RADIATION BALANCE AT OTTAWA DURING THE SNOW-MELT PERIOD

by
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ABSTRACT

Observations were made with two commercially available radiometers on the net radiation absorbed by an exposed snow surface during the snow-melt period at Ottawa, Ontario, Canada. Although a considerable difference was found between the net radiation recorded by the two instruments, no decision could be made as to their relative accuracy. Using the mean of the values of net radiation obtained for each observation period, the components of the energy balance at the surface were calculated. Although it was difficult to assess the accuracy of the estimates obtained for these components, these calculations indicated that evaporation during the observation periods was a large percentage of the net radiation, and amounted to between 20 to 25 per cent of the snow that was dissipated.

During 1959 and 1960, the Snow and Ice Section of the Division of Building Research, National Research Council of Canada, has been making observations on the radiation at various surfaces, including snow. The purpose of these observations has been two-fold: 1. to evaluate under field conditions various commercially available instruments for measuring net radiation, and 2. to determine the net radiation as one component of the total energy balance at the surface. The purpose of this paper is to explain some of the difficulties that were encountered in the use of two commercially available net radiometers, to compare observations made with them, and to present the components of the heat balance calculated from the observations made during the snow-melt period at Ottawa.

Net Radiation

Every body emits radiation in wavelengths which depend on its surface temperature. This paper is concerned with radiation in two wavelength bands which originate at surfaces in two very different temperature ranges. One of these is the radiating layer of the sun at an estimated temperature of about 6000° C. The radiated energy lies mostly in the wavelengths shorter than two microns. These are called short waves. Most terrestrial surfaces, including the ground, snow cover and clouds, are at temperatures ranging from about -40 to +40° C. Such surfaces radiate energy which lies mostly in the wavelength range from 5 to 50 microns. These are called long waves.

Snow, ice, water, and many dark coloured surfaces can be assumed to absorb most of the long-wave radiation that falls upon them. Dark surfaces also absorb most of the short-wave radiation that falls upon them, but light coloured surfaces such as clouds and snow reflect a large proportion of the short-wave

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*** Research Officer, Snow and Ice Section, Division of Building Research, National Research Council, Ottawa, Canada short-wave radiation. All transparent substances like glass transmit short-wave radiation, but only a few substances transmit long waves.

When short-wave radiation coming directly from the sun, or scattered by the sky, or reflected from clouds, strikes the natural ground cover, part of it is absorbed and part is reflected upward. Long-wave radiation is also emitted from moisture or clouds in the air and by the ground cover. The algebraic sum of all these upward and downward flows of radiant energy is called the net radiation.

Formulae are available for calculating separately the short- and long-wave components of the net radiation, for example, in Budyko (1) or in Johnson and Boyer (2). The equations for calculating the net long-wave component require observations on the air temperature and relative humidity. The equations for calculating the net short-wave radiation require measurement or calculation of the incoming radiation and a knowledge of the reflectivity or albedo of the snow. The proportion of the short-wave radiation reflected is highly variable It depends upon the condition of the surface. For example, fresh snow may reflect 95 per cent of the incident short-wave radiation, whereas a melting snow cover may reflect only 40 per cent. The proportion reflected will vary from day to day and even during the day (3). Because of the many assumptions that must be made to calculate net radiation of a snow surface, direct measurement is normally the most desirable way of estimating this quantity.

Instruments

The essential parts of the radiation instruments considered here are: (1) a horizontal, flat, black surface which will absorb the radiation falling on it; (2) a reference body, not exposed to the same radiation, or exposed differentl and (3) a thermopile to measure the temperature difference between the black surface and the reference body. Radiation falling on the black surface will increase its temperature in proportion to the radiant energy providing no othe influences affect the temperature. In the field, the wind speed has an important effect on the rate of heat loss and hence on the response of any such instrument. To minimize this influence, a transparent covering can be placed over the black surface, or a strong draft can be directed over the surface which will reduce the effect of changes in the natural wind. Examples of instruments which utilize the above principles in their construction are the Eppley pyrheliometer for measuring short-wave radiation and the Schulze, Beckman and Whitley and the CSIRO radiometers for measuring the net radiation.

