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An estimate of ground heat flux for a seasonal snow cover

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सार — तापमान प्रवणता विधि का उपयोग करते हुए दो स्थानों की धरातलीय ऊष्मा अभिवाह का आकलन किया गया है। धरातल की प्रभावी तापीय संचालकता का पूर्वानुमान लगाने के लिए प्रभावी मीडिया दृष्टिकोण अपनाया है। तुलना के लिए, तापीय जाँच विधि द्वारा धरातल की प्रभावी तापीय संचालकता का यथा स्थान (इन सिटू) पर मापन भी किया गया है। मापी गई तापीय संचालकता इसके आकलित मानों के अनुरूप हैं। धरातलीय हिम अंतरापृष्ठ के पिघलाव की दर का मूल्यांकन करने के लिए धरातलीय ऊष्मा अभिवाह के आकलित मानों का उपयोग किया गया है।

ABSTRACT. An estimation of ground heat flux for two locations has been done using temperature gradient method. Effective media approach has been adopted for predicting the effective thermal conductivity of ground. For comparison, *in situ* measurement of effective thermal conductivity of ground has also been done by thermal probe method. The measured values of thermal conductivity are in agreement with the calculated values. The estimated values of ground heat flux have been used to evaluate the melt rate at ground-snow interface.

Key words— Ground heat flux, Effective thermal conductivity, Temperature gradient, Snow cover, Snow melt.

1. Introduction

The influence of daily totals of ground heat flux is negligible as compared to the radiation convective and latent heat fluxes over the same period. The total amount of snow melt produced by ground heat flux over short periods of time (less than a week) can be safely ignored. However, its cumulative effect can be significant over a season. This flux also influences the temperature regime of snow cover near the ground surface & contributes to the conditioning of the snowpack for melt. In areas where snow temperature regime is near freezing point, melt can be produced as a result of the ground flux. Although the amount of water produced may be small, but its resultant effect on the thermal properties & infiltration characteristics of underlying soil may be significant (Gold 1957). Ground heat flux also affects the state of soil (*i.e.* unfrozen or partially or completely frozen), which in turn affects the infiltration rate at the time of melt (Goodrich 1982). Thus, ground heat flux is an important component of energy balance.

2. Review of methods

One method to measure soil heat flux is to use a heat flux meter (Granger 1977), in which a thin plate is placed in the soil normal to the direction of heat flow. Only a single measurement of temperature difference across the plate is required. However, the flux meter interferes with both liquid & vapour movement in soil, which limits its usage. The meter requires calibration in the medium (Philip 1961). Horton & Wierenga (1983) found that separate *in situ* calibrations were required for each placement of the meter.

In temperature integral or calorimetric method (Lattau & Davidson 1957), soil heat is computed from the change in heat storage in the soil profile over a given time interval. This method requires determination of the soil volumetric heat capacity at several depths. The volumetric heat capacity is usually estimated from measurement of bulk density and water content using

$$Cv\ h = 0.46\varphi_m + 0.60\varphi_o + \varphi_w \qquad (1)$$

where φ_m, φ_o and φ_w are the volume fractions of minerals, organic matter & water, respectively. The number of measurements required for accurate determination of soil heat flux can be large.

The null alignment method to determine ground heat flux is based on measurements of temperature & volumetic heat capacity in the upper 20 cm or 30 cm of soil. This method combines the concept of the temperature gradient & temperature integral methods. The method includes a procedure for determining thermal conductivity at subsurface depth. However, soil heat flux by this method can be accurately determined only when temperature & volumetric heat capacity are determined at several depths. For example, Kimbell & Jackson (1975) measured soil temperature at 0.5 cm intervals upto 10 cm of depth and at intervals of 2 cm between 10 & 30 cm of depths.

Ideally speaking, methods for determining soil heat flux do not require calibration, do not interfere with moisture movement and require only a few convenient measurements at each time interval. In view of the points discussed above the temperature gradient method has been used. The purpose of this study is to estimate the ground heat flux by a method that requires observation of temperature and moisture near the surface.

3. Methodology adopted

The estimation of ground heat flux has been done using the temperature gradient method. From this method ground heat flux Q_g is computed using the effective thermal conductivity of soil λ_g, and the gradient of temperature T, with depth z, *i.e.*,

$$Q_g = -\lambda_g \left(\frac{dT}{dz}\right) \tag{2}$$

Both λ_g and dT/dz must be known where Q_g is desired. The temperature gradient at a specific depth below the surface can be evaluated numerically using values of temperature measured at closely spaced intervals at and near the surface depth. The value of λ_g can be either measured using needle probe method or can be estimated using expressions cited in the literature. Moisture content can be determined by gravimetric method or by using soil moisture meter. In the present study it has been determined using gravimetric method. For the determination of effective thermal conductivity, expression used in cited in Singh *et al.* [1990 (a)]. At the same time, *in situ* measurements of thermal conductivity of soil were also done using needle probe method which is a transient method in nature.

