SNOWPACK METAMORPHOSIS AND ACCELERATED MELT RATES

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ABSTRACT

Numerous studies have been undertaken which observe the energy budget characteristics of melting snow covers. These investigations are normally based on measurements taken at snow research stations located in areas where deep, long-standing snowpacks can be expected to accrue most years. This paper will argue that the response of these snowpacks to the receipt of solar irradiance will be different from that encountered in more temperate environments. Moreover, changes in snowpack structure during melt episodes will alter the the surface albedo and result in an increased dominance of the radiative component of the energy budget. Such structural changes are not likely to be witnessed over shallow snowpacks; thus their melt rates and energy budgets will be dissimilar to those commonly encountered at snow research stations.

INTRODUCTION

The energy budget of melting snowpacks has received a considerable amount of attention over the years (e.g. Anderson, 1976; Granger and Male, 1978; and U.S. Army Corps of Engineers, 1956). These studies are usually based on direct measurement of the one-dimensional energy fluxes across the snow-air interface at well monitored snow research stations. These stations are typically located in high latitude or mountainous areas where deep, long-standing accumulations are likely to accrue each year. In general, absorbed solar radiation has been observed to be the dominant source of energy into the snow with sensible heat being a component of lesser importance. The existing research on snowpack energy balances has viewed the energy exchange at the surface as the result of current meteorological and solar irradiance conditions, or as the result of the displacement of one air mass by another (McKay and Thurtell, 1978).

This paper will argue that the energy budget and rate of ablation during a melt period will be influenced by previous episodes of accumulation and melt. Furthermore, the snowpack characteristics that influence the receipt of solar radiation will be dissimilar for regions that typically experience several distinct snowpacks during the winter and those that maintain a single continuous snow cover during most the accumulation season. Therefore, the conclusions derived from studies at

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the snow research stations should not be extrapolated to regions that characteristically experience shallow, short-lived accumulations.

SNOWPACK DENSIFICATION

Newly fallen snow typically has a surface albedo of about 0.90 but recrystallization quickly leads to a decrease in this value. As new layers are added to the existing cover, the albedo will again obtain high values. The addition of new snow to the existing cover not only affects the characteristics of the surface layer, but also influences the structure of the snowpack interior. In particular, compaction of the underlying layers occurs due to the weight of the additional mass. Furthermore, if an episode of partial melt occurs, some portion of the meltwater generated at the surface will be retained by the lower layers by capillarity or by refreezing upon contact with ice crystals at temperatures below 0 C. As the snowpack deepens with the addition of new snow, the degree of compaction and the availability of future meltwater increase. Thus, snowpacks that remain on the ground for a long period of time will have dense layers brought to the surface as the final melt episode occurs.

In contrast to the above scenario, some areas may experience intermittent snow covers which are melted away prior to subsequent snowfalls, and deep covers are not likely to accumulate. Under these conditions, the snowpack will have a low density throughout the ablation period.

The density of the surface layer at the time of melt exerts a major influence on the energy budget and the rate of ablation because of the inverse relationship between surface density and albedo. Dense surface layers, as should be found with melting snowcovers subject to meltwater retention and previous compaction, will likely have a greater sensitivity to the absorption of solar radiation and thus achieve greater melt rates than found in a shallow snowpack under identical meteorological conditions.

The influence of surface density on the albedo is commonly acknowledged, but little attention has been paid to determining a quantitative measure of this relationship. I have used published data from the Sleeper's River watershed near Danville, Vermont (NOAA, 1977a) for the melt seasons of 1968-69 and 1969-70 to obtain such a relationship. By regressing the albedo as a quadratic function of surface density I obtained

$$a = 0.82 - 2.3\rho^2 + 0.41\rho \quad (r^2 = .71),$$

where a is the albedo and ρ is the surface density in gm cm^{-3}. It should be noted that this function is obtained from data observed in the midmorning, and that the relationship will change slightly with differences in solar angle. Furthermore, the ratio of diffuse to total solar radiation was not taken into account. Nonetheless, the strength of the relationship is apparent, and the shortwave absorptivity can be expected to increase as denser layers are brought to the surface during melt. It should also be noted that a small absolute decrease in albedo can lead to a substantial relative increase in absorption (e.g., lowering the albedo from .80 to .75 results in a 25 percent increase in absorbed solar radiation).

