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Snowmelt in a Canadian Spruce Forest: A Sensitivity Study to the Canopy Cover

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ABSTRACT

This study investigates the dependence of net radiation at the snow surface to the overlying canopy density. The daily sum of the positive values of net radiation is used as an index of the snowmelt rate. Changes in canopy cover are represented in terms of shortwave transmissivity and sky view factor variations. The case study is a spruce forest in the Wolf Creek basin, Yukon Territory, Canada, and focus is on the spring climate. Of particular interest are the atmospheric conditions that favor an offset between the shortwave energy attenuation and the longwave irradiance enhancement by the canopy. Such an offset is favored in dry climates and at high altitudes, where atmospheric emissivities are low, and in early spring when snow albedo is high and sun elevation is low. A canopy cover increase causes a steady decrease in snowmelt, when the snow albedo is low, until a density close to the actual density of the studied spruce forest. Large snow albedo values cause a low dependence of snowmelt to the canopy cover or a steady increase in melting energy when the canopy cover increases. Boreal evergreen forests do not favor the appearance of a minimum snowmelt rate under some intermediate canopy cover.

INTRODUCTION

At high altitudes and latitudes, snow has a significant influence on hydrological and atmospheric processes. A large fraction of these regions is covered by coniferous forests with evergreen characteristics. The retention of needles throughout the winter leads to a large influence of the canopy on snow accumulation and melting processes (e.g., Kuz'min 1972, Hedstrom and Pomeroy 1998, Lundberg et al. 1998, Ohta et al. 1999, Pomeroy et al. 2002, Koivusalo and Kokkonen 2002). Trees shelter the snow surface from wind, reducing turbulent fluxes, such that sub-canopy snowmelt mainly depends on the radiative fluxes (Price 1988). The magnitudes of the net short- (positive) and net longwave (negative) radiative fluxes are reduced at the snow surface below a forest relatively to open sites (Harding and Pomeroy 1996, Hardy et al. 1997). As canopy coverage increases, two competitive radiative changes affect snowmelt at the ground surface: vegetation attenuates the transmission of shortwave radiation, but enhances longwave irradiance to the surface. The shortwave energy reduction is generally the dominant effect and melting is reduced (Link and Marks 1999). However, the longwave radiation increase may offset any reduction in shortwave irradiance—a situation that can be referred to as the "radiative paradox" defined by Ambach (1974). Sensitivity studies of snowmelt to the canopy coverage have been

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based only on modelling results (Yamazaki and Kondo 1992, Davis et al. 1997), as the difficulty of observing different snowmelt rates under various canopy covers is large.

The purpose of this study is to examine the sensitivity of net radiation components during snowmelt under a canopy to canopy characteristics with reference to atmospheric conditions. The study focuses on the larger and more dynamic daytime fluxes as during nighttime, the canopy limits the longwave losses of the snow surface and the snow temperature remains near the freezing point (e.g., Höller 2001). The daytime radiation fluxes are therefore considered the most important controls on the rate of snowmelt. The dependence of sub-canopy net radiation over snow to the canopy characteristics is described in terms of shortwave transmissivity and sky view factor. Not all processes can be resolved in detail in such a sensitivity study, but the parameters and the assumptions can be directly related to commonly available canopy characteristics and radiative measurements. Of particular interest are the atmospheric conditions that favour an increase in net radiation under dense forests.

