SNOWPACK CHARACTERISTICS OF AN ALPINE SITE IN THE SIERRA NEVADA

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ABSTRACT

A snow research site has been operated on Mammoth Mountain in the eastern Sierra Nevada of California since 1978. Records from this timberline study plot illustrate some of the characteristics of snowpack development and ablation in the high Sierra Nevada. In most years, a snowpack of at least 50 cm depth has been in place by the first of December. Mid-winter storms have deposited a few centimeters to a few meters of snowfall. Wind redistributes snow around the site and is a critical influence throughout the accumulation season. Snow depth usually reaches a maximum sometime in April. Over the period of record, peak depths have ranged from 2 to 8 m with water equivalence of 0.7 to 2.5 m. Sustained spring snowmelt usually begins in late April or early May after storms have become infrequent. Daily melt amounts in May tend to average about 20 mm per day. Snow cover usually disappears during June but has persisted until August.

INTRODUCTION

In light of the importance of the snow zone in the Sierra Nevada for supplying water to much of California's agricultural and urban lands, surprisingly little information exists about snowpack development at upper-elevation parts of the mountain range. Most of our knowledge about snow hydrology of the Sierra Nevada was developed at the Central Sierra Snow Laboratory (CSSL), which is located northwest of Lake Tahoe in the forest zone at 2100 m (U. S. Army Corps of Engineers, 1956; Miller, 1995; Kattelmann et al., 1996). Climate and snow cover characteristics at CSSL were summarized by Miller (1955), Smith and Berg (1982), Azuma and Berg (1990), and Osterhuber (1993). Much less information has been available about snow in the subalpine and alpine parts of the Sierra Nevada. A network of about two dozen snow sensors and about 70 snow courses distributed throughout the Sierra Nevada above 2500 m provides data about snow water equivalence for operational runoff forecasting. Compilation of these data indicates that the peak snowpack water equivalence averages about 0.7 to 0.9 m in this upper-elevation zone (Kattelmann and Berg, 1987). However, these sites are not particularly informative about the processes of snow accumulation and ablation in the alpine zone. Hydrology of a small catchment at treeline in Sequoia National Park was studied from 1986 to 1988 as part of the California Air Resources Board's program on acid precipitation (Dozier et al. 1989). This study yielded some short-term information about snowpack development in the high Sierra Nevada (e.g., Kattelmann, 1980; Kattelmann and Elder, 1993). Detailed monitoring of snow cover at high altitude has been conducted for a longer time period at a site in the eastern Sierra Nevada. A snow research station on Mammoth Mountain at 2930 m has been in operation for two decades to allow study of the alpine snow cover. This paper describes some of the basic characteristics of snowpack development at this treeline location in the Sierra Nevada.

The snow study plot is located on the north side of Mammoth Mountain (37°37'N, 119°2'W, 2930 m) southeast of Yosemite National Park in Mono County, California. Mammoth Mountain is on the crest of the Sierra Nevada at the end of southwest-northeast trending trough of the upper San Joaquin River. This topographic position results in high precipitation and high winds. The snow research site is within the Mammoth Mountain Ski Area, but is out of the way of ski area operations and recreational ski traffic. The original site was chosen because of the ease of winter access and opportunity to locate near a U. S. Forest Service meteorological station and a California Cooperative Snow Survey snow course and snow pillow (Davis and Marks, 1980). After establishment in 1978, the research site was incrementally improved to enable measurement of all components of the energy and mass balances of the snowpack (Davis et al., 1984). The study site was moved in 1987 to a new location about 300 m away from the original site. The ski area had plans to install a new lift near the first site that would have compromised the integrity of the area for snow research. Although the ski area later decided not to build the lift, their construction crew generously built a large instrument platform at the new site. A small

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laboratory partially-buried in the ground was added in 1991. The instrumentation and data-logging capabilities continue to be improved, particularly since a research project of the U.S. Army's Cold Regions Research and Engineering Laboratory has become actively involved in the snow studies at the site. The research station is administered jointly by the Institute for Computational Earth System Science and the Sierra Nevada Aquatic Research Laboratory, both affiliated with the University of California at Santa Barbara.

Snowpack properties and weather conditions have been monitored on Mammoth Mountain since the 1960s for ski area planning and operation and avalanche-hazard evaluation. Snow physics research on Mammoth Mountain began in the mid-1970s as Jeff Dozier's research group at U.C. Santa Barbara sought a more permanent home for their field efforts. Micrometeorological data collected at the snow study plot have been used for development and validation of point energy-balance models of snowmelt (Davis and Marks, 1980). Physical properties of the snow that affect radiometric characteristics have been studied to model and calibrate remote sensing data (Davis et al., 1994). The site and other parts of Mammoth Mountain have been used extensively for ground truth for remote sensing instruments carried on aircraft, satellites, and the Space Shuttle. The site has also been used for testing of non-contact sensors at close range, such as FMCW radar and spectrometers. Another active area of research at the snow study plot has been chemistry of snowfall, snow cover, and snowpack outflow. A snow science course offered by U.C. Santa Barbara has used the site for instruction several times in the past decade.

Instrumentation currently or recently in operation at the site includes the following: 3 radiometers for incoming radiation (filtered for 280-2800 nm, 700-2800 nm, and 4,000-50,000 nm); 2 radiometers for outgoing radiation (filtered for 280-2800 nm and 700-2800 nm); air temperature, relative humidity, and wind speed 8 m above the ground; air temperature, relative humidity, and wind speed 1.2 m above the snow surface; a heated tipping-bucket precipitation gage, 2 storm-snowfall collection boards, 2 wet-dry precipitation samplers, 8 snowmelt lysimeters of 1 m^2 area with conductance meters on 6 of them, 1 snowmelt lysimeter of 4 m^2 area, and temperature sensors at various depths in the soil and snowpack.

