Modeling snowpack and soil temperature and moisture conditions in a jack pine, black spruce and aspen forest stand in central Saskatchewan (BOREAS SSA)

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Balland, V., Bhatti, J., Errington, R., Castonguay, M. and Arp, P. A. 2006. **Modeling snowpack and soil temperature and moisture conditions in a jack pine, black spruce and aspen forest stand in central Saskatchewan (BOREAS SSA)**. Can. J. Soil Sci. **86**: 203–217. Impacts of climate change on above- and below-ground heat and moisture conditions were modeled so that other impacts on, e.g., local carbon (C) and C-based pools for nutrients and pollutants such as Hg can be predicted reliably. This paper shows how the 1998–2003 data for the jack pine (jp; *Pinus banksiana* Lamb.), black spruce (bs; *Picea mariana*) and aspen (ta; *Populus tremuloides*) sites of the Southern Study Area of the BOREAS project were used to estimate some of the hydrothermal soil responses at these locations to daily variations in precipitation and air temperature. This was done by initializing and calibrating a forest hydrology model that has the capacity to simulate flow and retention of moisture and heat, as modified by canopy closure, ground cover, forest-floor depth, and soil composition. The calculations and data revealed strong but predictable site-specific differences in soil temperature and frost penetration (jp: 1–2 m > ta: 0. 5–1 m > bs: 0–0.5 m), in soil moisture freezing (ta < bs < jp), and in moisture retention (jp < ta < bs). Apart from daily weather, these differences depended on soil texture (loamy/sandy texture impeded/encouraged soil freezing, respectively), and on the thermal insulation and moisture retention of the combined forest floor, moss and lichen layers (ta < jp < bs).

Key words: Jack pine, aspen, black spruce, soil moisture, soil temperature, frost penetration, snowpack, boreal conditions

Balland, V., Bhatti, J., Errington, R., Castonguay, M. et Arp, P. A. 2006. **Modélisation de la couche de neige et des conditions thermiques et hygrométriques du sol sous des forets de pin gris, épinette noire et tremble dans le centre de la Saskatchewan (BOREAS SSA)**. Can. J. Soil Sci. **86**: 203–217. Les impacts du changement climatique sur les conditions thermiques et hygrométriques des sols ont été modélisés, afin que d'autres impacts puissent être correctement prédits, comme, e.g., des puits locaux de carbone(C), de nutriments et de polluants comme Hg. Cet article décrit comment les données de 1998 à 2003 pour les sites « jack pine» (jp; *Pinus banksiana* Lamb.) (pin gris), « black spruce » (bs; *Picea mariana*) (épinette noire), et « aspen » (ta; *Populus tremuloides*) (tremble) de la région sud du projet BOREAS ont été utilisées pour estimer les réactions hydrologiques et thermiques des sols à ces endroits dues aux variations journalières des précipitations et de la température de l'air. Ces résultats ont été obtenus grâce à l'initialisation et au calage d'un modèle d'hydrologie forestière capable de simuler les flux et accumulations d'eau et de chaleur, en fonction de la fermeture du couvert, l'épaisseur de la couverture morte, et la composition du sol. Les simulations et les données ont révélé des différences fortes mais prévisibles entre sites concernant la température du sol et la pénétration du gel (jp: 1–2 m > ta: 0. 5–1 m > bs: 0–0.5 m), la quantité d'eau gelée (ta < bs < jp), et la rétention d'eau (jp < ta < bs). Mis a part les variations climatiques journalières, ces différences étaient dues à la texture du sol (texture limoneuse/sableuse gênant/encourageant le gel, respectivement), et à l'isolation thermique et la rétention d'humidité des couches de couverture morte, mousse et lichen combinées.

Mots clés: Pin gris, tremble, épinette noire, hygrométrie du sol, température du sol, pénétration du gel, couche de neige, conditions boréales

For the context of evaluating potential impacts of climate change on ecosystem functioning, it has become important to evaluate mechanisms by which forest ecosystems retain and release CO_2 and other carbon-affected substances (dissolved organic carbon, nutrients, Hg, etc.) at the soil-vegetation-atmosphere interface, summer through winter (Pastor and Post 1988; Yu et al. 2002; Lal 2003; Grigal 2002, 2003). This importance is accentuated for the boreal region, where climate change is expected to have strong ecosystem impacts through a significant and persistent change in length of growing season, depth of dormancy, soil moisture availability during summer, and frost-and thaw cycles during winter (McGuire et al. 2002). As such, dormancy, growth, drought, frost, CO_2 and methane production, and nutrient and Hg uptake and release are all in step with the annual progression of daily weather cycles, as expressed by incoming precipitation (rain, snow), air temperature, and the phenological responses of flora and fauna, and of the soil to these cycles. In general, higher temperatures coupled with adequate moisture supply stimulate growth as well as CO_2 uptake and release from the ecosystem (Winston et al. 1997; Rayment and Jarvis 2000). In contrast, a decrease in annual snowfall amounts could result in extended periods of soil frost. Thereafter, the occurrence of soil frost would diminish

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again if air temperature were to rise closer and closer to above-zero conditions during winter.

Within each ecosystem, local differences in hydrothermal properties above and below ground modify the extent of water, heat retention and frost penetration for the same local weather conditions (Sparrman et al. 2004). In turn, soil biological and chemical processes such as soil respiration, soil emission of trace gases, root growth, evapotranspiration, Hg methylization, and nutrient availability and uptake would all be affected by local differences in soil temperature and moisture conditions (Cao and Woodward 1998). Changes in soil moisture and temperature regimes affect forest productivity directly by limiting the availability of energy, water supply, and nutrients, on a daily basis (Kimball et al. 1997). In turn, all of this affects the general health of the forest: by definition, healthier vegetation has greater disease, insect, and drought resistances, and would also be adapted to make the required dormancy adjustments to cope with the recurring winter conditions (Yu et al. 2002).

By way of the Boreal Ecosystem-Atmospheric Study (BOREAS; Hall 1999; Sellers et al. 1997) and the Boreal Experimental Research and Monitoring Study (BERMS, see http://berms.ccrp.ec.gc.ca), data have become available that can be used to analyze the ecological effects of daily weather on soil temperature, moisture, snowpack and soil frost for select cover types and soil combinations (Fig. 1).

The specific objective of the research summarized in this paper was to analyze the snowpack and soil temperature and moisture data from the three southern study site locations of the BOREAS Project (Figs. 1 and 2, Table 1). These data were analyzed with the forest hydrology model ForHyM (Bhatti et al. 2000) as a theoretical and numerical guide to explore and describe site-specific differences such as:

1. the capacity of the forest canopies to retain snow, rain, and heat, and to filter solar radiation before it reaches the ground,
2. the hydrothermal properties (water retention, permeability, heat capacity, thermal conductivity) of the forest floor, as affected by the changing soil moisture conditions and the type of vegetation immediately above the forest floor,
3. the pattern of lateral, downward and upward soil moisture flows, as affected by local topography (slope), depth to water table, and extent of soil moisture stress.

The emphasis of this paper is placed on illustrating the concepts involved, and on visually demonstrating the extent of model-data agreement that was achieved for each of the three sites.

MATERIALS AND METHODS

Study Area and Sites

The BOREAS/BERMS study area is located in Central Saskatchewan (Fig. 1). The terrain of this area is generally flat to gently rolling, with mean elevation of 520 m. The vegetation cover is predominantly coniferous, with low species diversity. Understory vegetation is generally composed of sparse shrubs with extensive moss and lichen cover. The growing season generally lasts from May to October. For further details on vegetation and soil conditions, see Halliwell and Apps (1997). The particular study sites (Table 1, 50 × 50 m plots; meteorological towers at center; north-south orientations) refer to:

1. an upland jack pine (*Pinus banksiana*) site on sandy soil,
2. a lowland black spruce (*Picea mariana*) site also on sandy soil, and
3. an aspen (*Populus tremuloides*) site on loamy soil.

Old Jack Pine Site

This site (Fig. 2, top) is located approximately 100 km NE of Prince Albert, Saskatchewan near Narrow Hills Provincial Park (53.916°N, 104.692°W; elev. 579 m). The site is dominated by jack pine (*Pinus banksiana* Lamb.), with trees ranging in height from 12 to 15 m, and in age from 80 to 90 yr. The canopy leaf area amounts to 1.7 m^2 m^{-2}. The understory consists predominantly of isolated groups of alder (*Alnus crispa*) with an extensive surface cover of lichens (*Cladina* spp.), bearberry (*Arctostaphylos uva-ursi*, Sprengel) and bog cranberry (*Oxycoccus oxycoccos*). This coverage provides thermal insulation to the soil below during summer. During winter, this layer is permeated by snow, and therefore becomes part of the snowpack. The soil below is sandy, and well drained.