STUDY SITE AND MEASUREMENTS

Observations were made at high latitude in a sub-arctic spruce forest near Whitehorse, Yukon Territory, Canada. The study site was in the Wolf Creek Research Basin, located 15 km south of Whitehorse (western Canada, elevation: 750 m, 60°36′N, 134°57′W). A detailed description of the site can be found in Pomeroy et al. (2002). Observations were made in a mature, 12- to 18-m tall, dense white spruce forest (*Picea* glauca). Pomeroy et al. (2002) estimated the foliage area index, LAI’ (including clumping effects and stems, leaves and branches)—or “effective LAI” (Chen et al. 1997)—and the sky view factors to the underlying snow surface to be 3.3 and 0.13, respectively, from LI-COR LAI-2000 Plant Canopy Analyzer measurements (LI-COR 1992). The basin has a sub-arctic continental climate, characterized by a large variation in temperature, low humidity, and low precipitation. Mean annual temperature is in the order of –3°C, with summer and winter monthly mean temperatures ranging from 5° to 15°, and –10 to –20°C, respectively. Mean annual precipitation is 300 to 400 mm with approximately 40% falling as snow (Pomeroy and Granger 1997). Measurements of air temperature (below, within, and above the canopy), surface temperature (from above and below), net radiation (above and below), and shortwave radiation (above and below) were conducted from March to April 2003. Above-canopy incoming longwave radiation was derived from measurements at 21-m height: downward-looking infrared surface temperature (primarily canopy, but some surface), net and net shortwave radiation. Two Campbell dataloggers (21X and CR10) recorded every 30 minutes averages of 5-s time step observations. Ten recently calibrated Matrix pyranometers were randomly located beneath the forest canopy to achieve a spatially integrated measure of incoming shortwave radiation at the snow surface. The sub-canopy incoming longwave radiation was measured by two Eppley pyrgeometers also placed on the snow surface.

MODEL

The radiation equation

Assuming that longwave radiation from canopy needles, stems, and trunks can be represented by a mean canopy temperature and that longwave is transmitted without scattering or refraction in a forest canopy, the net all-wave radiation at the snow surface, R_n, below a forest can be written

$$R_n = V_f L_o\downarrow + (1 - V_f)\,\sigma T_c^4 - \sigma T_s^4 + K_o\downarrow \tau_c (1 - \alpha_s) \tag{1}$$

where V_f is the sky view factor of the snow surface, $L_o\downarrow$ is the above-canopy incoming longwave radiation, $\sigma = 5.67\ 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzman constant, T_c and T_s are the canopy and snow surface temperatures, respectively, $K_o\downarrow$ is the above-canopy incoming shortwave radiation (or global radiation), τ_c is the shortwave transmissivity of canopy including multiple reflections ($\tau_c = K\downarrow/K_o\downarrow$, with $K\downarrow$ the shortwave irradiance at the snow surface), and α_s is the snow albedo. The longwave emissivities of vegetation and snow are generally considered close to $\varepsilon = 0.97$ (Mellor 1977, Dozier and Warren 1982, Müller 1985, Oke 1987). However, as Equation (1) assumes that the snow and the vegetation surfaces are full emitters ($\varepsilon = 1$), it therefore follows that reflection of longwave by both surfaces may also be neglected (opaque material: $\alpha = 1 - \varepsilon$). The assumption is acceptable with respect to the accuracy of longwave radiation measurements (around ± 10%) and the desired simplicity of the radiative model used here. The time step is hourly to permit steady-state thermal conditions. Dense forests (V_f less than 0.5) are exclusively considered to allow for modeling the canopy as a horizontal homogeneous scattering medium. The analysis did not deal with snow retained in the canopy since much of the intercepted snow has dripped or evaporated in spring.

Shortwave transmissivity and sky view factor

A variety of canopy radiation models have been developed to simulate the changes in shortwave transmissivity as a function of above-canopy shortwave irradiance and canopy structure (e.g., Ni et al. 1997, Nijssen and Lettenmaier 1999). Such calculations require a detailed description of the canopy structure and separated measurements of the direct and the diffuse components of the above-canopy shortwave irradiance. In the coniferous Wolf Creek forest, no marked diurnal cycle of shortwave transmissivity was observed under clear sky conditions, roughly in accordance with the model function for extinction efficiency in pine of Pomeroy and Dion (1996). Indeed, the horizontal orientation of evergreen branches enhanced the transmission at low sun angles, compensating for the increased path length through the canopy (Ross 1975). A constant "effective" shortwave transmissivity was chosen by matching the cumulative shortwave irradiance beneath the canopy over a 20-day period ($\tau_c = \Sigma K\downarrow / \Sigma K_o\downarrow$, Figure 1). As a result, we obtained $\tau_c = 0.06$, which is close to the average of the hourly transmissivity measurements during daytime.