Data from the Sleeper's River watershed can be used to illustrate the importance of the albedo changes as a deep snow cover was depleted through the melt season of 1969-70. The first day of melt coincided with an increase in surface density. There was an albedo reduction as well, from 0.75 to 0.69. The surface density and albedo changes were the direct result of a melt episode which accounted for the loss of approximately one centimeter of water equivalent. Throughout the remainder of the melt season, there was a trend toward decreasing albedo except when fresh snowfall was added to the surface. Table 1 compares the daily means and standard deviations for the 17-day pre-melt and melt periods prior to and following April 8. The table indicates that the average incident daily solar irradiation was not significantly different between the two periods, but the absorbed insolation was more than doubled due to the significant change in the absorptivity of the snow (1 - a). A similar pattern was exhibited for the majority of years for which data were provided.

Table 1 -- Comparison of values for the 17-day melt and pre-melt periods during the 1969-70 season at the Sleeper's River watershed.

	daily mean	stan. dev.	t-value
$(1-a)_{\text{pre-melt}}$	.175	.052	
$(1-a)_{\text{melt}}$	.375	.041	12.11
$Q_{S,\text{pre-melt}}$	13.01	6.85	
$Q_{S,\text{melt}}$	15.15	8.07	0.46
$[(1-a)Q_S]_{\text{pre-melt}}$	2.51	1.78	
$[(1-a)Q_S]_{\text{melt}}$	5.70	3.19	3.49

a = albedo and Q_S = solar irradiation [MJm^{-2}].

APPLICATION OF NUMERICAL MODEL

The descriptive model presented in this paper states that internal changes in snowpack structure will affect the sensitivity of the snow to solar irradiance when deep snowpacks are melting, and that these changes will not occur for shallow covers not subject to much compaction or meltwater retention. In order to fully examine this hypothesis, detailed observations of the density profiles of snow covers throughout their depths are required. Unfortunately, such observations are difficult to come by. To circumvent this problem, an existing numerical computer model was modified to accept meteorological and solar irradiance input data from easily obtainable SOLMET tapes (NOAA, 1977b) and hourly precipitation data from the Wisconsin State Climatologist Office. The model was then applied to twelve years (1952-53 to 1963-64) of hourly data for Madison, Wisconsin, and daily summaries of modeled snowpack temperature, density and water equivalents were produced as output.

The model used was the SNOWBAL program written by Eric Anderson (1976) to determine the energy and mass balances of snowpacks. Figure 1 presents a flowchart describing the main features of the program. The model treats the snowcover as a variable number of distinct layers of finite thickness, across which occur the transfer of energy, vapor and meltwater.

The main program of the model first calls for specific information regarding various run options, reads the appropriate hourly values into arrays containing input data for a complete month, converts the hourly data into averages for a time increment selected by the user, and sequentially calls subroutines which perform various calculations. The routine adds new layers to the snowcover as additional snowfall occurs, and eliminates layers as ablation procedes. It also calculates changes in the layer temperatures, water equivalents, liquid water contents, and densities for each time increment, and prints daily and annual summaries of the input or loss of heat into the snowpack for each of the energy balance components. The program was written in FORTRAN IV for use on a CDC 6600 computer, but can easily be adapted to use on other hardware by some minor alterations of the input/output commands.

Certain modifications of the program were required to make it usable for this study. For example, the data available were not obtained from a snow research station. Rather, standard meteorological data from the NWS weather station in Madison was used. As a result, necessary readings such as the snowpack albedo were not available and empirical relationships were used to provide surrogate input data.

MODEL RESULTS

Despite the use of some empirically obtained data, the predicted dates of melt for the Madison snowcovers corresponded closely to those observed by the Weather Service. Figure 2 plots predicted versus observed dates of final melt for snowpacks of at least one centimeter of water equivalent over the twelve year period. The number of melt events plotted on the figure is less than the total number of snow covers analyzed during the period. This discrepancy exists because in some cases the model calculated accumulation episodes separated by total melt, while the observed record indicated a trace of snow on the ground between the two accumulation periods. Thus, the model treated these accumulations as separate events while the daily data record listed them as a single continuous snowpack.