3.1. *Effective thermal conductivity of soil* — In the evolution of these equations it has been considered that dry soil is formed by introducing a small dispersion of solid or air in an effective continuous medium which is composed of equal volume fractions of solid and air phases. A further dispersion of third phase — water in the above defined dry soil evolves moist soil. A brief outline of the expression [Singh *et al.* 1990 (a)] used for the calculation of effective thermal conductivity of moist soil is as under:

The effective thermal conductivity of moist soil can be obtained from the expression

$$\lambda_g = \lambda_{ecm}\left[1 + 3.844\,\frac{\lambda_s - \lambda_{ecm}}{\lambda_s + 2\lambda_{ecm}}\,\xi_s^{2/3}\right] \tag{3}$$

where $\xi_s = \varphi_s - 0.5$ and λ_s is the thermal conductivity of solid soil. Here φ_s is volume fraction of solid soil. λ_{ecm} is thermal conductivity of effective continuous media which is defined as

$$\lambda_{ecm} = 1.092\,(\lambda_s \lambda_{ma})^{1/2} \tag{4}$$

where λ_{ma} is the thermal conductivity of moist air and is defined as

$$\lambda_{ma} = \lambda_a\left[1 + 3.844\,\frac{\lambda_w - \lambda_a}{\lambda_{ws} + 2\lambda_a}\,\varphi_{ma}^{2/3}\right]$$

$$\text{for } 0 < \varphi_{ma} < 0.5 \tag{5}$$

$$\lambda_{ma} = \lambda_w\left[1 + 3.844\,\frac{\lambda_a - \lambda_w}{\lambda_a + 2\lambda_w}\,(1 - \varphi_{ma})^{2/3}\right]$$

$$\text{for } 0.5 < \varphi_{ma} < 1.0 \tag{6}$$

where φ_{ma} is the volume fraction of water in soil with respect to air or degree of saturation. Here λ_a, λ_w and λ_s are the thermal conductivity of air, water and solid soil respectively.

3.2. *Thermal conductivity measurements* — In order to check the applicability of these expressions to present conditions, measurement of effective thermal conductivity of soil has been carried out by transient thermal probe method. The thermal probe technique is based on the rate of heating or cooling of the sample during the transient heating of a line

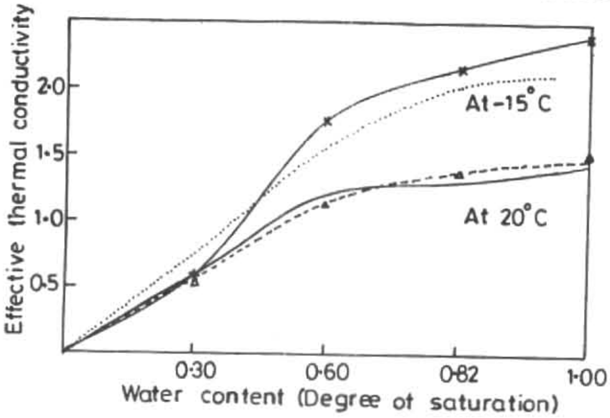

Fig.1. Comparison of measured (.....) and calculated values (—) of effective thermal conductivity with water content (degree of saturation) at two different temperatures

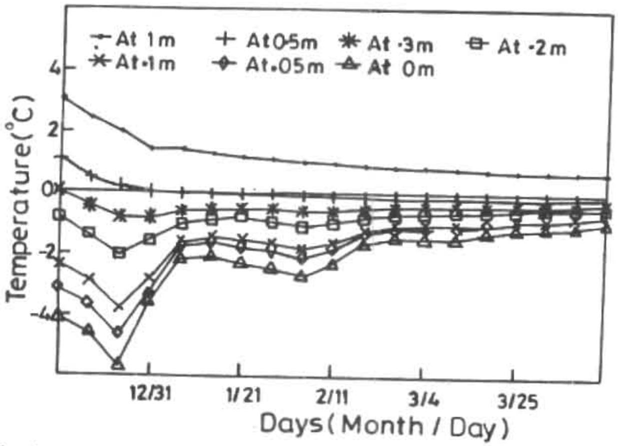

Fig. 3. Variation of weekly averaged ground temperature with days (month/day) at different depths from snow-soil interface, starting from December 10 for location 'B'

