Effects of needleleaf forest cover on radiation and snowmelt dynamics in the Canadian Rocky Mountains

C.R. Ellis, J.W. Pomeroy, R.L.H. Essery, and T.E. Link

Abstract: Radiation is the main energy source for snowpack warming and melt in mountain needleleaf forests, and runoff from these forests is the main contributor to spring river flows in western North America. Utilizing extensive field observations, the effect of needleleaf forest cover on radiation and snowmelt timing was quantified at pine and spruce forest sites and nearby clearings of varying slope and aspect in an eastern Canadian Rocky Mountain headwater basin. Compared with open clearings sites, shortwave radiation was much reduced under forest cover, resulting in smaller differences in melt timing between forested slopes relative to open slopes with different aspects. In contrast, longwave radiation to snow was substantially enhanced under forest cover, especially at the dense spruce forest sites where longwave radiation dominated total energy for snowmelt. In both pine and spruce environments, forest cover acted to substantially reduce total radiation to snow and delay snowmelt timing on south-facing slopes while increasing total radiation and advancing snowmelt timing on north-facing slopes. Results strongly suggest that impacts on radiation to snow and snowmelt timing from changes in mountain forest cover will depend much on the slope and aspect at which changes occur.

Résumé : Le rayonnement est la principale source d’énergie qui réchauffe et fait fondre la couche de neige dans les forêts alpines de conifères où le ruissellement contribue dans une large mesure au débit printanier des rivières dans l’ouest de l’Amérique du Nord. À l’aide de nombreuses observations sur le terrain, dans un bassin de tête de la partie est des montagnes Rocheuses canadiennes, l’effet du couvert de forêt de conifères sur le rayonnement et sur le moment de la fonte de la neige a été quantifié dans des stations occupées par des forêts de pin et d’épinette ainsi que dans des clairières avoisinantes dont la pente et l’exposition étaient variables. Comparativement aux clairières ouvertes, le rayonnement de courtes longueurs d’onde était très faible sous le couvert forestier, ce qui se traduisait par de plus petites différences dans le moment de la fonte entre les pentes couvertes de forêt et les pentes dégagées avec différentes expositions. À l’inverse, le rayonnement de longues longueurs d’onde sur la neige était substanllement plus élevé sous le couvert forestier, particulièrement dans les stations de forêt dense d’épinette où le rayonnement de longues longueurs d’onde dominait l’énergie totale pour la fonte de la neige. Dans les environnements tant de pin que d’épinette, le couvert forestier réduisait substantiellement le rayonnement total qui atteint la neige et retarde le moment de la fonte de la neige sur les pentes exposées au sud tandis qu’il augmente le rayonnement total et devance le moment de la fonte de la neige sur les pentes exposées au nord. Les résultats indiquent clairement que les impacts du rayonnement dus aux modifications du couvert forestier alpin sur la neige et sur le moment de la fonte de la neige dépendront beaucoup de la pente et de l’exposition aux endroits où ces modifications surviennent.

Introduction

Snowmelt is one of the most important hydrological events in mountain regions, responsible for soil moisture recharge (e.g., Grant et al. 2004), vegetation growth (e.g., Cooper et al. 2006), and ecosystem productivity (e.g., Arp et al. 2006). Mountain snowmelt is the source of the majority of river flows in western North America (Marks and Winstral 2001) and hence is of great importance to downstream water resource users. As much of the North American cold-region mountain terrain is covered by evergreen needleleaf forest, turbulent energy exchanges to subcanopy snowcovers are suppressed (Harding and Pomeroy 1996) and snowmelt is driven primarily by radiation (U.S. Army Corps of Engineers 1956). This is with exception of more coastal mountain environments where large amounts of snowmelt energy may be delivered through rainfall, having the potential to cause rapid melt and flooding (Beaudry and Golding 1983; Marks et al. 1998). However, for more interior mountain ranges, effective prediction of the timing and magnitude of snowmelt runoff is expected to require an understanding of how needleleaf forest cover influences radiation...
radiation for snowmelt across complex terrain. Extensive field studies by Golding and Swanson (1978) and Troendle and Leaf (1981) have shown the timing and rate of snowmelt to differ substantially between level forests and clearings. Yet comparatively little has been reported regarding the combined effects of forest cover and slope and aspect on snowmelt in mountain regions. Together, information of both forest cover and topography effects are expected to be important in anticipating how the changes in forest cover (e.g., clearcutting, fire, disease) may impact the timing of snowmelt in mountain regions (Gary 1980).

Quantification of net all-wave radiation to snow (\( R^* \)) is made by the sum of net shortwave (\( K^* \)) and net longwave (\( L^* \)) balances, each composed of incoming and outgoing fluxes, i.e.,
\[
R^* = K^* + L^* = K_{in} - K_{out} + L_{in} - L_{out}
\]
Here, \( K^* \) is related to \( K_{in} \) by the snow albedo (\( \alpha_s \)) through
\[
K^* = K_{in} - K_{out} = K_{in}(1 - \alpha_s)
\]

Forest cover has been observed to have a counteracting effect on radiation to snow by reducing shortwave irradiance via canopy extinction (i.e., reflection and absorption) (Ellis and Pomeroy 2007; Link and Marks 1999) while increasing longwave irradiance from foliage thermal emissions (Black et al. 1991; Reifsnyder and Lull 1965). Here, the reduction of shortwave irradiance in forests is commonly expressed in terms of the forest shortwave transmittance (\( \tau \)):
\[
\tau = \frac{K_{in}}{K_o}
\]
where \( K_{in} \) and \( K_o \) denote the subcanopy and above-canopy shortwave irradiance fluxes, respectively. The offsetting of shortwave reductions in forests by canopy longwave emissions is promoted particularly during conditions of high snow albedo (Jeffrey 1970) and in high latitudes or altitude environments where atmospheric longwave emissions are relatively low (Sicart et al. 2004).