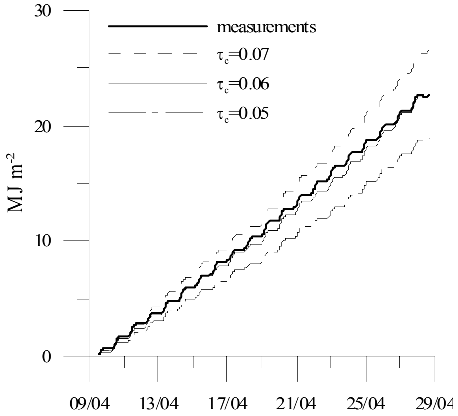

Figure 1: Sub-canopy shortwave irradiance ($K\downarrow$) measurements and calculations with canopy shortwave transmissivity $\tau_c = 0.05$, 0.06 and 0.07. Sum of hourly values, Wolf Creek forest, April 9–29, 2003.

The sky view factor (V_f) is a geometric ratio that expresses the fraction of radiation output from one surface that is intercepted by another (Oke 1987). For a snow surface beneath the forest, V_f is the fraction of the celestial hemisphere visible from beneath the canopy:

$$L\downarrow = V_f \, L_o\downarrow + (1 - V_f)\, \sigma \, T_c^4. \tag{2}$$

As the majority of the atmospheric longwave radiation ($L_o\downarrow$) received at the surface comes from the near-surface layer of the atmosphere, $L_o\downarrow$ is often written as (e.g., Brutsaert 1982)

$$L_o\downarrow = \varepsilon_{air} \, \sigma \, T_{air}^4 \tag{3}$$

where ε_{air} is the atmospheric emissivity and T_{air} is the air temperature near the ground. Assuming that the mean canopy temperature is close to the air temperature, $T_c \sim T_{air}$ (this assumption is discussed in section 4), the sensitivity of sub-canopy longwave irradiance to changes in sky view factor can be written as a function of the atmospheric emissivity:

$$\Delta L\downarrow / L_o\downarrow = (1 - 1/\varepsilon_{air})\, \Delta V_f. \tag{4}$$

Figure 2 shows changes in longwave radiation caused by reductions in sky view factor. In mid and high latitudes, the atmospheric emissivity ranges from 0.5 to 1 from clear to cloudy skies (Brutsaert 1982). The enhancement of longwave irradiance due to a sky view factor reduction is maximal under clear sky, when the atmospheric emissivity is low, but is independent of the forest density. The accuracy of longwave radiation measurements is generally no better than ± 10% (Halldin and Lindroth 1992). Thus, uncertainties on the sky view factor greater than ± 0.1 may cause significant errors in longwave radiation calculations under clear sky conditions (Fig. 2). This is an important point given the difficulty in ascertaining the accuracy of the canopy parameters.

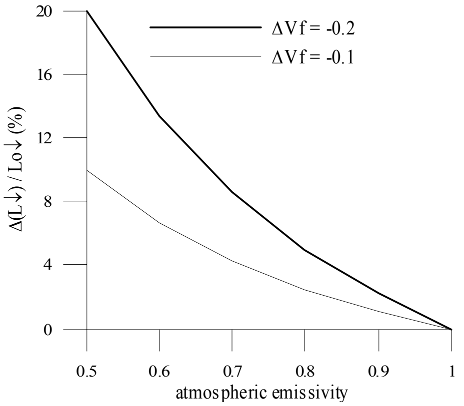

Figure 2: Relative changes in incoming sub-canopy longwave radiation caused by reductions in sky view factor of 0.1 and 0.2, as a function of the atmospheric emissivity ranging from $\varepsilon_{air} = 0.5$ (clear sky) to $\varepsilon_{air} = 1$ (clouds).

