SPATIALLY-DISTRIBUTED MODELING OF SNOW IN THE BOREAL FOREST: A SIMPLE APPROACH

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ABSTRACT

Simulations using physics-based, coupled canopy-snow models provided the basis for developing simple regression models of net energy transfer to snow cover in the boreal forest. The simple models were driven by incoming solar radiation to the top of forest canopies, forest species, tree height and canopy density. Maps of the forest characteristics provided the basis for spatially distributing snow predictions over two test areas in the boreal forest. Over both test areas, variation of incoming solar radiation explained much of the variance in net energy transfer to snow cover. We found the strongest correlations for the relatively open, discontinuous canopies of the northern boreal forest.

INTRODUCTION

Studies showing a potential role of the boreal ecotome in global atmospheric carbon exchange (Tans et al., 1990, e.g.) and sensitivity of the forest to climate change (Davis and Botkin, 1985, e.g.) motivated recent research focused on forest-atmosphere exchange and snow hydrology in the boreal forest. A recent paper suggests climate-induced changes to the boreal forest may have already occurred (Myneni et al., 1997). Snow covers the boreal forest floor for much of the year and comprises an important part of the annual water budget (Larsen, 1980). Snow also plays an important role in the exchange of energy between the atmosphere and land surface. For example, Bonan et al. (1992) carried out a large-scale modeling study on the effects of forest cover and snow on albedo. Their study showed a strong feedback between albedo and climate effects. Increasing albedo due to removal of trees in the boreal forest region caused dramatic decreases in air temperature over a wide region in their modeling results.

Forest canopies, particularly conifers, exert strong control on input of solar and longwave radiation to, and magnitude of wind over, an underlying snow surface. These in turn affect the air temperature and relative humidity in forest stands. Canopy characteristics therefore exert strong control on snow processes, which affect the timing of snow melting and thus seasonal changes of boreal forest albedo due to snow. This paper briefly reviews recent progress toward developing models of canopy and snow cover, suitable for scaling from individual forest stands to resolutions of thousands of km^2. We then describe derivation of parameters for a simple approach to predicting net energy input to snow cover in forest stands, based on incoming solar radiation above the forest canopy. Our studies form a small part of a much larger effort, the Boreal Ecosystem-Atmosphere Study (BOREAS), focused on improving our understanding of atmosphere-biosphere energy, water and trace gas exchange (Sellers et al., 1995).

BACKGROUND

Development of physics-based models of energy exchange between the atmosphere and snow on the forest floor has seen a major challenge in predicting the transfer from above the forest canopy to the snow cover. Over a wide range of climatological and forest conditions, radiation can dominate the components of the surface energy exchange over a snow cover during melting in boreal forests (Price and Dunne, 1976; Metcalfe and Buttle, 1995; Pomeroy and Dion, 1996; Hardy et al., in press). Research involving measurements of radiation show variation of transmitted solar radiation and net radiation at the scales of individual trees and forest stands. Many

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researchers have reported the difficulties in measuring components of the radiation exchange below forest canopies (Nadeau and Granberg, 1980; Petzold, 1981; Rowland and Moore, 1988; Metcalfe and Buttle, 1995; Pomeroy and Dion, 1996; Ni et al, in press, e.g.) because of large spatial and temporal variation as shadows of tree crowns sweep across the forest floor during the day. Approaches to deal with this variation have averaged measurements over time or used multiple radiometers to estimate subcanopy incoming radiation. Meteorological observations over snow in boreal forests have also shown that net turbulent exchange tends to be small relative to radiation primarily due to low wind speeds. Periods when synoptic-scale air movement dominates local-scale meteorology make the exception to this generalization (Harding and Pomeroy, 1996, e.g.) So development and testing of physics-based models of energy exchange that explain variation at different scales for different forest types have proven difficult.

