Solar radiation penetration through snow

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ABSTRACT: Experimental evidence is presented which indicates that solar radiation penetration and the albedo of snow are coupled and strongly affected by the properties of a shallow "active layer" adjacent to the snow surface. Rapid extinction of solar radiation occurs in snowpacks shallower than this "active layer", whereas in deeper packs it proceeds at a slower rate. The albedo of snow is influenced by the underlying ground when the depth of the pack is less than the "active layer".

Results are in general agreement with the diffusion model of Giddings and LaChapelle. It was found, however, that this model underestimates the intensity of radiation reaching an absorbing surface which is located below the active layer.

INTRODUCTION

In regions with shallow snow cover, such as those encountered on the Prairies and in Canada's North, the amount of incident solar radiation which penetrates the pack may have special hydrologic significance. Shortwave radiation that penetrates to the snow-soil interface is largely absorbed. A portion of this absorbed energy may, in turn, be conducted and re-radiated as longwave radiation back to the snowpack, a condition which would accelerate the melt rate and the release of water by the pack. The residual part (probably the larger quantity) of the absorbed radiation is retained by the soil. This net gain of heat by radiative transfer processes to partially frozen or frozen soils is believed to be a major factor influencing the amount of water absorbed during snowmelt. The ability of a soil, when either partially frozen or frozen to absorb and transmit water will largely depend on the coupling of soil moisture migration and heat transfer processes. In other words, the greater the amount of heat available for increasing the temperature and thawing the soil, the greater its infiltration rate.
If the amount of energy available to the soil surface is appreciable, it is necessary that this component be considered in flood flow and water resource forecasting models. Under such conditions, it is highly questionable whether simple, standard "Temperature-Index" models can be applied successfully for prediction purposes.

This paper presents quantitative data on the penetration of solar energy through snow, obtained from experiments conducted at the University of Saskatchewan, Saskatoon, Canada.

ALBEDO MEASUREMENT

Theoretical work by a number of researchers has suggested that the extinction and reflection processes in snow may be coupled directly (Trainor [1]; Dunkle and Gier [2]; and Giddings and LaChapelle [3]). Experimental support for this coupling phenomenon is provided by Giddings and LaChapelle from measurements of the penetration of monochromatic radiation through a disaggregated snow sample. They suggested that albedo data may be used alone as an indirect means of accounting for the energy involved in the radiation penetration process. To the hydrologist, this concept has considerable appeal because albedo data are much simpler to acquire than penetration data.

THE DIFFUSION MODEL

Giddings and LaChapelle [3], assuming the energy transfer through snow to be analogous to a diffusion process, developed the following equations that define steady-state, monochromatic, short-wave radiation penetration through an isotropic snow of high albedo to a horizontal black surface of infinite extent at depth $x$.

$$
\alpha = \frac{1 - \frac{w}{2}}{1 + \frac{w}{2}}
$$

$$
\alpha_x = \frac{1 - \frac{w(1 - y)}{2}}{1 + \frac{w(1 - y)}{2}}
$$

where

$$
y = \frac{e^{-bx} [A + \frac{w(A - 1)}{2}]}{w(A - 1) \cosh bx - A \sinh bx}
$$

$$
\frac{I_x}{I_0} = \frac{\frac{w e^{-bx}(1 + \tanh bx)}{\left[1 + \frac{w}{2} \left[1 + \frac{e^{-bx}(1 - \frac{w}{2})}{\frac{w}{2} \cosh bx + \sinh bx}\right]\right]} (\frac{w}{2} + \tanh bx)}
$$

where

$\alpha = \text{the albedo of a semi-infinite snowpack},$

$\alpha_x = \text{the albedo of the snowpack when an absorbing surface (absorptivity A) is placed at a depth } x, \text{ below the snow surface},$

$w = \text{a dimensionless parameter which is related to snow density and crystal size},$

$b = \text{an extinction coefficient},$
\( I_o, I_x \) = the downward flux of radiation at the snow surface and at depth \( x \), respectively.

When the snowpack is so deep that the underlying surface is assumed to exert no influence on the radiation pattern at depth \( x \), the same theoretical development yields the expression;

\[
\frac{I_x}{I_o} = e^{-bx}
\]  

To apply the model (Equations (3) and (4)) to practical cases, the values of the relevant parameters, \( w \) and \( b \), must be experimentally determined for the multi-wavelength case for a given snowpack.

**EXPERIMENTAL**

In their paper, Giddings and LaChapelle suggested that, in accordance with Equation (3), realistic measurements of the downward radiation flux through snow may be obtained from readings taken by a small black "sensing head" inserted in a large black surface. Following their suggestion, a simple experimental apparatus was constructed for use in the current study (see Fig. 1). As illustrated in the figure, the snow sample was supported by a glass plate that rested on a beam radiometer and supporting "light-tight" box. Both radiometer and box were painted black. The operating characteristics of the beam radiometer are detailed in Table 1 and Figure 2.