Fifty two snowpacks were analyzed for the period of study, accounting for 78 cm of water equivalent. Thus, there were over four episodes of snow on the ground each winter, on the average, in contrast to the long-standing continuous snowpack typical of many snow research stations. All but two of these snow covers represented water equivalents of less than five centimeters and were therefore not subject to significant densification.

The energy budgets during the days for which at least one millimeter of melt occurred were tallied for each individual cover. Of the fifty two snowpacks analyzed, forty one (79%) had sensible heat flux as the dominant positive energy budget component during melt while only eleven (21%)

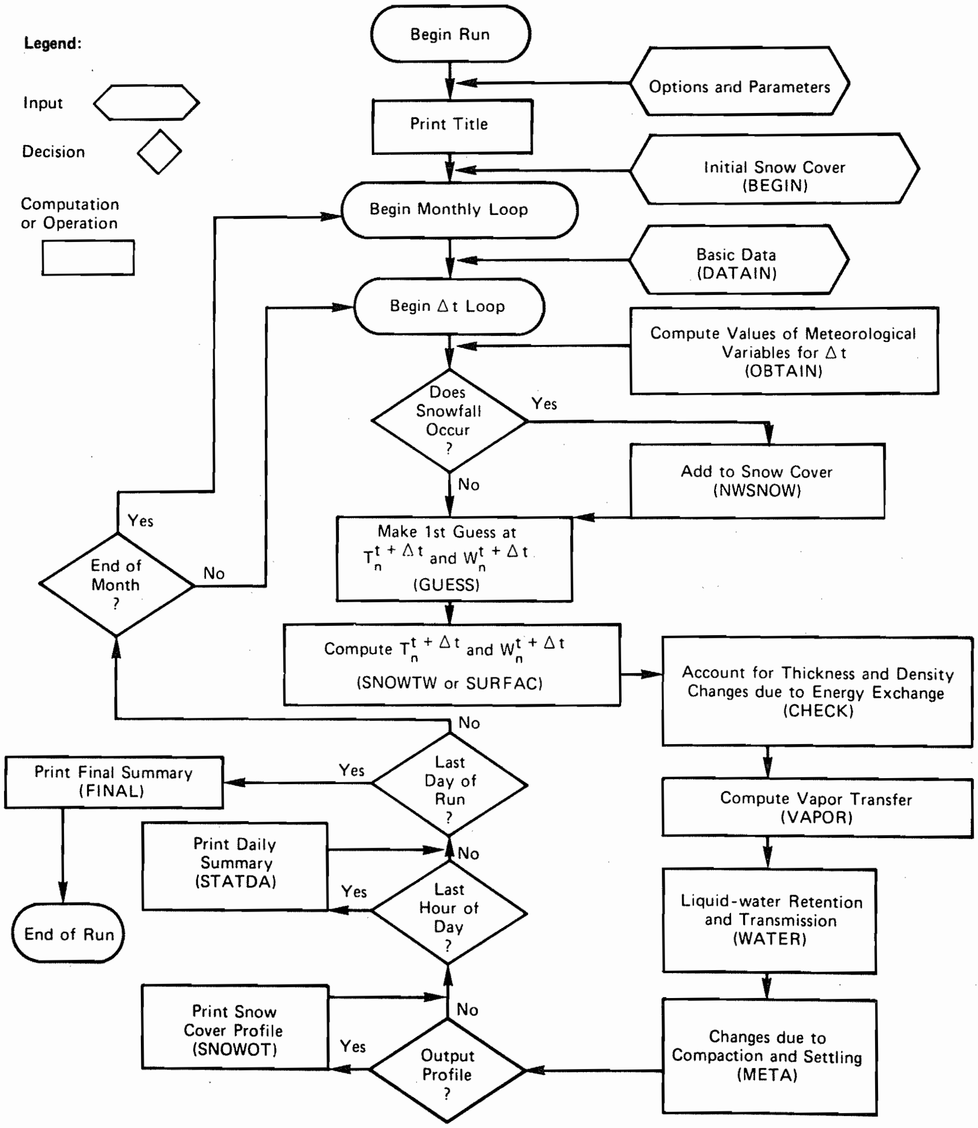

Figure 1. Flowchart of SNOWBAL program (from Anderson, 1976).

