DENSITY OF NEW SNOW IN THE CENTRAL SIERRA NEVADA

By

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INTRODUCTION

Information about snow accumulation is used in hydrologic modeling, engineering design, avalanche forecasting, and estimating deposition rates of atmospheric pollutants. Estimates of precipitation depth, however, often contain a high degree of uncertainty. In many cases, the only available records are of snow depth. Such data require the users to assume an average density for conversion of snowfall depth to snowfall water equivalent.

Routine snowfall measurements in the United States began before 1830 under the direction of the Smithsonian Institution. The first documentation of a snowfall depth conversion was found in a revision of instructions of the U.S. Signal Service issued in 1875: "Whenever for any cause snow cannot be melted, the depth will be measured and 10 inches of snow recorded as 1 inch of rainfall" (Henry, 1917). This so-called "general rule" of an average snowfall density of 100 kg m^{-3} is still used extensively today (Goodison, et al., 1981; Sevruk, 1986) despite numerous highly-variable measurements of snowfall density done before 1860 (Henry, 1917).

The most appropriate value of a universal conversion factor has been debated for more than 50 years (e.g., Seligman, 1936; Wilson, 1955; Keeler, 1969; MacNeil and O'Neill, 1977). However, regional snow climate and local site factors strongly influence measured snowfall density (Meister, 1986; Sevruk, 1986). Several investigators have tried to relate snowfall density to surface air temperature (e.g., Bossolasco, 1954; U.S. Army, 1956; Stashko, 1976; Meister, 1986) or upper air temperature (e.g., Diamond and Lowry, 1954; Grant and Rhea, 1974; MacNeil and O'Neill, 1977). However, considerable scatter limited the utility of these relationships. Studies of the physical determinants of snowfall density have identified crystal size and shape, riming, compaction, and wind effects as the most important factors, but were unable to formulate any predictive relationships (e.g., Mellor, 1964; Power, et al., 1964; Grant and Rhea, 1974). Additionally, settlement between the time of deposition and the time of measurement can double the density of new snow in as little as 24 hours (Church, 1941; Gray, et al., 1970).

This paper defines empirical relationships between snowfall density and environmental factors that could be used within the forested snow zone of the central Sierra Nevada.

SITE AND METHODS

This study was done at the Central Sierra Snow Laboratory (CSSL), operated by the U.S.D.A. Forest Service's Pacific Southwest Forest and Range Experiment Station, near Soda Springs, California. The laboratory lies a few kilometers west of the crest of the Sierra Nevada at elevation 2100 m. Winters are characterized by deep snowpacks (2 to 5 m) that begin to accumulate in December and persist through May. Temperatures range from -20°C to 15°C during winter when most of the annual precipitation occurs. While snow predominates, rain and mixed snow and rain also occur.

Data were obtained from two or three snow boards at 0800 and 1600 hours at least 5 days per week during water years 1984 through 1986. The snow boards were 36-cm squares of white-painted plywood with a 1-meter dowel attached to the center for locating purposes. They were placed 3 m apart about 15 m from the edge of the clearing, and had a similar exposure. When snow was deposited, an average board depth was obtained by inserting a metal ruler through the snow to the board at all four corners. A core was then obtained with a metal can 15.2 cm in diameter and 16.1 cm deep. The can was pushed down through the snow to the board, and the board and can were inverted. The can was slid sideways, clear of the board, capturing only the enclosed snow. The snow was then melted and measured in a 500 ml volumetric cylinder. A conversion factor transformed volume to equivalent water

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depth; density was calculated by dividing equivalent water depth by the measured snow depth.

Of the factors known to affect the density of snow, air temperature, wind speed, and humidity data are often available and could be used to predict snow density in the absence of manual measurements. The CSSL meteorological record includes hourly averages of each of these three variables. We assumed that the 0800 snow board depth and density were affected by the previous day's late afternoon and night weather (1700 to 0800 hours), and that the 1600 hour depth and density were influenced by the daytime weather (0900 to 1600 hours). On this basis, we calculated average air temperature, wind speed, and humidity values for the 16- or 8-hour period associated with each density measurement.

Regression equations were developed to predict density from the meteorological measurements by using both the entire data set and the 0800 data subset. We hypothesized that the night period represented by the 0800 subset would be less affected by post-deposition warm air temperatures and settlement than the values obtained at 1600 hours. Some outliers were identified, and under closer examination were found to be mixed rain and snow events or weekend snowfall that remained on the board through a daytime period. This information was eliminated from the data, and new regressions were estimated.