**TABLE 1**

Beam Radiometer Design Characteristics

1. **Sensor:** United Detector Technology PIN-10 Photo-Diode.
2. **Field of View:** 18°.
3. **Response to Radiation Variations:** Linear.
4. **Sensor Wavelength Band Width:** 0.3 - 1.2 \( \mu \) (approximately).

In the testing program, a sample of natural snow was placed on the glass plate and measurements taken of the depth of the sample, the intensity of radiation penetrating to the radiometer, and the incident solar radiation. Adjustments were made to the measurements of radiation penetration to account for the transmission properties of the glass plate. Incident solar radiation was measured with standard Kipp and Zonen and Eppley pyranometers. Reflected radiation was also obtained by suspending the beam radiometer over the surface of another snow sample, which rested on a black metal plate (absorptivity = 0.96). The conventional and beam radiometers were matched carefully by inverting them simultaneously over a fresh uniform snow cover and measuring the reflected radiation. In this manner, a conversion factor was obtained which was used to relate the readings of the different sensors. Measurements were repeated with different depths of the snow samples.

Equation (4) requires a sensing device to be found that does not disturb the radiation field above it. Giddings and LaChapelle suggested matching the reflectivity of the sensor to that of the snow. This has been attempted by using 3-mm diameter glass fibre optics.
sensing heads as illustrated in Figure 3. The fibre optics can transmit radiation in approximately the wavelength interval 0.4 to 2.0 \( \mu \mbox{m} \) and are compatible with the PIN-5 photodiodes on which they are mounted.

Measurements of albedo and radiation penetration were made only on days with no significant cloud cover and were limited to the period within an hour of solar noon. These restrictions were aimed at providing stable radiation levels during the period of measurement and at minimizing the effects on the radiation components caused by solar angle variations.

RESULTS AND DISCUSSION

Radiation Penetration to an Absorbing Surface

Several tests were conducted during the winter of 1970-71. The results obtained from two tests, typical of those obtained in other trials, are plotted in Figures 4 - 7 inclusive. They show observations of albedo or downward radiative flux plotted as a function of depth for uniform snow samples. In Figures 5 and 7, the solid line represents the extinction pattern predicted by the Giddings and LaChapelle model (Equation (3)). The downward fluxes shown in the figures have been normalized to the value incident on the snow surface. The points plotted at depths of less than 1 cm should be accepted as approximate because of the difficulties in measuring the component fluxes at shallow snow depths.

Two features of the data are particularly evident:

1. An extremely rapid extinction of downward solar radiation when the sample depth is less than 2 cm followed by a transition to a slower, more uniform decay rate at greater depths.
2. The albedo of snow over an absorbing surface increases rapidly with an increase in depth of snow cover (within 1 - 2 cm) and appears to become independent of sample depth when the cover is greater than approximately 4 cm.

These observations are qualitatively in agreement with those reported by Giddings and LaChapelle [3] for the monochromatic case. They provide support for the concept that the extinction and reflection processes in snow are coupled. In addition, data confirm that the albedo of a snow surface is not purely a surface phenomenon, but that it depends on the scattering properties of an "active layer" which may extend a depth of several centimetres beneath the surface of the pack. The observations, therefore, support the concept that, in the field, the albedo of the underlying ground surface will influence the apparent albedo of the snow surface particularly when the depth of the snow cover is less than some critical value (in the case of the experimental results, 2 - 4 cm).

The data were also used to determine the validity of the diffusion model for predicting solar radiation penetration to an absorbing surface (Equation (3)). In these tests, the diffusion model was extended to the multi-wavelength case in a direct manner by assuming that simple average values of the coefficients apply over the wavelength band seen by the sensor. Observed albedo values were used with Equations (1) and (2) to determine the values of \( \omega \) and \( b \). Specifically, measured albedo values and corresponding snow depths were used in Equation (2) to yield trial and error solutions for the extinction coefficient \( b \). Small observational errors in the measured value of the snow depth associated with a given albedo exerted a
strong influence on the value of $b$ obtained. It was necessary, therefore, to extend the calculations over a number of depths to obtain a stable consistent value for the coefficient. Table 2 summarizes the values of the parameters obtained from the two experimental tests.