Old Black Spruce Site

This site (Fig. 2, middle) is located in a "muskeg" forest near White Swan Lake (53.987°N, 105.117°W; elev. 628.94 m). This site consists of a matrix of poor fen vegetation on organic soils, alternating with black spruce (*Picea mariana*) growing on poorly drained sandy soils. The meteorological tower at this site stands on a locally raised area that supports a black spruce-feather moss community. Within the site, 15-m-tall black spruce trees dominate, with tamarack (*Larix laricina*) contributing about 15% to the forest canopy. The leaf area of the canopy amounts to 2.5 m^2 m^{-2} . Ground-level vegetation mostly consists of feather mosses (*Hylocomium splendens* and *Pleurozium schreberi*), with sparse Labrador tea (*Ledum groenlandicum*). The soils are covered with a 20- to 30-cm peat layer over coarse-textured sand. The combined moss and peat layer provides thermal insulation against hot air temperatures in summer, and against cold air temperatures in winter.

Old Aspen Site

This site (Fig. 2, bottom) is located near the south end of Prince Albert National Park, Saskatchewan (53.629°N, 106.198°W; elev. 600.63 m). The forest overstory consists of trembling aspen, averaging a height of 21 m. The 2-m-high understory consists of beaked hazelnut (*Corylus cornuta*), interspersed with alder. Total canopy leaf area amounts to 5.5 m^2 m^{-2}. The soil is a moderately well drained loam to clay loam. The surface soil at 1–7 cm is organic (leaf litter, plus fermentation layer); between 7 and 30 cm, the soil is derived from a till containing sand and clay. Below 30 cm, the soil is derived from a gravelly and clay-enriched till.

Measurements 1998–2003

Air temperature and total precipitation data were obtained for each study site from the BOREAS/BERMS database

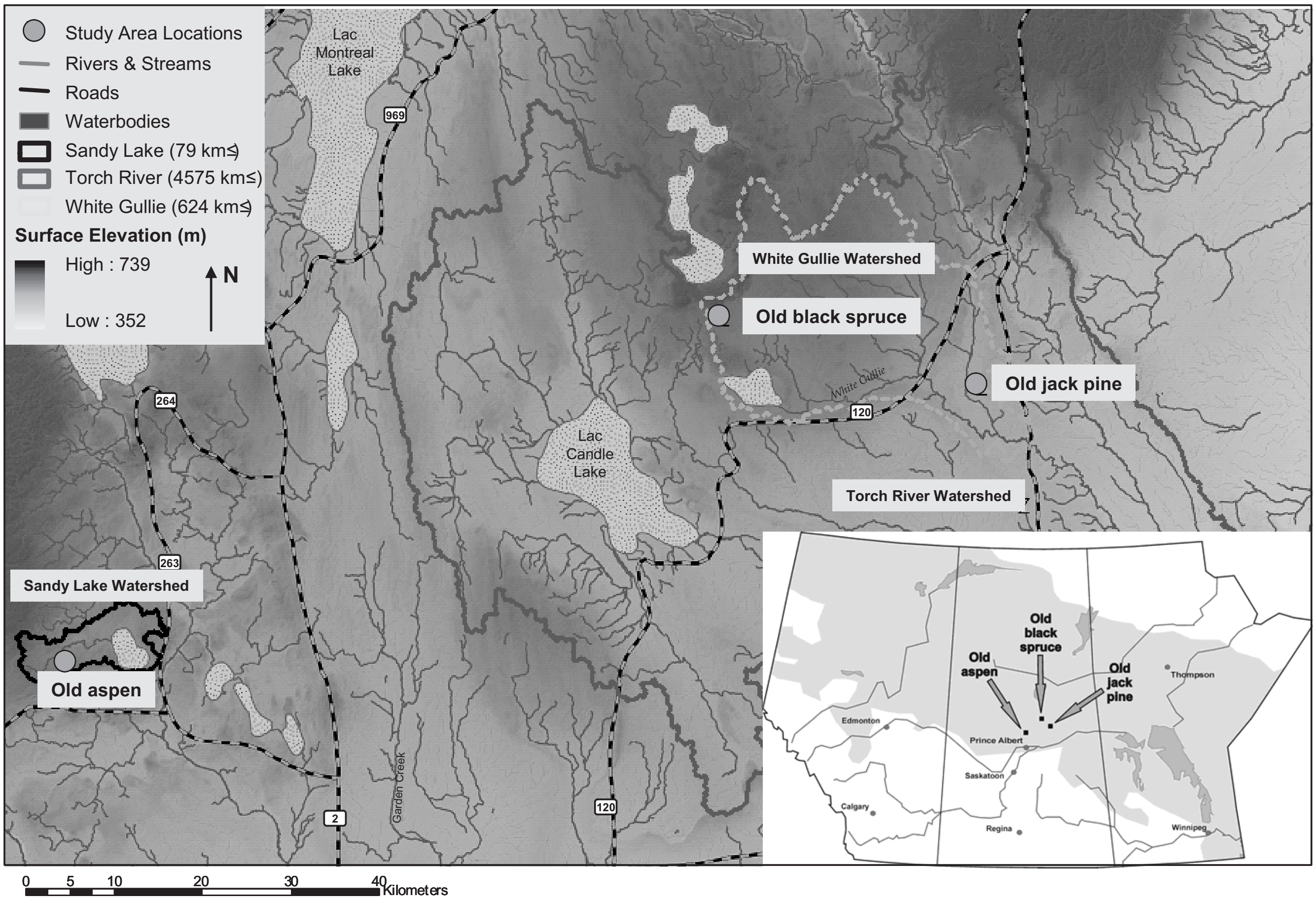

Fig. 1. Location of the three study sites (jack pine, black spruce, aspen), near Montreal Lake, Saskatchewan.

(http://berms.ccrp.ec.gc.ca/data/data_doc/BERMS_main.doc). These data were collected at approximately 30-min intervals at each of the study sites.

The air temperature data were used to decide whether the incoming precipitation was rain (when air temperature > 0°C) or snow (when air temperature < 0°C).

Daily snow-depth data were obtained from the BOREAS/BERMS database. These data were obtained with ultrasonic snow depth gages (UDG01 of Campbell Scientific) that were placed below the forest canopy at each of the three locations.

Soil temperatures were measured at 2, 5, 10, 20, 50 and 100 cm below the moss layer at the NE-SE and NW-SW corners of the study blocks, using Cu-Co Thermocouple sensors that were set to take temperature readings every 30 min. Volumetric unfrozen soil moisture readings were obtained with Campbell Scientific CS615 soil moisture probes. These probes were also installed at NE-SE and NW-SW corners of the study blocks, 7.5, 22.5, 45 and 105 cm below the surface of the forest floor.

For the purpose of hydrological modeling, the data were summarized as follows: daily averages for all air and soil temperature data, daily totals for rain, snow, and soil moisture, and daily snowpack depth. Records with missing data were identified, and the missing data were substituted in various ways: through interpolating the values immediately before and after the missing value when the time gap was small (a day), or by using the best-fitted regression equations from one weather station to the other when the data gap was long.

Model Description

The ForHyM model is an aspatial model that is designed to simulate all major water and heat fluxes through the main compartments of a forest ecosystem (canopy, snowpack if present, forest floor, rooted portion of the mineral soil, subsoil), at daily resolution. ForHyM requires daily weather (mean air temperature, rain, and snow), and rudimentary site descriptors as input (slope, aspect, elevation, soil depth, texture, organic matter and coarse fragment content, forest cover type) (Fig. 3, Table 1). The model calculates daily canopy interception, snow-pack depth, density and water equivalents, frost depth (frost occurs when at least some of the water becomes ice), soil moisture (frozen and unfrozen), and soil temperature, at any depth. Soil calculations extend from the top of the forest floor through the rooted soil down to a depth of 12 m, where soil temperature remains essentially constant year-round.

