ARCTIC
VOL. 39, NO. 2 (JUNE 1986) P. 172-176

The Radiation Budget of a Subarctic Woodland Canopy

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(Received 21 December 1984; accepted in revised form 4 July 1985)

ABSTRACT. Open woodland is a major sub-type of the circum global boreal forest zone. In Canada it dominates the basins of a number of large hydroelectric schemes in which snowmelt is a critical phase of the hydrologic cycle. The forest vegetation strongly influences the radiant energy flux to the snow and is therefore important in the production of snowmelt runoff and its prediction.

The radiation budget of a subarctic open woodland canopy in northern Quebec is computed from measurements of net allwave, solar and longwave radiation components over the snowpack at treeless and woodland sites. The canopy gains solar radiation both directly and from solar radiation reflected off the snowpack, the latter enhanced by the larger spacing between tree crowns. Canopy heating from absorbed solar radiation leads to a considerable longwave flux being emitted by the tree crowns. Overall, the radiant energy exchange in the open woodland behaves differently than for a closed crown forest. This is believed to be a function of a variety of canopy characteristics, not solely of tree crown density.

Key words: snowmelt, open woodland, radiation budget, northern Quebec

RÉSUMÉ. La forêt claire forme autour du monde un des sous-types importants de la zone de forêt boréale. Elle domine au Canada les bassins de quelques grands projets hydroélectriques dans lesquels la fonte des neiges comporte un des stades critiques du cycle hydrologique. La végétation forestière influence de façon importante le flux d'énergie de la neige et joue donc un rôle capital dans l'écoulement de l'eau de fonte et dans sa prédiction.

Le taux de rayonnement du couvert forestier subarctique dans le nord du Québec est calculé d'après des mesures des composantes du rayonnement total, solaire et de grande longueur d'onde de la neige à des sites boisés et non boisés. Les cîmes reçoivent un rayonnement solaire en direct et aussi par réflection du manteau nival, augmenté par un plus grand espacement entre les couronnnes des arbres. Le réchauffement du couvert par l'absorption du rayonnement solaire entraîne l'émission d'un flux de grande longueur d'onde important des couronnes des arbres. En général, l'échange d'énergie radiante dans la forêt claire se produit différemment dans une forêt à couvert épais. Nous croyons que cette différence résulte de la variété des caractéristiques du couvert, et non seulement de la densité des couronnes des arbres.

Mots clés: fonte des neiges, forêt claire, taux de rayonnement, nord du Québec

Traduit pour le journal par Maurice Guibord.

INTRODUCTION

The net flux of incoming and reflected solar radiation and incoming and outgoing longwave radiation supplies available energy for snowmelt, ground heating, evaporation and heating of the atmosphere at the earth's surface. In forested areas, physical characteristics of the canopy play an important role in determining the radiant energy exchange between forest, atmosphere and earth surface. In particular, the trees intercept a large portion of the daily solar radiation, which reduces the net solar flux below the canopy. At the same time the trees act as a source of longwave radiation to earth and sky. The net result of these two opposing effects depends on species, canopy morphology and distribution and height of the tree crowns. These features can, of course, vary greatly between species and among the same species in different environments, making it difficult to formulate a general model for radiation transfer within forests. However, specific information about a forest canopy is necessary to make accurate radiation balance predictions. To date most models of radiation exchange in forests have concentrated on closed crown forest types typical of the mid-latitude boreal forest (e.g., Reifsnyder and Lull, 1965; Gay and Knoerr, 1970). The present study examines the radiation budget of a particular and important boreal forest type, the subarctic open woodlands.

Open woodlands form a major subarctic zone in Canada and around the northern hemisphere (Fig. 1). This zone represents a transition between closed crown boreal forest and arctic tundra. Its most distinctive feature is its open structure, characterized by single crowns or small clumps with relatively large spacing in between. In the main, the spruce trees that dominate the open woodlands are short and narrow by southern standards, and this combined with the open spacing contributes to crown cover densities ranging between 5 and 30% (averaging about 15%). It is because of these distinctive structural elements that Hare and Ritchie (1972) recognize the open woodlands as an important North American bioclimate zone. This zone is an important feature of the Churchill Falls and Baie James hydroelectric catchments in northern Quebec-Labrador.