Although much focus has been placed on quantifying radiation for snowmelt in level needleleaf forests (e.g., Gryning et al. 2001; Metcalfe and Buttle 1995), how variations in topography (i.e., slope and aspect) and forest cover control radiation to snow in mountain systems is comparatively lacking in the literature. Such information would improve the understanding of how radiation to snow varies across complex terrain and help identify needs for future developments of spatially distributed snowmelt models (e.g., Marks et al. 1999).

The primary objective of this study is to quantify the effects of both forest cover and slope and aspect on radiation to snow and the timing of snowmelt in mountain environments. Particular focus will be placed on examining how topography and forest cover determine the relative amounts of shortwave and longwave radiation to snow, as well as their contributions to snowmelt energy in both lower elevation pine forest stands and higher elevation spruce forest stands. This will be accomplished through analysis of radiation and other field meteorological observations, as well as snow survey data collected at paired forest and clearing sites of varying elevation, slope, and aspect located in a headwater basin in the eastern slopes of the Canadian Rocky Mountains. Although analysis relies primarily upon field observations, appropriate corrections and estimations of radiation fluxes and meteorological variables are made where necessary.

**Observation sites and instrumentation**

**Observation sites**

All field observations were made at the Marmot Creek Research Basin (MCRB), Alberta, Canada (50°57’N, 115°09’W) (Fig. 1). Elevation of the basin ranges from 1550 to 2750 m above sea level (a.s.l.), with the lower elevations covered by lodgepole pine forest (\( P. contorta \) var. latifolia Engelm. ex S. Wats.) and upper elevations covered by Engelmann spruce (\( P. engelmannii \) Parry ex Engelm.), subalpine fir (\( A. lasiocarpa \) (Hook.) Nutt.), and subalpine larch (\( L. lyallii \) Parl.). During the spring of 2005, near-surface meteorological observations were made at the following sites: level pine clearing (LPC), level pine forest (LPF), north-facing pine forest (NPF), southeast-facing pine clearing (SPC), and southeast-facing pine forest (SPF). Similar observations were made during the spring of 2008 at level spruce clearing (LSC), north-facing spruce forest (NSF), and south-facing spruce forest (SSF) sites. Snow surveys were conducted at all pine and spruce sites during their respective study periods, as well as at north-facing spruce clearing (NSC) and south-facing spruce clearing (SSC) sites located adjacent to the NSF and SSF sites, respectively. To allow a greater comparison of radiation and snowmelt between sloping clearing and forest sites, simulations of shortwave irradiance were made to a hypothetical north-facing pine clearing (NPC) site of the same slope and aspect as the NPF site, as well to the non-instrumented NSC and SSC sites using standard radiation correction procedures for topography. The locations of all study sites at the MCRB are shown in Fig. 1, with descriptions of the topography and forest cover at each site provided in Table 1. Analysis of both the 2005 pine and 2008 spruce meteorological and snow survey data sets focuses on two primary observation periods: (i) an extended observation period from 15 February to 15 May at both pine and spruce sites, allowing the comparison of meteorological conditions over the same springtime period, and (ii) the period during snowpack warming and melt, from 13 March to 4 April 2005 (day of year (DOY) 72 to 95) at the pine sites and from 30 March to 29 May 2008 (DOY 90 to 150) at the spruce sites. Reference meteorological conditions observed at the LPC and LSC sites during the respective extended February to May observation periods, as well as the snowpack warming and melt periods, are given in Table 2.

**Instrumentation**

**Radiation sensors**

Radiometers at the meteorological observation sites were positioned approximately 1.5 m above the snow surface and inclined parallel to their respective ground surfaces; thus radiation fluxes always refer to the direction normal to the ground surface. Incoming and outgoing shortwave and longwave fluxes were measured, respectively, using recently
Fig. 1. Map of the Marmot Creek Research Basin (MCRB) showing the locations of the level pine clearing (LPC), level forest pine forest (LPF), north-facing pine clearing (NPC), north-facing pine forest (NPF), southeast-facing pine clearing (SPC), southeast-facing pine forest (SPF), level spruce clearing (LSC), north-facing spruce forest (NSF), south-facing spruce forest (SSF), north-facing spruce clearing (NSC), and south-facing spruce clearing (SSC) sites. Inset at bottom indicates the general location of the MCRB.