Models with process-level detail have simulated changes in snow properties and melting rates of snow covers under various forest types. For example, Barry et al. (1990) and Metcalfe and Buttle (1995) used point measurements under forest canopy to drive energy balance and snow process computations. Yamazaki and Kondo (1992) used a two-layer canopy model coupled with a simple snow model to study the effects of canopy properties on melting rates. Recently, Hardy et al. (in press; submitted) coupled a modified geometric-optical, radiative-transfer model (GORT - Ni et al., in press) of forest canopy to a detailed model of snow (SNTHERM - Jordan, 1991). They showed that solar radiation transmitted through mature jack pine, black spruce and leaf-off aspen dominated energy transfer to boreal snow cover. With the exception of air temperature measured in the canopies, Hardy et al. (in press) used meteorological measurements above the forest to drive the upper boundary conditions. Davis et al. (in press) took this approach to examine the effects of conifer canopy properties on snow melting rates. They found in model studies that solar radiation was the major component of energy transfer to snow cover for forest property types of the northern boreal forest. But in the southern boreal forest of Saskachewan, Canada, many conifer stands had sufficient height and canopy density so that longwave radiation from the tree crowns and increased sensible heat transfer became important terms as well (Davis et al., in press).

METHODS

This paper derives from the work of Hardy et al. (in press; submitted) and Davis et al. (in press). We used physics-based models to develop parameters for a simple approach to spatially distributing estimates of net energy transfer to snow cover. The simple approach was based on correlations between incoming solar radiation above forest canopy and modeled net energy transfer to snow below the canopy. We used a set of coupled canopy-snow model runs from Davis et al. (in press) who, along with Hardy et al. (in press; submitted) described details of the models, measurements and procedures. We used a canopy model, GORT, to predict the transmission of solar radiation through different canopies and provide factors we used to estimate the canopy and sky contributions to incoming longwave radiation. We predicted other meteorological factors with empirical relationships from field measurements. We used a snow process model SNTHERM to calculate the surface energy balance and snow melting rates, driven by GORT and forest properties. Measurements of meteorological variables provided dynamic input to both models, which ran at a time step of 15 minutes from mid-winter through the end of snow melting. Forest inventory maps of tree species, tree height and canopy density provided the means to spatially distribute the regression models.

Forest Characteristics

This study concentrated on the range of forest types and properties over two test areas, at either end of a transect spanning most of the range of temperature and precipitation of the central Canadian boreal forest (Sellers et al., 1995). The modeling subarea in the BOREAS Northern Study Area (NSA) near Thompson, Manitoba, occupies an area 1200 km^2 (NW corner: 56.055° N, 98.72° W; SE corner: 55.726° N, 98.18° W). The modeling subarea in the BOREAS Southern Study Area (SSA), near Prince Albert, Saskatchewan, occupies an area of 2000 km^2 (NW corner: 54.319° N, 106.23° W; SE corner 53.513° N, 106.32° W). Forest information consisted of species cover, crown density and tree height. BOREAS Staff at NASA Goddard Space Flight Center produced categorical data layers, expressed as raster form, gridded to 30 m. These data derived from forest cover data for the SSA from the Saskatchewan Environment and Resource Management, Forestry Branch - Resource Unit (Lindemas, 1985), and for the NSA from the Manitoba Natural Resources, Forest Management (Becker et al, 1996). Height class was not available for the NSA, so we used cutting class as a surrogate of the height class through a limited set of cross tabulations with measurements reported by BOREAS Terrestrial Ecology groups (Sellers et al., 1995).

Physics-Based Models

The GORT model developed by Li and Strahler (1985; 1992) and modified by Ni et al. (in press) predicted incoming solar radiation at the snow surface from incoming solar radiation at the top of the canopy, the ratio of beam to diffuse radiation and characteristics of the forest stand. We selected a range of stand characteristics that encompassed the full range of melting rates observed in the field. For each category of either canopy density or tree height on the forest maps, we used the mean value of the range of the class. We derived the extinction properties from field measurements of solar radiation at the top of jack pine, black spruce and aspen stands and at the snow surface underneath the canopy (Hardy et al., submitted; Ni et al., in press) along with other measurements. Forest maps and meteorological measurements over the northern and southern test areas provided the basis for calculating incoming solar and longwave radiation from mid-winter through spring.

The one-dimensional model, SNTHERM, predicted snow melting rates. Model runs were initialized in late-winter at peak snow accumulation using measured profiles of snow density, grain size and temperature made by field teams during a 1994 winter campaign. We also used these initial conditions to calculate a total cold content, or thermal deficit required to melt the snow, for our simplified approach. Measurements from other BOREAS investigators provided variables characterizing the soil, which included temperature profile and textural class. The model computed heat conduction between the soil and snow. Liquid water reaching the base of the snow pack was drained off in this version of the model and did not enter the soil (Jordan, 1991). We assumed the same initial snow and soil conditions for all model runs. Surface boundary conditions were driven by: incoming solar and longwave radiation (estimated using the GORT model); wind speed, air temperature and humidity measured in and above the canopies, respectively, and precipitation. A simple linear regression based on field data estimated wind speed, given a measurement above the canopy. We scaled the surface wind speed based on tree height using the regression relationship described by Hardy et al. (in press). No adjustment was made for canopy density.