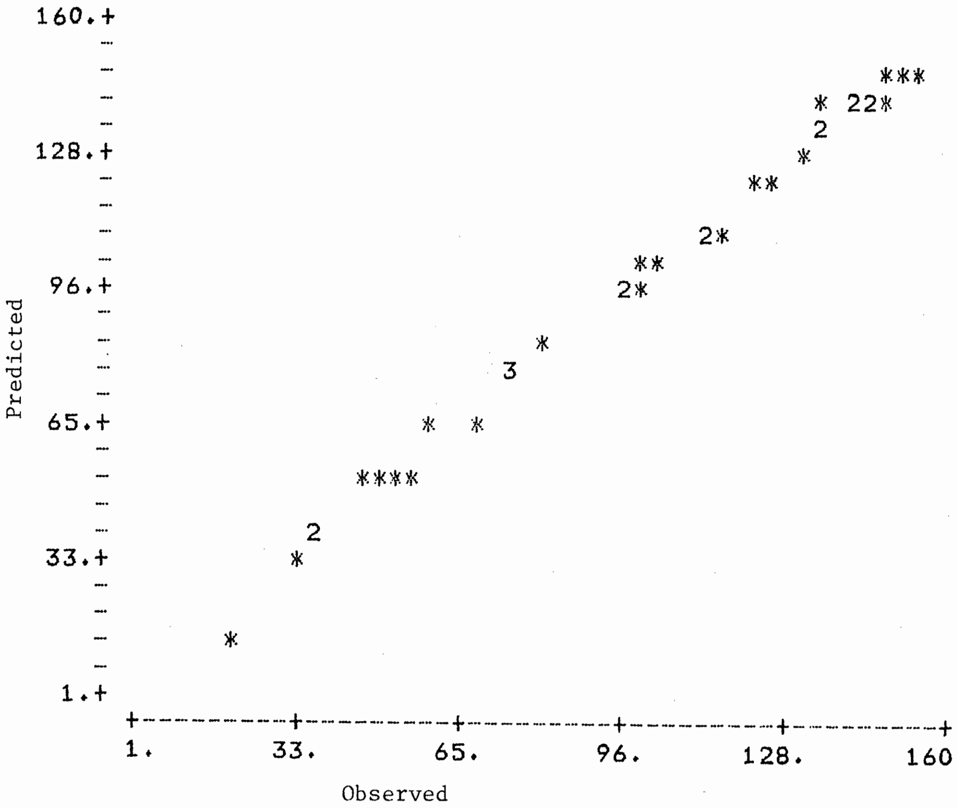

Figure 2. Predicted versus observed dates of melt (expressed as number of days since November 1).

responded mostly to absorbed solar irradiance, according to the model. For all the days in which melt occurred, absorbed solar irradiance accounted for 374 MJm^{-2}, or 85% of the 442 MJm^{-2} of sensible heat received. Net longwave radiation represented a loss of 531 MJm^{-2} from the melting snowpacks while latent heat transfer across the snow-air interface accounted for a relatively minor deficit of 58 MJm^{-2}. Heat transfer between the soil and snowpack was not examined because of the number of additional assumptions necessary for its inclusion. Other studies have shown this to be a component of relatively minor importance, however.

The dominance of sensible heat in the energy budgets is due partly to the density-albedo relationship described earlier. The seasonal availability of solar radiation also played a role in determining the receipt of insolation. Snowpacks which melt during the mid-winter are likely to be more strongly influenced by turbulent heat fluxes than those melting in the spring because of the lower sun angles and shorter periods of daylight. The effect of the density-albedo relationship can be demonstrated, however, using modeled output from the 1961-62 melt season for Madison.

The 1961-62 season witnessed the largest accumulation of snow for the twelve-year period of record with a maximum water equivalent of 7.3 centimeters on March 11. Slightly over twelve centimeters of snow fell during the period of continuous cover between mid-December and late March, with two episodes of significant partial melt occurring prior to the final melt event. The final melt episode occurred between March 11 and 23.