**TABLE 2**

Values of the Controlling Parameters of the Diffusion Model

<table>
<thead>
<tr>
<th>DATE</th>
<th>$a$</th>
<th>$w$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>28/3/71</td>
<td>.85</td>
<td>.1622</td>
<td>.42</td>
</tr>
<tr>
<td>4/4/71</td>
<td>.85</td>
<td>.1622</td>
<td>.43</td>
</tr>
</tbody>
</table>

Giddings and LaChapelle stressed the importance of snow crystal size in the extinction/reflection process. Crystal-size distribution for the snow samples used on 28/3/71, determined crudely by sieving (Abele [4]), is presented in Table 3. Similar data could not be obtained for samples tested on 4/4/71 as gradual snowmelt was taking place during the observations and the results obtained from the sieve analysis proved unusable. It was noted, however, that the snow was clean, fine-grained, and several days old.

**TABLE 3**

Snow Crystal Size Distribution by Weight - 28/3/71

<table>
<thead>
<tr>
<th>Grain Size (mm)</th>
<th>Per Cent by Weight Less Than</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>99.2</td>
</tr>
<tr>
<td>0.84</td>
<td>71.6</td>
</tr>
<tr>
<td>0.589</td>
<td>28.8</td>
</tr>
<tr>
<td>0.42</td>
<td>6.4</td>
</tr>
<tr>
<td>0.25</td>
<td>0.5</td>
</tr>
<tr>
<td>0.149</td>
<td>0</td>
</tr>
</tbody>
</table>

Insertion of the "wavelength-averaged" coefficients into Equation (3) yielded the predicted extinction curves that are superimposed on the experimental data plotted in Figures 5 and 7. The fit of the theoretical curves to the experimental data appears reasonably good through the "active layer" — that small layer immediately adjacent to the snow surface. At greater depths, however, the diffusion model, as applied, greatly underestimates the measured downward radiation flux. Careful examination of the data presented by Giddings and LaChapelle [3] revealed a similar tendency for the monochromatic case.

One surmises that the differences between the diffusion model and the experimental data may be largely attributed to certain restrictive assumptions underlying the development of the theoretical equations. Of particular concern is the concept that multi-wavelength radiative transfer in snow can be assumed to be a "random walk" process. This may or may not be realistic for the monochromatic case. In addition, the isotropic restriction imposed on the snow sample by the model is a severe one and whether or not such a condition prevails in natural snow may be questioned. It is suggested, therefore, that the underestimation in the results obtained from Equation (3) for the multi-wavelength situation at greater snow depths arises mainly from the fact that the extinction of radiation
in snow is wavelength dependent. Liljequist [5] supports this supposition, as he concluded that extremely rapid extinction of infrared wavelengths occurred within snow. Thus, incoming solar radiation would experience a rapid decrease in intensity immediately on entry into a snowpack, followed by a slower rate of decay as its spectral distribution narrowed to include only visible wavelengths. The simple averaging technique used in this study to determine the magnitudes of the pertinent parameters was incapable of accounting for wavelength dependent effects. In addition, the non-isotropic character of the snow samples probably also exerted an influence.

To develop a truly valid test of the diffusion model, measurements of the penetration of radiation of different wavelengths would be required. Utilizing such results, it may be possible to obtain integrated values of the parameters that may be used to predict extinction curves for the complete solar spectrum.

**Radiation within a Deep Natural Snowpack**

Data obtained from the fibre optics system are presented in Figure 8. It is evident from the figure that the observed radiation values fit the exponential decay model (Equation (4)) fairly well. As the data were obtained from measurements within undisturbed snow, departures from the model may be plausibly attributed to the natural layering of grain sizes within the pack. Simultaneous testing of Equations (3) and (4) on identical snow samples would provide a final evaluation of the compatibility of results from the two systems.

**PRACTICAL IMPLICATIONS OF OBSERVATIONAL RESULTS**

As stated previously, the primary objective of the study was concerned with the magnitude of the flux of solar radiation which penetrates a shallow snowpack to reach the underlying soil. For the tests conducted, estimates of the radiant energy reaching an absorbing surface at different depths were determined. These are presented in Table 4. In deriving these estimates, it was assumed that the extinction curves obtained from measurements in the wavelength interval 0.3 – 1.2 μ were representative of the total solar spectrum. This limitation was not considered to be serious as most of the energy in the solar spectrum (~75 per cent) falls within this wavelength band.

**TABLE 4**

<table>
<thead>
<tr>
<th>DATE</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>28/3/71</td>
<td>1.08</td>
<td>.45</td>
<td>.36</td>
<td>.15</td>
<td>.10</td>
<td>.06</td>
<td>.04</td>
</tr>
<tr>
<td>4/4/71</td>
<td>1.14</td>
<td>.46</td>
<td>.23</td>
<td>.12</td>
<td>.07</td>
<td>.05</td>
<td>.03</td>
</tr>
</tbody>
</table>

It can be noted from Table 4 that, at a depth of 1 cm, the radiative heat input to a black surface was measured in the range 25 – 30 ly/hr. For field situations, in which the natural soil would probably have an albedo of approximately 15 per cent, these quantities would not be greatly reduced. Similarly, with a depth of snow cover of 10 cm, the measurements indicate a possible radiative heat input to the soil in the order of 2 ly/hr near noon. That is, in percentage terms, approximately 40 per cent of the incident solar
radiation reached a surface at a depth of 1 cm and about 3 - 4 per cent reached a depth of 10 cm.