Regression Models

Analyses of energy fluxes over snow under various stands in the boreal forest have suggested that solar radiation incident to the top of the canopy controls net radiation under the canopy (Harding and Pomeroy, 1996; Pomeroy and Dion, 1996). Our preliminary analyses of coupled canopy-snow model runs (Hardy et al., in press; submitted; Davis et al., in press) suggested high correlation between incident solar radiation at the canopy top and net energy input to the underlying snow cover. We used the method of least squares to perform polynomial regressions using cumulative incoming solar radiation at the canopy top as the independent variable and the net energy of the snow cover as the dependent variable. The output of the SNTHERM model provided estimates of the energy fluxes at the upper and lower boundaries of the snow cover, which we used to calculate the net energy of the snow at each time step for each model case. The shapes of the cumulative energy flux curves (Hardy et al., in press; submitted) for various stand-scale model results suggested a second-order polynomial model, which we applied.

Spatial Distribution of Regression Models

Our objective for this study consisted of visualing the spatial and temporal variability of the snow cover ablation. We used the forest inventory maps to provide an image data baseline to construct snow duration estimates for the 1994 ablation season. We formed the baseline from the categorical combination of land cover attributes tree species, tree height and canopy density. Coupled canopy-snow modeling runs estimated net energy flux to snow cover for a range of canopies that encompassed forest properties in each study area (Davis et al, in press). Results from coupled model runs took the form of polynomial regression equations. We did not perform coupled model runs for every combination of tree species, height and canopy density in this study. Rather we scaled the regressions between results from coupled model runs using predicted solar radiation beneath the forest canopy as the surrogate. We assumed spatially uniform snow conditions for this exercise, using the cold content calcuated from the initial conditions of the physics-based model runs. Areas in the image of combinations of land cover class were simply reassigned values depending on snow duration for each class. We constructed images for each study area that showed the timing of complete melting of different areas from the day the first land cover class completely melted to the end of snow cover ablation.

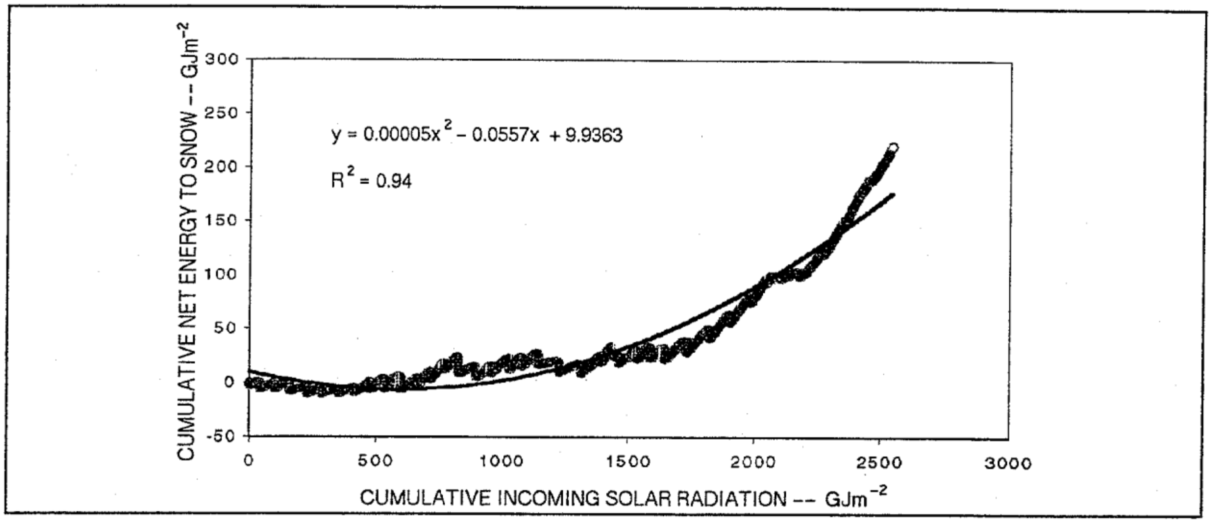

Figure 1. Quadratic fit to relationship between modeled cumulative net energy to snow cover and measured cumulative incoming solar radiation at top of jack pine canopy with 4 m tree height and 10 percent canopy density. Duration of period was 20 days from start to end of melting.