An increase in shortwave transmissivity is associated with an increase in sky view factor as follows:

$$V_f = f(\tau_c). \tag{5}$$

A linear approximation is

$$V_f = A\tau_c + B \tag{6}$$

where A and B are two constants ($A > 0$).

Pomeroy et al. (2002) derived an empirical relationship between the sky view factor (V_f) and the foliage area index (LAI') from LI-COR LAI-2000 measurements in several coniferous forests of northern Canada ($r^2 = 0.97$):

$$V_f = a - b \ln(LAI') \quad (7)$$

where a and b are two constants equal to 0.45 and 0.29, respectively.

The LI-COR LAI-2000 derives the sky view factor beneath the canopy and the foliage area index from measurements of canopy gap fractions (e.g., Welles and Norman 1991). Thus, Equation (7) may be in fact a feature of the calculations done by the LAI-2000 Analyzer. Shortwave transmissivity can be related to the foliage area index by a Beer's law relationship:

$$\tau_c = e^{-k\,LAI'} \tag{8}$$

where k depends on the above-canopy shortwave irradiance (zenith angle and spectral distribution) and on the canopy structural properties other than the foliage area index (e.g., Pomeroy and Dion 1996). Using Equations (7) and (8), the sky view factor of snow is related to the canopy shortwave transmissivity by a logarithmic relationship:

$$V_f = a - b \ln[-\ln(\tau_c) / k]. \tag{9}$$

In the evergreen Wolf Creek forest, the effective canopy shortwave transmissivity during snowmelt and foliage area index equal 0.06 and 3.3, respectively, resulting in k = 0.85 as a mean value in spring.

Figure 3 shows that Equation (9) remains close to the one-to-one line $V_f = \tau_c$. When the sky view factor tends to zero, the shortwave transmissivity tends to a minimum value around 2% ($\tau_{c,\,minimum} = \exp(-k \exp(a/b))$. $\tau_{c,\,minimum}$ represents the diffuse shortwave radiation reaching the ground below a theoretical completely closed forest. Measurements in the Wolf Creek forest are in agreement with Equation (9). Figure 3 shows that measurements in a sub-alpine pine forest near Fraser, Colorado, USA (Rowlands et al. 2002), are also in agreement with Equation (9). As the sky view factor beneath the Fraser forest was derived from fish-lens photographs, Figure 3 tends to show that the empirical relation between V_f and LAI' observed in the Canadian boreal forests (Equation 7) is not an artifact of the LI-COR LAI-2000 measurements.

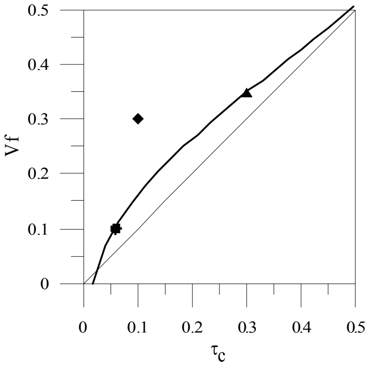

Figure 3: $V_f = f(\tau_c)$ derived from Equation (9). Points show measurements: the spruce forest in Wolf Creek (round), a pine forest in Fraser, Colorado (triangle), and a pine forest in Quebec (Vezina and Pech 1964, diamond).

The shortwave transmissivity measured by Vezina and Pech (1964) in a pine forest in Quebec, Canada, is too low relatively to estimates of V_f from their studies (Fig. 3). However, Vezina and Pech (1964) used a "crown closure"—not defined in the study—and not a sky view factor, to quantify the canopy density. The deviation of their data from Equation (9) (Fig. 3) may be due to differences in describing the forest structure and/or to different climatic conditions. The relation between V_f and τ_c from Equation (9) can be adapted to different climates and forests by calibrating the parameters a and b for species, tree growth form, and tree heights.