Table 1. Topographic and forest cover descriptions of pine and spruce study sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Elevation (m a.s.l.)</th>
<th>Slope gradient (°)</th>
<th>Slope aspect (°)</th>
<th>Forest coverage</th>
<th>No. of hemispherical images/LAI’ measures</th>
<th>LAI’</th>
<th>Sky view factor (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPC</td>
<td>1457</td>
<td>0</td>
<td>—</td>
<td>None</td>
<td>1</td>
<td>0†</td>
<td>0.96</td>
</tr>
<tr>
<td>LPF</td>
<td>1492</td>
<td>0</td>
<td>—</td>
<td>Continuous</td>
<td>46</td>
<td>1.48</td>
<td>0.21 0.22</td>
</tr>
<tr>
<td>NPF</td>
<td>1480</td>
<td>29</td>
<td>351</td>
<td>Continuous</td>
<td>32</td>
<td>1.57</td>
<td>0.10 0.19</td>
</tr>
<tr>
<td>NPC*</td>
<td>1480</td>
<td>29</td>
<td>351</td>
<td>None</td>
<td>—</td>
<td>0*</td>
<td>— 0.96</td>
</tr>
<tr>
<td>SPC</td>
<td>1526</td>
<td>27</td>
<td>128</td>
<td>None</td>
<td>1</td>
<td>0†</td>
<td>— 0.93</td>
</tr>
<tr>
<td>SPF</td>
<td>1523</td>
<td>26</td>
<td>125</td>
<td>Discontinuous</td>
<td>57</td>
<td>1.33</td>
<td>0.32 0.34</td>
</tr>
<tr>
<td>LSC</td>
<td>1848</td>
<td>0</td>
<td>—</td>
<td>None</td>
<td>1</td>
<td>1.19</td>
<td>0.11 0.09</td>
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<tr>
<td>NSC</td>
<td>2040</td>
<td>29</td>
<td>347</td>
<td>None</td>
<td>1</td>
<td>1.19</td>
<td>0.11 0.09</td>
</tr>
<tr>
<td>NSF</td>
<td>2037</td>
<td>28</td>
<td>348</td>
<td>Continuous</td>
<td>26</td>
<td>1.8</td>
<td>0.11 0.16</td>
</tr>
<tr>
<td>SSC</td>
<td>2012</td>
<td>27</td>
<td>176</td>
<td>Continuous</td>
<td>1</td>
<td>0†</td>
<td>— 0.95</td>
</tr>
<tr>
<td>SSF</td>
<td>2008</td>
<td>28</td>
<td>176</td>
<td>None</td>
<td>21</td>
<td>2.4</td>
<td>0.13 0.09</td>
</tr>
</tbody>
</table>

Note: Site codes: LPC, level pine clearing; LPF, level forest pine forest; NPF, north-facing pine forest; NPC, north-facing pine clearing; SPC, southeast-facing pine clearing; SPF, southeast-facing pine forest; LSC, level spruce clearing; NSC, north-facing spruce clearing; NSF, north-facing spruce forest; SSF, south-facing spruce forest. SD, standard deviation.

*Hypothetical site assigned the same slope and aspect as the NPF and the same sky view factor (v) as the LPC.

†Value refers to the centre of the clearing and does not include surrounding vegetation.
site radiometers (obs.) were corrected (corr.) to that of the irradiance (both abbreviated here as forest trunks. Observations of daily shortwave and longwave LPF and SPF sites, being located at varying proximity to tioned randomly near the permanent site radiometers at the site. The single array radiometers were spatially posi- the permanent site radiometers were corrected to that meas- errors were considered solely random and are specified ac- brated radiometers at all study sites, systematic instrument errors were considered solely random and are specified ac- cording to the manufacturer in Table 3. In forests, the accu- calibrations of radiometric observations are provided in Table 3. Radiometers were calibrated and measurements were stored by Campbell Scientific data-loggers (models 23X, 10X), with observations acquired every 10 s and time-averaged values stored at 15 min inter- vals. Shortwave and longwave fluxes at each site were measured by single radiometers, with the exception of the SPF site where two additional upward-facing pyranometers and pyrgeometers were deployed to better account for the increased spatial variation of forest cover. Accurate measurements of radiation in the field are chal- lenging due to both instrument and sampling errors, each of which may be random or systematic in nature (Moore and Rowland 1990). However, with the use of recently cali- brated radiometers at all study sites, systematic instrument errors were considered solely random and are specified ac- cording to the manufacturer in Table 3. In forests, the accurate measurement of incoming radiation (i.e., irradiance) is further complicated by the heterogeneous spatial distribution of canopy cover (Link et al. 2004; Pomeroy et al. 2008), which among the forest study sites was most pronounced at the LPF sites. To account for potential sampling errors at these sites, shortwave and longwave irradiance from the permanent site radiometers were corrected to that measured by an array of 10 pyranometers and 12 pyrgeometers at each site. The single array radiometers were spatially positioned randomly near the permanent site radiometers at the LPF and SPF sites, being located at varying proximity to forest trunks. Observations of daily shortwave and longwave irradiance (both abbreviated here as $I_{\text{in}}$) from the permanent site radiometers (obs.) were corrected (corr.) to that of the array by the mean bias (MB) coefficient between the two, i.e.,

\[ \text{corr. daily site } I_{\text{in}} = (\text{obs. daily site } I_{\text{in}}) + \text{MB} \]

\[ = (\text{obs. daily site } I_{\text{in}}) + \frac{\sum_{t=0}^{n} I_{\text{in}}(\text{array})}{\sum_{t=0}^{n} I_{\text{in}}(\text{site})} \]

where $t = 0$ to $t = n$ define the start and end of the time period of array observations. Differences in irradiance between the permanent site observations and array observations at the LPF and SPF sites are stated in terms of both absolute magnitudes and MB in Table 4. Although uncertainty exists in how representative MB values are over the extended observation period due to effects such as changing solar eleva- tions, resulting errors are likely small, considering the small changes in shortwave and longwave spatial variation in these forests over daily time scales or longer (Pomeroy et al. 2008; Essery et al. 2008). This is further supported by the MB values calculated over hourly time scales at both sites, which compared well to daily values, with the exception of early morning and late evening periods.