Throughout the calculations, the principles of mass and heat conservation are strictly obeyed, as moisture and heat are simulated to pass from the atmosphere to the forest canopy, from the canopy to the snowpack when present,

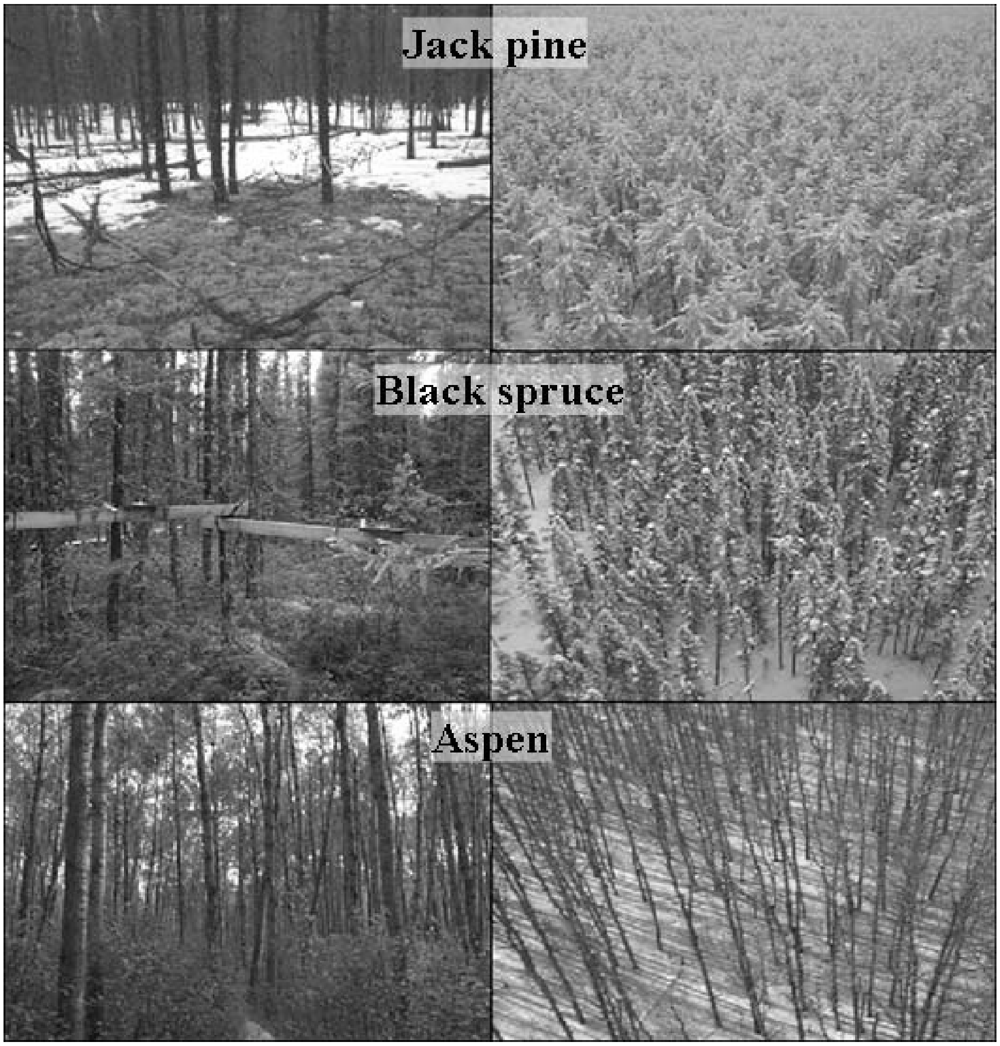

Fig. 2. Photographs of below (left) and above (right) forest canopy conditions of the jack pine (top), black spruce (middle) and aspen (bottom) sites of this study.

from the snowpack when present to the forest floor, and from the forest floor to the soil and to the subsoil. The heat flow calculations for the snowpack and the underlying soil layers are based on determining the temperature at the ground surface by considering the energy balance at this surface. This balance is obtained by explicitly addressing all major incoming and outgoing heat fluxes. The transmission of heat from one soil layer to the next is based on an implicit difference formulation of the heat flow equation, and by accounting for changes in heat capacity and thermal conductivity as these parameters change with texture, soil bulk density, organic matter and coarse fragment content, soil moisture, and change of phase (Arp and Yin 1992; Yin and Arp 1993). For a more recent update on theoretical and numerical developments regarding hydrothermal flow through frozen and unfrozen soils, see Webb (1997), Peck and O'Neill (1997), and Albert et al. (2000).

The application of ForHyM to each of the three study sites is schematically represented in Fig. 4, in reference to the hydrothermal summer and winter configurations of the mineral soil, forest floor, snow, and other layers when present (i.e., moss, reindeer lichen, shrubs). Further details about the soil conditions at each site as needed for the modeling purpose are presented in Tables 1 and 2.

Theoretical Considerations

Prior to this application, the model was calibrated for forest conditions at Kejimkujik National Park in Nova Scotia (Balland 2002), within the forest of the University of New Brunswick in Fredericton (Balland 2002), within deciduous and coniferous forest conditions in Northern New Brunswick (Steeves 2004), and within the Turkey Lakes watershed in Ontario (Arp and Yin 1992; Yin and Arp 1993). These calibrations led to a generalized means to initialize the model, by starting with hydrothermally derived "default" values for the parameters that are used to calculate interception (precipitation, light), snow-pack density,

Table 1. ForHyM initialization: soil profile specifications for the jack pine, black spruce and aspen sites of the study area

Site	Soil layers	Thickness (cm)	Texture	OM fraction
Jack pine	Forest floor	3–9[z]		0.515
	A	30	Sand	0.003
	B	30	Sand	0.001
	C1	45	Sand	0.001
	C2	45	Sand	0.001
	Subsoil layers	100	Sand	0
Black spruce	Forest floor	10–15[y]		0.88
	A	2	Loamy sand	0.028
	B	15	Sandy loam	0.01
	C1	25	Sandy loam	0.002
	C2	30	Sandy loam	0.001
	Subsoil layers	100	Sand	0
Aspen	Forest floor	8		0.77
	A	10	Sandy loam	0.015
	B	45	Sandy clay loam	0.011
	C1	20	Sandy clay loam	0.041
	C2	20	Loam	0.053
	Subsoil layers	100	Loam	0

[z]Forest floor thickness = 3 cm; reindeer moss thickness = 6 cm in summer, permeated by snow in winter.
[y]Forest floor thickness = 10 cm; moss layer on top = 5 cm.

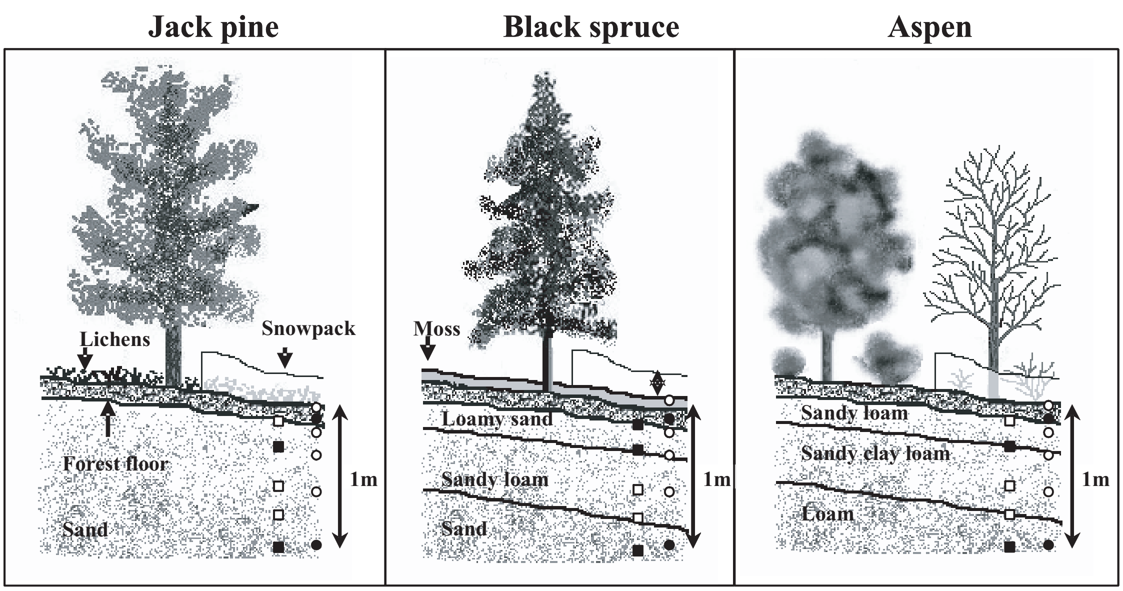

Fig. 3. Approximate locations of the temperature (circles) and soil moisture (squares) sensors within the soil profiles at the three study sites; results are shown for the solid symbols only.

snowmelt, infiltration, interflow, percolation, moisture and heat retention, and thermal conduction. These values were obtained from a semi-empirical analysis of local and global soil data that relate:

- soil bulk density to soil texture, organic matter content and soil depth,
- water retention and soil moisture flow to soil porosity, texture and organic matter, and
- soil thermal conductivity to texture, organic matter, coarse fragment content, soil mineralogy and soil moisture (Balland 2002; Balland and Arp 2005).