The Eppley pyrheliometer uses a white or reflecting horizontal surface as a reference body and protects both the black and white surfaces by enclosing ther in a glass bulb. The instrument is sensitive only to short-wave radiation coming directly from the sun or reflected by dust or clouds. A second instrument mounted upside down would be needed to measure the short-wave radiation reflected from the ground or snow.

The Schulze net radiometer is essentially two instruments, one facing upward and one down. The reference body is a piece of aluminum shielded from radiation and hence ordinarily at about air temperature. The two black surfaces are protected by two hemispherical domes of polythene which are transparent for both long and short waves. This instrument can be used to measure either total incoming or total outgoing radiation or their difference which is the net radiation.

If only the net radiation is required then the instrument can be simplified by measuring the temperature difference between upward and downward facing black surfaces and hence obviating the necessity for a separate reference body. Such an instrument protected by polythene hemispheres was recently developed by the CSIRO in Australia (4) and is now available commercially.

The Beckman and Whitley net radiometer is another instrument using a single black plate exposed to both incoming and outgoing radiation. An electrically driven fan directs air horizontally across both the top and bottom of the plate to reduce the effects of the natural wind. Other instruments have been constructed using forced ventilation to minimize the effect of the wind, one of which is described in a paper by Suomi et al (5).

Calibration

None of these instruments gives an absolute measure of the radiation energy received. All of them have to be calibrated by being exposed to a known source of radiation or by comparison with other instruments that have been reliably calibrated. The Eppley pyrheliometer, which measures only short-wave radiation, is calibrated by the manufacturer to an accuracy that is probably better than that for a total net radiometer. It can, therefore, be considered in this work as a reliable standard for short-wave radiation.

The calibration factors for the net radiometers (if they are supplied by the manufacturer) are less reliable and should be checked. Since these instruments are to be used for both short- and long-wave radiation they should be checked in both wavelength ranges. In the short-wave range, they can be compared with an instrument such as the Eppley. This can be done on a clear day when the solar radiation is reasonably constant, by exposing both instruments in the open to the direct radiation from the sun and noting their readings. Both instruments should then be shaded from this direct radiation, keeping other conditions the same. The observed change in radiation measured by the net radiometer should be equal to that measured with the short-wave instrument.

In the long-wave range the instrument can be calibrated by mounting it in a box and exposing it to known but independent sources of long-wave radiation above and below the instrument. Such calibration boxes are described by MacDowall (6) and Funk (4) but were not available at the time of the observations reported in this paper.

A long-wave calibration factor for the Schulze radiometer was obtained by exposing the instrument, one side at a time, to the inside of a blackened cone kept at a known temperature. Under these conditions the long-wave radiation can be calculated and compared with the output of the radiometer. There is some question as to whether the temperature of the reference body will be improperly influenced by this procedure and hence the calibration factor obtained is not as reliable as one might wish.

It was found that the calibration constants for the two thermopiles of the Schulze radiometer were not the same. The sensitivity of the instrument to short-wave radiation was not the same as for long wave. As a result, it was not possible to measure the net radiation directly. It was necessary to separate the short- and long-wave components of the incoming and outgoing radiation. To do this accurately requires the measurement of the short-wave components of the radiation separately by using, for example, two Eppley instruments, one facing upward and the other down. Unfortunately, only observations on the incoming short wave were available. To separate the two components of the outgoing radiation it was necessary to assume a value for the albedo of the snow. The analysis of the observations required appreciable calculation time. Amback (3) had to use a similar procedure for analyzing observations made in the Antarctic with the same type of instrument. The experience demonstrated that this design of the Schulze radiometer is not convenient for routine observations in the field.

