

SNOW ABLATION MODELING IN CONIFER AND DECIDUOUS STANDS OF THE BOREAL FOREST

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ABSTRACT

Both coniferous and deciduous forests alter the energy exchange and the accumulation and ablation of snow on the ground. Snow ablation modeling at the stand scale presents challenges to account for the variability in snow cover and the large variations of solar and thermal radiation incident to the forest floor. Previous work by the authors coupled a one-dimensional snow process model (SNTHERM), modified for forested conditions, with a model of radiation interactions with forest canopies to successfully predict snow ablation in a mature jack pine stand. Now, we use the same approach and model snow ablation in black spruce and aspen stands and verify the modeling effort by comparison with field data. A new routine is added to SNTHERM to account for forest litter on the snow surface, thereby affecting the albedo. We conducted field work during March 1996 in central Saskatchewan. We measured snow pack physical properties, meteorological parameters within the forest canopy, and incoming solar and thermal irradiance beneath the forest canopy. At peak accumulation snow depths in black spruce tree wells were approximately 65% of that measured in forest gaps. Snow in the aspen stand ablated 26 days before snow in the black spruce stand and both results compare favorably with available measured data.

INTRODUCTION

The boreal forest represents 77% of the total forested area in Canada (Jones, 1987), and remains snow covered for six to eight months of the year. The Boreal Ecosystems Atmosphere Study (BOREAS) is a large scale, multi-disciplinary project focused on understanding how the boreal ecosystem would respond to a change in climate (cf. Sellers *et al.*, 1995). BOREAS investigators conducted intensive field studies between 1993-1996 in the boreal forest of central Saskatchewan and northern Manitoba, Canada. Two BOREAS test areas, which bracket the range of annual temperature and precipitation in the central boreal forest, were selected for detailed modeling studies (Sellers, *et al.*, 1995). In the south, the modeling subarea occupies 2000 km² and is composed of 55% conifer cover and 6% deciduous cover. In the north, the modeling subarea occupies 1200 km² and is composed of 40% conifer cover and 8% deciduous cover. Preliminary predictions based on climate models suggest that the boreal regions of interior, western Canada are among the most sensitive areas in the world to warming responses of greenhouse gases (Manabe and Wetherald, 1986). According to Bonan *et al.* (1992), continental warming, and the associated reduction in vegetation height, would result in a large increase in the wintertime albedo and dramatic decreases in the air temperature of the northern high latitudes. Our overall contribution to BOREAS is to develop models, which will predict spatial distributions of snow properties and processes important to the hydrology of the area and the remote sensing signatures from snow-covered boreal scenes. These include depth, density, grain size and melting rate and are important to estimating the volume and timing of snowmelt.

The purpose of this paper is to apply our previously described approach for modeling snow ablation in a boreal jack pine forest (Hardy *et al.*, in press) to two additional boreal forest types and verify the modeling effort using field data. The first is a mature black spruce stand; the second a deciduous, mature aspen forest. The approach described by Hardy *et al.* (in press) couples a one-dimensional snow process model (Jordan, 1991) modified for forested conditions, with a geometric-optical radiative transfer model which describes radiation interactions with the forest canopy (Li *et al.*, 1995). Additional modifications to these models are described herein.

PRIOR WORK

Forests are well known to alter both the accumulation of snow on the ground as well as snowmelt rates. Tree species and forest structure affect the distribution of snow on the forest floor (Hardy and Hansen-Bristow, 1990; Golding and Swanson, 1986). In conifer forests, tree wells develop around the stems during winter when the canopy intercepts incoming snow, which results in

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its depletion beneath the tree crown. Around leafless deciduous trees, *Sturm* (1992) observed snow cones at tree trunks resulting from a combination of snow settling away from the trunk and snow sloughing off the branches. The net effect of most forest canopies is a snowpack with spatially heterogeneous depth and SWE. In the boreal forest, *Pomeroy and Schmidt* (1993) observed SWE beneath a tree canopy equal to 65% of the undisturbed snow and *Pomeroy and Dion* (1996) measured subcanopy snowfall at approximately 68% of the above-canopy snowfall. In Alaska's taiga, *Sturm* (1992) found snow depths at the tree trunks equal to approximately 20% of the undisturbed snow. *Hardy et al.* (in press) measured 60% less snow in boreal jack pine tree wells than measured in forest openings at maximum accumulation.