heat source embedded in the sample. The thermal probe consists of a helical heating coil and a copper-constantan thermocouple (temperature sensor). The temperature response changes depending upon the thermal properties of soil in which the thermal probe is placed. These probes were designed, developed and calibrated indigenously. The expression [Singh *et al.* 1990 (b)] used for the calculation of thermal conductivity of the soil is

$$\lambda g = \frac{Q}{4\pi L} \frac{\ln (t_2/t_1)}{(T_2 - T_1)} \qquad (7)$$

where T_1 & T_2 are temperatures at time t_1 & t_2 respectively, and Q is power per unit length(L) supplied to the probe heater. The obtained results were compared with the calculated values . Fig. 1 shows the comparison of measured and calculated values of effective thermal conductivity with water content in degree of saturation for two values of temperature under frozen and unfrozen state of ground. It was found that estimated values were in close agreement

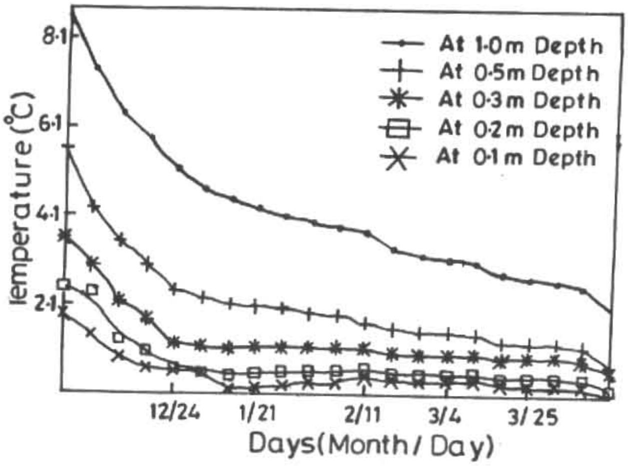

Fig. 2. Variation of weekly averaged ground temperatures with days (month/day) at different depths from snow-soil interface, starting from November 26 for location 'A'

with the measured values.

3.3. *Temperature measurements* — Soil temperatures were measured at several depths for two different locations—one was in Pir Panjal ranges (location A) and the other was in Great Himalayan ranges (location B). The temperature was measured using precision type linear thermistors which were embedded in the soil prior to the first snowfall. These temperature sensors were placed at depths of 0.00, 0.05, 0.10, 0.20, 0.30, 0.50 & 1.00 meter (total seven depths for observation) and were connected to data logging equipment (MTX trade name) which continuously scans the output of each sensor and stores the instantaneous values at each hour (Clock hour). Although the data logger continuously scans each channel at the rate of 4 sec but data is stored in the memory at hourly basis because of replacement of storage memory at remote location and difficulty in frequent retrieval. Then the daily and weekly average of the ground temperature data was taken. The data were collected from November to April *i.e.* for total duration of about six months, but presented for lesser period as relevant to the present study. The data logger used for the purpose was microprocessor based, rugged compact battery operated system which retrieves data from all the sensors, processes it and displays the same. Following were the main features of the data logger system.

(a) Display—Digital

(b) Data storage—250 MB

(c) Storage medium—Removable

(d) Operating range — −30 °C to + 40 °C

(e) Measuring speed—4 sec per channel

(f) No. of channel—selectable from 1 to 24

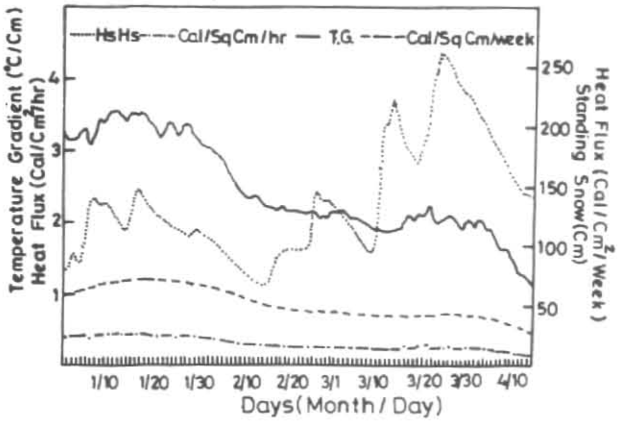

Fig.4. Variation of temperature gradients (T.G.) (—) and heat flux/hr (-●-) both on y_1 axis, heat flux per week (-----) and standing snow (HsHs) (....) both on y_2 axis with days (month/day) for location 'A'