**Temperature sensors**

Snow and canopy foliage temperatures were measured every 10 s, with average values recorded and stored at 15 min intervals during the respective study periods at the meteorological observation sites, as were the south-exposed trunk surface temperatures at the LPF, SPF, NSF, and SSF sites. Temperatures were measured using Exergen IRt/5-K-
50F/10C (capacitor removed) infrared thermocouples (IRt/c) (Exergen Corporation, Watertown, Massachusetts), with an expected error to that of true temperature ranging from ±0.01 °C at 0 °C, to ±2 °C at 24 °C (Omega Engineering 1994), which were housed within reflective enclosures to minimize errors from shortwave heating. Air temperatures were measured approximately 2 m above the ground surface at all sites using Vaisala HMP45A combination temperature–humidity sensors housed within Gill radiation shields, with an expected error of ±0.1 °C (Vaisala 2008).

**Description of forest cover density**

At all study sites, upward-looking hemispherical images were obtained at positions corresponding to each of the permanent site radiometers and array radiometers during overcast sky conditions for the purpose of digital analysis. Images were acquired using a Nikon Coolpix 5000 digital camera fitted with a 183° field of view fisheye converter lens. Estimates of the effective leaf-area index (LAI'), defined here as being equal to one-half of the total plant surface area not self-shaded by foliage clumping effects per unit ground surface area, were made at the LPF, NPF, SPF, SPC, NSF, and SSF sites from hemispherical image analysis using GLA 2.0 software (Frazer et al. 2000). This software computes the angular distribution of gap and non-gap fractions of a hemispherical forest scene by the division of image pixels into ‘sky’ and ‘non-sky’ classes. Alternatively, the sky view factor (v) of each forest site was approximated as the measured shortwave transmittance (at the LPF and SPF sites, mean array irradiance was used for this purpose) during cloud-covered days when radiation variations across the sky hemisphere are relatively small. At the LPC and LSC sites, where surrounding terrain occupied the sky view, v was estimated from analysis of digital elevation data of the MCRB and surrounding area.

**Snow surveys**

Measurements of snow water equivalent (SWE) were obtained from surveys of snow depth and density repeated approximately every 2 to 3 weeks prior to snowmelt and every 2 to 3 days during snowmelt. Snow depth measurement were performed along established transects at a spacing of approximately 1 m at the clearing sites and about 0.5 m at the forest sites to account for the greater spatial variation of forest snow depth. Determinations of snow density were made from snow mass measurements taken at every fifth depth sample using either an ESC-30 snow tube (and calibrated scale) or a Perla-style (RIP) snow cutter scoop in which samples were taken along the vertical profile of a dug snow-pit and weighed in the field using an electronic balance. At the meteorological observation sites, the relating of snow survey areal depths to continuous point depth measurements acquired by a SR50 sonic ranger allowed the construction of a continuous and spatially representative data set of snow depth and SWE for each site.

**Results**

**Shortwave irradiance (\(K_{in}\))**

Over the extended February to May period at both the
pine and spruce locations, mean daily shortwave irradiance ($K_{in}$) between sites varied substantially, ranging from approximately 1.5 MJ m$^{-2}$ at the north-facing forests (NPF and NSF sites) to greater than 15 MJ m$^{-2}$ at the south-facing clearings (SPC and SSC sites), equal to a ratio of approximately 0.1 and 1.2 to that observed at their respective level clearings (LPC and LSC sites) (Table 5). Overall, forest cover acted to greatly reduce the absolute differences in $K_{in}$ produced by slope and aspect effects, especially between the spruce forest sites where the low forest shortwave transmittances ($\tau$) of 0.12 at the NSF site and 0.11 at the SSF site gave corresponding low daily $K_{in}$ values of 1.5 and 1.7 MJ m$^{-2}$. By comparison, shortwave transmittances exhibited much greater variation among the pine forest sites, with mean $\tau$ values ranging from 0.34 at the SPF site to 0.13 at the NPF site, producing corresponding daily $K_{in}$ magnitudes of 5.4 and 1.4 MJ m$^{-2}$ (Table 5).

In the pine forest, the high shortwave transmittance ($\tau$) through the SPF resulted in a pronounced increase in the ratio of daily subcanopy $K_{in}$ to above-canopy $K_{in}$, with decreased ratios at the lower transmittance LPF and NPF sites. Consequently, differences in subcanopy $K_{in}$ between the pine forest sites increase progressively as above-canopy $K_{in}$ increases, as observed at the LPC site (Fig. 2). By contrast, the low $\tau$ through the spruce forest results in little response in subcanopy $K_{in}$ at either the NSF site or the SSF site to changes in above-canopy $K_{in}$ observed at the LSC site (Fig. 3). As a result, similar low magnitudes of subcanopy $K_{in}$ are maintained at both the NSF and SSF sites regardless of changing above-canopy $K_{in}$.