Differentiation of the radiation equation

Replacing V_f by $f(\tau_c)$ from Equation (5), the differential function of the net radiation with respect to the shortwave transmissivity ($dR_n/d\tau_c$) is nil when net radiation is independent of canopy density, or when some intermediate canopy cover causes an optimum value of net radiation (maximum or minimum).

We investigate the climatic conditions leading to

$$dR_n / d\tau_c = (L_o\downarrow - \sigma\, T_c^4)\, f'(\tau_c) + K_o\downarrow (1-\alpha_s) = 0 \qquad (10)$$

where $f'(\tau_c)$ is the differential function of $f(\tau_c)$: $f'(\tau_c) = A$ or $-b / [\tau_c \ln\tau_c]$, depending on whether $f(\tau_c)$ is derived from Equation (6) or Equation (9).

The first term in Equation (10), representing the longwave fluxes, is generally negative as the canopy emissivity is greater than the atmospheric emissivity. The second term, representing the shortwave flux, is positive and is generally larger than the longwave term as the attenuation of shortwave radiation by the canopy is most often the dominant process (e.g., Harding and Pomeroy 1996). However, Equation (10) permits quantification of the atmospheric conditions leading to an offset between the shortwave energy reduction and the longwave irradiance increase such that net radiation does not decrease with increasing forest density. For instance, at high altitude or in dry areas, atmospheric emissivity is low and so $L_o\downarrow$ is low, in early spring solar angles are low and so $K_o\downarrow$, and after fresh snowfall the sub-canopy snow albedo is high.

Considering the logarithmic relation $V_f = f(\tau_c)$ from Equation (9), $f'(\tau_c)$ becomes large for small shortwave transmissivities (Fig. 4). Indeed under very dense forests, Equation (9) causes a rapid decrease in V_f, and hence an increase in sub-canopy longwave irradiance, for only a small decrease in shortwave transmissivity (Fig. 3). The relation derived from Pomeroy et al. (2002) (Equation (9)) reinforces the influence of longwave fluxes on energy available for snowmelt, leading to more frequent situations of the "radiative paradox" where $dR_n/d\tau_c \leq 0$.

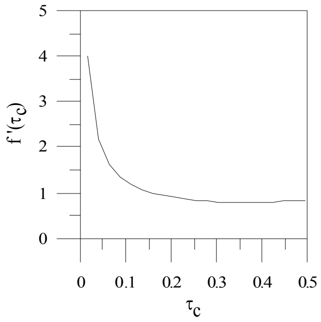

Figure 4: $f'(\tau_c) = df(\tau_c)/d\tau_c$ from Equation (9).

RESULTS

Air and canopy temperatures

T_c is the downward looking radiant temperature of canopy and integrates the emission of the vegetation elements at different heights (Equation (1)). In the Wolf Creek forest during snowmelt, the thermal gradient in the air below and above the canopy remained small during daytime (Figs. 5a and 5b). The temperature of the vegetation at the top of the canopy remained close to the air temperature whereas the low trunks are sensibly colder (Figs. 5c and 5d).