Running the model for each site based on its local weather and soil information showed that the model performed well, but also required a number of process-based adjustments to get the best possible data-model agreement for the snowpack, the soil temperature, and the unfrozen soil moisture content. These were the main adjustments:

1. *Canopy transparency*: foliage within boreal forest canopies is generally not uniformly distributed across the entire area, but occurs: in the narrow crowns of well-spaced black spruce trees, in bunches along branches and twigs of well-spaced jack

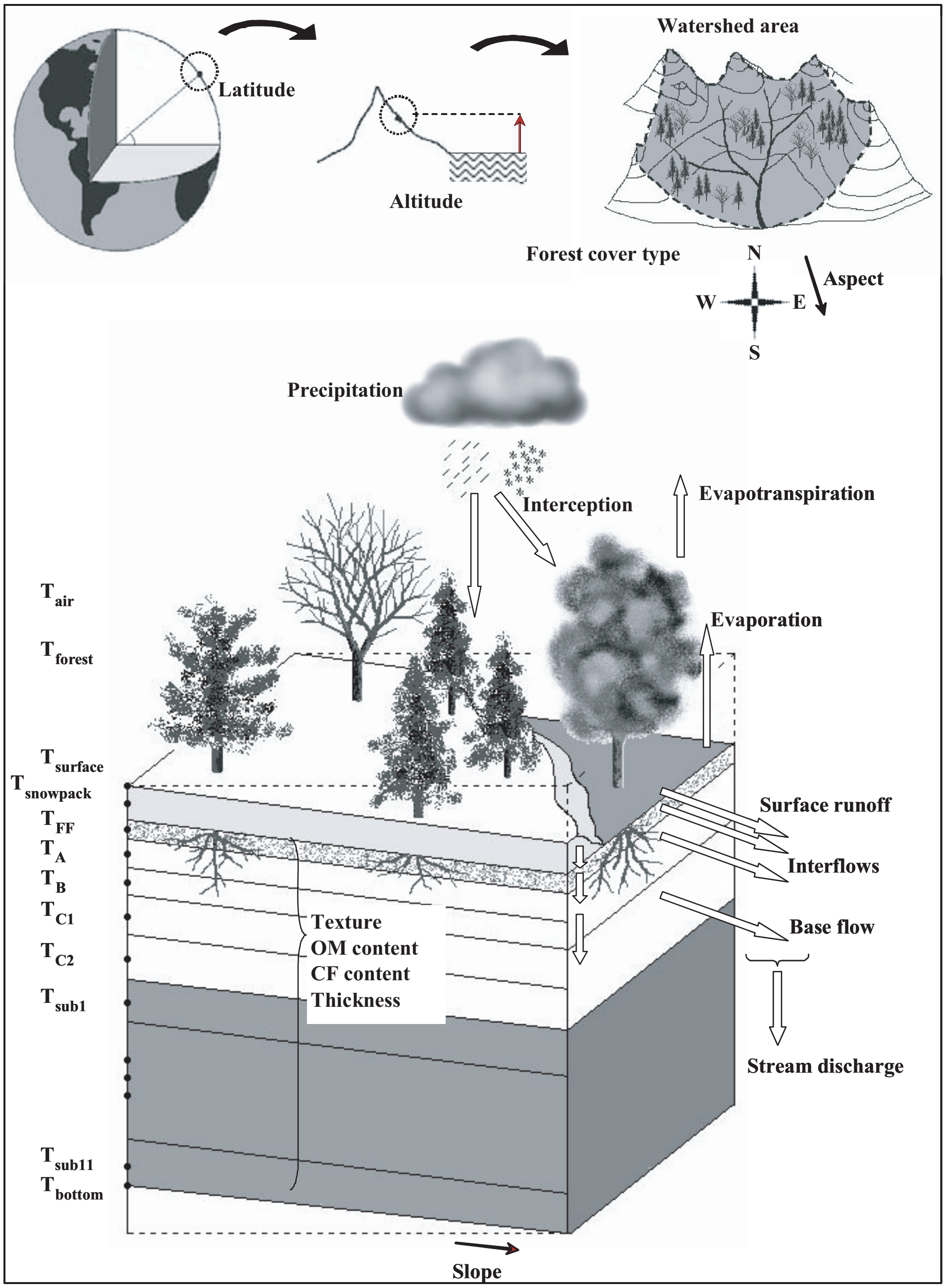

Fig. 4. Overview of the forest hydrology model ForHyM. Depicted are: basic input parameters, and structure of the layers used for soil moisture and temperature calculations.

pine, and individually along the twigs of well-spaced and slender aspen trees (Fig. 2). As a result, there is more light reaching the ground than what would occur with a continuous single or multiple leaf-layer models for the canopy. Hence, the leaf areas, as quoted above, were multiplied by a canopy transparency factor that was empirically determined by comparing the model simulation with the field-observed values for the snowpack, and for the forest floor moisture content and temperature, for each of the three sites. The resulting values of this factor are listed in Table 2.

2. *Fraction of light reflected from the ground surface (albedo)*: the moss layer on the black spruce would be more reflective of the incoming light than a forest floor with no moss cover. This

Table 2. Model calibrations for the jack pine, black spruce and aspen sites of the study area

Site	Canopy transparency adjustments	Snowfall adjustments	Air temperature adjustments	Soil layers	Permeability adjustments		Thermal conductivity[z] adjustments	Maximum frost fraction[y]
					downward	lateral		
Jack pine	0.27	1.25	0°C	Forest floor	1	0.5	1	1
				A	1	0.005	1.09	1
				B	1	0.005	1.07	1
				C1	1	20	1.09	1
				C2	1	20	1.09	1
				Subsoil layers	1	20	0.50	1
Black spruce	0.17	1	–1.6°C	Forest floor	1	0.5	1	1
				A	1	0.005	1	1
				B	1	0.005	1	1
				C1	0.2	1	1.07	1
				C2	0.2	1	1.06	1
				Subsoil layers	0.2	1	1	1
Aspen	0.11	1	0°C	Forest floor	1	0.1	1	0.75
				A	0.5	0.005	1	0.8
				B	0.5	0.005	1.12	0.4
				C1	0.002	0.2	1.35	0.4
				C2	0.002	0.2	1.42	–
				Subsoil 1	0.002	0.2	0.98	–
				Subsoil 2	0.002	0.2	0.85	–
				Subsoil (deeper)	0.002	0.2	0.74	–

[z]Adjustments to default modeled thermal conductivities (multipliers).
[y]Limit of the ice/(water + ice) fraction for each soil layer.

consideration implied that an upward adjustment needed to be made to the default value for the ground-surface albedo (its default value represents the no-moss cover situation, midday, mid-summer). For the moss-covered ground surface of the black spruce site, the best-fitted albedo value was found to be 0.25. For the aspen and jack pine site, the albedo remained at its default value of 0.12.

3. *Reducing the near-ground air temperatures of the black spruce site by 1.6°C, year-round*: the soil temperature simulations for this site indicated that the air temperature near the ground level needed to be consistently cooler than what was suggested by the on-site air temperature measurements; this adjustment was not needed for the other two sites. A somewhat cooler ground temperature than elsewhere is generally obtained with moist-to-wet ground surface conditions in depressions, especially under forest cover.

4. *Adjusting snowfall amounts at the jack pine site*: the snowpack simulations required that the snow input for the site be increased by a factor of 1.25. This increase could be due to a slightly better snow-catch efficiency of the jack pine canopy than the other two sites. Greater snow-catch efficiency might be indicated by the differences in branch, twig and foliage architectures during winter.