In most snowmelt situations, net radiation overwhelms turbulent exchanges as the most significant driving force, with incoming solar irradiance of primary importance. Even in boreal conifer forests, radiation dominates the snow surface energy exchange during snow ablation (*Price and Dunne*, 1976; *Metcalfe and Buttle*, 1995; and *Hardy et al.*, in press). *Pomeroy and Dion* (1996) concluded that under clear skies, canopy structure and solar angle control the timing and rate of snow ablation under conifer canopies due to the effect of canopy on net radiation. *Metcalfe and Buttle* (1995) observed that a single measure of net radiation was inadequate to estimate snowmelt using the energy balance approach when modeling the influence of canopy structure on snowmelt in the boreal forest. *Barry et al.* (1990) empirically adjusted the densification, metamorphism and liquid water retention algorithms of *Anderson's* (1976) energy and mass balance model to predict snow processes in a balsam fir forest. *Barry et al.* (1990) used point measurements of incoming solar, reflected solar and net all-wave radiation. Other investigators related canopy properties to the amount of radiation reaching the snowpack or snowmelt rates (*Bohren*, 1972; *Yamazaki and Kondo*, 1992; *Metcalfe and Buttle*, 1995; *Pomeroy and Dion*, 1996). In general, they found that as canopy density increased, radiation and snowmelt rate decreased. *Yamazaki and Kondo* (1992), coupling a two-layer canopy and snowmelt model, found that under some conditions, snowmelt increased under dense canopy due to decreased terrestrial radiative losses. Under leafless deciduous canopies the net radiation alone is a good predictor of snow ablation and the turbulent contribution to melt is minimal (*Hendrie and Price*, 1979; *Price*, 1988). Our goal, in modeling snow ablation and energy exchanges at the stand scale, is to incorporate as much process level detail as possible at a high temporal resolution. We propose that successful physically based modeling at the stand scale is necessary to have confidence in spatially distributed modeling efforts.

METHODS

We modified the snow model SNTHERM and coupled it with the canopy radiation model GORT for runs of snow ablation in the black spruce and aspen sites. Our model study was validated with field measurements. We initialized SNTHERM with measurements of snow properties and temperatures and used measured values of soil temperature, precipitation, within canopy air temperature, and relative humidity from the Saskatchewan Research Council towers. We used GORT-derived values of subcanopy solar radiation and determined the thermal radiation by considering the relative contribution from the atmosphere and the canopy (see *Hardy et al.*, in press). The above-canopy winds were modified based on a correlated relationship with the winds at 2 m height. SNTHERM adjusted the albedo to accommodate shallow snowpack and accumulated litter. We ran the model twice in the black spruce site; first to represent canopy openings and secondly to represent the shallower snow in the tree wells.

Site Description and Available BOREAS Data

Data collection for this study focused on stands of mature black spruce (*Picea mariana*) and mature aspen (*Populus tremuloides*) north of Prince Albert, Saskatchewan (53.9° N, 104.7° W). The mean annual air temperature near this site is 0.1°C. The black spruce site consists of relatively uniform stands of black spruce trees with ages up to 155 years and tree heights up to 10 m. The aspen site consists of 60 year old trees of uniform height (21 m). At the aspen site, *Shewchuk* (in press) of the Saskatchewan Research Council measured standard meteorologic parameters continuously, beginning in the fall of 1993, and provided 15-minute averaged data (Table 1). Similar data were collected from a mature jack pine site (*Hardy et al.*, in press) and used as a proxy for the nearby (20 km) black spruce site. Additional data from BOREAS used in this work include bi-monthly snow survey data (snow depth, density and water equivalence) and stand characteristics (canopy closure, stand density and tree height) (*Sellers et al.*, 1995).

Table 1. Measured Meteorological Parameters at the mature aspen site. Sensors are on a 37 m tower near the center of the site. Tree heights are approximately 21.5 m.

| Parameters Measured | Height (m) | Accuracy | Sensor |
|--------------------------------|------------------|--------------|-----------------------------|
| Air temperature | 23.7 | +/- 0.4 °C | Vaisala HMP35C |
| Within-canopy temperature | 4.0 | +/- 0.25 °C | Campbell Scientific 107F |
| Relative humidity | 23.7 | +/- 3 % | Vaisala HMP35C |
| Wind speed and direction | 23.7 | 5%, 2 degree | RM Young wind monitor |
| Precipitation | N/A | 5% | Belfort gauge |
| Snow depth | N/A | +/- 0.01 m | Campbell Scientific UDG1 |
| Incident solar radiation | 36.7 | 5% | Eppley pyranometer |
| Incoming terrestrial radiation | 36.8 | 2% | Eppley pyrgeometer |
| Soil temperature | -0.1, -0.2, -0.5 | +/- 0.4 °C | Campbell Scientific 107 BAM |