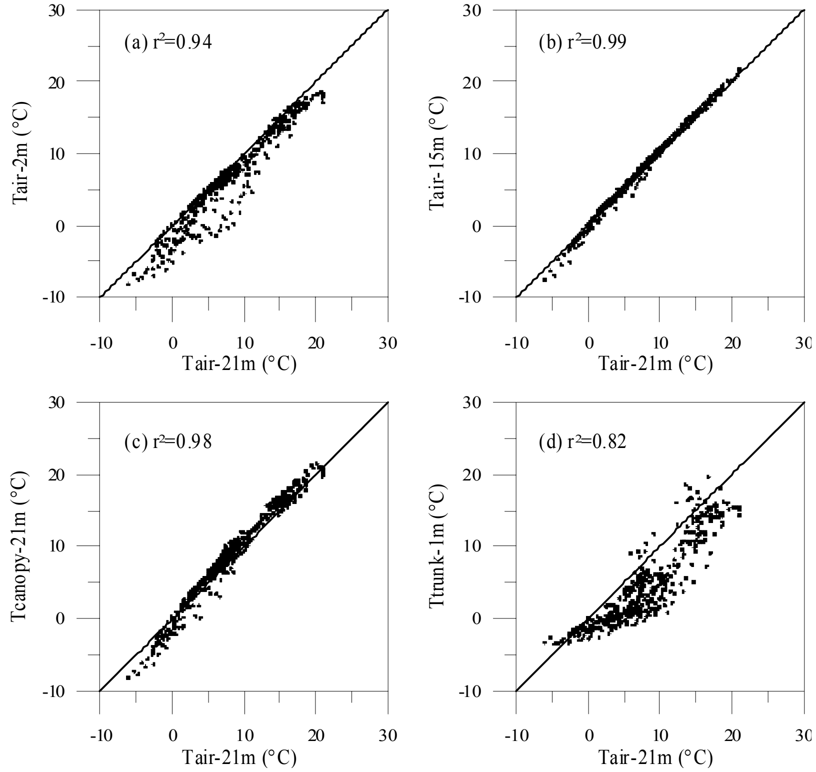

Figure 5: Comparisons between air and canopy temperatures, half-hourly averages during daytime (0800–2000h), Wolf Creek forest, April 11–30, 2003. Temperatures are plotted against the air temperature at 21-m height (canopy height is 18 m). (a) and (b) show the air temperature at 2-m and 15-m height, respectively. (c) shows the top of canopy temperature derived from infrared measurements. (d) shows the temperature of trunks at 1 m height measured by thermocouples.

Under clear sky, the enhancement of longwave irradiance below the dense forest of Wolf Creek is about 50% as a mean value during daytime ($L_o\downarrow$ = 210 W m^{-2}, $L\downarrow$ = 320 W m^{-2}). The radiant canopy temperature (T_c), derived from measurements of sub-canopy longwave irradiance (Equation (2)), is similar to the above-canopy air temperature during daytime (r^2 = 0.94, slope is 0.93, mean difference is 1.2°C with rms error of 1.9°C, Fig. 6). The errors in calculating sub-canopy irradiance using T_{air} instead of T_c in Equation (1) are small: the mean difference is 6 W m^{-2} and rms error is 10 W m^{-2} (Fig. 6).

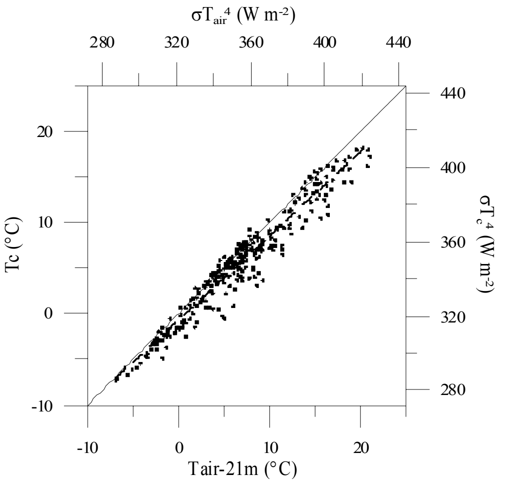

Figure 6: Hourly averages of the air temperature at 21-m height and the downward-looking radiant temperature of canopy (T_c) during daytime (0800–2000h), Wolf Creek forest, April 11–30, 2003. The dashed line is the fit to the data.

Dependence of net radiation to snow on canopy coverage

The daily sums of the positive values of net radiation at the snow surface were calculated as a function of sky view factor and effective shortwave transmissivity (Fig. 7). Calculations have been conducted from measurements of $L_o\downarrow$, T_{air}, and $K_o\downarrow$ in the Wolf Creek forest for one clear and one cloudy day, and for three different snow albedos.