5. *Adjusting the default value for the hydrothermal parameters of the snow-pack and soil, by layer*: the default values for soil bulk density, field capacity, permanent wilting point, thermal conductivity, heat capacity, and soil permeability at saturation were generated for the forest floor, the A, B and C layers, and the subsoil layers, based on the information listed in Table 1, as described by Balland (2002). These default values remained untouched, except for the permeability and thermal conductivity adjustments noted in Table 2. Among these, the largest adjustments needed to be made for the downward flow (infiltration) for the aspen site (a reduction of 500), the lateral flow (interflow) for the A and B layers of the jack pine and black spruce sites (a reduction by 200), and the lateral flow for the subsoil of the jack pine site (an increase by 20). The reasons for these changes vary: lateral and downward flow of water can, in general, not be expected to be the same, even under the same hydraulic gradient. For example, in the more porous top soil, lateral flow would only occur when the subsoil is saturated. In contrast, lateral flow would dominate in the more compacted subsoils, due to a gradually increasing soil bulk density. Within ForHyM, it is assumed that downward percolation is restricted, on a daily basis, by the availability of unsaturated pores, and by the permeability of each soil layer. Lateral flow is initiated once the soil moisture content in any layer exceeds the field capacity of that layer, and when the layer below that layer is saturated, i.e., cannot accommodate more water. The actual amount of "net lateral flow loss" from each soil layer is subject to calibration, to account for site-specific "obstacle" variations against lateral flow, especially in top soils (e.g., changes in terrain, slope, mounds and pits, soil density, and soil composition). Lateral as well as downward flows are assumed to follow Darcy's law, with the appropriate considerations made to defining the average length of the vertical and lateral flow-paths at each site, and to determining the associated hydraulic gradients. For lateral flows, flow-path length and gradients were related to the average ridge-to-valley length, and to the difference in elevation. For vertical flow, flow-path length and gradients

were obtained from layer depth and depth of saturation above that layer.

6. *Adjusting the thermal conductivities*: the best-fitted values for the thermal conductivities were generally close to the anticipated default values (Table 2), especially for the black spruce site. For the sandy soil, thermal conduction in the topsoil was estimated to be somewhat higher than the default value for a sandy soil. In the subsoil, thermal conductivities were estimated to drop to one half of the default value. This could be due to: a change in sand mineralogy (e.g., less crystalline, less quartz), or change in moisture (being drier than calculated). The last possibility would be more plausible than the former, because the upper soil horizons would likely receive upward capillary flow during summer and winter, thereby not only reducing the moisture content of the subsoil (see below), but also lowering the ability of that subsoil to conduct heat.

7. *Soil freezing*: allowing all of the soil water to freeze should restrict the depth of frost penetration into the soil, and should also retard the rate at which the frozen soil will thaw, especially if the soils are saturated or nearly saturated. Freezing restrictions should also be greater in fine-textured soils than in coarse-textured soils, because the larger mineral surface and the extensive network of fine pores in fine-textured soils would interrupt ice formation, which would mostly be confined to the inside of the larger pore spaces. As a result, fine-textured soils should be prone to super-cooling, and would thereby remain unfrozen to some extent, even at sub-zero temperatures. In the model, super-cooling was recognized by restricting the extent of soil moisture freezing with increased fineness of soil texture, and with increased soil bulk density. It was further assumed that freezing would stop once the unfrozen soil moisture content would fall below the permanent wilting point (PWP). Consequently, the amount of soil freezing was simulated to be fairly unrestricted for sandy soils at the jack pine and black spruce sites, but restricted for the fine-textured soil of the aspen site. As listed in Table 2, this restriction was estimated to increase with increasing soil depth, in keeping with the decrease in volumetric pore space, as the bulk density of the soil is expected to increase from the A layer to the subsoil.

8. *Upward capillary flow*: there should be upward soil moisture flow when the upper soil layers become dry during summer, and icy during winter. This flow would be strongest when the subsoil is saturated and remains saturated when the high water table below remains close to the soil surface (e.g., the C layer or slightly below). Appreciable upward flow was suspected to occur at the depressed black spruce site: the simulations suggested that this should be so because the calculated soil moisture content of the upper soil layers would be much lower than corresponding field determinations. The extent of upward capillary flow would be limited on the jack pine site because of the low water retention capacity of the subsoil at this site. However, the lowering of this subsoil moisture content due to upward capillary flow during summer and winter was likely underestimated by the calculations, thereby requiring a downward adjustment of the heat conduction coefficient.

Criteria Used to Determine Quality of Model Fit

Data and model output were graphed on the same scales, to allow for direct visual data-model comparisons. Complete agreement between model calculations and sensor measurements for temperature and moisture were not expected because of:

- considerable lateral and vertical heterogeneities of the general soil conditions; these heterogeneities affect the hydrothermal conditions in the immediate vicinity of the soil moisture and temperature sensors,
- differences of the sensor-produced data and the weather-guided modeling scale, i.e., the former scale is pertinent to the immediate vicinity of each soil moisture and temperature sensor; the latter is pertinent to the scale of the forest stand, and it is assumed that the tower-based air temperature and precipitation measurements are reflective of the overall heat and water input into the forest site.

The final snowpack depth, soil temperature and moisture calibrations were all adjusted such that they would consistently fall between the corresponding sensor readings from separate locations and soil depths within the same stand, summer through winter. These adjustments were necessary so that the simulations properly addressed:

- the differences in the canopies to admit light and precipitation (rain, snow) to the forest floor or to the snowpack on top of the forest floor when present;
- the thermally insulating properties not only of the forest floor, but also of the vegetation layer immediately above the forest floor, and of the snowpack when present;
- the extent to which the moisture in the soil would be subject to freezing; lack of freezing at sub-zero temperatures was calculated to produce a deeper heat loss from the same soil;
- potential contributions of upward capillary flow in the summer as well as in the winter.

For the sake of brevity, the comparisons presented below are limited to illustrating the data-model consistency for snowpack depth, and for the highest and lowest sensor positions at each of the three locations only, i.e., the positions of the sensors placed in the forest floor, and placed about 1 m deep into the soil.

RESULTS AND DISCUSSION

Snowpack

Observed and simulated snowpack accumulations are plotted in Fig. 5 versus time. In each case, the agreement between the observations and the simulations was satisfactory: all sites showed a similar year-to-year snow depth pattern, with a maximum snowpack depth of about 40 cm. Simulated timing of snowmelt coincided closely with observed disappearance of the snowpack in each spring. The jack pine snowpack simulations produced the best overall fit, but only after introducing a 1.25 adjustment factor for snow fall. For the black spruce and aspen sites, snowpack depths were slightly over- or under-simulated. Snowpack depth, as modeled, was a result of estimating: snow fall