In the past there have been some studies of the radiant energy regime of open subarctic woodlands, such as albedo measurements by Jackson (1960) and Davies (1962) and solar radiation modelling by Wilson and Petzold (1973). However, as yet none have presented a complete radiation budget for a woodland canopy.

METHODS

Sites and Instrumentation

The study was conducted in the vicinity of Schefferville, Quebec (Fig. 1), where open woodlands cover approximately 63% of the landscape. Selected radiation balance components were measured simultaneously over the snowpack at treeless and open woodland sites during the 1983 snowmelt season (April-May). The treeless site was located near the outskirts of the Schefferville townsite. There net radiation was measured with a net pyrradiometer (Swissteco), and incoming and reflected solar radiation were measured with two dome solarimeters (Lintronic), one facing upward and one inverted toward the snow. These instruments were supported on a 1 m tripod stand, located atop the centre of a large (approx. 40 m × 50 m) snowdrift. This situation was most advantageous for prolonging

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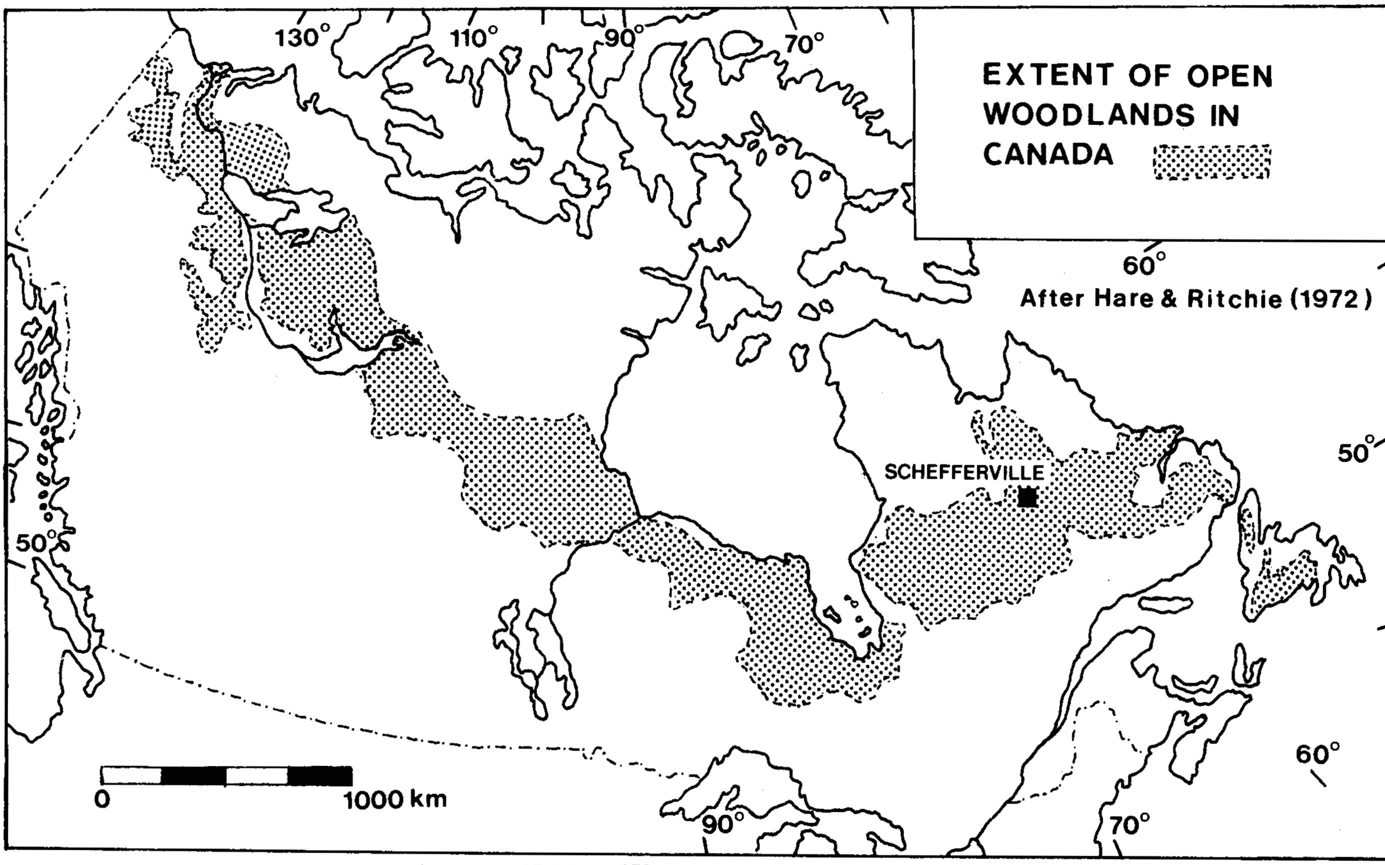