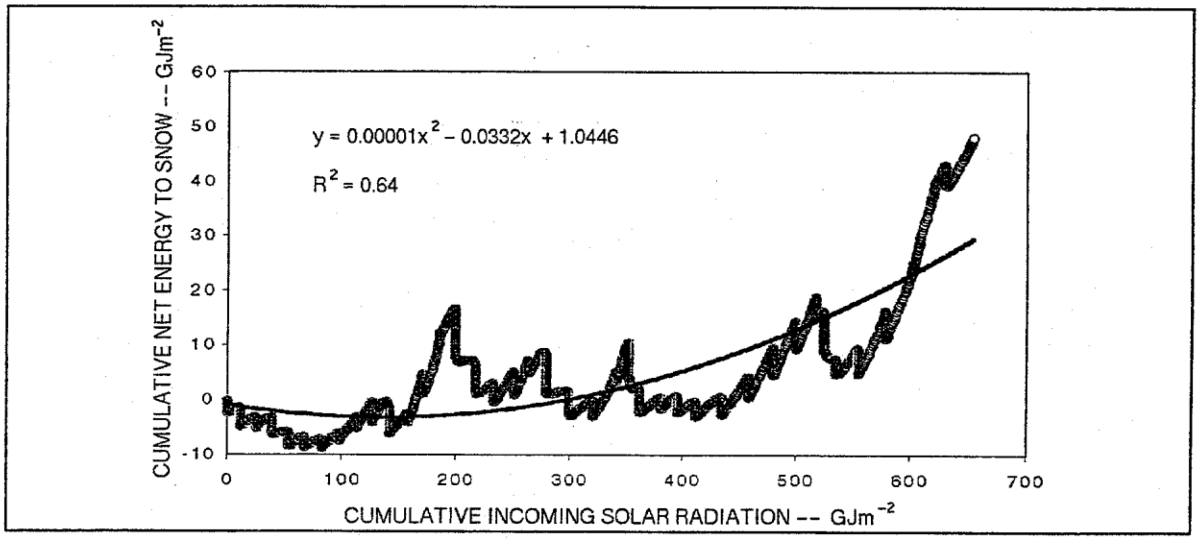

Figure 2. Quadratic fit to relationship between modeled cumulative net energy to snow cover and measured cumulative incoming solar radiation at top of jack pine canopy with 8 m tree height and 60 percent canopy density. Duration of period was 20 days from start to end of melting.

RESULTS

Stand Scale Modeling Results

Net energy gain by snow cover under jack pine and black spruce stands was highly correlated to incoming solar radiation at the canopy top for most tree height and canopy density characteristics in the northern study area. The degree of correlation decreased with increasing tree height and canopy density, from ca. $R^2 > 0.94$ for relatively open, discontinuous forest stands to correlation coefficients of ca. $R^2 = 0.6$ for the highest, densest conifer forest stands. For example, Figure 1 shows cumulative net energy input to snow cover under jack pine with 4 m tree height and 10 percent canopy density in the northern study area, and Figure 2 shows a similar plot under black spruce with 8 m tree height and 60 percent canopy density. About half of the conifer stands in the northern study area have canopy densities less than 50 percent and 60 percent of the conifer-covered area has canopy density less than 70 percent (Davis et al., in press). On the other hand, 87 percent of the conifer stands in the southern study area have densities greater than 55 percent, according to forest inventory data.

Net energy gain by snow cover under defoliated aspen was highly correlated to incoming solar radiation at the canopy top even for tall mature stands. Figure 3 shows cumulative net energy input to snow cover under mature aspen with 21 m tree height and 83 percent canopy density in the southern study area. The correlation coefficient was about $R^2 = 0.95$ from mid-winter through melting of the snow cover.