DENSITY AND TEMPERATURE RESULTS AND DISCUSSION

For a sample of 403 boards (including replications) over 3 years, the average density was 12 percent, or 120 kg m^{-3} (Table 1); and ranged from 2 to 32 percent. The 95 percent confidence interval around the mean was ± 0.50 percent. The standard deviation was 4.9 percent. Densities as high as 60 percent were encountered in the raw data, but they were eliminated because on-site visual observations classified the events as mixed rain and snow. The average air temperature at 1 m for all events was $-3.1^{\circ}C$. Snowfall was recorded at temperatures as high as $2.2^{\circ}C$. The average density of the 0800 subset of data observations (N=261) was 11.8 percent, only marginally different from the average of the complete data set. The confidence interval around the mean for the 0800 subset increased slightly to ± 0.53 percent as the standard deviation of the density declined to 4.4 percent, and the average air temperature fell to $-3.5^{\circ}C$.

Table 1. Average density and temperature for new snow during water years 1984-86 at the Central Sierra Snow Laboratory, Soda Springs, California.

Data Set	N	Density			Temperature	
		Mean	95% Conf. Int.	Range	Mean	Std. Dev.
		Percent			°C	
All	403	12.0	±0.48	2 - 32	-3.1	2.6
Night only	261	11.8	±0.53	2 - 27	-3.5	2.8

The differences in depths and densities between replicates was slight, showing that the measurement technique was consistent. The average difference in density for all board pairs was 0.13 percent (N=282). The snow depth differences were similarly small between the board pairs and averaged 0.12 cm (N=298). The small differences in depth and density are not surprising because the boards were fairly close to each other and the depths from each board were averages of four measurements.

While windspeed and humidity were thought to be density-controlling factors, both factors had such low correlations with density and added so little to the regressions that we dropped them from the analysis. Windspeeds are typically less than 2 m/s in the CSSL clearing, and humidity is typically close to 100 percent whenever snow is falling. Air temperature at 1 m above the snow was positively correlated with snow density (r=0.52), and while scatter is great, the trend toward increasing density with increasing temperature is evident (Figure 1).

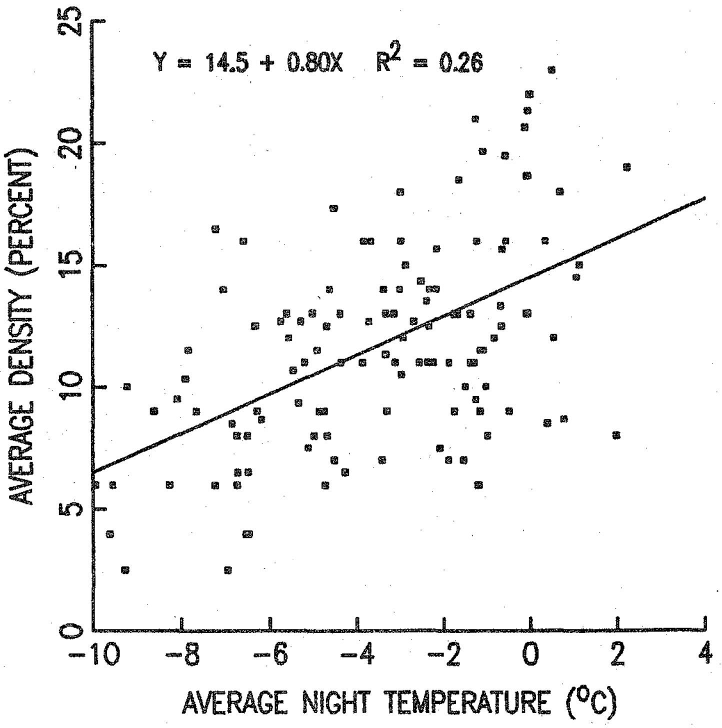

Figure 1. Scatterplot and regression line of night temperatures and average snow board densities in water years 1984-86 at the Central Sierra Snow Laboratory, Soda Springs, California.

To develop a predictive tool, we regressed density on temperature for both the complete and the night-only data set. The resultant equations and their fit statistics were:

All Data: Density = 14.9 + 0.96*Temperature $R^2 = 0.27$
Std. Error = 3.8 percent
Night: Density = 14.5 + 0.80*Temperature $R^2 = 0.26$
Std. Error = 3.7 percent

As is evident from the coefficient of determination (R^2) and the scatter in Figure 1, a range of snow densities can occur at any particular temperature. The poor regression fit and large standard error suggest that other factors must have a large effect on the observed density. While wind and humidity were found not to be important, it was hypothesized that upper air temperature might be a crucial factor since snow crystals are formed in the upper atmosphere. Diamond and Lowry (1953) used the 700 mb air temperature with density data from CSSL and found a correlation coefficient of 0.64, only slightly improved from the 0.52 found here. A flaw with their study was the use of upper air temperatures measured in Oakland, 240 km to the southwest of CSSL. Radiosonde data collected closer to CSSL might provide a better correlation. The use of local radiosonde data, however, decreases the utility of the predictive relationship due to the paucity of local upper air temperature measurements.