Field Measurements

The 1996 field campaign occurred during late February and early March at both the black spruce and aspen sites. The field campaign coincided with the time of peak snow accumulation at both sites. At this time, we measured snowpack properties and subcanopy meteorology. We measured snow properties beneath tree crowns and in the canopy gaps, small openings usually much less than one tree height. We assessed snow depth variability through 100 randomly located measurements and measured snow densities at 3-cm vertical resolution using a 100-cm³ density cutter and an electronic balance (accurate to +/- 0.1 g). A Canadian snow sampler obtained depth-integrated density and SWE. Snow surveys, conducted bimonthly by other BOREAS investigators, in or near the main test areas provided a time series of depth and SWE as well as standard deviation of depth. These data were the average of five measurements.

An array of 10 Eppley pyranometers (0.3 to 3.0- μ m wavelength) and 2 Eppley pyrgeometers (8 to 50- μ m wavelength), randomly placed on the snow surface in the forest stand, measured the solar irradiance for validation of the GORT model and the thermal radiation respectively. The radiometers sat on a small box, to provide stability on the snow surface, and the instrument level was checked daily. Some radiometers were adjacent to a tree stem while others were located in small forest openings. All radiometers were randomly shuffled daily during four consecutive clear days at the black spruce site. Four sets of locations on the four clear days provided a data set of 40 pyranometer locations for a normalized clear day. Relocating the 10 pyranometers provided a measure of the spatial variability of incoming solar irradiance beneath the forest canopy. Due to inaccessibility of the aspen site, the radiometers remained in one location for the entire 4 days.

Other measurements during the four days consisted of 2.0-m wind speed and direction, 2.0-m air temperature and relative humidity collected from a portable tower near the radiometer array. We used an R.M. Young wind sensor to measure wind speed and direction and a Vaisala temperature/relative humidity probe. A Campbell Scientific CR10 datalogger measured all parameters every 10 sec. and stored them as 1-min. averages.

Snow Process and Energy Budget Model

SNTHERM is a one-dimensional mass and energy balance model for predicting snowpack properties and processes (Jordan, 1991), and forms the foundation for this modeling effort. SNTHERM was developed and validated for open snow fields and was first applied to a conifer forest by Hardy *et al.*, (in press). This is its first known application to a deciduous forest. Hardy *et al.*, (in press) provide more details on SNTHERM and how it was applied to a jack pine stand. Two new modifications, both related to the snow albedo, have been made to SNTHERM since Hardy *et al.*, (in press) which are described below.

SNTHERM already accounts for changes in albedo due to grain growth, sun angle and cloud cover but preliminary model runs in both the black spruce and aspen sites, suggested a lower albedo than predicted by SNTHERM during late season ablation. This phenomenon was also observed in modeling snow ablation in the jack pine forest (Hardy *et al.*, in press). To address this problem, we built in a routine to automatically reduce albedo (exponential reduction to soil albedo) when radiation penetrates through the snowpack to the underlying soil. The shallow snow correction (adjustment) is a

function of optical depth and grain size, and for older snow, significantly reduces albedo for depths less than 10 to 15 cm. For this work, we added a new routine to estimate litter fall on the forest floor thereby reducing the subcanopy snow albedo as forest litter accumulates (Pomeroy & Dion, 1996; Oke, 1987). The fraction of litter in or on the snow pack was increased throughout the entire snow season according to eq. (1).

$$lc = 1.0 - (1.0 - lr)^{\text{day}} \quad (1)$$

where lc is the fractional litter coverage ($\text{m}^2 \text{m}^{-2}$) and lr is the daily litter rate ($\text{m}^2 \text{m}^{-2} \text{d}^{-1}$). For example, given a lr of 0.01 (or 1% per day), the snow would have a lc of 0.45 or 45% after 60 days. Litter accumulates on the snow surface beginning with the first snow fall. Since our model runs begin at peak accumulation, the litter content of the initial snow layers were computed by eq. 1 based on the number of days between snow events leading to maximum accumulation. We used a litter rate of 0.005 d^{-1} and 0.001 d^{-1} for the black spruce and aspen site respectively (Table 2). The albedo of the litter was based on results of Oke (1987). There are two ways the fraction of litter on the snow surface can increase. Either existing snow layers melt leaving behind their litter on the snow surface, or additional litter accumulates on the snow surface through time.