SNOWPACK ACCUMULATION

During early autumn, occasional storms have deposited a few centimeters of snow that remained for only a few hours to a few days. Both radiation and stored heat in the ground usually melted snow from the first few minor storms of each season. Some of the early storms had high rain/snow levels and resulted in some precipitation occurring as rain at the elevation of the site. Twice during the period of record, large storms at the end of October deposited about a meter of snowfall, some of which did not melt and established continuing snow cover for the season. Snowfall in November has varied from zero to a couple of meters. Snow cover tends to be thin and discontinuous into mid-November. In most years, a snowpack of at least 50 cm depth has been in place by the first of December. In a couple of exceptions, when autumn precipitation was minimal, the snow cover was thin or patchy through December. Under these conditions of thin snow cover and clear nights, substantial temperature gradients were present that developed a layer of depth hoar. When the early-season snowpack was deeper, strong temperature gradients were not sustained, and kinetic-growth forms were not observed in the base of the snowpack.

After snow cover became nearly continuous and deep enough to prevent solar radiation from reaching the ground, the snowpack grew with additions from each successive storm. Mid-winter storms have deposited a few centimeters to a few meters of snowfall. One or two large storms have accounted for up to a third of the total accumulation in some winters. Storms affecting the area often occurred in clusters interspersed with days to weeks of clear weather. Substantial riming was observed during many storms, and large accumulations of rime that fell off of trees became incorporated in the snowpack. Wind redistributed snow around the site, and snow depths have changed by more than a meter in a few hours during windy periods without precipitation. Rainfall rarely occurred during winter or spring at this site. Notable exceptions occurred in January 1980, May 1996, and January 1997. Snow depth usually reached a maximum sometime in April. Because of the absence of storms in mid and late winter of 1997, peak accumulation occurred on January 26 this year. This date of peak snow was more than six weeks earlier than other dates of peak accumulation during the past two decades. Over the period of record (1978 to 1997), peak depths have ranged from 2 to 8 m with water equivalence of 0.7 to 2.5 m.

Snowfall from individual storms that was isolated from the underlying snowpack with a snow board has ranged in density from about 50 to 200 kg m^{-3}. The new snow settled rapidly to densities of 200 to 300 kg m^{-3} within a few days after deposition. Further densification increased average densities to 350 to 400 kg m^{-3} before the snowpack became wet. Because the snowpack usually remained dry during winter, stratigraphic horizons from different storm layers were not particularly distinct. The most visually-prominent layers were buried snow surfaces that melted slightly while exposed and formed a crust of melt-freeze grains. Former snow surfaces that were mechanically altered by wind were sometimes visible as well. The rainfall of early January 1997 created a complex set of ice lenses throughout the snow that had been deposited before the warm storm. In most years, snow temperatures in the upper meter of the snowpack ranged from -2 to -10°C, except for short periods of mid-winter melt or very cold temperatures when the near-surface layer was affected. The base of the snowpack generally remained near 0°C throughout the winters except when snow cover was shallow.

SNOWPACK ABLATION

Snowmelt has been observed during all parts of the snow season, but was generally minimal from December through March. During warm, storm-free periods, a couple of millimeters of melt could be generated, but the water tended to refreeze near the surface forming a distinctive crust. Sustained spring snowmelt usually began in late April or early May after storms became infrequent and the energy balance became positive. Few storms occurred during spring in most years, but snowmelt ceased for a few days during and shortly after the deposition of a few centimeters of snow and the restoration of high albedo. After the snow surface first began to melt, the small amount of water was refrozen in the near-surface layer and did not penetrate more than a few centimeters into the snowpack. As the amount of melt increased, more of it was able to percolate deeper into the snowpack and eventually reached the base of the snowpack. Some of this initial pulse of melt water was frozen at layer interfaces and formed an intricate stratigraphic profile of discontinuous ice lenses. Density of the snowpack also increased as the formerly cold, dry snow became wet. Average densities in early May were about 450 kg m^{-3} and increased to about 600 kg m^{-3} for snow that persisted into July. The significance of evaporation from the snowpack at Mammoth Mountain remains a topic of debate. Although the potential for high rates of sublimation when snow becomes entrained in the air stream during wind scour (e.g., Schmidt, 1972) seems to be well accepted, opinions differ about the opportunity for evaporative losses from the snow surface (Stewart, 1982; Leydecker and Melack 1995). This topic will continue to be studied at Mammoth Mountain.

Daily melt amounts have averaged about 20 mm per day in May and about 30 mm per day in June. Melt production varied greatly from day to day, depending on the energy balance. The amount of nighttime refreezing influenced the production of melt water on the following day. Typical depths of freezing during spring at our study site ranged from 10 to 20 cm, and required enough energy to melt 1 to 5 mm of water equivalence for warming on the next morning. Additional delay was caused by hydraulic routing within the snowpack. The lag between the daily onset of melt and the first appearance of water at the base of the snowpack decreased from 12-16 hours in the first week of melt to about 1-3 hours in the last week before snow disappearance (Kattelmann and Harrington, 1995). Snow cover usually disappeared during June but has persisted until August.

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