The period between mid-December and the onset of total melt was relatively invariant with regard to snowpack density (as calculated by the model). As 0.7 cm of water equivalent were added to the snowpack between January 5 and 7, there was a decrease in density from 0.25 to 0.19 gm cm^{-3}. Within two days, settling and compaction brought it back up to 0.21 gm cm^{-3}. A very gradual increase then ensued. By March 11, the first day of the final melt episode, the density attained a value of 0.28 gm cm^{-3}. By March 23, the overall density of the snowpack had increased to 0.42 gm cm^{-3}.

A more detailed description of the change in density through the accumulation and melt periods can be obtained from Figures 3 through 5, where each bar represents a layer of about one centimeter in thickness. Figure 3 presents a density profile of the snowcover as it existed at the end of the day on February 4, following an episode of partial melt. The density of the snowpack as a whole was 0.29 gm cm^{-3} although the majority of the layers were between 0.25 and 0.29 gm cm^{-3}. The unusually dense fifth layer originated on January 2 when it was at the surface, and apparently resulted from a partial melt which did not percolate down through the lower layers. The mean density of the top four layers was 0.26, compared to 0.29 gm cm^{-3} for the bottom five. The difference between these zones resulted partly from the retention of melt water percolating downward and partly from compaction.

Figure 4 illustrates the snow structure as it existed at the end of March 12, near the onset of the final melt episode. The upper four layers were accumulations from the previous 48 hours when 2.4 cm of precipitation fell as both snow and rain. There was an overall increase in density with depth, but the middle region is characterized by a decline in this parameter. This pattern appears to have originated on March 7 when above-freezing temperatures and moderate wind speeds led to minor melt yields at the surface which percolated only through the top few centimeters of the cover. Temperatures greater than 0 C occurred every day between March 7 and 12 but no water was released at the base of the