FIG. 1. The "open woodland" zone in Canada, after Hare and Ritchie (1972).

the period of meaningful comparison with the woodland site, as the shallower snowpack in most open areas disappeared at least two weeks before the pack in the woodland began to break up.

The woodland site was situated on a low, wooded ridge .75 km west of the open site. From a survey of aerial photos it appeared that the woodland canopy was relatively uniform over the ridge; therefore a 30 m × 30 m study plot was selected for a detailed survey. It was found that the black spruce (*Picea mariana*) trees averaged 7.05 m in height, with a mean branch radius and mean distance between trees of 1.05 m and 6.5 m respectively. Crown cover density was calculated to be 18%. These values are typical of the "open lichen woodlands" dominant in the Schefferville area, as defined by Fraser (1956).

The instrumentation in the woodland site was located near the centre of the study plot. Net allwave radiation was measured with a net pyrradiometer (Middleton) aspirated with nitrogen gas and incoming solar radiation and albedo measured with a pyrano-albedometer (Middleton). These instruments were operated side by side, 1 m above the snow surface on a tripod stand and located at a point equidistant from all tree crowns in the vicinity. This point was representative of the openness of the canopy and the point of maximum snow accumulation. The signals were recorded on Rustrak type stripchart recorders, supplied with 12 volt DC power. Although a single sensor is usually not sufficient to obtain a representative sample from beneath a forest canopy, it was felt that because of the highly porous nature of the open woodlands, the single instruments employed here were adequate.

All radiation data at both sites were monitored on a 24-hour basis and accompanied by daily screen air temperature, wind speed, snow depth and density measurements 15 April-15 May 1983, with only minor interruptions due to instrument failure. Full details of the instrumentation and procedures are presented in Lafleur (1984).

Components of the Radiation Budget

The radiation balance at the top of the woodland canopy or at the ground surface beneath can be expressed as

$$Q_* = K{\downarrow}(1-\alpha) + L_* \quad (1)$$

and

$$L_* = L{\downarrow} - L{\uparrow} \quad (2)$$

where Q_* is net (allwave) radiation, $K{\downarrow}$ is the incoming solar radiation flux, α, the albedo, is the ratio of reflected to incoming solar ($K{\uparrow} / K{\downarrow}$). L_* is net longwave radiation, and $L{\downarrow}$ and $L{\uparrow}$ are the incoming and outgoing longwave components respectively. In order to compute a radiation budget for the three-dimensional canopy, measurements of all incoming and outgoing fluxes above and below the woodland canopy are required. However, as all the necessary measurements were not available for the present study, some radiation components were indirectly calculated from the available measured data as described below.

Initially, for the two sites, incoming and reflected solar radiation and net radiation were measured over the snowpack and net longwave (L_*) was calculated as the residual in (1). Since the distance between the two sites was less than 1 km, the incoming solar flux measured at the treeless site ($K{\downarrow}_o$) was taken to equal the incoming flux at the top of the woodland canopy. The solar flux reflected from the top of the woodland canopy-snowpack mosaic ($K{\uparrow}_T$) was approximated by the expression

$$K{\uparrow}_T = K{\downarrow}_o (1-\tau)\, \alpha_{tc} + K{\downarrow}_o (\tau^2) \alpha_s \quad (3)$$

where τ is a coefficient for transmission of solar radiation through the canopy, α_S is the snow albedo and α_{tc} is the tree crown albedo. This expression is approximate in so far as solar transmission through the canopy is assumed to be isotropic (i.e., τ is the same for solar radiation passing upward and downward through the canopy) and multiple reflections off the tree crowns are ignored. Given the open nature of this canopy and the small albedo of the tree crowns, it is believed that the error associated with these assumptions is only a few percent.