Considering $\tau_c = V_f$ (e.g., Yamazaki and Kondo 1992, Gusev and Nasonova 2001), the positive radiative energy steadily decreases as the forest becomes denser (Equation (6) with $A = 1$, $B = 0$, and $\alpha_s = 0.5$, dashed lines, Figs. 7a-b). The logarithmic relation between V_f and τ_c (Equation (9)) causes a minimum of energy when the forest is very dense: at a sky view factor near to 0.15 and a shortwave transmissivity slightly less than 0.1 (solid lines, Figs. 7a-b). The curvature of Equation (9) is in agreement with low snowmelt rates generally observed in forested environments; a different curvature would cause a maximum of positive net radiative energy for some intermediate canopy cover (Fig. 7). During the observation period, the measured snow albedo was low, around 0.5, due to forest litter lying on and within the snowpack (e.g., Hardy et al. 2000). However, albedo measurements in forested environments may be biased towards underestimated values since elements of vegetation generally fall in the field of view of the hemispherical pyranometers. For larger values of snow albedo, positive values of net radiation to snow become quite independent of canopy cover ($\alpha_s = 0.7$, Fig. 7c), or even increase with canopy cover for the situation of a clean snowpack ($\alpha_s = 0.8$, Fig. 7d).

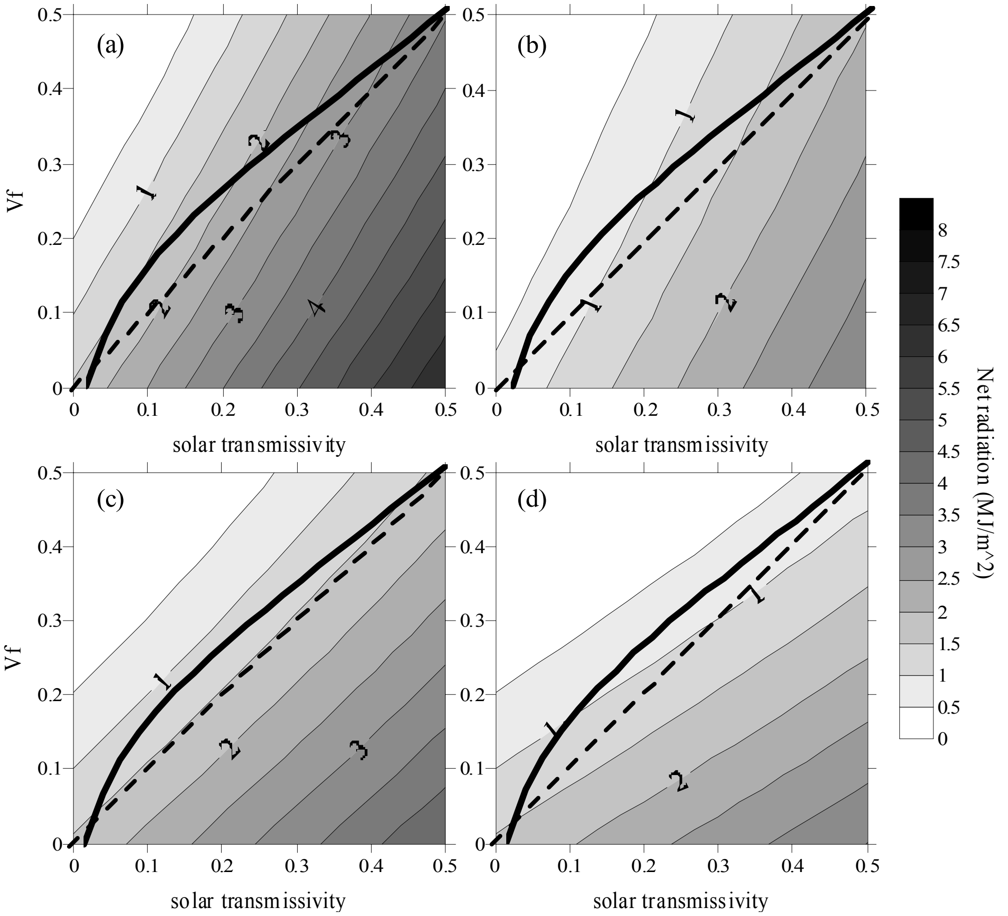

Figure 7: Daily sums of the positive values of net radiation as a function of sky view factor (V_f) and shortwave transmissivity (τ_c), Wolf Creek forest, spring 2003. (a) and (b) show April 13 (clear sky) and 18 (cloudy), respectively, with snow albedo measurements $\alpha_s = 0.5$. (c) and (d) show April 13 with snow albedo $\alpha_s = 0.7$ and 0.8, respectively. Dashed line is the one-to-one line. Solid curb shows Equation (9).

DISCUSSION AND CONCLUSION

This study investigates the dependence of net radiation at the snow surface to the canopy density, in which the canopy is described in terms of shortwave transmissivity and sky view factor. The focus is on the spring seasonal snowmelt period.

The sky view factor controls the apportionment of sub-canopy longwave irradiances originating from the atmosphere and from the vegetation (Equation (2)). It can be measured by fish-eye photographs or can be indirectly derived from radiation measurements (Welles 1990). However, the accuracy associated with sky view factors estimations is rarely discussed. Ambiguous concepts, related to three-dimensional architecture data or derived from two-dimensional surface reflectance values, are sometimes mixed up: crown closure, canopy density, canopy closure…. Here, a sensitivity study shows that the required accuracy on the sky view factor is about ± 0.1, whatever the forest density (Fig. 2). High accuracy is crucial in dry climate characterized by low atmospheric emissivities.