Table 2. Values used in above equation to incorporate litter fall on the snow surface for both black spruce and aspen forests.

| | Black Spruce | Aspen |
|-------------------------------|--------------|-------|
| litter rate (percent per day) | 0.005 | 0.001 |
| litter albedo | 0.15 | 0.2 |
| number of days with snow | 185 | 159 |
| total litter coverage (%) | 60 | 15 |

Geometric Optical Radiative Transfer Model

Li *et al.* (1995) developed the hybrid geometrical-optical radiative-transfer (GORT) model to estimate the radiation environment above, within, and below discontinuous forest canopies. The model evolved from reflectance models of forest canopies based on geometric optics (Li and Strahler, 1986; 1992), in which the primary factor influencing the reflectance from a forest canopy is the three-dimensional geometry of trees and their proximity. The current GORT model incorporates a radiative transfer component to account for the contribution of multiple scattering within and between crowns and horizontal branch structure (Ni *et al.*, in press). The full hybrid GORT model allows calculation of all solar radiation components both below the canopy, and within the canopy as a function of height. Specific applications of GORT to boreal conifer forests are described in both Hardy *et al.* (in press) and Ni *et al.* (in press).

Specific parameters are required to run GORT as described in Hardy *et al.* (in press) and Ni *et al.* (in press). The forest parameters required for GORT include those characteristics of species and those specific to individual stands. For this study, these are given for both the black spruce and aspen sites (Table 3). Ni *et al.*, (1997) discuss the methods used to collect the field data for tree parameters.

Table 3. Parameters used by GORT for characterization of tree geometry and radiative properties at the old black spruce and aspen stands: b/R is the ratio of the vertical crown radius (b) to horizontal crown radius (R) (BOREAS Experiment Plan, 1995).

| Parameters | Black Spruce | Aspen |
|---------------------------------------|--------------|-------|
| Horizontal crown radius, R (m) | 0.59 | 2.12 |
| Vertical crown radius, b (m) | 2.13 | 5.38 |
| b/R | 3.62 | 2.54 |
| FAVD - BAVD (m^{-1}) | 8.12 | 0.061 |
| Stem density (stems m^{-2}) | 0.804 | 0.114 |
| Tree Height (m) | 10.92 | 21.5 |

In the context of the current research, the greatest challenge with regard to radiation modeling involved applying the GORT model to the deciduous aspen stand in the leaf-off condition. Our previous use of this model had been with evergreen conifers where needles were the dominant attenuators (Ni *et al.*, in press). The dominance of needles in this regard is reflected in the use of the term "foliage" area volume density (FAVD) to describe the density of attenuating material in a canopy, when in fact this parameter also includes the density of the woody material in the canopy. However, in the case for aspen stands in the winter when they have dropped their leaves, branches and twigs become the dominant attenuators. To apply the GORT model in this situation, it was necessary to

incorporate a "branch" area volume density, or BAVD. Initially, we were unaware of field measurements to calibrate this parameter, so the GORT model was run with a range of BAVD values to determine an appropriate value, which yielded an estimate of 0.065 m^{-1} . Later, field measurements were located from another study (*Blanken*, pers. comm.) which could be used to estimate the BAVD of the aspen stand. Interestingly, this estimate (0.061) was very close to our fitted value. The fact that these two independent methods produced similar results was encouraging.

Model Runs

Simulations in the conifer and deciduous sites provided data for comparisons of average energy fluxes and snow depth variations (precipitation, ablation, compaction, and evaporation) for the stands. The black spruce site was located 20 km west of the jack pine site; therefore we assumed the meteorological measurements above the jack pine site represented those above the black spruce site. Measurements of meteorology were available from the deciduous site (aspen) as noted above. We ran both simulations (black spruce and aspen) from approximately the time of peak SWE (day 61) until complete ablation.

Because forest canopies are well known to affect radiative and turbulent components of the energy balance, we constructed our SNTHERM input data stream to account for the differences associated with forested environments. GORT predicted the incoming solar radiation on the snow surface for the black spruce and aspen stands. The results from GORT directly substituted for that obtained from the tower measurement at the top of the canopy. Additionally, the fraction of visible radiation (f_{vis} , $0.3-0.7 \mu\text{m}$) was 0.33 for the black spruce site and 0.4 for the aspen site in these simulations. These values take into consideration an estimated average albedo (0.75), grain radius and the strong absorption by the pine needles in the visible spectrum.