Some physical appreciation of the importance of the radiative flux as it may contribute to heating the soil may be obtained from the following simplified analysis. If it is assumed that all the heat is retained by the soil, an input of 30 lly would be equivalent to that required to thaw a 15 mm layer of frozen soil having a moisture content of 25 per cent by volume at a temperature near 0°C. Alternately, the same amount of heat input would be equivalent to that required to raise the temperature of 12 cm of soil having a specific heat of 0.5 cal/cm³/°C from -5°C to 0°C.

On the Prairies, where the depth of snowpack recedes fairly uniformly to shallow depths during the snowmelt period, it must be concluded that the energy exchange at the underlying surface may exert a pronounced effect on the total energy budget and consequently on the melting process. It may also be surmised that, as the snowpack ripens, the quantity of radiation that penetrates the pack will be increased. Weller [6] supports this inference with data which show that the extinction coefficient decreases as the grain size of the snow increases, as in a ripening pack. Thus, it is believed that the amount of radiation penetration through these shallow packs will have a pronounced effect both on the rate of melt release and the amount of water absorbed by the soil during the melt period.

**SUMMARY**

The results of these studies suggest:

1. The albedo and the extinction of solar radiation in snow are coupled and largely controlled by the properties of a thin "active layer" at the snow surface.
2. The albedo of a snow surface is independent of the depth of the pack provided the depth is greater than the thickness of the "active layer".
3. The simple diffusion model, which describes radiation penetration in snow when extended to the multi-wavelength situation, appears to seriously underestimate the solar radiation penetration to an absorbing surface below the active layer.
4. The radiative heat flux through snow during the melt season may be of significant magnitude for snowpack depths as great as 10 cm.

**ACKNOWLEDGMENTS**

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**REFERENCES**

Fig. 1. Schematic diagram of the experimental apparatus for measurement of the downward flux of solar radiation
Fig. 2. Spectral characteristics of PIN-10 and PIN-5 photodiodes (as supplied by manufacturer)
Fig. 3. Fibre optics radiation measuring system.

Fig. 4. Albedo of snow over a black plate, April 4, 1971. Snow density = 0.26
Fig. 5. Downward flux of solar radiation through snow, April 4, 1971
Fig. 6. Albedo of snow over a black plate, March 28, 1971. Snow density = 0.19
Fig. 7. Downward flux of solar radiation through snow, March 28, 1971
Fig. 8. Solar radiation penetration through undisturbed snow as measured by fibre optics system (relative units)

DISCUSSION

K.S. Davar (Canada) - The experimental results appear to be valid for homogeneous snow. It is well known that the snow structure varies with age (and depth). How would such variation of snow structure affect the model results?

A.D.J. O'Neill (Canada) - This paper used data from 1970-71. During 1971-72 we carried out more extensive tests and found that
for sufficiently uniform snow samples, of which we obtained three or four, the Giddings and LaChapelle model was excellent, even in the simple manner in which it was applied. The predicted extinction curves were much better than the ones just shown. However, where a snow sample which had the common layering with increasing crystal size with depth due to aging was involved, the model was poor and I think it is completely unrealistic to hope that it could handle variations in crystal size or in density with depth.

M.C. Quick (Canada) - It is my understanding that the red end of the spectrum gets absorbed first and the blue end penetrates farthest. Have you integrated the thermal energy reaching each layer, or do you intend to do so? Do you have data on the spectral distribution that could allow you to make this calculation?

A.D.J. O'Neill (Canada) - The literature certainly states that blue light penetrates to greater depths. I personally have done no work with spectrally broken-up light. These were rather simple tests using a sensor which was sensitive over quite a broad wavelength band.

M.R. de Quervain (Switzerland) - Albedo is usually taken as a number related to the structure of a given snow surface. I wonder to what extent albedo is affected by the direction of the incoming light, in particular sunlight. The reflectivity of a film crust is the extreme example of a highly directed reflection. But, on an actual snow surface, scattering of light may also be directed to a certain extent. Do your albedo measurements really include this directed component of the reflected light?

A.D.J. O'Neill (Canada) - We took all our measurements on clear days as close to solar noon as possible. During 1972 we did look at one or two cases where the snow had a surface ice crust and the model does not work very well when you have strong specular reflection. The model worked best with winter snow which was rather fresh with small crystal size and where the light reflection was somewhat diffuse.