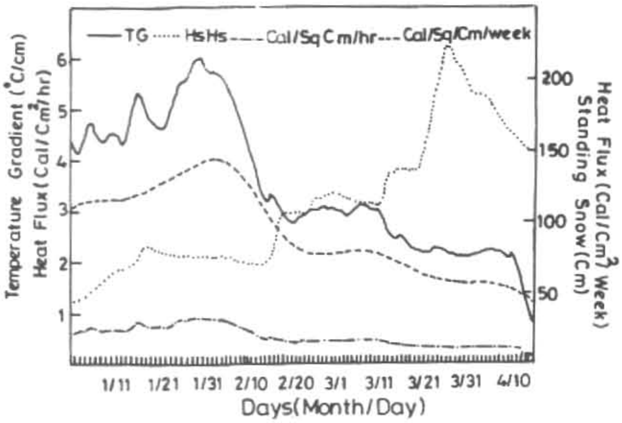

Fig.5. Variation of temperature gradients (T.G.) (—) and heat flux/hr (-●-) both on y_1 axis, heat flux per week (-----) and standing snow (HsHs) (....) both on y_2 axis with days (month/day) for location 'B'

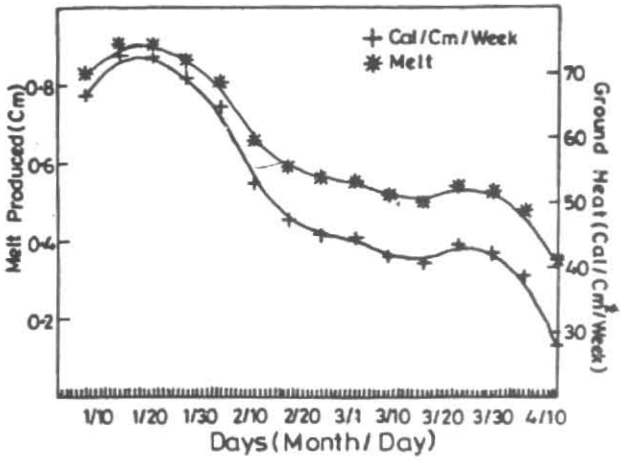

Fig .6. Variation of ground heat flux and melt produced with days (month/day) for location 'A'

Fig.7. Total weekly accumulated snow melt occurred during the season due to ground heat flux for location 'A'

(g) Compatible—PC/XT/AT

(h) Power supply—12 V DC

(i) Sensor—Linear thermistor having accuracy of ± 0.15 °C and resolution of 0.1 °C.

4. Results and discussion

The observed weekly averaged values of ground temperature profiles at different depths are presented in Figs. 2 & 3. In Fig. 2, weekly averaged temperature profiles with days, at various depths from snow-soil interface, are presented for location A. In this figure the temperature profiles at interface and at a depth of 0.05 m have not been shown because temperatures at these points are either 0 °C (especially at interface) or fluctuates about 0°C. It is evident from this figure that initially ground temperature were high and then there was a decrease because of the extraction of heat by snow.

Fig. 3 presents the variation of weekly averaged temperatures, at different depths from snow-soil interface, with days, starting from December 10 (the day snow fall occurred and got depleted, then again it occurred on December 31 and started building up) to April 15, for location B. Temperature profiles are shown at seven depths starting from snow-soil interface to a depth of 1.0 m. The downfall in temperatures at the interface & to subsequent depths upto 0.3 m, is mainly due to snow depletion that occurred on 9/10 December, and then ground got exposed to atmosphere. Since during January 20 to February 15, there was no appreciable snowfall so there was again a downfall in ground temperatures upto a depth of 0.2 m. This is due to penetration of diurnal wave through the snow cover. From the record of temperature at depth of 1.0 m, it is indicative that there is continuous inflow of heat from ground to snowpack.

In Figs. 2 & 3, temperature distribution after April 15 has not been shown, because snowpack becomes isothermal and shallow, due to which heat transfer wave may penetrate through the snow, and affect the temperature beneath the snowpack.