Measurements of subcanopy wind speed for four days allowed wind speeds to be estimated from above canopy measurements, based on the following expressions:

$$ws_{for} = \max [(ws_{above} 0.0761) - 0.0964, 0] \quad (2)$$

for the black spruce site, and

$$ws_{for} = \max [(ws_{above} 0.272) - 0.2384, 0] \quad (3)$$

for the aspen site, where ws_{for} is the subcanopy wind speed and ws_{above} is the wind speed above the canopy. Predicted subcanopy wind speeds in the black spruce forest were very low during the modeling period (range 0 to 0.4 m/s) and therefore the corresponding turbulent fluxes were small. The predicted subcanopy wind speeds ranged from 0 to 1.8 m/s in the aspen site. All model runs used initialized soil temperatures from measurements at depths of 0.1, 0.2, and 0.5-m and field measurements of snow depth, density, temperature and grain size. Turbulent fluxes were computed by SNTHERM (*Hardy et al.*, in press) using values of 0.005 m and $1.0 \text{ W m}^{-2} \text{ K}^{-1}$ for the roughness length and windless exchange coefficient, respectively. We assumed that the roughness lengths for momentum, heat, and water vapor are equal.

Areas occupied by forest openings and tree wells were run separately for the black spruce site. Meteorological data input for tree wells were identical to that used for forest openings. Tree well model runs varied from the runs of forest openings in the initial snow depth and the amount of accumulated snowfall during precipitation events. Field measurements and values extrapolated from the bi-weekly snow survey data initialized the snow depth at both sites. Initial snow depths in the tree well were 65% of the forest gap snow depths for the black spruce site and were based on field measurement in canopy openings and tree wells. Therefore, accumulated snowfall was also only 65% of that measured in the forest openings. Only one model run was required in the aspen site due to the minimal effect of tree crowns on the snow depth. Snow survey data were compared with measured and modeled depths.

RESULTS

Snow Distribution

At peak accumulation in the aspen site, snow distribution patterns around the tree stem were different than observed in the black spruce site. Tree wells were absent; adjacent to the south side of the trunk an ablation hollow had formed, while the north side showed a slight cone of deeper snow. The average snow depth, based on 100 random measurements, was 35.8 cm with a standard deviation

of 9.7 cm. Where tree wells were present in the black spruce forest, the average snow depth was 40.3 cm with a standard deviation of 11.7 cm. Black spruce tree wells accumulated approximately 65% of the snow depth measured in the forest openings.

Radiation Receipt Compared

Measured values of incoming solar radiation on the snow surface show high spatial and temporal variation in both the black spruce and aspen sites (Fig. 1a and 1b) compared to incoming solar above the canopy. This variability characterizes the sensitivity of patterns of radiation to species and other variables, such as canopy closure, tree and stand geometry. All data were collected during nearly clear sky conditions in early March. The diffuse radiation is essentially the "bottom" curve of the plot of radiation values. The patterns of radiation in the black spruce forest are characterized by maximum diffuse radiation of only 20 W m^{-2} and individual total radiation peaks averaging only 2.5 peaks per day exceeding 100 W m^{-2} . The patterns of radiation in the deciduous aspen forest are characterized by maximum diffuse radiation less than 100 W m^{-2} and individual total radiation averaging 4.2 peaks per day exceeding 300 W m^{-2} .

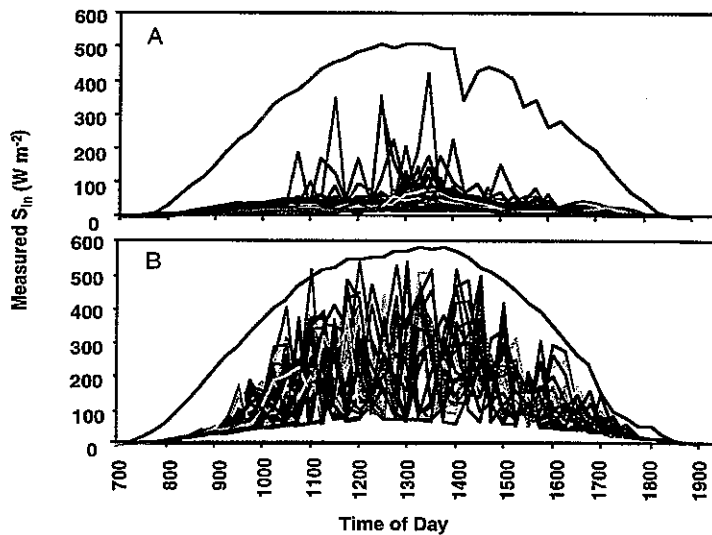


Figure 1. Measured data comparing above-canopy solar radiation with subcanopy incoming solar radiation at the snow surface in the black spruce (a) and the aspen (b) stands. Both plots present subcanopy data collected over 4 days and are in 15-min intervals. Above-canopy measurements are for one day.