The Beckman and Whitley radiometer was calibrated by the manufacturer. This calibration was used in determining the net radiation during the spring thaw period. In the summer of 1960, the thermopile of the radiometer was repainted The calibration of the instrument for combined long and short waves was then checked in the field by placing it over a large metal plate whose surface had been painted with Parson's optical black paint. The plate was first cooled several degrees below air temperature before exposing it to incoming radiation The net radiation absorbed by this surface was then determined during periods when the radiation and wind speed were almost constant and the plate warmed up from a few degrees below the air temperature to a corresponding temperature above the air temperature. The plate should then have gained by convection just as much heat as it lost by convection. The measured change in heat content of the plate would be due to heat gain by radiation. The calibration constants obtained by this technique agreed to within 10% with that given by the manufacturer. Although this technique is simple and straightforward, further study is required to show that it is adequate for calibrating radiometers

No attempt was made to determine the effect of wind speed and direction on the calibration constant of the Beckman and Whitley radiometer. This effect can be appreciable. This and other factors which can affect the accuracy of the instrument are discussed in the paper by Suomi et al (5).

For the observations at Ottawa, the Schulze radiometer was mounted on a horizontal beam, 9 feet long, which could be rotated so that the instrument was over undisturbed snow. The instrument was between 12 and 24 inches above the snow cover and in such a position as to minimize the shadow effect. The Beckman and Whitley was mounted between 24 and 36 inches above the snow surface.

The scatter diagram in Figure 1 will give some idea of the accuracy of the net radiation observations from March 15 to 30, 1960. Each dot represents the net radiation in calories per square centimetre for one day as recorded by the two instruments. If the instruments agreed exactly then, of course all the dots would lie on the diagonal straight line. On the three days (28, 29, 30 March) when the net radiation was more than 180 cal per sq cm the agreement was reasonably good (12 per cent or less). On most of the other days the percentage difference was large because the radiation was very small.

Energy Balance at a Snow Surface

In spite of the inaccuracies and difficulties mentioned above, the net radiation measurements were used in estimating the energy balance at a snow surface during the spring snow-melt period. This energy balance, for the surface of the snow can be stated in the following simple form:

$$Q_r + Q_c + Q_e + Q_m + Q_s = 0$$

where Q_r is the net radiation and is positive when the net energy flows downward to the surface.

Q_c is the heat moved to the surface by convection and is positive when the air is warmer than the snow surface.

Q_e is the evaporative component. It is positive when heat is being supplied to the surface by condensation or deposition of frost and is negative when heat is being used for evaporation or sublimation.

Q_m is the heat that is used to melt the snow which does not evaporate. It is positive when heat is being supplied to the surface by freezing and is negative when heat is being used to melt snow.

TABLE I

Energy Balance Components at the Snow Surface

Period	Net Radiation Instrument	Solar Radiation, cal/cm^2	Q_r Net Rad, cal/cm^2	Q_c Conv, cal/cm^2	Q_e Evap, cal/cm^2	Q_m Melt, cal/cm^2	Q_s Cond, cal/cm^2	Evaporated or Sublimated, in. of water	Melted in. of water
1959									
Mar. 17-30	Schulze	5717	2305	785	-2290	-800	0	1.33	3.93
1960									
Mar. 14-20	Schulze		530	-20	- 385	-105	-20		
	B and W		330	-10	- 170	-130	-20		
	Mean	1879	430	-15	- 275	-120	-20	0.16	0.59
Mar. 20-26	Schulze		695	-265	- 430	0	0		
	B and W		340	-130	- 210	0	0		
	Mean	2696	520	-195	- 325	0	0	0.19	0
Mar. 26-31	Schulze		820	360	- 850	-330	0		
	B and W		735	280	- 655	-360	0		
	Mean	1853	780	320	- 755	-345	0	0.44	1.70
1960 Total									
Mar. 14-31		6428	1730	110	-1355	-465	-20	0.79	2.29
1961									
Jan. 1-15	B and W		-1150	$Q_c + Q_e$					
	CSIRO		-760						
	Mean		-955	1580		0	375		

Q_s is the heat conducted through the snow cover to the surface. It is positive when heat is flowing upward to the surface or when the surface is colder than the body of the snow.

Observations

The net radiation observed with the Schulze instrument during the snow-melt periods of 1959 and 1960 and with the Beckman and Whitley in 1960, are shown in Table I. Included for comparison purposes is the incoming short-wave or "Solar radiation obtained with an Eppley pyrheliometer.