The solution for the complete longwave balance was more complicated, since only L_* at the snowpack was available. Rearranging and expanding according to the Stefan-Boltzmann Law, (2) may be written

$$L\downarrow = L_* + \epsilon\sigma T^4_s + (1-\epsilon)\, L\downarrow \qquad (4)$$

where ϵ is the snow surface emissivity, σ is the Stefan-Boltzmann constant (5.67×10^{-8} $Wm^{-2°}K^{-4}$) and T_s is the snow surface temperature. During the melt T_s was taken as 0°C (273.15°K) and ϵ was assigned a value of .94, a good approximation for this study according to Price and Petzold (1984). Employing these values and rearranging,

(4) yields $$0.94L\downarrow = L_* + 296.7 \qquad (5)$$

or $$L\downarrow = (L_* + 296.7)/.94 \qquad (6)$$

and finally $$L\downarrow = 1.06L_* + 315.6 \qquad (7)$$

This simple linear relationship was used to calculate the total downward longwave flux to the snow at each site during hours when the snow was known to be melting. As with the solar flux, the incoming flux at the top of the woodland canopy and transmission through the canopy were assumed to be isotropic.

The total downward longwave flux at the woodland snowpack ($L\downarrow_w$), computed from (7), can be separated into two components, one emitted directly from the tree crown surfaces, and the remainder is that portion of $L\downarrow_o$ that passes through the canopy to the snow. For this study the portion of $L\downarrow_o$ that reaches the woodland snowpack was calculated using the hemispherical view factor (P), a measure of that portion of the sky seen by the snow and expressed as a decimal fraction. P at this site was estimated to be .76 (Lafleur, 1984). The canopy-emitted longwave component was then calculated as the residual, *viz.*, $L\downarrow_{tc} = L\downarrow_w - P(L\downarrow_o)$ (8)

RESULTS

Results for the study are presented in Figure 2 and Table 1. Solar and longwave radiation fluxes at the woodland site on a typical snowmelt day in April are depicted in Figure 2. Daily incoming solar radiation measured at the treeless site ($K\downarrow_o$) on this day was 17.3 MJ m^{-2} d^{-1}, of which 13.5 MJ m^{-2} d^{-1}, or 78%, reached the woodland snowpack ($K\downarrow_w$). This agrees well with a linear regression of $K\downarrow_w$ on $K\downarrow_o$ computed for 28 daily totals during the study. The following relationship was produced

$$K\downarrow_w = 0.015 + .779\,(K\downarrow_o),\ r^2 = .98 \qquad (9)$$

Since the intercept is small, (9) indicates that on average 78% of the incident solar flux over the canopy reaches the snow surface; hence 22% is intercepted by the trees and absorbed or reflected back.

The tree crowns were assigned an albedo of .12, and the snow albedo was measured and found to be .70. Using these values, the reflected solar flux at the top of the woodland ($K\uparrow_T$) calculated from (3) was 7.9 MJ m^{-2} d^{-1} (Fig. 2), where τ was equal to .78 (from above). The total albedo, then, for the woodland-