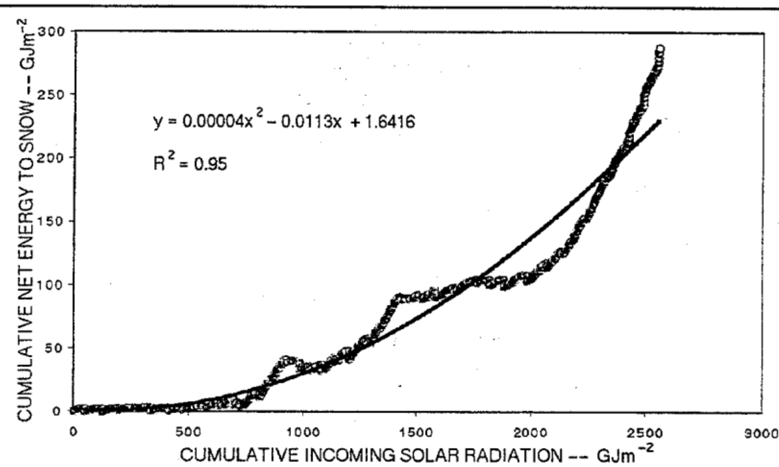

Figure 3. Quadratic fit to relationship between modeled cumulative net energy to snow cover and measured cumulative incoming solar radiation at top of aspen canopy with 21 m tree height and 60 percent canopy density. Duration of period was 20 days from start to end of melting.

Spatially Distributed Modeling Results

Forest inventory data showed that black spruce and black-spruce dominated stands comprise about 33 percent of the forest cover in the northern study area. Jack pine and jack-pine dominated stands comprise about 7 percent, aspen and deciduous forest about 8 percent and treed muskeg about 39 percent. Figure 4 shows a preliminary image of snow cover duration for 1994 over the northern study area. Dark gray shades correspond to areas that melted out first, while light gray shades correspond to areas that retain snow the longest. The southern study area is comprised of 30 percent black spruce or black-spruce dominated forest, 25 percent jack pine or jack-pine dominated forest, 24 percent treed muskeg and about 6 percent aspen or deciduous-species dominated forest. Figure 5 shows a preliminary snow-cover duration image for 1994 over the southern study area. As in Figure 4, dark gray shades correspond to areas that melted out first, while light gray shades correspond to areas that retain snow the longest.

DISCUSSION

We consider the stand scale regression models and the snow duration images as preliminary results based on two assumptions, which require investigation. First, we modeled energy transfer from the atmosphere through canopy to snow for one snow melt season. Therefore, the fitted parameters for the regression models relate specifically to the weather patterns from mid-winter to spring over the study areas. The period we selected guided the choice of the polynomial model. Clearly, incoming solar radiation and net energy flux to