In Figs. 4 & 5, average temperature gradient and heat flux per hr (Y_1 axis) along with snow profile and heat flux per week (Y_2 axis) are presented for A and B locations, respectively. While calculating heat flux for A location the soil has been regarded as a single homogeneous layer in unfrozen state and for B location the soil has been considered to be made up of two distinct homogeneous layers with frozen and thawed regions of different thermal properties. To evaluate effective thermal conductivity of frozen and thawed regions, resistors approach has been applied. The effect of the variation of temperature and water content on effective thermal conductivity of soil at shallow depths has not been considered here. In both the cases soil was taken to be 85% saturated as was also found by observation at A location. These assumptions constitute a considerable idealization when compared with real snow conditions.

Fig. 6 presents weekly ground heat flux (Y_2 axis) and amount of melt produced (Y_1 axis) because of ground heat flux A location whereas Fig. 7 depicts the total accumulated snow melt that occurred due to ground heat flux at location A during the whole season. The snow melt calculations presented in these figures have been evaluated using latent heat equation. The total ground energy available at snow-soil interface has been utilized to produce melt since the snow near interface is at 0°C at location A. Melt produced has been presented in mm (height) by making use of density information available from weekly straitigraphy profiles, whereas at location B the total energy has been consumed in satisfying the cold content of snow.

5. Conclusion

The calculations presented here are primarily intended to illustrate the major features of snow-ground thermal interaction in general. The conclusions drawn are essentially qualitative. The results presented here can be useful in studying the effects of snow cover on long term, periodic, steady-state equilibrium ground temperatures, since in permafrost cases, mean annual ground temperatures are also extremely sensitive to the presence of snow cover. Due to the presence of snow cover the width of the maximum-minimum temperature becomes narrower over a period of time and mean temperature becomes closer to 0 °C.

The temperature profiles shown in Fig. 2 for location A, does not go below 0 °C at soil-snow interface, whereas for location B temperatures go below freezing point of water upto a depth of 0.3 m (may be after 0.3 m also, but not below 0.5 m) as can be seen from Fig.3. Thus another conclusion that can be drawn from this study is that temperature penetration is strongly related to ground heat flux and thermal properties of ground when snow cover is present.

This study clearly indicates that there is a continuous upward flux of heat from the underlying ground to the snowpack during winter & spring months which results from thermal energy stored in the ground during summer and early winter when no snow cover exists. During summer months, the ground surface is heated, primarily by solar radiation and as a result the thermal gradient is directed into the ground. Consequently, heat is conducted downwards into the ground, the amount being dependent upon the thermal gradient and conductivity of ground itself. The ground surface is suddenly cooled by early snowfall or cold air temperature, resulting in an upward gradient near the surface, while deeper in the soil, the gradient is still directed downwards. Further during winter, with snow on the ground, surface is cooled to 0 °C or below, and the thermal gradient remains directed upwards. This flux influences the temperature regime of snow near the ground and contributes to the preparation of snowpack for melt. Early in the season some of the heat conducted to the bottom of the snowpack is being consumed in repining the pack, without producing melt. This indicates that some of the heat is used to bring the bottom layer to 0°C and to saturate it to its maximum free water holding capacity.

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References

Granger, R.J., 1977, "Energy exchange during melt of a prairie snow cover", M. Sc. Thesis, Dept. of Mech. Engg., Univ. of Saskatchewan.

Gold, L.W., 1957, "Influence of snow cover on heat flow from ground, IUGG General Assembly, *Snow & Ice*, Vol. 4, IASH Publ., **44**, 13-21.

Goodrich, L.E., 1982, "The influence of snow cover on ground thermal regime," *Canadian Geotech. J.*, **19**, 421-432.

Horton, R. and Wierenga, P.J., 1983, "Determination of the mean soil temperature for evaluation of heat flux in soil," *Agric.Meteorol. Publication.*

Kimbell, B.A. and Jackson, R.D., 1975, "Soil heat flux determination : a null alignment method, " *Agric. Meterol.*, **15**, 1-9.

Leattau, H.L. and Davidson, B., 1957, "Exploring the atmosphere's first mile," Pergamon Press, Elmsford, N.Y.

Philip, J.R., 1957, "The theory of heat flux meters", *J. Geophys. Res.*, **66**, 571-579.

Singh, A.K., Singh, R. and Chaudhary, D.R., 1990(a), "Prediction of effective thermal conductivity of moist porous materials,"*J. Physics D: Applied Physics*, **23**, 698-702.

Singh, A.K., Singh, R. and Chaudhary, D.R., 1990(b), "Thermal conduction through frozen-unfrozen sandy soils- experimental results", Multiphase Transport & Particulate Phenomenon, Vol. 1, Hemisphere Publishing Corporation, USA, 75- 81.