# The Tundra Microclimate During Snow-Melt at Barrow, Alaska

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ABSTRACT. The microclimate of the tundra during spring of 1971 (29 May to 17 June) at Barrow, is described and analysed in terms of the heat balance at the terrestrial surface and the effects of terrain parameters on the heat balance components. Changes through the snow-melting period are large. Within 2 weeks 35 cm. of snow are removed, soil interface temperatures increase by 15°C. and the dry snow environment is replaced by a saturated water-soaked tundra surface. As a result, evaporation rates are high: up to 6 mm. day$^{-1}$ occurs immediately after the snow melt. The latent heat required for this is 40 times higher than during the pre-melting period.

RÉSUMÉ. *Microclimat de la toundra à la fonte des neiges, à Barrow, Alaska.* Les auteurs décrivent et analysent le microclimat de la toundra au printemps 1971 (29 mai au 17 juin) à Barrow, en termes de bilan thermique à la surface terrestre et d'effets des paramètres du terrain sur les composantes de ce bilan. Pendant toute cette période de fonte des neiges, les changements sont très grands. En deux semaines, l'ablation de la neige atteint 35 cm, les températures à la surface du sol montent de 15 degrés et le milieu de neige sèche est remplacé par une surface toundrique saturée d'eau. Ces changements impliquent des taux d'évaporation élevés, jusqu'à 6 mm$^{-1}$ par jour immédiatement après la fonte, ce qui demande une chaleur latente de 40 fois supérieure à celle de la période d'avant la fonte.

РЕЗЮМЕ. *Микроклимат тундры в районе Барроу (Аляска) в период снеготаяния.* Охарактеризован микроклимат тундры в районе Барроу по данным наблюдений весной (с 29 мая по 17 июня) 1971 г., и выполнен анализ теплового баланса земной поверхности, а также влияния характеристик последней на составляющие этото баланса. За период снеготаяния микроклиматические условия сильно изменились. Всего лишь за две недели снежный покров, имевший толщину 35 см, сошел, температура почвы повысилась на 15°С, и на месте поверхности сухого снега обнажилась насыщенная водой тундра. В результате этих изменений интенсивность испарения резко возрасла, достигнув 6 мм/сутки сразу после окончания таяния снега, а поглощение скрытой теплоты парообразования оказалось в 40 раз более высоким, чем до начала снеготаяния.

## INTRODUCTION

As part of the International Biological Program's (IBP) Tundra Biome project at Barrow, Alaska, the microclimatic regimes of that region are being investigated. This follows previous studies of a micrometeorological nature in the vicinity of Barrow by Mather and Thornthwaite (1956), Weaver (1965), Kelley and Weaver (1969) and others. The Tundra Biome's intensive study site is situated on the open tundra approximately 3 km. inland from Barrow at 71°18′ N., 156°41′ W., and is characterized by low-polygonal patterned ground, with occasional regions of high polygons, and a water-saturated surface with numerous

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puddles and ponds, typical of the Barrow region throughout summer. Permafrost beneath the site is continuous down to 400 m. according to Brewer (1958).

Micrometeorological observations have been carried out at this site by the University of Alaska since May 1970 (International Biological Program 1970). The instrumentation used for this purpose consists of a 16 metre-high tower with wind speed and direction, and temperature sensors at 0.5, 1, 2, 4, 8 and 16 metres height above the tundra surface. Soil temperatures were measured with thermocouples, at 0, 2, 4, 6, 8, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 400 and 600 cm. depth below the surface, snow temperatures at 5 cm. vertical spacings from the surface. A rigid wire frame kept the snow temperature sensors at fixed vertical levels, even when high snow accumulation occurred. Incoming and reflected short-wave radiation were measured with Eppley precision pyrheliometers; net all-wave radiation with a CSIRO net radiometer. Light extinction in the snow was investigated, using small selenium photocells. Recently Cambridge dew-point sensors have also been added to the tower. A standard Class A evaporation pan was read once daily, all other data were recorded automatically every 30 minutes on punched paper tape by a data acquisition system employing a high-resolution Hewlett-Packard digital voltmeter. From these measurements an energy balance of the terrestrial surface can be synthesized, and the microclimatic regime of the near-surface layer can be expressed in terms of the energy balance. The results presented here are for the period 28 May to 19 June 1971, covering the entire time of spring snow-melting at Barrow. The snow break-up in the northern parts of Alaska is usually rapid and, as demonstrated below, is accompanied by rather startling changes in the microclimatic regimes of the near-surface.