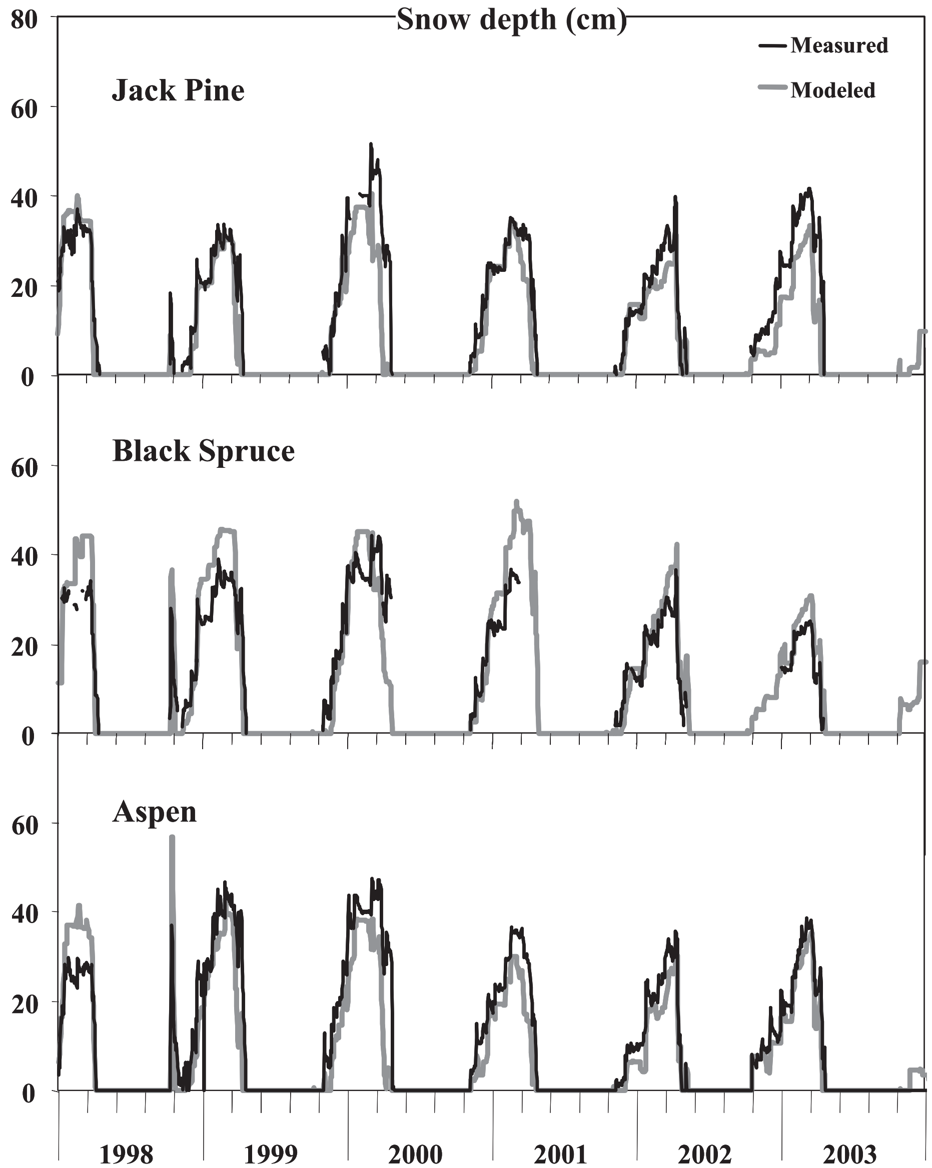

Fig. 5. Measured and modeled snowpack accumulations at the three study sites, from 1998 to 2003.

from total daily precipitation and air temperature, snow interception, and snow pack density. Snow interception was highest for the black spruce site, intermediate for jack pine site, and least for the aspen site, as to be expected from the actual amount of forest leaf area during winter. Initial snowpack density (density of freshly fallen snow) was allowed to vary from 0.10 (aspen, black spruce) to 0.11 g cm^{-3} (jack pine). Variations in the field would likely be larger than this, and the numbers would also increase towards higher values (e.g., 0.15 g cm^{-3}) in warmer winters. Overall, the snowpack simulations produced a good correspondence between the simulated and field-observed snowmelt season at each site.

Soil Temperature

Simulated and measured soil temperatures were also in good agreement, as shown in Figs. 6 and 7 at 5 cm below the forest floor (jack pine, black spruce) or 5 cm below the mineral soil surface (aspen), and at 1 m depth for all three sites. The agreement at the other monitored soil depths was similar across all sites. For the forest floor, measured and simulated temperatures were found to be warmer in summer under jack pine than under black spruce. During summer, the forest floor was simulated to be warmer for the jack pine site when the insulating effect of the reindeer lichen layer was ignored. During winter, sub-zero forest floor temperatures were quite variable from day to day. Figure 6 (top,

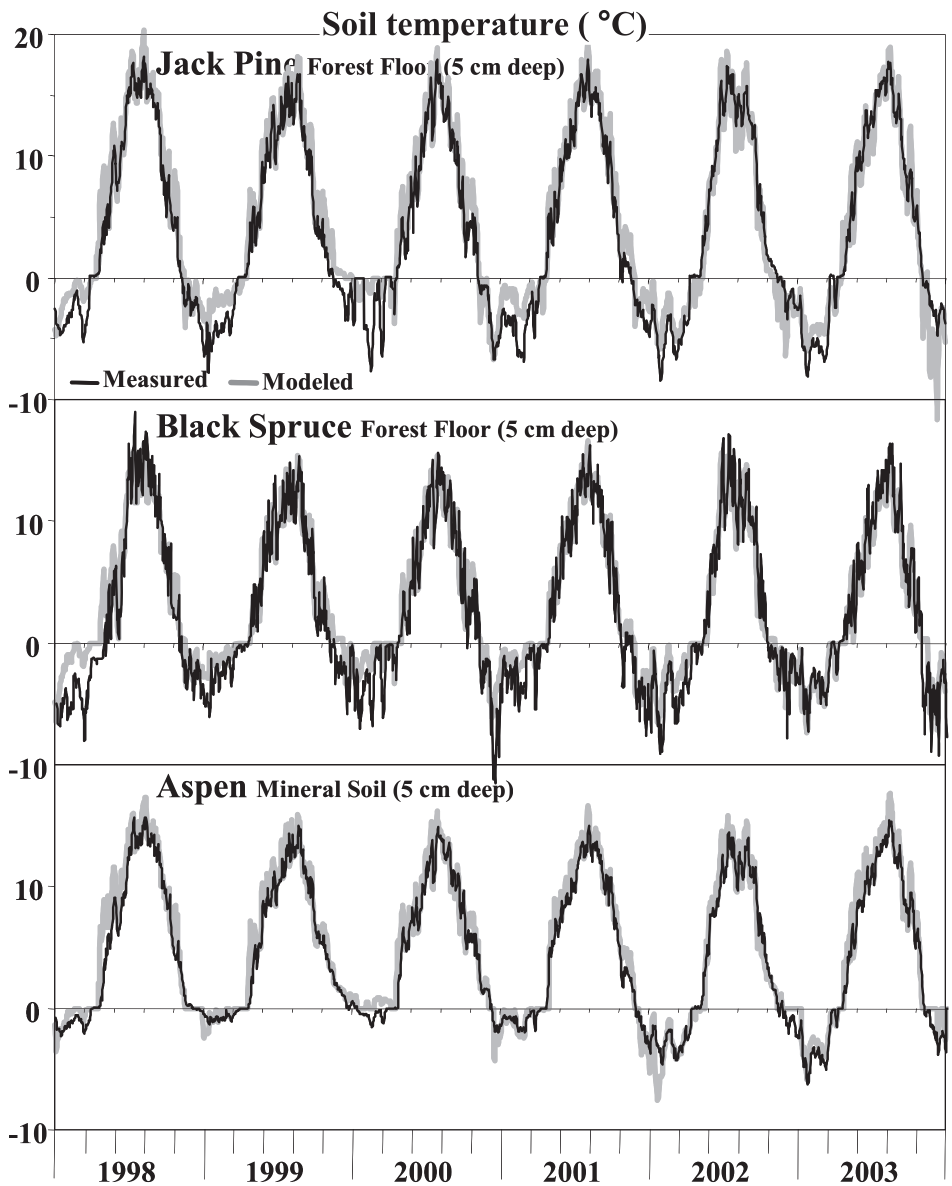

Fig. 6. Measured and modeled soil temperatures in the forest floor (5 cm deep) for the jack pine (top) and black spruce sites, and in the mineral soil (5 cm deep) for the aspen site, from 1998 to 2003.

middle) shows the observed and simulated forest floor temperatures for the jack pine and black spruce sites. Within the mineral soil, measured and simulated temperatures became less variable with increasing depth, as to be expected. Figure 6 (bottom) shows the observed and simulated soil temperature for the aspen site 5 cm into the soil. Soil temperatures during winter were coldest at 100-cm depth for the jack pine site, somewhat less cold for the aspen site, and least cold for the black spruce site (Fig. 7). This sequence likely established itself on account of site-specific circumstances: thermal insulation is low on the jack pine site, and high on the black spruce site, as already discussed. On the aspen site, soil insulation during winter would mainly be due to the presence of the snowpack. Within the soil, penetration of sub-zero temperatures is less deep on the aspen site compared with the jack pine site on account of the higher moisture content and therefore the higher heat capacity of the aspen soil.

