STORAGE AND REDISTRIBUTION OF SNOW UPWIND OF AN AVALANCHE CATCHMENT

R. A. Schmidt and Hal Hartman

Abstract.—Checking fetch storage and computing evaporation from drifting snow can improve estimates of avalanche loading. Density of residual snow on a 600m fetch at Snowmass Ski Area in Colorado was 85% of the mean density in drifts of completely relocated snow with equal depth. Predicted winter evaporation is almost 20% of drifting from the fetch. This paper suggests a method for estimating sublimation from drifting during individual storms.

INTRODUCTION

Procedures that quantify the loading of avalanches by drifting snow increase the efficiency of snow safety programs. The objective of this paper is to examine adjustments to snowfall extrapolations from a mid-mountain study plot that may improve accuracy of these drift-loading computations.

Hartman (1984) describes a method of estimating the portion of snowfall relocated from an extensive alpine fetch into avalanche catchments during separate storm periods. Snowfall amounts, measured in a tree-sheltered study plot, are increased in proportion to elevation, to predict what would have fallen under calm conditions on the fetch—the area upwind of the catchment. Snow stakes, read in both fetch and catchment after each storm, measure the percentage of storm snowfall remaining on the fetch and the percentage of wind-relocated snow deposited in the catchments. Shallow pits are dug to determine density in the top 50 cm of snow on the fetch, and in the catchments when it is possible to do so safely.

Such measurements indicate avalanche loading from windblown snow may be as low as 6% of the water removed from the upwind fetch during some storms. Hartman suggests the large differences between computed drifting and measured loading may result from underestimated storage on the fetch, sublimation loss during transport, and transport beyond the catchment. The first two, fetch storage and sublimation loss, receive additional consideration in this paper.

FETCH STORAGE

Depth stake measurements on fetch areas offer speed of data input so essential to a timely, efficient snow safety program—speed lacking even with "hasty" pit measurements of density. Yet stake readings combined with such densities can still lead to errors in estimating fetch storage for individual storms. On windswept fetches, adequate sampling of erosion and deposition zones is critical, and snow settlement during a storm can also cause misleading measurements.

One way to check the snow stake procedure is to periodically compare the estimated residual from

Figure 1.—This photo of the western portion of Snowmass Ski Area, viewed from the north, shows the location of the 600m fetch transect that provided the snow depths in figure 2. Mean wind direction during drifting (245° mag.) is from the right, along the transect.


2R. A. Schmidt, USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. 80526.

3Hal Hartman, Snowmass Ski Area, Snowmass, Colo. 81615
storm computations with a more detailed measure of fetch storage. To demonstrate, a transect of snow depth at 20 m intervals across the fetch shown in figure 1 yielded the data plotted in figure 2. Full-depth pits at two locations on the transect, and at the Study Plot, provided density profiles also shown in figure 2.

The first question answered with these data was, "How much snow water-equivalent (WE) is stored on the fetch?" The analysis requires a relationship between depth and density of wind-drifted snow. For snow completely relocated and deposited behind snow fences or topographic catchments, density \((D, \text{ kg/m}^3)\) is well determined by

\[
D = 522 - (304/1.4852) [1 - \exp(-1.4852)]
\]

where \(Z\) is snow depth in meters (Tabler 1985). The function is plotted in figure 3, along with mean densities and snow depths for each pit. Average densities at the two pits in the fetch were approximately 85% of those expected in completely wind-deposited drifts of the same depth. Summing 0.85 times the density from equation (1), evaluated for the thirty depth readings on the fetch transect, gave a mean WE of 0.50 m on the 600 m upwind of the avalanche catchment.

Our next question was, "How does this estimated fetch storage compare with total precipitation estimated by extrapolation from the Study Plot?" The snowpack WE measured at the Study Plot (elevation 3170 m) was 0.45 m on 1 March (fig. 2). Using the precipitation-elevation increase (5.4% per 100 m) determined from previous studies at Snowmass, estimated WE for the fetch transect (at 3600 m) would be about 25% greater, or 0.56 m, suggesting that only 6 cm WE was relocated by wind.

Routine evaluation of equation (1), if facilitated by a programmable calculator, provides an easy check on fetch storage estimates that may justify calibrating such a function for a given fetch. The objective is to adjust the procedure by...
which precipitation and fetch storage are estimated, until the sum of storm storage estimates agrees closely with periodic checks of residual storage as described above. This procedure helps identify locations where additional drift contributions are coming from an unexpected source, or where a more complex precipitation-elevation relationship is required.