## GENERAL MICROCLIMATE PATTERN DURING SPRING

The average snow depth at the IBP site on 28 May 1971 was 38 cm., approaching the annual maximum of approximately 44 cm. There was no snow melting before 28 May. The general relationship between snow ablation and soil and air temperatures is presented in Fig. 1. Soil temperature at 2 cm. depth and air temperature at 2 m. height are shown. Some minor melting began on 1 June when the air temperature at 2 m. height rose to $-0.5°$C. and was accelerated on 4 June when air temperatures exceeded 0°C. Within 13 days from first melt the complete snow pack had disappeared. Vigorous melting from 4 June converted the 8°C. temperature gradient across the snow pack to near-isothermal conditions due to percolation and heat conduction within 2 to 3 days. This is shown in Fig. 1 by the steep rise in the soil temperature at a depth of 2 cm. during that period. Snow-free patches of tundra began to appear during the mid-phases of melting and generally centred on knolls and tufts of high vegetation. These bare features absorb solar radiation and heat up quickly to 10°C. above the temperature of surrounding snow-covered terrain (See Fig. 1 for 15 to 19 June). Small-scale heat advection from bare tundra to the remaining snow then accelerates the melting process. With complete disappearance of the snow cover, a greater amount of solar energy is absorbed by the tundra surface, thus more heat is made available for heating the air. The startling changes that take place

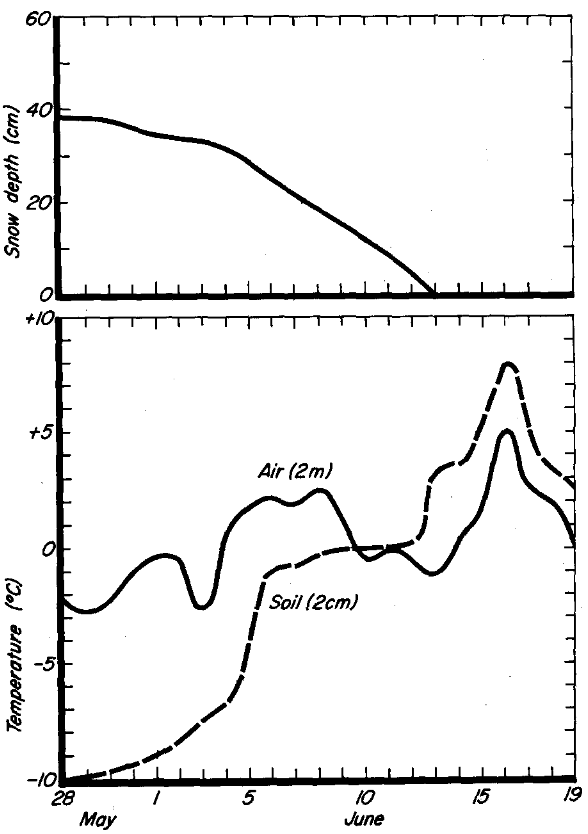


FIG. 1. Effect of snow cover on air and soil temperatures. (Daily mean values).

in the microclimatic regime of the near-surface layer within two weeks are illustrated in Fig. 2. An organism living in the soil close to the surface experiences an environmental temperature increase of 15 degrees C. The formerly dry snow environment will be replaced by a saturated water-soaked tundra surface. Finally light intensities at the interface will be increased by 2 orders of magnitude, because only 1 per cent of the incident light at the upper snow boundary was found to reach the soil interface. The steep temperature gradients in the top 10 cm. of the soil (Fig. 2) reflect the low thermal conductivity of $0.28\text{x}10^{-3}$ cal. gm.$^{-1}$deg.$^{-1}$ sec.$^{-1}$ of that layer which is composed of organic materials, as compared with the lower strata of inorganic soils with a thermal conductivity of $2.2\text{x}10^{-3}$ cal. gm.$^{-1}$ deg.$^{-1}$ sec.$^{-1}$, both values having been measured previously (International Biological Program 1970).