We compare the results of the modeled understory solar radiation with the field measurements collected in the black spruce site in early March 1996, using canopy parameters collected in the field during late February, 1996 (Fig. 2a). The field measurements are the average of 10 pyranometers distributed randomly throughout the stand (*Ni et al.*, in press). Each point in the graph corresponds to a 15 minute time interval. The model estimates fit well for the vast majority of the time intervals of the pyranometer measurements, but are too low for the times with the highest irradiance reaching the snowpack. The model is underestimating the canopy transmissivity in these instances. Fig. 2b shows a similar plot for the aspen site using field measurement collected in March 1996. Note that the amount of radiation getting to the snow in this stand is considerably higher than the black spruce stand. The strength of the fit for these data throughout the range of observed values is encouraging. Interestingly, even without leaves, the transmission in aspen stands in the snowmelt season is surprisingly low. For the aspen stand, we measured transmission to be only 35% for a typical day during the snowmelt season. Similarly, we compared the measured vs. modeled (see *Hardy et al.*, in press) incoming thermal radiation at the snow surface in the black spruce site (Fig. 3). The measured thermal radiation is the average of 2 pyrgeometers. In this case the model slightly overpredicts the incoming thermal radiation.

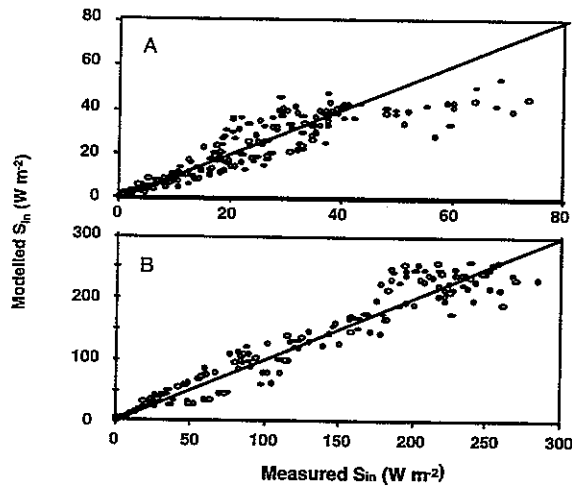


Figure 2. GORT modeled vs. measured subcanopy incoming solar radiation (S_{in}) at the snow surface in the black spruce (a) and the aspen (b) stands. The line has a slope of 1.

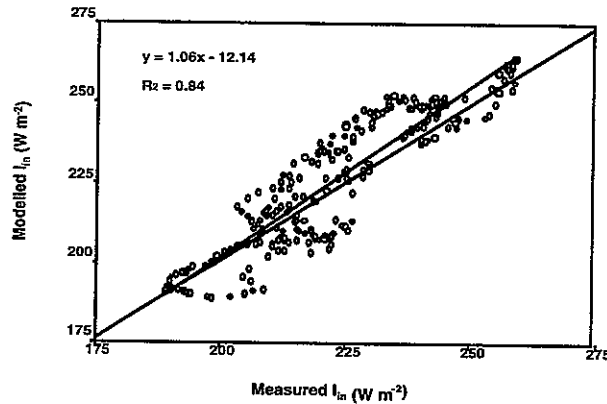


Figure 3. Modeled incoming thermal radiation (I_{in}) on the snow surface vs. average measurements of two pyrgeometers. The thin line has a slope of 1. The thick line is the linear regression.