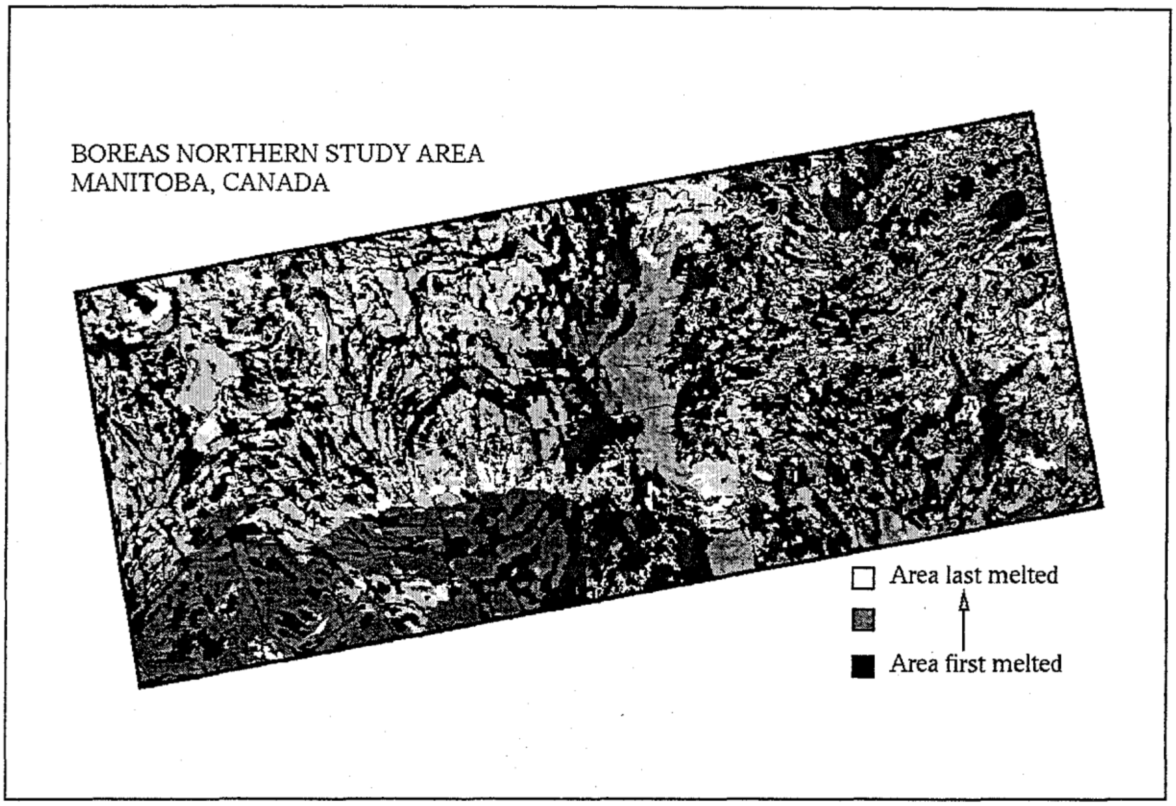

Figure 4. Model-generated image of snow cover duration from time of complete melting of first land cover class. Period of complete ablation from melt out of open areas (black) to the tallest, densest black spruce stands (white) was 20 days, driven by 1994 meteorological measurements.

the surface over an annual cycle follow patterns that would require higher-order polynomial models. Use of coupled canopy-snow modeling results from more than one season will lead to more robust regression analyses that should estimate bounds of variability. Second, we assumed identical snow cover under forest canopy with different properties, as well as over open areas. Field observations have long shown that snow water equivalent and other snow properties relate to land cover type, which exerts strong influence on depositional and post depositional processes. For example, our field data showed much less snow in 1994 over large open areas than clearings in forest and different amounts under aspens than jack pine or black spruce. Harding and Pomeroy (1996) showed less snow under mature jack pine than nearby forest clearings. The net effect of these snow cover variations would expand the period of melting. Simulation of snow cover accumulation in the boreal forest represents a very challenging task.

Our simple approach to predicting net energy input to snow cover and hence melting rates was based on a single physical variable, incoming solar radiation, and some parameters specific to forest stands as characterized by standard forest inventory data. Our premise was that the annual cycle of increasing solar radiation in the spring directly warms snow cover and warms forest canopy, which increases air temperature and the downward component of longwave radiation, etc.. Wide use of degree-day approaches (Zuzel and Cox, 1975, e.g.), which use air temperature and thus imply an important role for sensible heat exchange, have the obvious advantage of using a variable that is both easy to measure and commonly exists in extensive historical record. However, turbulent exchange components of energy transfer over snow in the boreal forest appeared small in earlier analyses (Harding and Pomeroy, 1996; Hardy et al., in press; submitted), while they should not be ignored in physics-based modeling. Lack of complete success in using the degree day approach has motivated recent development of empirical models using radiation indices as well as degree-day factors (Kustas et al., 1994; Brubaker et al., 1996). Our approach followed a similar track, except that we used fully-