## SPECIFIC EFFECTS BY TERRAIN PARAMETERS

The physical nature of the terrain under investigation obviously affects the exchange of energy at its surface, and hence the microclimate. One obviously important terrain parameter is the albedo of the surface. Fig. 3 shows typically how it can affect air temperature. Diurnal variations of global (short-wave incoming) and net radiation and air temperature are shown for typical, partly-

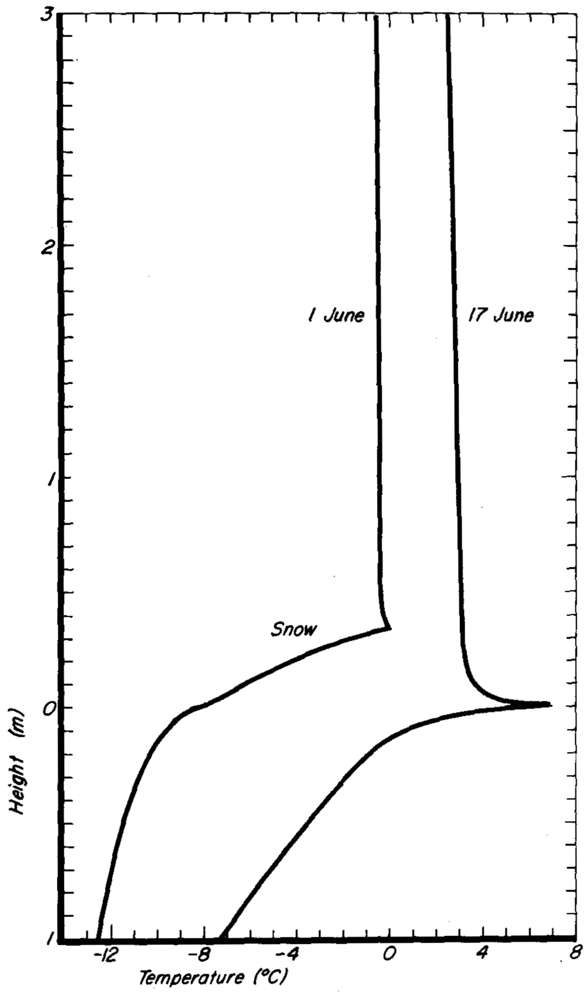


FIG. 2. Vertical profiles of temperatures before and after snow-melt. (Daily mean values)

cloudy days at Barrow: one with, the other without a snow cover on the surface. The albedo of the snow-covered surface is approximately 82 per cent, that of the bare tundra 17 per cent. About equal amounts of solar energy are incident on the surface on both days (top diagram, Fig. 3 shows approximately equal areas under the 2 curves) net all-wave, i.e., available radiation energy for conversion into sensible or latent heats, is shown to be quite different for the 2 days (centre diagram). Very little energy is available on the day when the snow cover is present, since most of it is reflected back into space. The opposite is true when the snow has disappeared and the tundra absorbs more solar energy. As a consequence the diurnal variation in air temperature on the snow-free day shows fluctuations which are similar to those of the available energy. When snow is on the ground little correlation exists as shown in the lower part of Fig. 3, although a temperature increase does appear to occur around noon which would have to be interpreted in terms of the total energy balance. This simple example serves

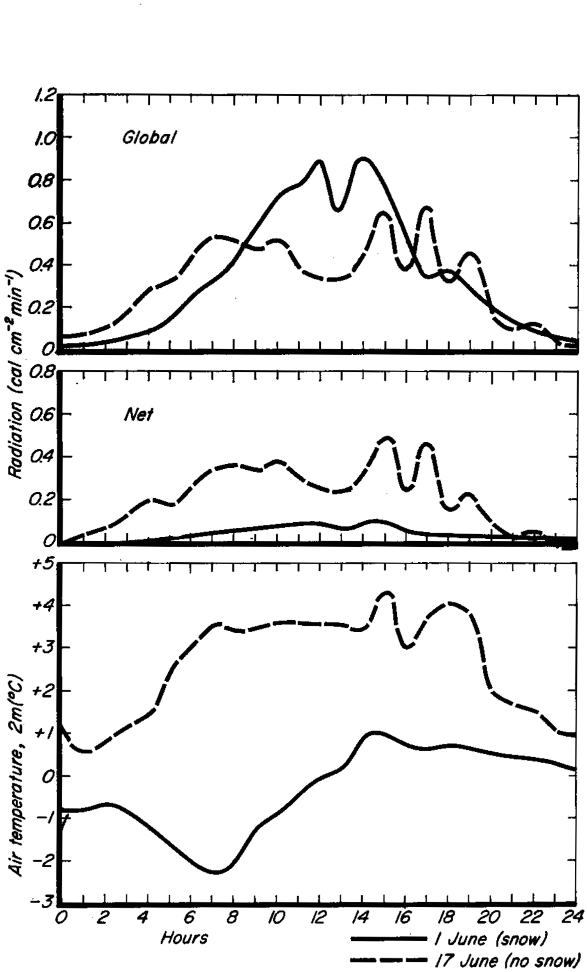


FIG. 3. Effect of radiation on diurnal air temperature before and after snow-melt.

to demonstrate the pronounced differences in response which the terrain characteristics can introduce into the energy balance, and the relatively simple nature of the observations which are necessary to illustrate these responses. The complete change of albedo from snow to tundra vegetation is documented in Fig. 4.