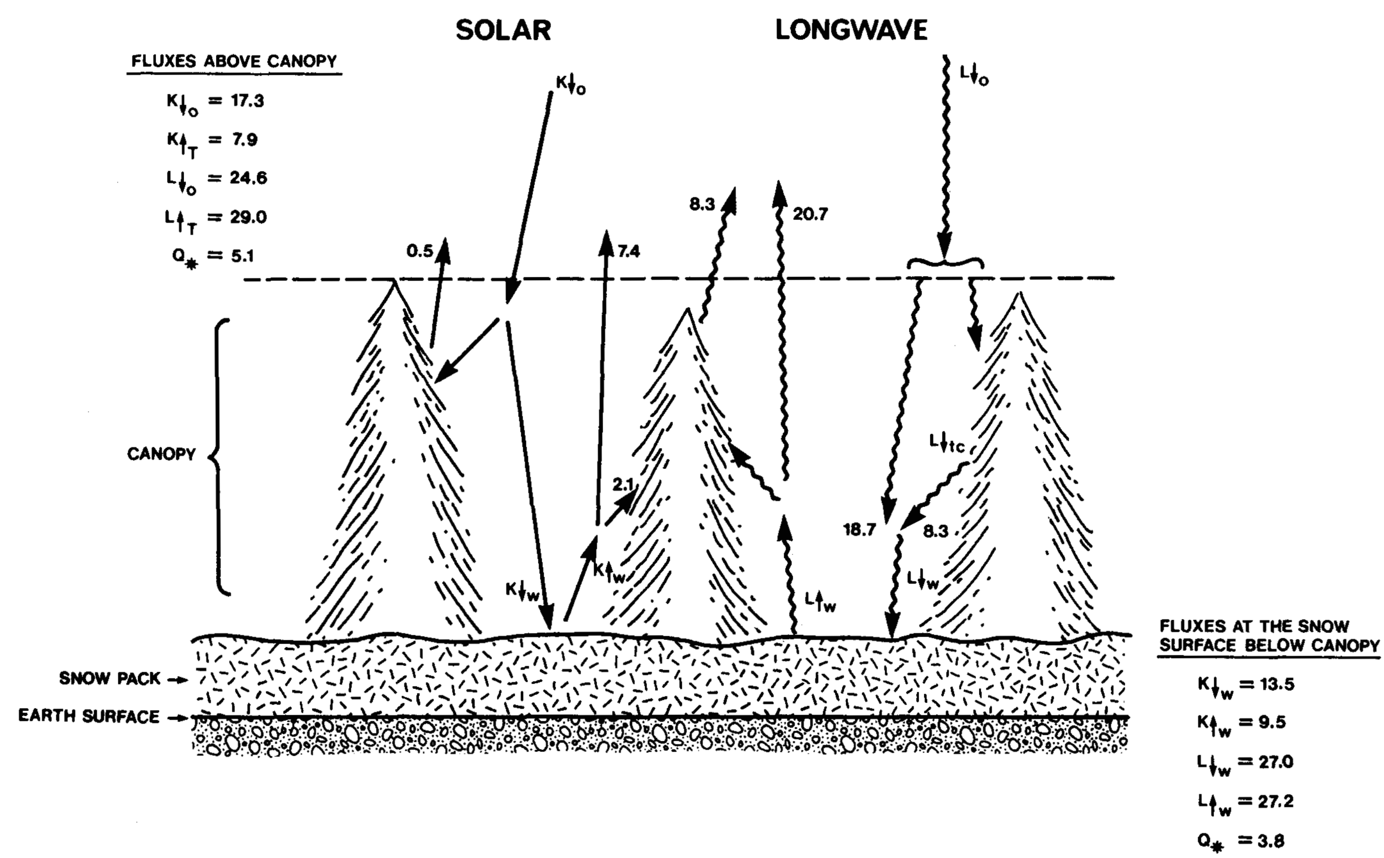

FIG. 2. Radiant energy transfer in a subarctic open woodland (canopy density = .18) during snowmelt. Fluxes are daily totals (MJ m^{-2} d^{-1}) for a typical sunny melt day, 28 April 1983.

TABLE 1. Components of the radiation balance in subarctic open woodland and treeless situations; the values are averages for a 12-hour daytime period (MJ m^{-2})

		Woodland					Treeless			
			Longwave from					Longwave from		
		Solar	Atmos.	Canopy	Snow	Net	Solar	Atmos.	Snow	Net
Atmosphere	Gain	6.7	—	4.1	10.3	—	9.7	—	13.6	—
	Loss	13.8	12.5	—	—	5.2	13.8	12.5	—	3.0
Canopy	Gain	3.7	2.9	—	3.2	1.6	—	—	—	—
	Loss	—	—	8.2	—	—	—	—	—	—
Snow	Gain	3.4	9.6	4.1	—	3.6	4.1	12.5	—	3.0
	Loss	—	—	—	13.5	—	—	—	13.6	—

snowpack complex was .46, which is considerably smaller than for the snow only.