Longwave irradiance ($L_{in}$)

As a result of canopy longwave radiation emissions, longwave irradiance ($L_{in}$) to snow at the forested sites was much greater than at the clearing sites over the February to May period (Table 6). Note here that as no observations of $L_{in}$ were made at the sloped clearing sites, values at these sites were assigned the same as their respective level clearing sites (i.e., LPC, LSC), as substantial differences of $L_{in}$ in the open are expected only from variations in longwave emissions from surrounding terrain during clear sky conditions (Sicart et al. 2004). As shown in Table 6, despite a lower overall $L_{in}$ at the spruce forest sites relative to the pine forests, the amount of subcanopy longwave enhancement was similar among both the pine and spruce forests. At the spruce forest sites, subcanopy longwave enhancements are attributed primarily to increased forest longwave emissions from the dense canopy coverage. Alternatively, at the sparser pine sites, subcanopy longwave enhancements are also ascribed to added longwave emissions from canopy heating via shortwave irradiance absorption (Pomeroy et al. 2009). Such heating is most marked at the SPF site, where the sparse canopy coverage and more southern orientation of the site allow increased penetration of shortwave irradiance and heating of the lower trunk layer of the canopy. Such heating may be substantial, as observed by south-exposed trunk temperatures being more than 20 °C warmer.

### Table 5. Mean daily shortwave irradiance ($K_{in}$) at each study site over the extended observation period of 15 February to 15 May stated in terms of mean irradiance and the ratio relative to the respective level clearing site (indicated by an asterisk (*)). For the forest sites, the mean shortwave transmittance of forest cover ($\tau$) is also given.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean daily $K_{in}$ (MJ m$^{-2}$ day$^{-1}$)</th>
<th>Ratio to level clearing site</th>
<th>Forest shortwave transmittance ($\tau$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPC*</td>
<td>13.2</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>LPF</td>
<td>2.9</td>
<td>0.22</td>
<td>0.22</td>
</tr>
<tr>
<td>NPC</td>
<td>10.5</td>
<td>0.80</td>
<td>—</td>
</tr>
<tr>
<td>NPF</td>
<td>1.4</td>
<td>0.11</td>
<td>0.13</td>
</tr>
<tr>
<td>SPC</td>
<td>15.8</td>
<td>1.20</td>
<td>—</td>
</tr>
<tr>
<td>SPF</td>
<td>5.4</td>
<td>0.41</td>
<td>0.34</td>
</tr>
<tr>
<td>LSC*</td>
<td>14.5</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>NSC</td>
<td>11.8</td>
<td>0.81</td>
<td>—</td>
</tr>
<tr>
<td>NSF</td>
<td>1.5</td>
<td>0.10</td>
<td>0.12</td>
</tr>
<tr>
<td>SSC</td>
<td>16.4</td>
<td>1.13</td>
<td>—</td>
</tr>
<tr>
<td>SSF</td>
<td>1.7</td>
<td>0.12</td>
<td>0.11</td>
</tr>
</tbody>
</table>

**Note:** See Table 1 or List of symbols for site codes.

### Fig. 2. Relation between the daily shortwave irradiance ($K_{in}$) observed at the level pine clearing (LPC) site compared with $K_{in}$ observed at the level pine forest (LPF), southeast-facing pine clearing (SPC), and southeast-facing pine forest (SPF) sites for the period of 3 April to 29 April 2005.

### Fig. 3. Relation between the daily shortwave irradiance ($K_{in}$) observed at the level spruce clearing (LSC) site compared with $K_{in}$ observed at the north-facing spruce forest (NSF) and south-facing spruce forest (SSF) sites for the period of 3 April to 29 April 2008.
than air temperatures during midday periods of high shortwave irradiance. Similar shortwave canopy heating effects on subcanopy longwave irradiance have been investigated and reported by Pomeroy et al. (2009) in various needle-leaf forest stands. Alternatively, no substantial longwave enhancement from canopy shortwave heating was observed at either of the spruce forest sites, which is attributed to the extinction of shortwave irradiance higher within the dense-canopies at these sites.

### Net shortwave radiation ($K^*$)

At sites at which both incoming and outgoing shortwave fluxes were observed, net shortwave radiation ($K^*$) to snow was determined via eq. 2. However, in forest environments, accurate determinations of $K^*$ to snow using $K_{out}$ observations are subject to error from the exposure of dark understory vegetation as snowcover ablates. To minimize such errors, $K_{out}$ observations were used in determining $K^*$ only during times of complete snowcover within the field of view of the downward-facing radiometer as determined from daily field notes and photographs of snowcover at each site during melt. For periods of partial snowcover, $K^*$ was instead estimated through a linear extrapolation of the daily snow albedo ($\alpha_s$) decay rates determined during continuous snowcover. Although this method is unlikely to provide an exact representation of the many factors governing snow albedo decay rates at each site, it does provide a general approximation of $K^*$ for the purpose of further analysis.

At the NPC site, $\alpha_s$ was approximated by values observed at the LPC site. However, at the NSC and SSC sites, where $\alpha_s$ observations from a nearby clearing were not available, daily $\alpha_s$ was instead estimated by regression relations developed between daily forest $\alpha_s$ values from radiometer measurements and $\alpha_s$ at the corresponding clearing site determined from reflectance measurements obtained using a portable spectrophotometer (FieldSpec-FR; Analytical Spectral Devices Inc., Boulder, Colorado). Spectrophotometer reflectance measurements were made at the NSC and SSC sites approximately every 48 h for a period of 10 days prior to and after the onset of melt (i.e., DOY 130) following the procedure outlined by Melloh et al. (2001) in which 50 spectrophotometer measurements were obtained at each site to reduce random sampling errors and to minimize the ratio of noise-to-signal returns. To account for the effects of varying angular reflectance from snow, measurements were obtained over a large range of angles to the snow surface. Best approximation of clearing $\alpha_s$ from forest $\alpha_s$ values were made via separate linear regression relations for the periods of pre-melt and melt (i.e., melt occurring at one or both sites), with strongest relations between clearing and forest sites on both slopes obtained for the pre-melt period (i.e., $R^2 = 0.90$ (NSC–NSF); $R^2 = 0.97$ (SSC–SSF)). By comparison, the slightly weaker relations during the melt period ($R^2 = 0.72$ (NSC–NSF); $R^2 = 0.73$ (SSC–SSF)) resulted from the divergence in snow albedo decay rates for melting and non-melting snow between the paired clearing and forest sites. To maintain a realistic representation of snow albedo, estimated $\alpha_s$ values were constrained to a minimum of 0.6, which closely corresponds to the lower limit of values obtained from spectrophotometer measurements over un-littered snow. Lastly, upon the complete disappearance of snowcover, $\alpha_s$ was set to 0.2 to approximate bare ground albedo.