The amount of relocatable precipitation \( P \) over fetch distance \( R \) is again determined by subtracting fetch storage from estimated precipitation. Distance \( R_m \) is a conceptual variable, defined as the distance required for complete sublimation of an average-sized drift particle, under average conditions of temperature, humidity, and wind speed that exist on the fetch during drifting, over the entire winter season.

By its definition, \( R_m \) varies from fetch to fetch. Yet for a large number of fetches in southeast Wyoming, at elevations from 2200 to 2900m, the single value \( R_m = 3000m \) provided very good agreement between measured and estimated drift transport (Tabler 1975). Surprisingly similar values or \( R_m \) were reported by Benson (1982), for the Alaskan North Slope.

Given such agreement in these differing climates, equation (2) seems at least a starting point from which to estimate the sublimation loss from a fetch such as that in figure 1. Dividing by \( P \) in equation (2) gives the fraction of relocated precipitation that sublimates:

\[
\frac{Q_o}{(P \cdot R_c)} = 1 - \left( \frac{R_m}{2R_c} \right) [1 - 0.14 \left( \frac{R_c}{R_m} \right)] \tag{3}
\]

If the average conditions that give \( R_m = 3000m \) apply to the fetch in figure 1 (\( R = 500m \)), 18.7% of the drifting would evaporate during a winter (fig. 4).

Equations (2) and (3) estimate losses through sublimation over the winter season, while our interest here is primarily with the loss during individual storms or avalanche cycles. However, equation (2) is derived from examination of the physics involved, and it should apply to time periods as short as a storm, if the variable \( R_m \) could be adjusted to reflect storm conditions. Unfortunately, experimental verification has not been extended this far.

As an alternative, predictions using equation (3) with \( R_m = 3000m \) might be adjusted directly for humidity and temperature different from those averages thought to yield the 3km value. Intensive psychrometer measurements by Tabler, during drifting events in southeast Wyoming, gave 72% mean relative humidity when these measurements were weighted by drifting intensity (Tabler and Schmidt 1972). For the same winter, weighted mean temperature during drifting was -7.7C. These means (say, 75% RH and -8C) are assumed to approximate the values that yield \( R_m = 3000m \). Humidity and temperature are measured near the transected fetch (fig. 1) as part of the Snowmass snow safety program, so adjusting avalanche loading estimates for sublimation losses is possible. When humidity is at saturation (100%), \( Q_o/(P \cdot R_c) = 0 \). Losses increase to those predicted by equation (3) when humidity is approximately 75%. A proposed adjustment for humidity is \( 4[1-(RH/100)] \), a factor that varies from 4 to 0 as humidity increases from 0 to 100%. Figure 4 shows approximate percentages of drift lost through sublimation at humidities above and below 75%.
Because the evaporation loss predicted by equation (3) is expected to double for each 10°C increase in temperature during drifting (T less than 0°C), multiplying by $2^{[T - T_m]/10}$ yields a first approximation for temperatures differing from the mean $T_m = -8°C$. Both temperature and humidity adjustments are multiplicative, so either may be applied first to the values predicted for fetch distance $R_c$ under mean conditions (the center curve, Fig. 4).

![Figure 4](image)

**Figure 4.** The center curve is percentage of drifting snow that evaporates over fetch distance $R_c$, as predicted by equation (3) with $R_m = 3000m$ (Tabler 1975). These values are multiplied by $4[1 - (RH/100)]$ to approximate the effect of humidity (RH) different from 75%, and by $2^{(T - T_m)/10}$ when temperature during drifting (T, degrees C) is not equal to $T_m = -8°C$.

### SUMMARY

In examining factors that might improve estimates of avalanche loading by drifting snow, methods of accounting for snow storage on the fetch and for evaporation losses during transport have been suggested.

1. Periodic, detailed measures of snow on the fetch allow a check on storm computation. Equation (1) provides a functional form useful for this check, and may guide us to an improved procedure.

2. A 20% average loss through sublimation of drifting snow seems likely on the 600m fetch used as an example, and a range from 0 to 40% also seems reasonable for individual storms, using the suggested adjustment factors.

### LITERATURE CITED