Additional observations made during the snow-melt period allowed the complete energy balance to be determined. The values obtained for the various components are given in Table I. The technique used to obtain this balance is decribed in detail in a paper by Gold and Williams (7). Briefly, the amount of snow melted Q_m was obtained by measuring the changes in the total mass of the snow over the period analyzed. Combining this with the radiation observations allowed $Q_c + Q_e$ to be obtained from a solution of the energy balance equation. $Q_c + Q_e$ were then separated by assuming Bowen's ratio to be valid. The necessary air temperature and vapour pressure observations were part of the measurement program.

The observations for the spring of 1960 had to be terminated on 31 March when less than half of the snow cover had melted, because of the occurrence of rain. By 4 April, isolated snow and ice patches only were still present in the observation area.

Discussion

As shown in Table I, a large difference exists between the net radiation measured by the two instruments, particularly during the first two periods of observation in 1960. This difference is probably due in part to the inadequacy of the calibration methods and to factors associated with the construction of the instrument. Since there is no standard with which the instruments can be compared, it is impossible to say which observations are the more accurate. Experience has shown that both instruments are subject to errors that are difficult to correct for. For the points to be made in the ramainder of this discussion, an accurate value for the net radiation is not necessary, and so the mean of the Schulze and Beckman and Whitley observations will be used.

The observations contained in Table I illustrate certain facts concerning the energy balance at a snow cover. The incoming short-wave radiation was about the same in 1960 for the periods 14 to 20 March and 26 to 31 March. During the first period the net radiation is about 25 per cent of the incoming short wave and during the latter period over 40 per cent. The long-wave radiation loss should not be greatly different for the two periods. The increase in the net radiation was due largely to the decrease which occurs in the albedo of the surface when the snow ages and particularly when it becomes wet.

About two and one half inches of snow fell on 22 March. Following the snowfall, the air temperature did not rise above -5°C until 26 March. As a result, the albedo of the snow was likely quite high during this period. This would explain why the net radiation was only about 20 per cent of the incoming short-wave radiation. The incoming short-wave radiation for 20 to 26 March was about 45 per cent higher than for the other two periods.

During the snow-melt period the heat associated with evaporation or sublimation can be a large percentage of the net radiation, but since it requires about 675 calories to sublimate or melt and evaporate one gram of snow, and only 80 calo-

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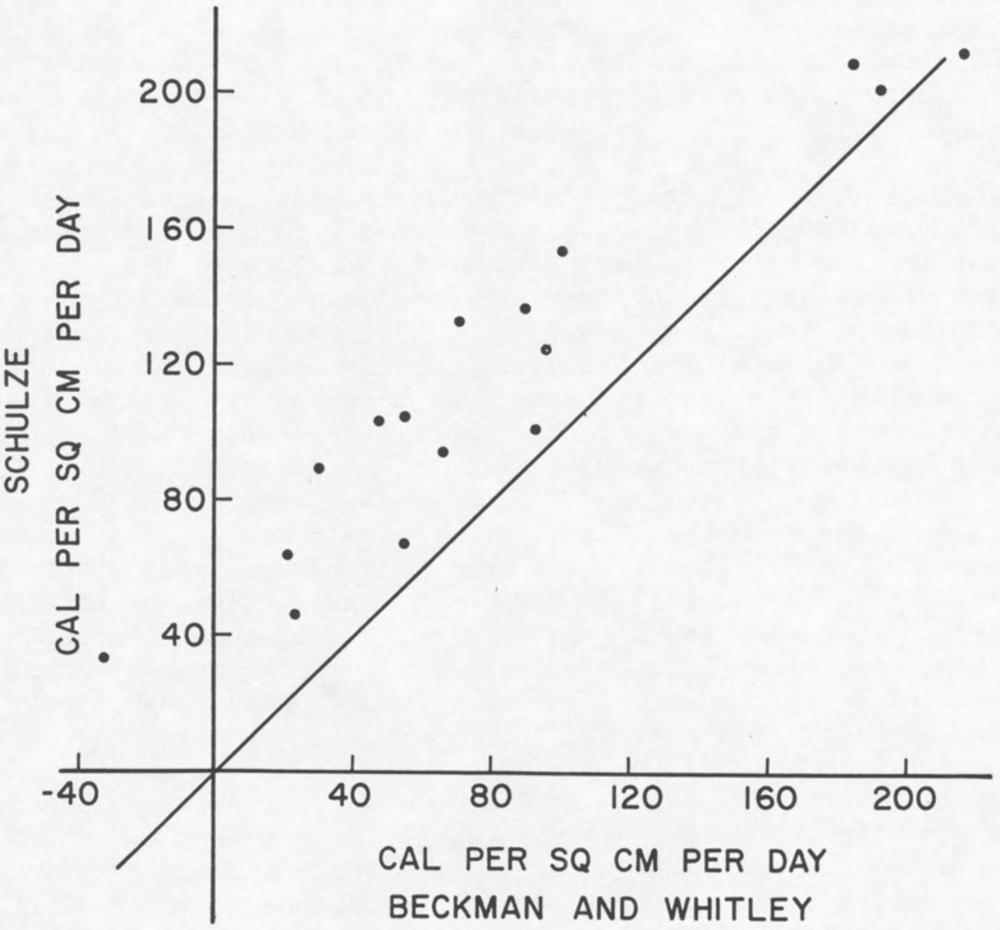