Litter Adjustment

An example of the litter adjustment to albedo for the black spruce shows how the adjustment worked (Fig. 4). The top plot (Fig. 4a) shows the modeled snow depth from the time of peak accumulation (March 1) to complete ablation. Fig. 4b shows the computed percentage of litter coverage on the snow surface for the same time period. Note how the litter coverage goes to zero following a snowfall, then slowly increases to a maximum of 60% (refer back to Table 2). Finally, Fig. 4c compares the albedo before and after the albedo adjustments made to SNTHERM. The solid line shows SNTHERM's albedo prior to the adjustments for litter and thin snow. The dotted line shows the new albedo after considering radiation penetration through shallow snowpacks and accumulated litter on the snow surface. Note the comparison with albedo measurements made by *Harding and Pomeroy* (1996) in a jack pine forest. Although *Harding and Pomeroy's* (1996) measurements of snow surface albedo were made in 1994, they were made at the time of peak snow accumulation and after a snow storm. They provide some reassurance that our predictions are reasonable. Also, note that the albedo goes to 0.8 after a new snowfall and gradually decreases as the litter accumulates and the snowpack thins.

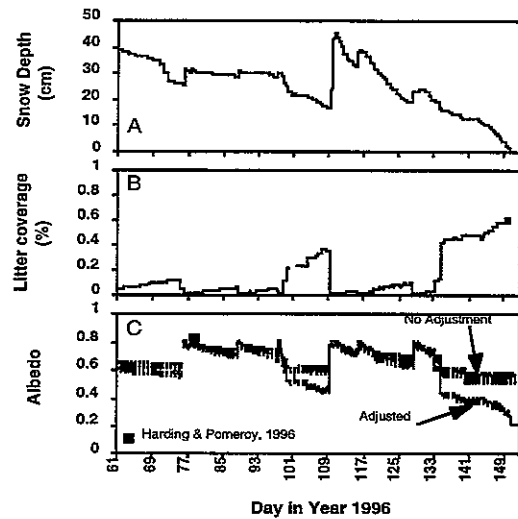


Figure 4. Effect of the albedo adjustments on snow depth (a), litter coverage (b) and the time series of albedo (c). The solid squares are albedo data collected in 1994 by *Harding and Pomeroy* (1996) under a jack pine canopy.

Model Runs

The coupled SNTHERM and GORT models provide a time series of cumulative radiative and turbulent exchanges for the entire modeling period (from peak accumulation to complete ablation) in the black spruce (Fig. 5a) and aspen sites (Fig. 5b). These figures show the magnitude of the components in the energy balance. The relative magnitude of the fluxes in the aspen stand at the time the snow disappears (day 125) is nearly twice that in the black spruce on the same day. At both sites, latent heat is negligible and sensible heat is positive, albeit small. For the black spruce (Fig. 5a) the net energy responds to the increased thermal radiation component late in the ablation season. At the aspen site, the net energy is controlled more by the solar component.

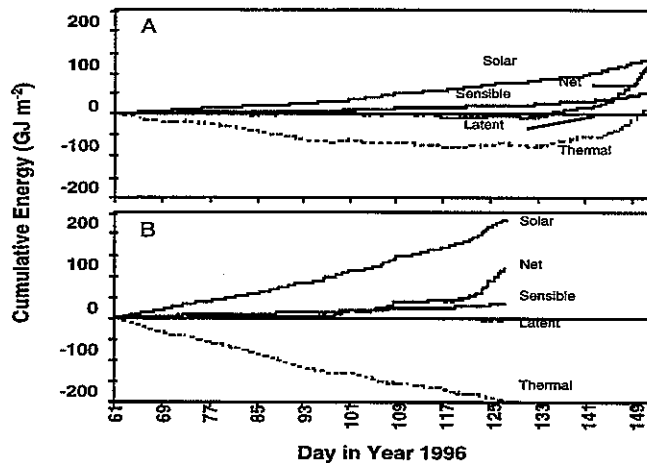


Figure 5. The modeled cumulative energy in both the black spruce (a) and the aspen (b) stands. Values are given for net solar, net thermal, sensible, latent and overall net energy.

Modeled output for snow depth shows complete ablation in black spruce forest openings by day 151 (Fig. 6a). These model results are compared with snow survey measurements made by

BOREAS investigators in a nearby black spruce forest. Vertical lines are standard deviations of depth for the snow survey measurements. Modeled output agrees well with snow survey data until late in the ablation season when the models underpredict the ablation rate. The model run for the tree wells began at a depth of 25 cm and show complete ablation by day 147, four days prior to snow in the canopy openings. Field observations support the ablation in tree wells prior to the canopy openings. Similarly, modeled output for snow depth shows complete ablation in the aspen stand by day 125 (Fig. 6b). These model results compare favorably with snow survey measurements.