Another important terrain parameter is the physical roughness of the surface. This roughness can be parameterized by the aerodynamic roughness length $z_o$, defined under adiabatic neutral stability conditions of the atmospheric layer by

$$\ln \frac{z}{z_o} = \frac{uk}{u^*} \qquad \text{———(1)}$$

where u indicates wind speed at height z, u* the slope of wind profiles increasing logarithmically with height, called the friction velocity, k is von Karman's constant (0.428). From measurements of u at various heights z, $z_o$ and u* can be obtained.

Changes in $z_o$ under neutral conditions as the snow melts are shown in the lower diagram in Fig. 4. Smooth snow has a $z_o$ value of 0.01 cm. When melting begins the roughness value increases to about 0.3 to 0.4 cm. because of changes in the relief of the snow surface. The $z_o$ value increases slowly with the disap-

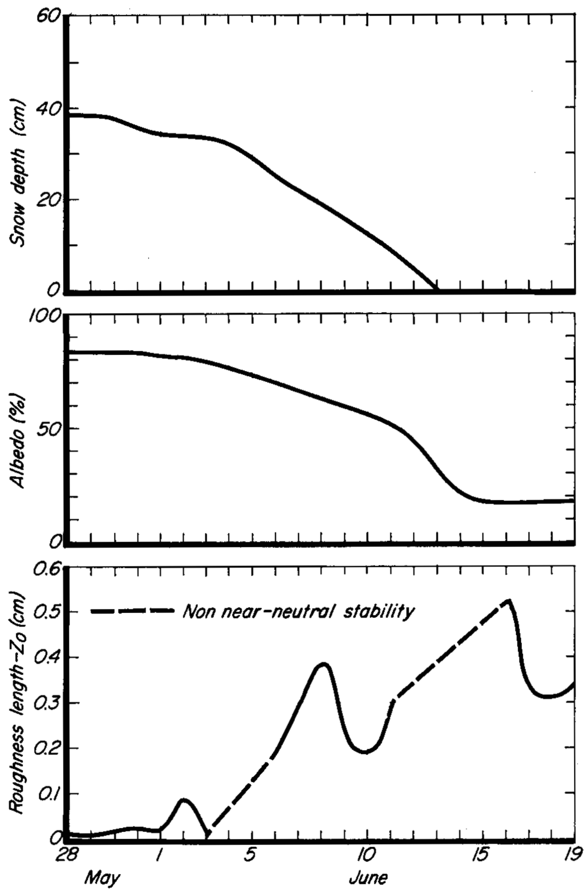


FIG. 4. Effect of snow cover on terrain parameters. (Daily mean values)

pearance of snow and appearance of tundra vegetation. Maximum $z_o$ values reach 2 to 4 cm. at the end of August (not shown in Fig. 4). The significance of the $z_o$ value lies in its effect on the viscous drag of the atmosphere and the exchange of sensible heat by eddy diffusion in the presence of vertical temperature gradients. The expression for eddy sensible heat transfer is:

$$Q = c_p A \frac{d\theta}{dz} t \qquad \text{——(2)}$$

where

$$A = k\rho u^* z \qquad \text{——(3)}$$

and Q = eddy heat flux, $c_p$ = specific heat of air at constant pressure (0.24), A = Austausch or heat exchange coefficient, $\frac{d\theta}{dz}$ = potential temperature gradient, $\rho$ = air density.

A as defined in equation (3) is strictly applicable for adiabatic conditions only, but a correction due to Lettau (1949) has been applied to all data. This correction allows for non-adiabatic cases and has the form:

$$A = \frac{Aa}{(1+Ri)}2 \qquad \text{——(4)}$$

where Aa = Austausch coefficient for adiabatic conditions, Ri = Richardson number (a stability parameter equal to zero for adiabatic cases).

## VARIATION OF ENERGY FLUXES DURING SPRING

The heat balance for the period of snow melting can be symbolized using the equation written in the form:

$$N + Q + S + E = 0 \qquad \text{———(5)}$$

where N = net radiation (measured directly)

Q = eddy heat flux of sensible heat (computed from measured wind and temperature profiles, using equations (1), (2), (3) and (4) ).