COMPARISON OF NET RADIOMETERS
MARCH 15-30, 1960

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ries to melt the same amount, the amount of water lost by evaporation or sublimation may be a relatively small proportion of the water equivalent of the snow cover. In Table I, evaporation or sublimation and snow melt are given in inches of water as well as in calories per square centimetre. If the net radiation is approximately correct, then about 25 per cent of the snow which disappeared during the observation periods in 1959 and 1960 was lost by evaporation or sublimation.

During the period 1 to 15 January 1961, further observations were made on the net radiation using the Beckman and Whitley and the Australian CSIRO instrument. It was found that the daily average was about -60 cal/cm^2/day, indicating that if the albedo of the surface is quite high at that time of the year when the incoming short-wave radiation is a minimum, the long-wave radiation loss can exceed the short-wave radiation gain. Earlier observations by Gold (8) show that the cooling ground would contribute to the surface about 25 cal/cm^2/day under the conditions which prevailed. This means that the average daily sum of $Q_c + Q_e$ for the period was about +35 cal/cm^2/day.

If sublimation occurred, therefore, the heat gain to the surface by convection must have exceeded about 35 cal/cm^2/day. In order for this convective heat gain to have occurred, the average temperature of the snow surface would have been about equal to the average frost point of the air with the result that sublimation would have been slight. If the snow surface temperature was below the frost point of the air, frost formation would have occurred. These observations indicate that the amount of snow lost by sublimation at exposed sites in the Ottawa area during the winter is probably small as compared with that lost by evaporation during the spring-melt period.

The snow cover in the Ottawa area is shallow, normally between 30 and 60 cm deep (12 to 24 inches) in the open. It begins to disappear when the mean air temperature is about 0°C. During the early stages of melting, there is a tendency for the snow to lose heat to the air by convection. As the snow-melt period progresses and the average air temperature increases, this tendency is reversed because the temperature of the snow surface cannot rise above 0°C. Since the cover is shallow, the snow would normally disappear before the convective term becomes the dominant quantity in the energy balance. If the cover is very deep so that the snow-melt period is prolonged, then advection of warm air into the region can have a very marked effect on the character of the snow dissipation. The convective component can become very large and the evaporative component will be suppressed or even reversed, that is condensation may occur. The same effect can occur with shallow covers under certain abnormal weather conditions. The very rapid dissipation of the snow after 31 March 1960, due to rainfall and subsequent warm weather is one example.

Since the observations reported in this paper were made in the open, the results can not be considered valid for forest conditions. Geiger (9) discusses the effect of trees on the radiation balance. Although trees will decrease considerably the amount of short-wave radiation reaching the snow surface, forests in general do absorb more of this radiation than a snow cover. This additional absorbed radiation will be utilized by transpiration from the trees and in raising the temperature within the forest cover. During the spring-melt period the increased temperature will favour convection and suppress evaporation, but the loss of moisture through transpiration may be significant. Miller (10) gives a good discussion of the effect of forest cover on the melting of snow based on observations made in California and Montana.