### Net longwave radiation ($L^*$)

Similar to that of reflected shortwave irradiance, no direct observations of longwave exitance from snow ($L_{out}$) were obtained at the NPC, NSC, and SSC sites. Instead, $L_{out}$ was estimated from snow surface temperatures ($T_a$) at these sites using the following the longwave-psychrometric formulation by J.W. Pomeroy and R.L.H. Essery (unpublished):

$$
T_s = T_a + \frac{\varepsilon_s(L_{in} - \sigma T_a^4) + \lambda_s(\omega_a - \omega_s)\rho_s r_s}{4\varepsilon_s\sigma T_a^3 + (c_p + \lambda_s \Delta)\rho_s r_s}
$$

where $\varepsilon_s$ is the thermal emissivity of snow (0.98) (Oke 1987), $\sigma$ is the Stephan–Boltzmann constant ($5.67 \times 10^{-8}$ W·m$^{-2}$·K$^{-4}$), $\omega_a$ and $\omega_s$ are the specific and saturation mixing ratios (dimensionless), respectively, $c_p$ is the specific heat capacity of air (MJ·kg$^{-1}$·K$^{-1}$), $\rho_s$ is the density of air (kg·m$^{-3}$), $\lambda_s$ is the latent heat of sublimation for ice (MJ·kg$^{-1}$), $r_s$ is the aerodynamic resistance (s·m$^{-1}$), and $\Delta$ is the slope of the saturation vapour pressure curve (kPa·K$^{-1}$). Estimates of $T_s$ by eq. 5 were made using $T_a$ observations from the paired forest sites, as well as wind speeds, which were adjusted to account for forest sheltering effects in proportion to forest cover density (Ellis et al. 2010). Comparisons of simulated $T_s$ with those observations at the LPC site over a two-week period show good estimation using the approach, with mean observed and simulated $T_s$ values for the period equal to $-13.7$ °C and $-12.5$ °C, respectively, which were both substantially colder than the mean air temperature of $-8.1$ °C over the period.

From simulations of $T_s$, the net longwave radiation ($L^*$) at each site was resolved as the balance of incoming longwave irradiance to snow and longwave exitance from snow by

$$
L^* = \varepsilon_s(L_{in} - \sigma T_s^4)
$$

### Table 6. Mean daily longwave irradiance ($L_{in}$) at each study site for the extended observation period of 15 February to 15 May stated in terms of mean irradiance and the ratio and difference relative to the respective level clearing site (indicated by an asterisk (*)).

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean daily $L_{in}$ (MJ·m$^{-2}$·day$^{-1}$)</th>
<th>Ratio to level clearing site</th>
<th>Difference to level clearing site (MJ·m$^{-2}$·day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPC*</td>
<td>22.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>LPF</td>
<td>25.9</td>
<td>1.17</td>
<td>3.9</td>
</tr>
<tr>
<td>NPC</td>
<td>22.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>NPF</td>
<td>26.1</td>
<td>1.18</td>
<td>4.1</td>
</tr>
<tr>
<td>SPC</td>
<td>22.2</td>
<td>1.01</td>
<td>0.2</td>
</tr>
<tr>
<td>SPF</td>
<td>26.6</td>
<td>1.21</td>
<td>4.6</td>
</tr>
<tr>
<td>LSC*</td>
<td>19.8</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>NSC</td>
<td>19.8</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>NSF</td>
<td>24.2</td>
<td>1.22</td>
<td>4.4</td>
</tr>
<tr>
<td>SSC</td>
<td>19.8</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>SSF</td>
<td>24.4</td>
<td>1.23</td>
<td>4.6</td>
</tr>
</tbody>
</table>

**Note:** See Table 1 or List of symbols for site codes.
Net radiation and ablation rates during periods of snowpack warming and melt

Time series data of SWE, as well as magnitudes of daily net shortwave ($K^*$) and daily net longwave radiation ($L^*$), are shown over the respective periods of snowpack warming and melt at the pine sites (2005) in Fig. 4 and at the spruce sites (2008) in Fig. 5. Here, the comparison between pine and spruce sites reveals a marked difference in snow accumulations, with those at the higher elevation spruce location approaching roughly fivefold the accumulations at the lower elevation pine sites. Although it must be noted that this comparison is made between observations from different years, snow survey data from other years indicate that these amounts largely typify snow accumulations at these loca-
tions, both in absolute terms and in the relative amounts between sites. Large differences in snow accumulations are also seen between that in the open and that under forest cover, with interception losses ranging from about 40% to 60% in both pine and spruce forests.