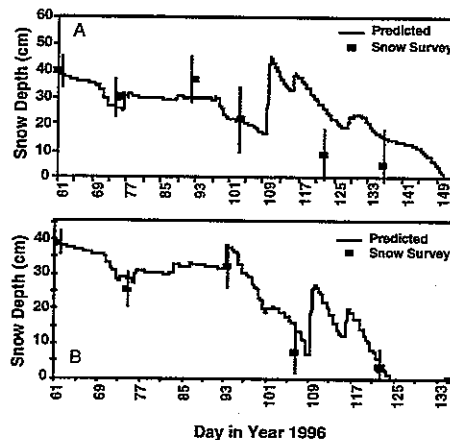


Figure 6. Model results showing the snow ablation in the black spruce (a) and the aspen (b) stands. The solid squares are data from the bi-weekly snow survey. The vertical lines are standard deviations of snow survey depths.

DISCUSSION

Physically-based, modifications to SNTHERM improved its capability for predicting energy exchanges and snowpack properties and processes in black spruce and aspen forests. These modifications take into consideration the ability for radiation to penetrate shallow snowpacks and thereby result in a lower albedo than would be expected for deep snow. Additionally, the accumulation of forest litter on the snow surface reduced the snow surface albedo. With these new modifications, the coupled SNTHERM and GORT models, along with physically based meteorological adjustments, provided good estimates for the timing of snowmelt in mature black spruce and aspen stands. The relative timing for the complete ablation in the black spruce canopy gaps, black spruce tree wells and the aspen site correspond with expectations in that the aspen site ablates first, followed by black spruce tree wells and finally the black spruce canopy gaps. Due to the well-known variability of snow depth in forested environments, it is difficult to have complete confidence in the absolute timing of snowmelt based on the average of five measurements, as was done with the snow surveys.

At the black spruce site, it appears the coupled models underpredicted the ablation rate late in the season. There are several factors to consider in this analysis. First, and likely the most important, GORT underpredicts incoming solar radiation for the higher values of radiation in this black spruce forest (Fig. 2a). Higher values of solar radiation are expected late in the ablation season as the sun angle increases. The simulation for this stand is the first to exhibit this problem, and further research is necessary both to understand the nature of the problem and to resolve it for future applications. If GORT underestimated the canopy openness factors in the black spruce forest and thereby reduced the transmission of solar radiation through the gaps, then this would also result in overprediction of the thermal radiation component (more longwave emission from canopy). Another consideration is that the location of the snow survey site is different from the black spruce forest we modeled. Although forest inventory maps show the canopy density to be similar between the two sites, the tree heights were shorter than in our modeling area which would allow more radiation penetration through the canopy. Also the snow survey data include measurements from both canopy openings and tree wells, which would mean smaller values of snow depth due to the reduced accumulation in tree wells. Finally, in the aspen site, modeled snow ablation agrees well with snow survey measurements.

The influence of trees on hydrological processes has important implications for distributed snowmelt modeling. For the boreal forest region of Canada, much of the necessary data for

distributing snowmelt can be obtained from remotely sensed imagery (canopy closure, snow cover), the Atmospheric Environmental Service (AES) of Canada (surface weather and climate data), and Canadian published maps (soils, terrain, hydrology, forest characteristics). These data, along with improved relationships between snow distribution and forest canopy, provide information necessary for distributed snowmelt modeling.

CONCLUSION

Both coniferous and deciduous forests alter the energy exchange and the accumulation and ablation of snow on the ground. This work presented improved efforts to model snow ablation at the stand scale. We extended previous work in a jack pine forest and improved on our methodology to model snow in black spruce and aspen stands. The coupling of the mass and energy transfer model for snow, SNTHERM, with the geometric-optic radiative-transfer model for canopy, GORT, provided a sound, physically-based approach to modeling snow ablation in boreal forests.

New modifications to existing albedo controls in SNTHERM improved the model for forested applications. Albedo modifications include an addition of a litter factor and reductions due to radiation penetration through shallow snowpacks. Two model runs were carried out for the black spruce stand. Canopy openings and tree wells used the same meteorological data, except snow accumulation, and were initialized with different snow properties. Only one run was carried out in the aspen stand. The relative timing of snow ablation for all runs agreed with measurements. Modeled snow ablation agreed reasonably well with the available measurements in black spruce and aspen forests. This stand scale, physically based modeling approach provides good estimates of the delivery of water to the soil system. These methods will ultimately be coupled with remote sensing products to spatially distribute snow properties and processes throughout the boreal region.

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