Because the ratio of the evaporation to the snow melt or the evaporation to net radiation differ considerably under differing weather conditions, it is impossible to generalize on this ratio from the present observations. If the relative amounts of evaporation and melt are to be determined (even approximately) then it is probable that all the observations necessary for estimating a complete heat balance at the snow surface must be made. The observations for the two winters in the Ottawa area suggest that, for the conditions which prevailed in the open during the snow-melt periods observed, the evaporative loss was between 75 and 100 per cent of the net radiation. It is interesting to note that the maximum calculated rate of evaporation was about 0.09 inch of water loss per day. This is about twice the maximum rate reported in the literature for evaporation during snow-melt periods (11).

SUMMARY

Observations of the net radiation were made with two commercially available radiometers over an exposed snow surface during the snow-melt period at Ottawa, Ontario, Canada. A considerable difference was found between the net radiation as determined with the two instruments. Since there was no standard with which the instruments could be compared, it was not possible to say which instrument was more accurate. Using the mean of the values obtained for each observation period, the importance of the albedo of the snow surface in determining the amount of energy available for melting and evaporating the snow was demonstrated. The components of the energy balance at the surface were calculated, again using the mean of the readings of the two instruments for the net radiation. This calculation showed that under the conditions which prevailed, the energy used for evaporation during the observation periods was not greatly different from the net radiation. The amount of snow evaporated was about 25 per cent of the snow that was dissipated. Since the convective heat loss can be a major component in the energy balance during the snow-melt period, it is impossible to draw conclusions regarding the relative magnitude of the evaporative, convective and snow-melt components from observations on net radiation and amount of snow dissipation only.

REFERENCES

(1) Budyko M. I. The heat balance of the earth's surface. Translation of "Teplovoi balans emnoi Poverkhnosti", Gidrometeorologicheskoe izdatel'stve, Leningrad 1956 by U. S. Dept. of Commerce 1958.

(2) Johnson O. A. and Boyer P. B. Application of snow hydrology to the Columbia Basin. Jour. of the Hydraulics Div., Proc. of the Amer. Soc. Civ. Eng. Vol. 85, No. HY1, Jan. 1959 p. 61-81.

(3) Ambach W. Investigations of the heat balance in the area of ablation on the Greenland Ice Cap. Archiv für Meteorologie, Geophysik und Bioklimatologie, 10 (3), 279-288, 1960.

(4) Funk, J. P. Improved polythene-shielded net radiometer. Jour. of Scientific Instruments. Vol. 36, No. 6, p. 267-270, June 1959.

(5) Suomi V. E., Matti Franssila, Islitzer N. F. An improved net-radiation instrument. Jour. of Meteor. Vol. 11, No. 4, p. 276-282, Aug. 1954.

(6) MacDowall J. Total-radiation fluxmeter. Meteorological Magazine, Vol. 84, No. 993, p. 65-71, Mar. 1955.

(7) Gold L. W. and Williams G. P. Energy balance during the snow melt period at an Ottawa site. International Assoc. for Scientific Hydrology, International Union of Geodesy and Geophysics, 12th General Assembly, Helsinki, Finland, 1960.

(8) Gold L. W. Influence of snow cover on heat flow from the ground. Int. Assoc. of Sci. Hydrol., Int. Union of Geod. and Geoph. 11th General

Assembly, Toronto, Canada, 4, p. 13-21, 1957.

(9) Geiger R. The climate near the ground. Harvard University Press, 1950.

(10) Miller D. H. Transmission of insolation through pine forest canopy, as it affects the melting snow. Mitteilungen der Schweizerische Anstalt für das forstliche Versuchswesen Bd. 35, Heft 1, p. 57-79, 1959.

(11) Williams G. P. Evaporation from snow covers in Eastern Canada. National Research Council, Division of Building Research, Research Paper no. 73, Ottawa, Jan. 1959. (NRC No. 5003)