid operation. Both the dielectric and density measurements can be made within two minutes. This rapid measurement period allows a large sample size to be obtained before conditions change. Dilution and alcohol calorimetry techniques of liquid water measurement may be more accurate than the dielectric moisture meter (Boyne and Fisk, 1987), but the speed of the meter seems necessary to obtain an adequate sample size.

Errors in the determination of liquid water content involve uncertainties in the dielectric measurement, density measurements and initial calibration (Boyne and Fisk, 1987; Perla and Bonner, 1988). Consistent readings were obtained when measurements were repeated in the same sensor slot a few minutes apart. In an earlier test at the Central Sierra Environmental Studies Laboratory, consistent results were obtained between our meter and another meter in the same sensor slot. Battery voltage and atmospheric humidity seemed to affect the performance of the meter. Our sampling design was to make five (sometimes ten) measurements about 20 cm apart in a layer and measure layers every 20 cm from the surface downward. This spacing was necessary because of the density measurements.

RESULTS

When the snowpack temperature was less than -2 °C, no liquid water was indicated by the meter. As temperatures approached 0 °C and when liquid water was visible on the snow surface, a few zones were found with 0.5 to 1 percent liquid water by volume even though most of the snow had not yet thawed. For the first week after the snowpack became isothermal, almost all of the measurements were between 0.5 and 3.0 by volume with a few higher values of up to 6 percent. As more water flowed through the snowpack, average values for layers were generally 1 to 3 percent. Two pits sampled in mid-May, one month after the main part of the study, had average values of 3 to 5 percent by volume at 1200 to 1300 PST.

Liquid water content was variable in several respects. Values within the same layer were rarely consistent. Usually, these differences were less than 2 percent by volume, but in about one-quarter of the 140 layers sampled, the minimum and maximum values within the same layer differed by at least 2 percent by volume. There were a few cases where the minimum value was 0.5 or 1 and the maximum value was 5 or 6. When the sensor was inserted horizontally into a visibly wet layer, the meter went off-scale, indicating a liquid water content in excess of 10 percent by volume.

The average values for each layer varied considerably between layers (Figure 1). Although most average values were 2 percent or less by volume, average values of one or two layers within some snow pits were 3 or 4 percent. During the early afternoon sampling period, average values were generally greater in the upper layers than in the lower layers. When sampling was repeated in the same afternoon, average values were higher during the second measurement period. There were also substantial differences in average values between pits on the same day, although exposure and time of day were not identical.

DISCUSSION

The tendency for liquid water content to be less than 3 percent by volume and often about 1 percent is probably related to the low melting intensity in the first two weeks following the onset of sustained snowmelt. However, such values are lower than values commonly discussed and assumed as a water holding capacity (often 5 percent by volume) in many snowmelt models. The few field measurements reported in the literature were generally made later in the snowmelt season and are greater than the values from this study. However, a recent set of measurements with the dielectric moisture meter were in the same range as those reported here (Denoth and Wilhelmy, 1988; Denoth, 1989). In another study, liquid water content calculated as a cumulative difference between snowmelt and release from the base of a snowpack varied between 2.5 and 3.5 percent by volume throughout the early part of a melt season in the Swiss Alps (Martinec, 1989).

These low values of liquid water content are consistent with the concept of water being concentrated in semi-vertical channels and at layer interfaces. If most of the water is flowing or in temporary storage in a small volume of the snowpack, the bulk of the snowpack would appear to be relatively dry. Obtaining accurate measurements of the volume of the snowpack conducting most of the water and of the amount of liquid water in such volumes is difficult.

The variability of the measured liquid water contents and the local accumulation of water impose some difficult conditions on designing a sampling scheme. Variability in liquid water content has also prevented comparison of different measurement techniques in natural snowpacks (Boyne and Fisk, 1987). Although more than 1000 measurements were made over two weeks, the sampling plan used in this pilot study was inadequate to provide anything more than an indication of the general magnitude and variability of liquid water content. A detailed sampling scheme with special attention to zones of accumulated water may be necessary to assess an average liquid water content at any single point and time. The question of the utility of average values of liquid water content in the early melt season must also be considered. If water flow occurs mainly in channels (e.g., Marsh and Woo, 1984), then we need to know about the liquid water regime in the channels and not just somewhere nearby. If snowpack stability is often determined by the accumulation of water at interfaces (e.g., Kattelmann, 1984; Conway, *et al.*, 1988; Heywood, 1988), then we should be most interested in liquid water near such interfaces.

CONCLUSIONS

Liquid water contents measured at Emerald Lake in the early part of the melt season generally ranged from 1 to 3 percent by volume and were lower than most values mentioned in the literature, either measured or assumed. However, individual measurements were occasionally higher (5 to 8 percent), suggesting a highly variable distribution of liquid water. Considerable variation was noted within layers, between layers, between snow pits, and over time. A very detailed sampling scheme would seem necessary to account for concentrations of water when assessing an average liquid water content.

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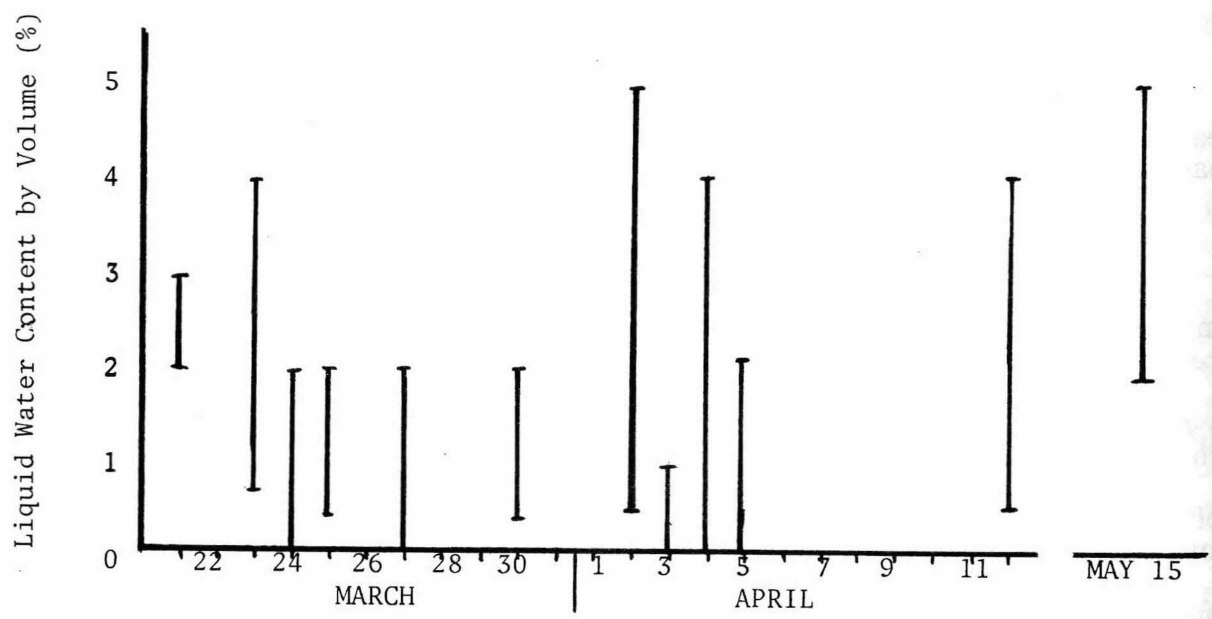

Figure 1. Range of Liquid Water Contents Averaged by Layer