Soil Moisture

Model calculations and measurements for the unfrozen soil moisture content (Figs. 8 and 9) were generally not in as good agreement as what was obtained for the simulated and measured soil temperatures. However, there were general similarities in observed and simulated soil moisture trends

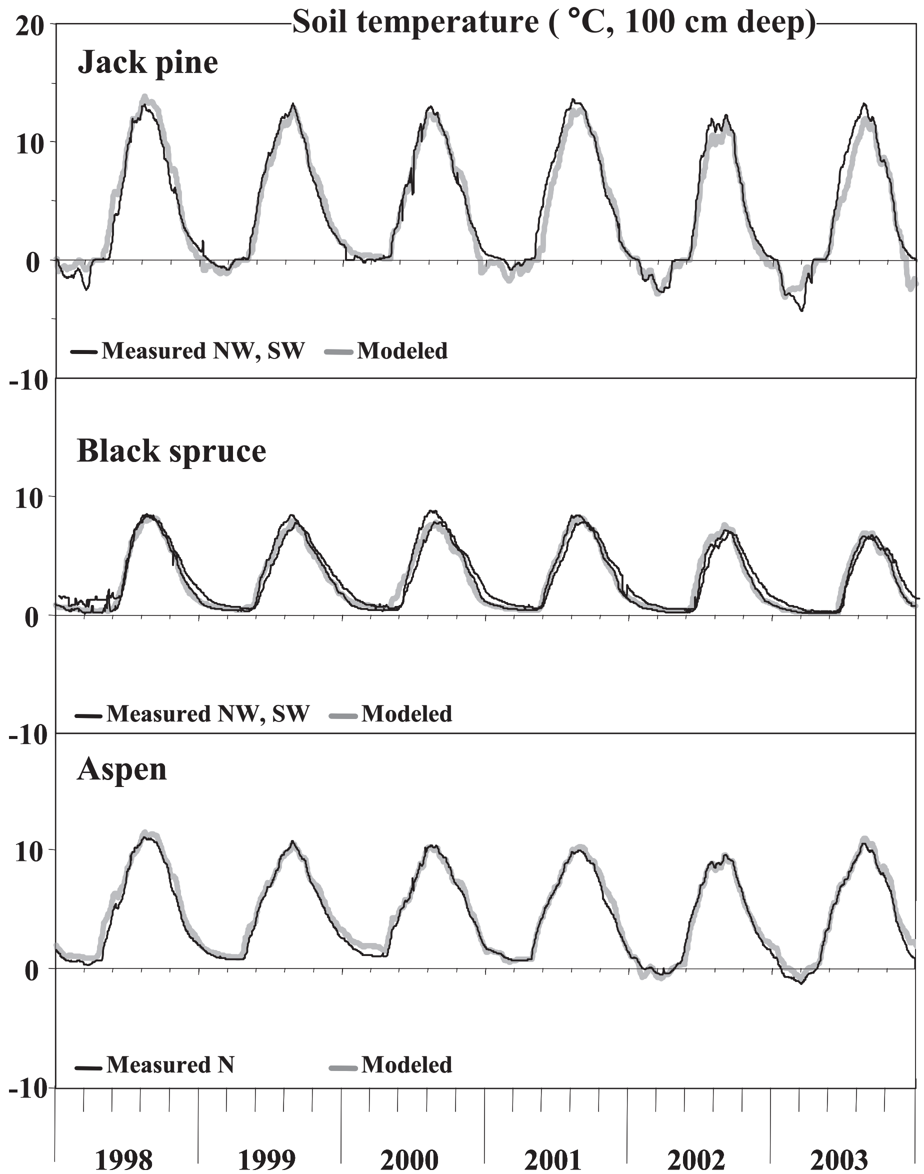

Fig. 7. Measured and modeled soil temperatures 100 cm below the soil surface at the three study sites, from 1998 to 2003.

with regard to season, in spite of major differences in cover type and soil texture among the three sites. Variations within the data, and variations in the comparisons between the field determinations and the simulations were likely due to differences in local conditions (fine-scale mounds and depressions), and actual sensor surroundings. Here, soil organic matter, texture and coarse fragment content as well as soil bulk density next to each sensor would determine what the actual soil moisture reading would be at that location. In contrast, the model calculations correspond to average soil conditions only, based on the soil texture and organic matter estimates in Table 1. Since these estimates were used to calculate soil pore space, soil saturation point, field capacity, permanent wilting point and soil permeability, it is therefore not surprising that any two soil moisture probes, even when placed at the same depth but at different locations within the stand, differ from one another, and from the estimated model values as well.

Simulated soil moisture levels were found to be drifting towards lower values during extended periods of drought and frost when no allowance was made for upward capillary flow. During summer, upward capillary flow was set to occur in proportion to the difference between the soil moisture content between the soil layers from top to bottom. During winter, upward capillary flow was set to be proportional to the extent of ice formation in the soil. This extra water would not add to the general soil moisture level, but would accumulate as ice in the soil layer with the freezing front.

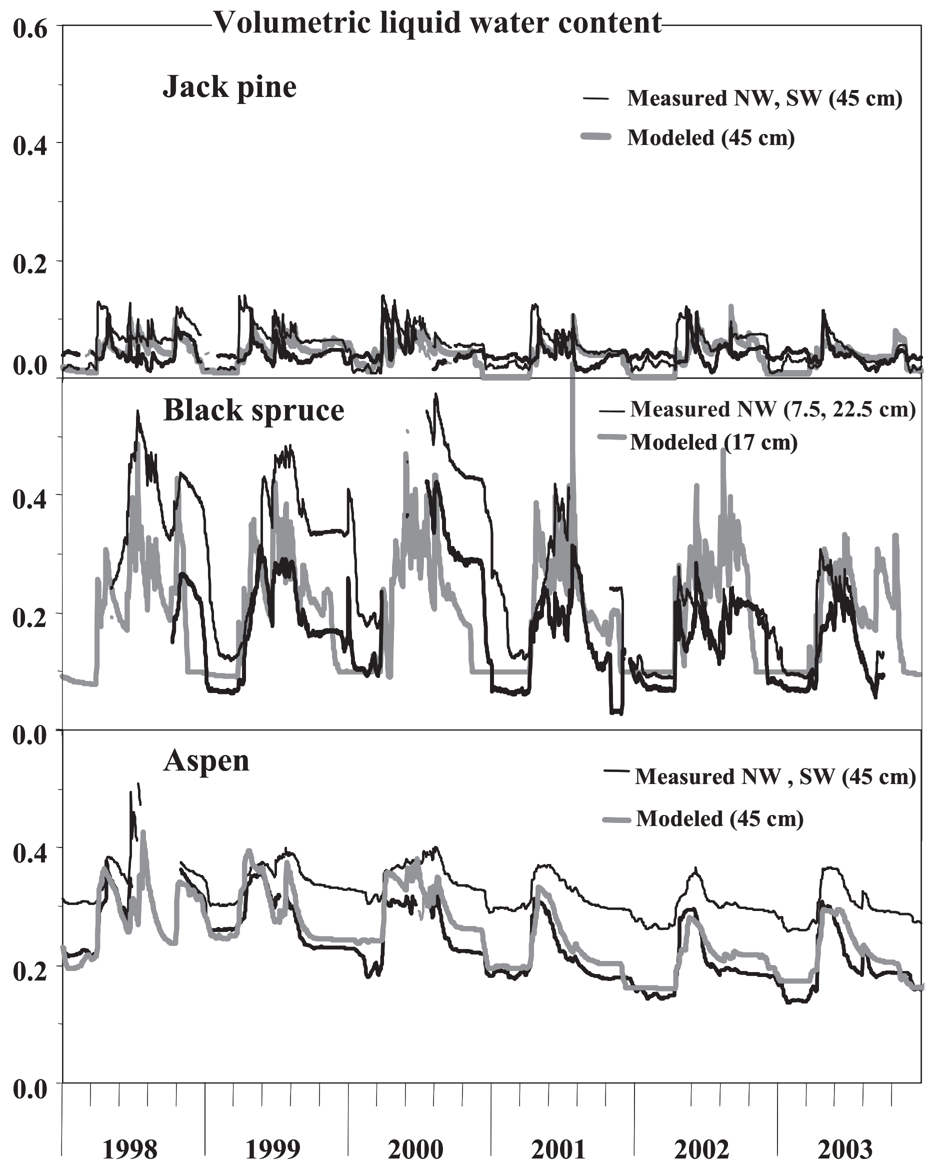

Fig. 8. Measured and modeled soil moisture levels in the top 25-cm portion of the soil at the three study sites, from 1998 to 2003.