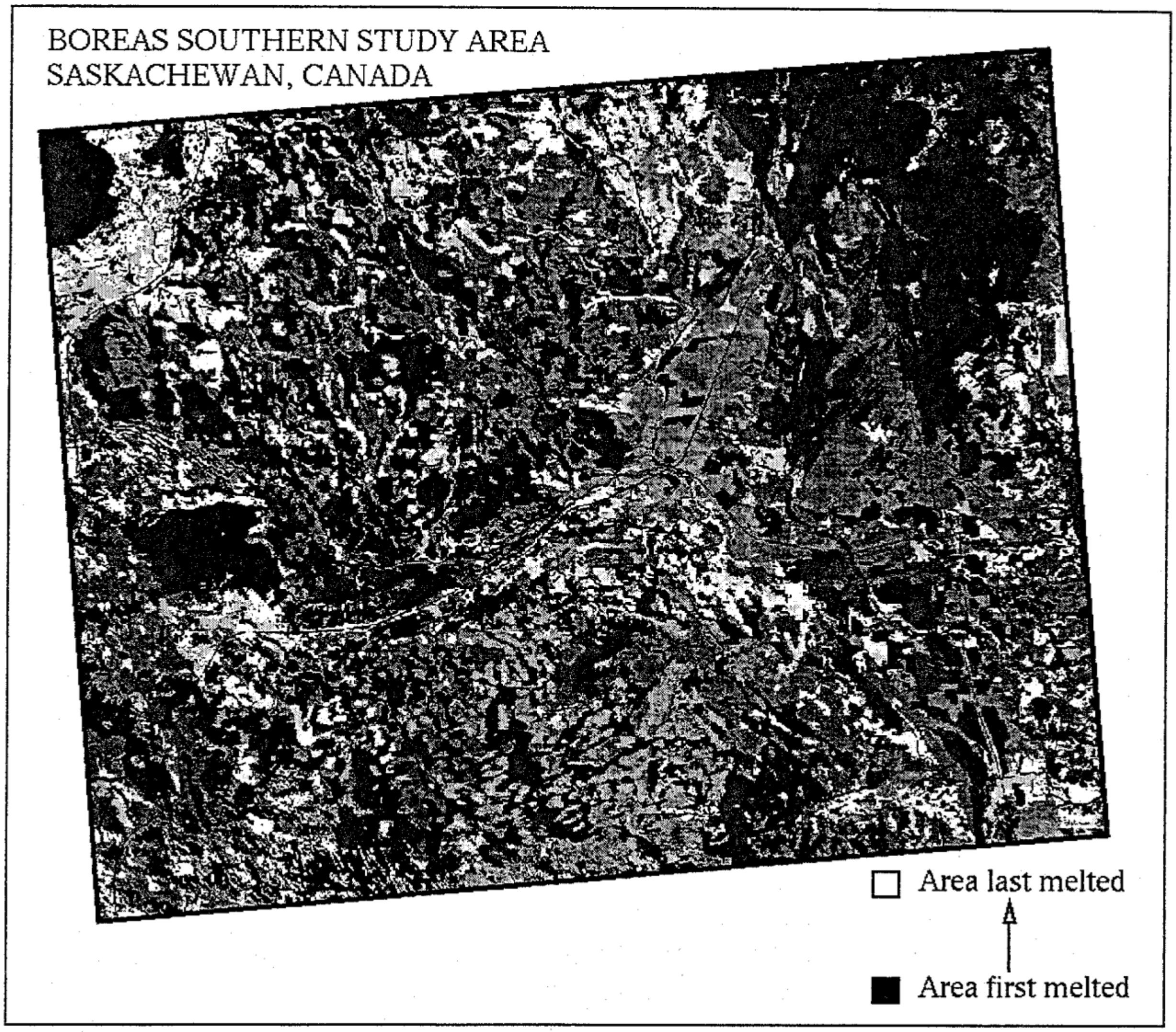

Figure 5. Model-generated image of snow cover duration from time of complete melting of first land cover class. Period of complete ablation from melt out of open areas (black) to the tallest, densest black spruce stands (white) was 23 days, driven by 1994 meteorological measurements.

developed, process-detailed models to calibrate the regression parameters. Recent success in estimating incoming radiation from satellite sensors (Gu and Smith, in press, e.g.) has motivated these efforts. Since we used image-based data layers, and simple regression coefficients associated with each image area, the calculations were explicitly distributed in space and computationally efficient.

CONCLUSIONS

Coupled canopy-snow models provided the basis for development of simple polynomial regression models to predict snow melting in the boreal forest. Regression parameters were specific to the meteorological parameters of the ablation season of 1994 at two areas in the Canadian boreal forest, as well as to forest properties derived from standard forest inventories. In the northern study area, incoming solar radiation explained most of the variance in net energy transfer to snow cover, as estimated by physics-based models. In the southern study area, variation of incoming solar radiation still explained much of the variance of net energy transfer to snow cover, but the correlations were weaker.

ACKNOWLEDGEMENT

NASA grant POS-12856-F provided the main support for this work. US Army Project 4A762784AT42 supplemented the funding. Thanks to other BOREAS investigators for measurements and help in the field, especially B. Goodison and his team (HYD-4) from AES Canada, as well as our field assistants S. Burak, R. Kattelmann, B. Neissen, D. Pilant and A. Harby. Thanks also for the extensive support of the BOREAS Staff effort at Goddard Space Flight Center.

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