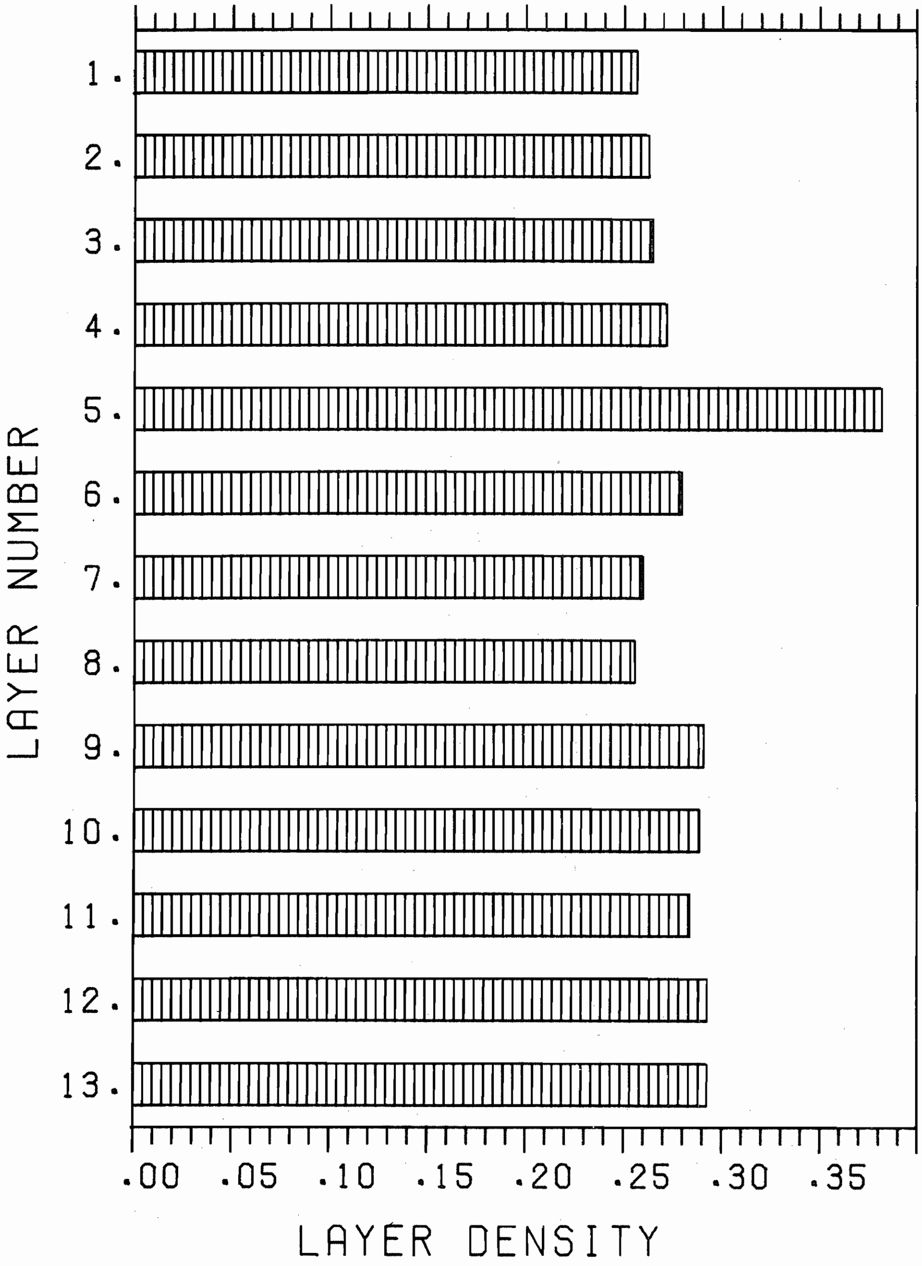

Figure 3. Snow structure on February 4, 1962.