Depth of Frost Penetration

For the three sites, simulated heat flow from the forest floor into and through the mineral soil differed strongly, as follows: low moisture content in the mostly sandy soil underneath jack pine allowed for 1–2 m deep frost penetration (Fig. 10, left). In general, sandy soils conduct heat better than fine-textured soils (Balland 2002). In contrast, the water in the fine-textured soil underneath the aspen site was observed and simulated to remain partially unfrozen, even at sub-zero soil temperatures (Figs. 8 and 9, bottom; Fig. 10, bottom right). Simulating the soil moisture on the aspen site to freeze completely produced a strong and un-realized delay of the return to above-zero soil temperatures after each snow-melt season. For the black spruce site, the situation differed again: frost penetration into the soil was simulated to be mainly limited by the high moisture content, and therefore by the high heat capacity of the soil at this site.

The plots in Fig. 10 indicate to what extent and at which depth the soil should remain frozen after the return of above-zero air temperatures, and how fast (or slowly) all of the soil would thaw again after each winter. For the aspen site, thawing of the partially super-cooled soil was calculated to occur quickly. Entering a completely frozen state would not only have reduced the depth of sub-zero temperatures, but also would have unrealistically delayed the return to the completely unfrozen condition in the spring.

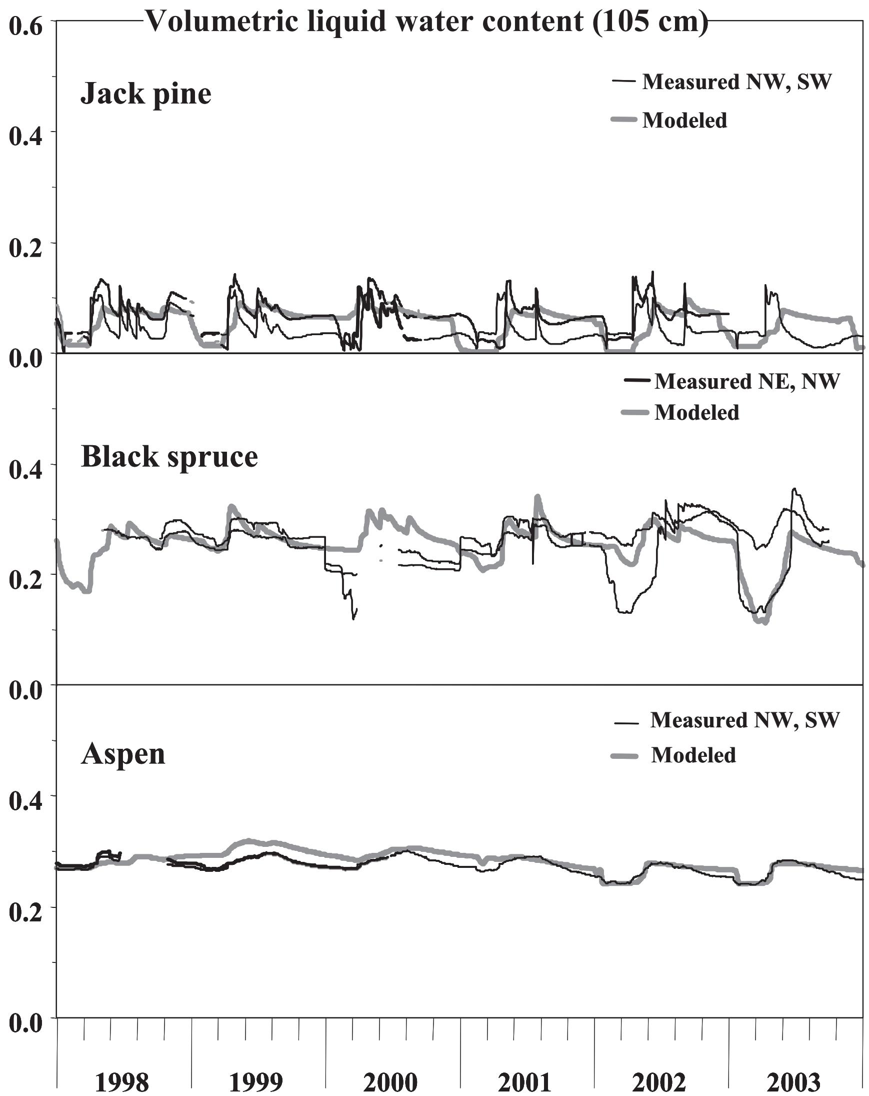

Fig. 9. Measured and modeled soil moisture levels 105 cm below the soil surface at the three study sites, from 1998 to 2003.

Thawing of the soil was calculated to occur more quickly from the top downward, than from the bottom upwards. This was a direct reflection of the difference in soil temperature gradients: steep on the top as the surface soil adjusts to the quickly changing weather conditions above, and shallow below, on account of small temperature differences with increasing soil depth. The time required for the jack pine and black spruce soil to thaw completely after the return of above-zero temperatures was calculated to vary from about 2 wk to 2 mo: as to be expected, years with deep frost penetration also had a prolonged thawing period.

CONCLUSION

Altogether, the data and the model calculations of this study revealed a rich and site-dependent complexity of year-round hydrothermal responses to changing weather conditions at the three boreal forest sites. With ForHyM and other similarly designed forest hydrology models (e.g., Levine and Knox 1997), these complexities can now be addressed for the purpose of further exploring hydrologically based C, nutrient and Hg responses to changing forest and climate conditions, summer-through-winter.

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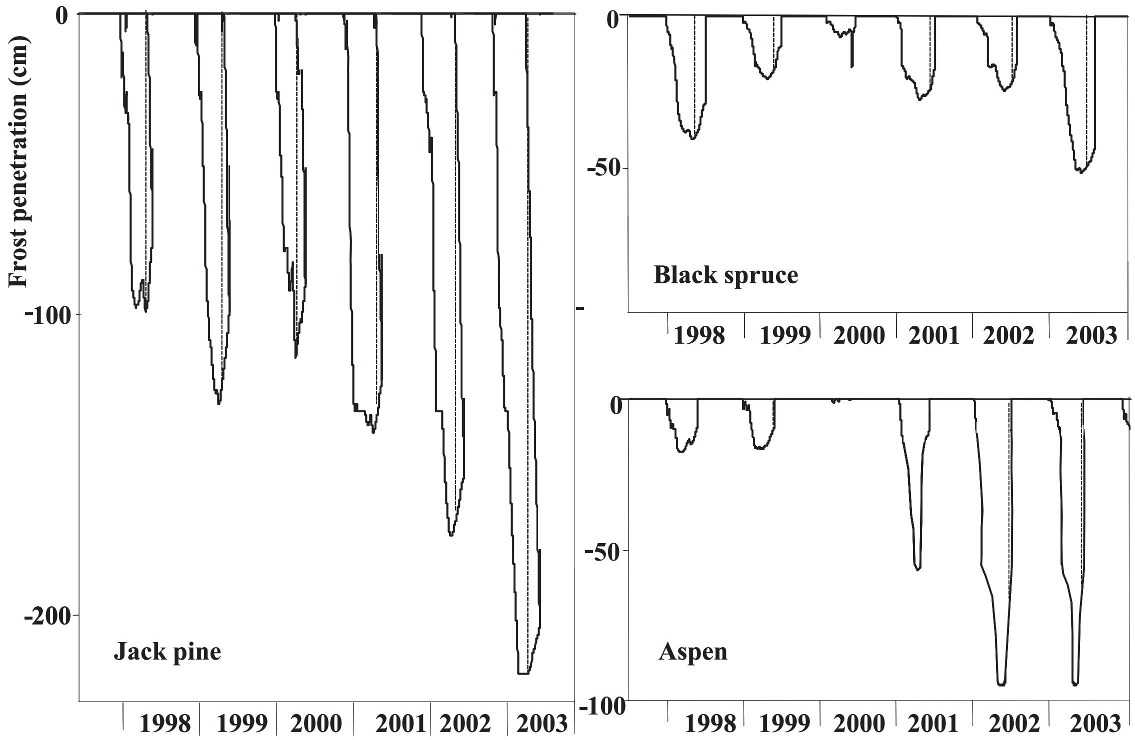

Fig. 10. Simulated depth of frost penetration at the three study sites, from 1998 to 2003. Vertical lines (dashed) for jack pine and black spruce identify segment of the soil profile still frozen after return of non-freezing air temperatures.

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