The longwave fluxes, shown in Figure 2, indicate that both above and below the canopy the total outgoing flux is greater than the incoming fluxes, which results in a net longwave deficit in each case. However the net longwave loss is appreciably smaller below the canopy, because of the downward longwave flux (8.3 MJ m^{-2} d^{-1}) emitted from the tree crowns ($L\downarrow_{tc}$). The $L\downarrow_{tc}$ flux represents about 31% of $L\downarrow_{w}$ and 29% of $L\uparrow$ above the canopy.

Radiation budgets for the treeless and woodland sites computed for daytime periods of 12 hours' duration are given in Table 1. The data are average values calculated from the daytime energy totals for 15 days when the snow at both sites was known to be melting and are organized into an iterative model of the three principal microclimate layers of snow, canopy and atmosphere. The net allwave gain to the snow is larger at the woodland site than at the treeless snowpack. Although net solar input to the woodland snow is 0.7 MJ m^{-2} less than at the treeless site, this is offset by a longwave gain of 1.2 MJ m^{-2}. This greater longwave flux at the woodland snowpack is aided by the 4.1 MJ m^{-2} input from the canopy, which is unaccounted for at the treeless site. Considering that the canopy represents about 24% of the sky hemisphere (i.e., 1-P), the longwave gain from the canopy is, on average, 41% greater than the longwave flux from the equivalent portion of the treeless sky. Another interesting feature in Table 1 is that the canopy layer displays a net gain of 1.6 MJ m^{-2} for the daytime period. Solar inputs are primarily responsible for this gain, of which almost one-third is solar radiation reflected from the snowpack (Fig. 2).

Since the open woodlands and treeless areas represent the two most extensive terrain units of the subarctic landscape, climatologically it is important to compare net radiation over these surfaces. Q_* at the top of the woodland canopy is equal to the sum of net values for the canopy and snow layers in Table 1. This value, 5.2 MJ m^{-2}, is 1.7 times greater than the net gain at the treeless snowpack. This difference arises because the absorbed solar flux is much larger over the woodland in winter (α = .46) than over the open, treeless snow cover (α = .70).

DISCUSSION

We have calculated fluxes of solar and longwave radiation in a subarctic open woodland from measurements of solar and net allwave radiation over the snow surface at treeless and woodland sites. An important assumption made here is that solar and longwave radiation transmission through the woodland canopy is isotropic. While this is probably true for the longwave flux, it may not be the case for the solar flux because branch orientation and colour are different for the incoming flux than for the reflected solar flux. The actual value for solar transmission out of the canopy is probably slightly lower than for the downward flux. However, because of the porous nature of the canopy, the difference is only a few percent at most, which is within the instrument error and may be ignored for most radiation budgeting purposes. It is also assumed that the incoming solar and longwave fluxes at the treeless site are equal to the incoming fluxes above the canopy at the woodland site. Since the distance between sites is less than 1 km, this is a valid assumption for hourly and daily totals.

For most studies, direct measurement of the individual longwave fluxes is difficult. In this study, we exploit the fact that the snow surface temperature is held constant at 0°C during melt, and a simple linear expression is developed to calculate the total downward longwave flux to the snow in both forest and treeless environments. Provided the snow emissivity is known with some certainty, this expression could be used wherever solar and net allwave fluxes are measured over melting snow.