The radiant canopy temperature T_c was deduced from the comparison between the longwave irradiances below and above the canopy (Equation (2)). In Wolf Creek, T_c is slightly lower than the air temperature above the canopy, but the difference remains small (1.2°C as an average, Fig. 6). A large part of the longwave emission by the canopy probably originates from needles and small branches in thermal equilibrium with air. Air temperature can therefore be used as a substitute for the canopy radiant temperature of dense coniferous forests. In more open forests, trunks tend to be more heated by direct shortwave radiation, causing large thermal differences between vegetation and air when wind speed is low (Otterman et al. 1988), which may lead to large errors on L↓ considering $T_c = T_{air}$. The resolution of the temperature distribution through the canopy requires complex energy balance calculations, which may also lead to strong uncertainties. An important point would be to document the distribution of incoming longwave energy according to the angle of incidence in order to distinguish the trunks emission from the needles one.

The equation of net radiation allowed quantification of the atmospheric conditions that cause an offset between the shortwave energy attenuation and the longwave irradiance enhancement by the canopy (Equations (1) and (10)). Such an offset is favored in dry climates and at high altitudes, where atmospheric emissivities are low, and in early spring when snow albedo is high and sun elevation is still low.

As the snow surface beneath a canopy is not greatly cooled during the night, the daily sum of the positive values of the net radiation is a good index of the snowmelt rate. The relation between snowmelt and canopy cover depends on the relation between shortwave transmissivity and sky view factor (Fig. 7). Measurements in boreal forests suggest a double logarithmic dependence of the sky view factor according to the shortwave transmissivity (Equation 9). Fixing the minimum shortwave transmissivity (around 2%) corresponding to a completely closed evergreen forest, the curvature of Equation (9) can be adapted to different climates and canopy structural characteristics by fitting two parameters.

In the spring climate of Wolf Creek, a canopy cover increase causes a steady decrease in snowmelt, when the snow albedo is low, until a density close to the actual density of the studied spruce forest (Fig. 7). Large snow albedo values cause a low dependence of snowmelt to the canopy cover or a steady increase in melting energy when the canopy cover increases (Fig. 7). As the canopy density of the Wolf Creek forest ($V_f = 13\%$) is close to the maximum value of natural environments, boreal evergreen forests do not favor the appearance of a minimum snowmelt rate under some intermediate canopy cover.

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