S = subsurface sensible heat flux (computed from measured changes in the subsurface temperatures and assuming a constant soil heat capacity).

E = latent heat of melting and evaporation (computed as a remainder term to balance equation (5) ).

Advection of heat on a large scale is considered to be negligible. The sign convention is that a heat flux towards the surface is termed positive (heat source), and away from the surface, negative (heat sink).

Fig. 5 shows the heat balance components computed for each day. Heat sources are almost exclusively provided by radiation, although on a few days inversion conditions have caused a sensible heat flux to the surface. As the snow disappears, the amount of heat available to the surface increases strongly. Heat sinks are sensible heat fluxes to warm the snow, soil and air, and latent heat. Table 1 summarizes these results. The study period is divided into 3 phases: 1) a premelting (29 May to 3 June), 2) melting (4 to 13 June), and 3) post-melting period when all snow has already melted (14 to 17 June). Net incoming radiation increases by an order of magnitude over the total period and accounts for most of the heat source. This heat is partially used to warm the air (the magnitude also increasing by an order) but it remains constant as a percentage of the total available heat. Subsurface sensible heat available to heat the snow and ground is roughly constant in magnitude but decreases from 62 per cent of the total available heat in the pre-melting stage to only 9 per cent in the post-melting period. Latent heat undergoes the greatest changes through the 3 phases. It increases by a factor of 40 and changes from consuming 7 per cent of the total energy to 73 per cent. In the pre-melting period the small amount of available heat is mainly used to heat the snow and soil. During the melting period most of it is used to melt the snow, and in the post-melting period most energy is used to evaporate water from the saturated tundra surface.

Some independent checks can now be used to verify the magnitude of the latent heat flux. As noted, the snow cover was 35 cm. thick when melting began on 4 June. Its mean initial density as measured, was 0.25 gm. $cm.^{-3}$. It required 9 days to melt the snow, or in equivalent heat units an average 78 cal. $cm.^{-2}$ $day^{-1}$ (using a latent heat of melting of snow to be 80 cal. $gm.^{-1}$). From the heat balance, the latent heat of melting and evaporation combined for the same period is shown to be 83 cal. $cm^{-2}$ $day^{-1}$ (Table 1). Considering that evaporation for the pre-melting period amounts to only 7 cal. $cm.^{-2}$ $day^{-1}$ (Table 1), and