In general, the effect of forest cover on snowmelt timing differs substantially with slope and aspect. On south-facing aspects, the start of snowmelt was delayed under forest cover relative to in the open by approximately 8 days at the pine locations (Fig. 4a) and 15 days at the spruce locations (Fig. 5a). On level topography, observations at the pine sites show snowmelt beginning at both the LPC and LPF sites on
DOY 85, with slightly more rapid snowmelt at the clearing site. Similarly, snowmelt began on DOY 130 at both the NSC and NSF sites, but with much slower melt at the clearing site where a substantial snowpack remained until the end of the observation period.

In addition to melt rate differences between paired forest and clearing sites, overall slower snowmelt rates were observed at the pine sites relative to the spruce sites. Here, mean daily melt rates ranged from 4.6 to 1.6 mm SWE/day–1 at the pine SPC and NPF sites, respectively, compared with more rapid melt rates ranging from 12.9 to 5.4 mm SWE/day–1 at the spruce SSC and NSC sites. Note that there were no snow data from the hypothetical NPC site for the purpose of snowmelt rate comparison. Among the pine forest sites alone, considerable differences in melt rates were also observed, equal to 3.7, 2.8, and 1.6 mm SWE/day–1 at the SPF, LPF, and NPF sites, respectively. In comparison, much higher melt rates were observed in the spruce forests, but with little difference between north-facing and south-facing sites, with corresponding melt rates of 11.3 and 11.1 mm SWE/day–1 at the NSF and SSF sites, respectively.

Over the period of snowpack warming and melt, radiation at all pine and spruce clearing sites is shown to be largely dominated by net shortwave (Figs. 5 and 6), as net longwave (L*) was strongly negative. Longwave losses were especially pronounced at the pine clearing sites, where mean L* losses exceeded 3 MJ-m⁻²-day⁻¹, as compared with the more modest longwave losses of less than 2 MJ-m⁻²-day⁻¹ at the spruce clearing sites. Alternatively, much smaller K* and L* balances were realized at all forest sites, with slight negative and positive L* balances among the pine forest sites, but substantial L* gains at the spruce forests, which dominated total radiation to snow. Longwave gains to snow at the spruce forest sites were most pronounced during snowmelt events (i.e., periods starting at DOY 104, 118, and 130) when air and canopy temperatures were above freezing and longwave exitance (Lout) was limited by the restriction of snow surface temperature (Ts) to a maximum of 0°C.

A summary of the mean daily net radiation terms during the main snowmelt event at the pine study sites (starting on DOY 84) and the spruce study sites (starting DOY 130) is shown in Fig. 6. At each site, radiation terms are shown compared with the mean amount of energy consumed by melt (Qm; MJ-m⁻²-day⁻¹) as determined from the mean snowmelt rate (M; kg-m⁻²-day⁻¹) by

\[ Q_m = \beta \lambda_f M \]

where \( \beta \) is the fraction of ice in wet snow, which was specified in eq. 7 equal to 0.96, and \( \lambda_f \) is the latent heat of fusion for ice (MJ-kg⁻¹). Overall, there is a general correspondence between \( R^* \) and \( Q_m \) among sites (Fig. 6), with \( R^* < Q_m \) at the clearing sites a possible consequence of additional energy contributions to melt provided by turbulent exchanges (Ellis et al. 2010). At all sites, \( R^* \) is positive over the melt period, with the exception of the hypothetical NPC site where longwave losses exceed shortwave gains, resulting in a slightly negative \( R^* \) balance. Apparent in Fig. 6 are the distinct differences in radiation balances between forest and clearing sites, with large shortwave gains and longwave losses at the clearing sites compared with the relatively small forest radiation balances. Marked differences are also seen in the shortwave and longwave contributions to \( R^* \) be-
tween the pine and spruce forests, with more shortwave-dominated radiation at the pine forests and more longwave-dominated radiation at the spruce forests.

Discussion and conclusions

The above results illustrate the strong control that both slope and aspect, as well as forest cover, have on the amounts of radiation to snow and the timing of snowmelt in Canadian Rockies mountain environments. At these latitudes during spring, topographical self-shading of north-facing slopes contributes to producing substantial differences in shortwave irradiance between opposing open south-facing and north-facing landscapes. By contrast, shortwave differences from slope and aspect effects are much reduced under forest cover, especially in the spruce forests where the high shortwave extinction by the dense canopy cover resulted in only small shortwave contributions toward net radiation to snow and melt energy. As a result, longwave fluxes dominated radiation to snow in the spruce forests and represented the main energy source for snowpack warming and melt. Longwave gains to spruce snowcovers were particularly pronounced during periods of above-freezing air and canopy temperatures, which were large enough to facilitate rapid snowmelt. In contrast, shortwave fluxes dominated radiation to snow in pine forests during snowpack warming and melt, as the sparser canopy cover allowed for greater shortwave transmittance while simultaneously reducing canopy thermal emissions relative to spruce forest cover. Higher shortwave transmittance through the pine canopies also resulted in a sizeable variation in shortwave radiation to pine forest snowcovers due to slope and aspect. Although variations in pine forest shortwave may be partly attributed to the small differences in canopy coverage between sites, variations are also attributed to slope and aspect controls on above-canopy irradiance and beam extinction pathlength through sloping canopies. However, such slope and aspect controls were not observed under spruce forest cover, where they were effectively masked by the dense canopy coverage. Due to the sensitivity of subcanopy shortwave irradiance to small variations in canopy coverage, a major limitation of the paper is its reliance on field observations, which do not allow for an exact delineation of forest cover controls from slope and aspect controls on forest shortwave radiation. Such an examination could be performed through focused modelling exercises in which environmental factors could be controlled and shortwave irradiance across mountain landscapes could be assessed over a much wider range of topography and forest coverages. However, models have their own shortcomings and uncertainties that were largely avoided by this field data approach.