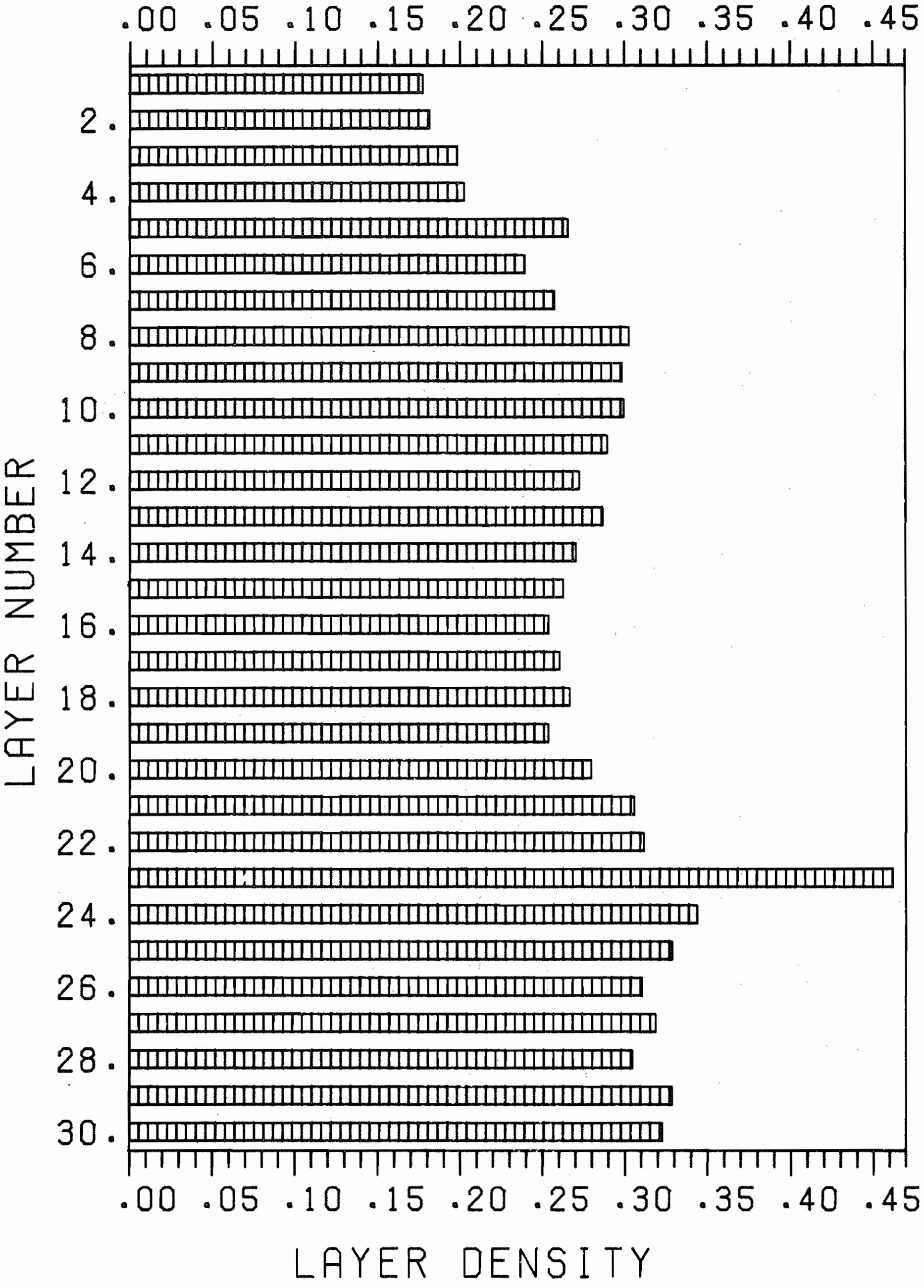

Figure 4. Snow structure on March 12, 1962.

pack until March 10. By this date, the division of the snow cover into three zones of different density had been well established.

By March 18 (Figure 5), 2.4 of the 7.0 cm of water equivalent existing six days earlier had been released. The snowpack became more homogeneous and compact with a total density of 0.36 gm cm^{-3} and a surface layer density of 0.37 gm cm^{-3}. The increase in density coinciding with further melt continued until the last day of snow on the ground when it reached 0.42 gm cm^{-3}.

The effect of density changes on the energy budget and melt rates can be demonstrated by comparing the days of March 17 and 22. On the earlier of the two days, a maximum temperature of 4 C along with a mean wind speed of 3.8 m sec^{-1} and a daily global irradiation of 18.9 MJm^{-2} combined to yield 0.60 cm of melt water equivalent. On March 22, 1.43 cm of water equivalent was melted although the maximum temperature (3 C), mean wind speed (2.9 m sec^{-1}) and solar irradiation (16.6 MJm^{-2}) were all less than they were on the seventeenth. This was clearly a response to the greater surface density following the five days of melt and a 38 percent increase in estimated shortwave absorptivity as the albedo went from 0.74 down to 0.64. At the same time, the ratio of absorbed solar irradiation to sensible heat transfer increased to 3.84 from 1.69.

CONCLUSION

A simple descriptive model has been presented and illustrated by the use of observed data from a snow research site and the application of a digital model to standard meteorolgical observations. The results indicate that the energy exchange into a melting snowpack is determined not only by the current meteorological conditions, but also by changes in snowpack structure as a response to prior episodes of accumulation and melt. Snow covers representing numerous accumulations throughout a season without intervening periods of total melt will be more sensitive to the absorption of solar radiation than those originating from snowfalls following the ablation of existing covers. Thus, they will melt faster and have a greater radiative component in the energy balance.

The results of this study have some practical applications. The accumulation of snowfall throughout a winter can represent an important resource, either as a major component in the water supply for a region, as in much of the western United States, or as a major source of revenue in areas where recreational activities are important to the local economy. Furthermore, the rapid ablation of deep snowpacks can result in serious flooding in many areas. It is therefore important that planners be able to predict the timing and rate of melt. Toward this end, temperature index models relating melt to easily obtainable meteorological variables have been developed by regression techniques. This study has isolated an additional variable that can be easily entered into such a regression equation and improve our ability to forecast melt events. Finally, the findings presented here demonstrate the problems inherent in extrapolating the results of snow laboratory studies to many areas of the United States and Canada where snowpacks may undergo several episodes of complete melt during the course of a snow season.