A coefficient of determination of 35 percent was achieved with the raw data set that included some mixed rain and snow events. The combination of the extreme densities associated with the rain-compacted events and the use of a polynomial (the square of air temperature) produced a better coefficient of determination. The average density was slightly less than 13 percent, about 1 percent higher than the final data set. It could be argued that removal of those points removed the type of precipitation that differentiates the Sierra Nevada from the Rocky Mountains. The purpose of this study, however, was to restrict the analysis to snowfall. Therefore, we deleted the data on mixed and rain-on-snow events from our analysis. If one wished to convert depth data collected at a National Weather Service station, a value even higher than 13 percent might be appropriate because of the greater occurrence of mixed rain and snow events at the lower elevations where such sites are usually found.

CONCLUSIONS

Research carried out at the Central Sierra Snow Laboratory confirmed the unsuitablity of the 10 percent density value for converting snowfall into snow water equivalent, or vice versa, at this site. For water years 1984 through 1986, new snow density averaged 12 percent (120 kg m^{-3}) -- a significant difference from the 10 percent value that is common in the literature. A regression equation relating air temperature to density was estimated, but the coefficient of determination was only 27 percent. Local upper air temperatures might be a better predictor of snow density than average surface air temperature.

REFERENCES

Bossolasco, M., 1954: Newly Fallen Snow and Air Temperature, Nature 174(4425):362-363.

Church, J.E., 1941: The Melting of Snow, Proceedings of the Central Snow Conference, 21-32 pp.

Diamond, M. and W.P. Lowry, 1954: Correlation of Density of New Snow with 700 mb Temperature, Journal of Meteorology 11(6): 512-513.

Goodison, B.E., H.L. Ferguson, and G.A. McKay, 1981: Measurement and Data Analysis, In Gray, D.M. and D.H. Male (eds.), Handbook of Snow, Pergamon Press, Toronto, 191-274 pp.

Grant, L.O. and J.O. Rhea, 1974: Elevation and Meteorological Controls on the Density of Snow Snow, In Santeford, H.S. and J.L. Smith (eds.), Advanced Concepts in the Study of Snow and Ice Resources, National Academy of Sciences, Washington, D.C., 169-181 pp.

Gray, D.M., D.I. Norum, and G.E. Dyck, 1970: Densities of Prairie Snowpacks, Proceedings of the 38th Western Snow Conference, 24-30 pp.

Henry, A.J., 1917: The Density of Snow, Monthly Weather Review 45:102-113.

Keeler, C.M., 1969: Some Physical Properties of Alpine Snow, Research Report 271, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., 70 p.

MacNeil, C.F. and A.D.J. O'Neill, 1977: Measurement of the Water Equivalent of Freshly Fallen Snow in Canada's Atlantic Provinces. Proceedings of the 34th Eastern Snow Conference, 118-129 pp.

Meister, R., 1986: Density of New Snow and Its Dependence on Air Temperature and Wind, Proceedings Workshop on the Correction of Precipitation Measurements, B. Sevruk (ed.), Eidgenossische Technische Hochschule Zurich, 73-80 pp.

Mellor, M., 1964: Properties of Snow, Monograph III-A1, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., 105 p.

Power, B.A., P.W. Summers, and J. D'Avignon, 1964: Snow Crystal Forms and Riming Effects as Related to Snowfall Density and General Storm Conditions, Journal of the Atmospheric Sciences 21(3):300-305.

Seligman, G., 1936: Snow Structure and Ski Fields, Macmillan and Company, London, 555 p.

Sevruk, B., 1986: Conversion of Snowfall Depths to Water Equivalents in the Swiss Alps, Proceedings Workshop on the Correction of Precipitation Measurements, B. Sevruk (Ed.), Eidgenossische Technische Hochschule Zurich, 81-88 pp.

Stashko, E.V., 1976: Water in Freshly-Fallen Snow, Proceedings of the 44th Western Snow Conference, 20-21 pp.

U.S. Army Corps of Engineers, 1956: Summary Report of the Snow Investigations: Snow Hydrology, North Pacific Division, Portland, OR, 437 p.

Wilson, W.T., 1955: The Density of New-Fallen Snow, Weekly Weather and Crop Bulletin 42(51):7.