Despite its openness, the subarctic woodland canopy studied here exerts a strong influence on the radiation regime at the snow surface (Fig. 2 and Table 1). The effect of the tree crowns is to reduce the solar inputs to the snow by 22% and enhance the total downward longwave flux by about 10%. This contributes to a net allwave (Q_*) difference of 0.6 MJ m^{-2} in favour of the woodland snowpack compared to the treeless site. Although 0.6 MJ m^{-2} would account for about 1.8 mm more snowmelt at the woodland site, this may be offset by a larger convective flux of sensible and latent heat at the treeless site. The comparison of fluxes over the woodland and at the treeless snowpack produce a more exaggerated result. Here, there are large differences between the surface albedos. The albedo of the canopy-snowpack complex is .46, which compares well with a value of .32 measured by Rouse (1984) over an open woodland in northern Manitoba with a crown density of 60%. The albedo of the treeless snowpack is .70. We suspect that this difference is typical for most of the snow season and may even be larger during mid winter, when the sun is lower in the sky and woodland canopy absorbs a larger portion of the incident solar radiation. These albedo differences are reflected in the net allwave values over the woodland and at the treeless site, 5.2 and 3.0 respectively. Early into the melt this difference would decrease, or even reverse, as the shallow snow covers disappear from the treeless terrain, decreasing the albedo, while snow remains in the woodland.

Table 1 illustrates the importance of the woodland canopy as a distinct microclimate layer separating the snow and the bulk of the atmosphere. For the daytime period the canopy layer receives a net gain of 1.6 MJ m^{-2}, and it is suggested that solar inputs, direct and reflected from the snow, are responsible for this. In most closed crown forests, reflection from beneath the canopy is only of minor consequence to the canopy radiation budget; thus the upper portions of the canopy receive the majority of solar heating. For the subarctic woodland, reflection from the snow appears to be an important factor, where the open canopy structure permits whole tree crowns to be heated by solar radiation.

The 1.6 MJ m^{-2} gained by the canopy layer is considerable and must be dissipated by means other than radiative. This is accomplished firstly by heating the fabric of the non-transpiring tree crowns. Although measurements of leaf surface temperature were not available for this study, Rouse (1984) reports that the temperature of spruce trees in an open woodland near Churchill, Manitoba, averaged 6.6°C higher than air temperatures and 12.6°C higher than the snow surface temperature. Since only a small amount of energy is required to heat the tree crowns, most of this energy is constantly moved away from the crown surfaces as sensible heat convection. Given that the open structure of the canopy is conducive to air circulation and that there is a continuous positive temperature gradient between the crowns and surrounding air, then the sensible heat flux in the woodland may be large. This may have been responsible for the consistently higher air temperatures recorded at the woodland site than at the treeless site.

We realize, of course, that the results presented and discussed here are specific to the distinct silvicultural characteristics of the woodland we studied. Changes in these forest characteristics would markedly influence the results of a similar study. As anticipated, the results here are not like those expected for a denser, closed crown boreal forest. The reduction in solar radiation is less important to the snow surface radiation balance than the increased input of longwave from the tree crowns. The opposite is true for closed crown forest. The range of crown density for which this holds cannot be determined from the available information. The crown density parameter, however, is not entirely responsible for this result. We feel that other characteristics of the canopy, such as branch orientation, tree height and crown radius, are also important. Therefore we suggest that results similar to those presented here could not be duplicated for a spruce forest in more southerly latitudes given the same crown cover density.

CONCLUSIONS

Our analysis provides an illustration of the importance of the open woodland vegetation type in the radiation microclimate of the subarctic landscape in spring.

At the snow surface, open woodlands decrease incoming solar radiation but increase longwave radiation. The latter, being more important, produces net allwave values equal to or greater than those in treeless situations. Since radiation inputs are usually the largest energy source for snowmelt in the subarctic, this implies that open woodlands do not inhibit snowmelt as does closed crown boreal forest. They may even enhance it.

The radiation balance at the top of the canopy is important in regional climate. Open woodlands enhance the Q_* flux by 1.7 times and therefore are the distinctive, important, climate zone envisaged by Hare and Ritchie (1972).

The unique morphology of the woodland vegetation, as well as its spacing, are important in producing these results. Large-scale removal of trees could have drastic consequences on the regional climate and the hydrologic regime.

ACKNOWLEDGEMENTS

This work was supported by NSERC, DINA, Trent University and the McGill Subarctic Research Station, Schefferville. We are grateful to the Departments of Geography at McMaster and Toronto (Scarborough) for the loan of instruments and advice.

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