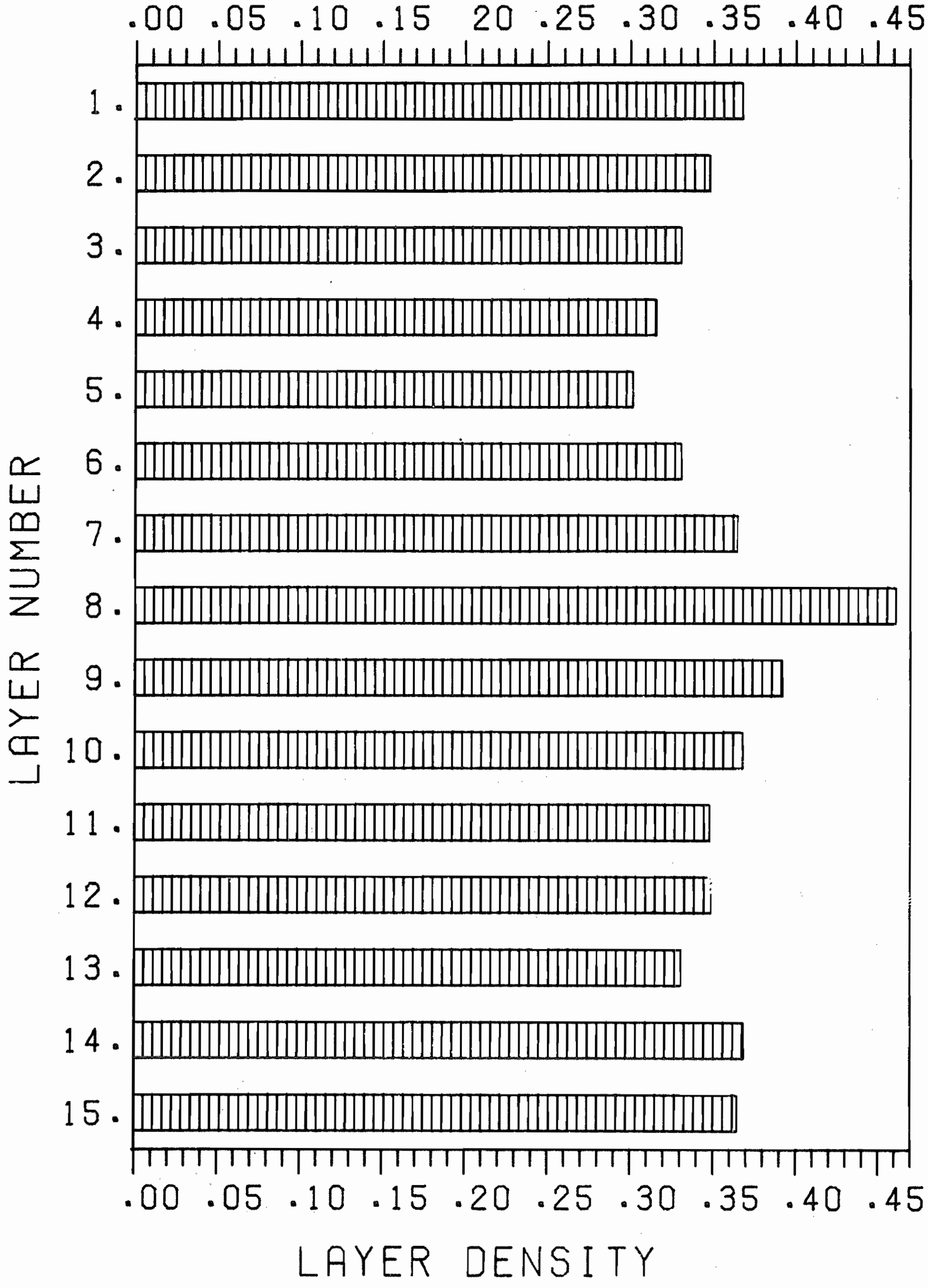

Figure 5. Snow structure on March 18, 1962.

REFERENCES

Anderson, E.A., 1976, A Point Energy and Mass Balance of a Snow Cover, NOAA Technical Report NWS 19, 150 p.

Granger, R.J. and D.H. Male, 1978, Melting of a Prairie Snowpack, Journal of Applied Meteorology, 17:1833-1842.

McKay, D.C. and G.W. Thurtell, 1978, Measurements of the Energy Fluxes Involved in the Energy Budget of a Snow Cover, Journal of Applied Meteorology, 17:339-349.

NOAA, 1977a, NOAA-ARS Cooperative Snow Research Project - Watershed Hydro-Climatology and Data for Water Years 1960-1974, Office of Hydrology, National Weather Service, Silver Spring, Maryland.

NOAA, 1977b, Solmet, Volume I - User's Manual TD-9724, Hourly Solar Radiation - Surface Meteorological Observations, National Climatic Center, Asheville, North Carolina.

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