In general, snowmelt rates were much more rapid at the spruce forest and clearings sites relative to the pine sites. This difference is largely ascribed to the elevation differences between the lower pine and higher spruce site locations. At the higher elevation spruce sites, the increased snowfall and cooler temperatures result in deep cold snowpacks of high thermal deficits. Consequently, melt of these high-elevation snowpacks occurs later in the spring, when shortwave irradiance is greater due to higher solar angles and longer days and forest longwave emissions are larger due to warmer canopy temperatures. As a result, shortwave and longwave gains to snow would be expected to be substantially higher during these later spring melt periods, which are capable of producing faster melt compared with the earlier melt periods at the lower elevation pine sites, when potential shortwave and longwave gains to snow are less.

Observations at both pine and spruce locations show that slope and aspect may strongly influence forest cover effects on radiation to snow and snowmelt timing. On north-facing landscapes, shortwave reductions by forest shading are offset or slightly exceeded by longwave enhancements from canopy emissions, resulting in similar or greater amounts of radiation to forest snow. At the spruce sites, increased radiation to snow at the north-facing spruce forest corresponded with a sizeable advancement in the start of snowmelt relative to the nearby north-facing clearing where low shortwave gains and high longwave losses resulted in a large thermal deficit and delayed melt of the deep snowpack. By contrast, radiation to snow was less under pine and spruce forest cover on south-facing slopes compared with that in the open, as canopy shortwave reductions exceeded canopy longwave enhancements. In addition to reduced radiation, forest cover on south-facing slopes also resulted in a substantial delay in the start of snowmelt and slower overall melt rates at both the pine and spruce locations. Such results suggest that the snowmelt timing in similar mountain basins may be most sensitive to changes in forest cover on south-facing landscapes.

Compared with south-facing and north-facing sites, the effects of forest cover on radiation to snow and snowmelt timing were less pronounced on level topography. At the level pine sites, shortwave reductions under the forest canopy were counterbalanced by longwave emissions from the canopy, resulting in only slightly decreased radiation and snowmelt rate under forest cover. Thus, unlike the marked effects of forest cover on radiation and snowmelt timing observed at the sloping sites, the results suggest less striking forest effects on level topography as the small decrease in radiation observed under pine forest cover would likely be eliminated or reversed with only slight increases in either snow albedo or canopy temperature over the winter. However, these results are instructive as they demonstrate how responses in snowmelt timing from forest cover changes on level topography may provide an unreliable proxy of effects on sloping topography. Instead, observations illustrate the potentially large variation in radiation to snow and snowmelt timing that may result from differing combinations of forest cover and slope and aspect, as well as changing springtime meteorological conditions. Such information is expected to be useful toward anticipating how forest cover changes across similar mountain headwater basins may impact the timing of river flows generated from spring snowmelt.

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References


List of symbols

\( c_p \) specific heat capacity of air (kJ kg\(^{-1}\) K\(^{-1}\))

\( C \) Celsius (°)

DOY day of year

\( K_m \) shortwave irradiance (MJ m\(^{-2}\))

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$K_a$ above-canopy shortwave irradiance (MJ·m⁻²)
$K_{out}$ reflected shortwave irradiance (MJ·m⁻²)
$K^*$ net shortwave radiation (MJ·m⁻²)
LAI effective leaf area index (m²·m⁻²)
$L_{in}$ longwave irradiance (MJ·m⁻²)
$L_{out}$ longwave exitance (MJ·m⁻²)
$L^*$ net longwave radiation (MJ·m⁻²)
LPC level pine clearing study site
LPF level pine forest study site
LSC level spruce clearing study site
$M$ snowmelt (kg·m⁻² or mm SWE)
MB mean bias index
MJ mega joules [1 × 10⁶ joules]
n count
NPC north-facing pine clearing study site
NPF north-facing pine forest study site
NSC north-facing spruce clearing study site
NSF north-facing spruce forest study site
$R^*$ net all-wave radiation (MJ·m⁻²)
$R^2$ correlation coefficient
SPC southeast-facing pine clearing study site
SPF southeast-facing pine forest study site
SSC southeast-facing spruce clearing study site
SSF southeast-facing spruce forest study site
SWE snow water equivalent (kg·m⁻² or mm)
$T_a$ air temperature (°C or K)
$T_s$ snow surface temperature (°C or K)
$\alpha_s$ snow albedo
$\beta$ fraction of ice in snow
$\Delta$ slope of saturation vapour pressure curve (kPa·K⁻¹)
$\varepsilon_s$ thermal emissivity of snow
$\lambda_f$ latent heat of fusion (MJ·kg⁻¹)
$\lambda_s$ latent heat of sublimation (MJ·kg⁻¹)
v sky view factor
$\rho_a$ density of air (kg·m⁻³)
$\sigma$ Stephan–Boltzmann constant (5.67 × 10⁻⁸ W·m⁻²·K⁻⁴)
$\tau$ forest shortwave transmittance
$\omega_a$ specific mixing ratio of air
$\omega_s$ saturation mixing ratio of air