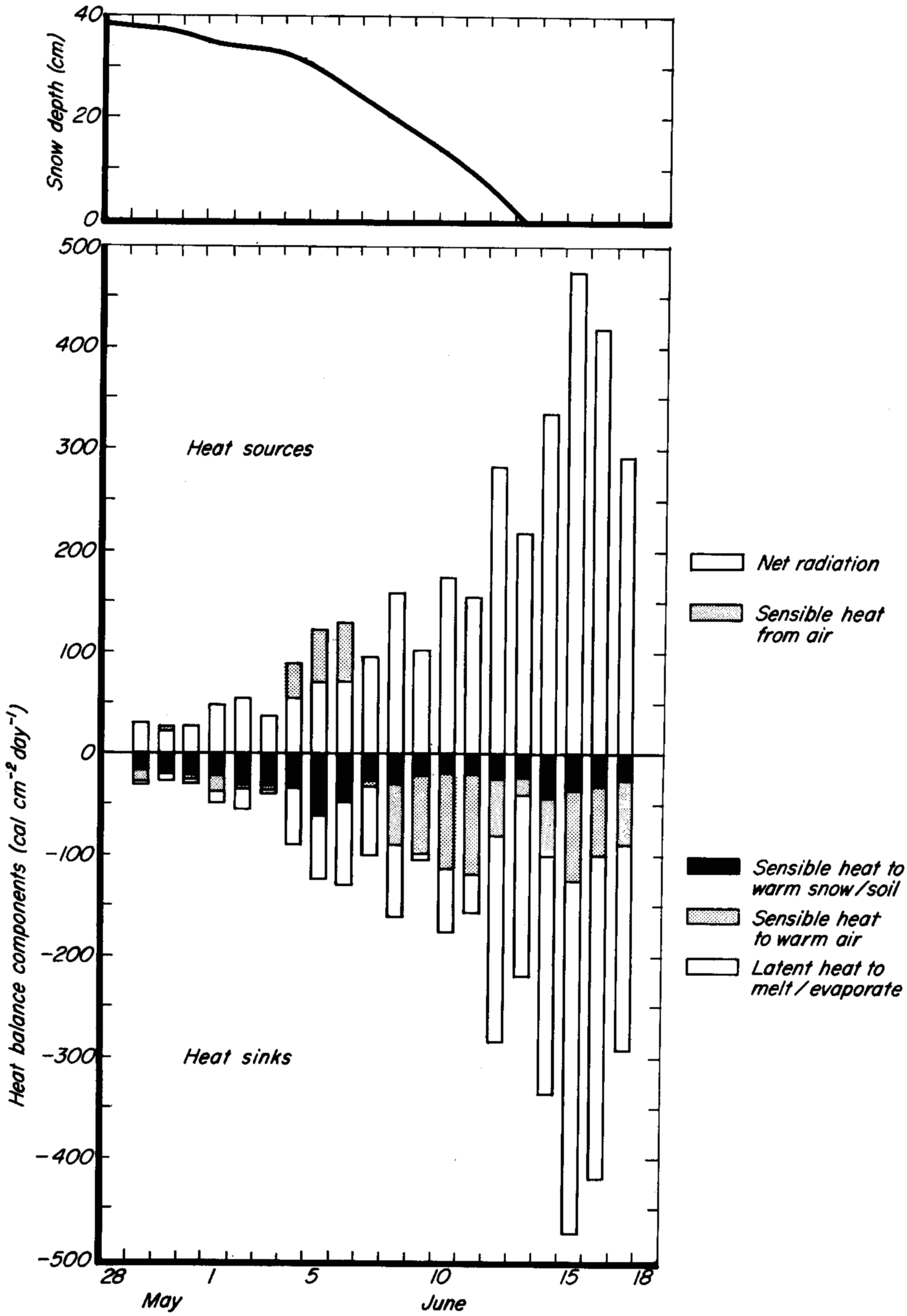


FIG. 5. Heat balance through the melting period.

assuming that it does not increase appreciably during melting the remainder heat balance value appears to be in good agreement with the directly computed melting heat value. The latent heat of evaporation for the post-melting period can also be checked against heat equivalents of observed evaporation from a Class A evaporation pan. These pan measurements are probably quite accurate during the post-melting period when the tundra is covered with water puddles. Installed on 23 June, the pan value of evaporation was 3.5 mm. $day^{-1}$ on the average to 30 June. The highest reading of 6.4 mm. $day^{-1}$ was soon after installation. These values correspond to latent heat totals of 209 and 381 cal. $cm.^{-2}$ $day^{-1}$ cited in Table 1. The remainder computations of E thus are assumed to correspond to correct values.

TABLE 1 The heat balance through the snow-melting period, Barrow, Alaska, 29 May to 17 June 1971

| Period | Net Radiation | | Eddy Sensible Heat (To warm air) | | Sensible Heat (to warm snow and soil) | | Latent Heat (to melt and evaporate) | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Source* | *Sink* | *Source* | *Sink* | *Source* | *Sink* | *Source* | *Sink* | |
| *Pre-melting* | +37 | 0 | 0 | −7 | 0 | −23 | 0 | −7 | cal $cm^{-2}$ $day^{-1}$ |
| *(29 May-3 June)* | +100 | 0 | 0 | −19 | 0 | −62 | 0 | −19 | per cent |
| *Melting* | +139 | 0 | +15 | −41 | 0 | −30 | 0 | −83 | cal $cm^{-2}$ $day^{-1}$ |
| *(4-13 June)* | +90 | 0 | +10 | −27 | 0 | −19 | 0 | −54 | per cent |
| *Post-melting* | +380 | 0 | 0 | −70 | 0 | −33 | 0 | −277 | cal $cm^{-2}$ $day^{-1}$ |
| *(14-17 June)* | +100 | 0 | 0 | −18 | 0 | −9 | 0 | −73 | per cent |

## CONCLUSIONS

A straigthforward approach has been used to explain elements of the tundra microclimate. With relatively simple observations of physical responses to the supply of heat, for example air temperature changes and snow ablation, the microclimatic perturbations due to changes in terrain characteristics can be documented at a fairly simple level. To understand detailed energy transfer mechanisms controlling the tundra microclimate, considerably more elaborate investigations are necessary, as has been demonstrated. This study has shown the great changes of the near-surface climatic environment that can occur in a relatively short time during spring when the surface conditions are changing most rapidly. While these changes in microclimate are perhaps strongest during snow-melt, they also exist at other times, as will be shown in a future paper.

## ACKNOWLEDGEMENTS

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