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Measurements and modelling of snow interception in the boreal forest

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Abstract:

Snow accumulation and ablation processes are particularly important to the hydrology of cold climate forests. In order to calculate the distribution of snow cover and the loss of snow to sublimation, the amount of snowfall intercepted by forest canopies must be determined. This paper introduces a physically-based snowfall interception model that scales snowfall interception processes from branch to canopy. Previous models of snow interception have neglected the persistent presence and subsequent unloading of intercepted snow in cold climates and hence have only been applicable to regions where snow is quickly lost from the canopy. To investigate how snow is intercepted at the forest stand scale, measurements of wind speed, air temperature, above- and below-canopy snowfall, accumulation of snow on the ground and the load of snow intercepted by a suspended, weighed, full-size conifer were collected from spruce and pine stands in the southern boreal forest. These data show that interception increases at a declining rate with increasing snowfall, to a point where the intercepted load overcomes the strength of branches to support it. Leaf area, tree species and initial canopy snow load determine the snow storage capacity of the canopy. These factors, canopy coverage and snowfall are used to calculate snow interception, presuming an exponential decay in incremental interception as cumulative snowfall increases. The subsequent unloading of intercepted snow is additionally modelled as an exponential function of time. The sensitivity of the combined model to temperature, wind speed, snowfall, snow load and canopy structure is examined for weekly time-steps. The examination shows that interception efficiency is particularly sensitive to snowfall amount, canopy density and time since snowfall. A comparison of the model with weekly measurements of snow interception suggests that the method can be used to calculate snow interception successfully in a physically-based manner. © 1998 John Wiley & Sons, Ltd.

KEY WORDS snow interception; snow accumulation; leaf area index; snow hydrology; boreal forest; hydrological models; sublimation; land use hydrology

INTRODUCTION

The hydrology of northern forests is influenced by interception of snowfall in coniferous canopies and the subsequent retention, release to the ground or sublimation of this snow. The importance of specific processes to the development of snow cover varies with climatic region, local weather patterns, tree species and canopy density. Monitoring the sublimation of snow is particularly important because the spring snow cover on the ground determines the dynamics of snowmelt and runoff in the boreal forest. As much as 60% of cumulative snowfall may be intercepted by the boreal forest in mid-winter and annual sublimation losses amount to between 30–40% of annual snowfall for complete coniferous canopies (Pomeroy and Schmidt, 1993). Quantifying the amount of intercepted, and eventually sublimated, snow in forest canopies is needed to

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predict hydrological changes associated with climate change, reforestation, logging, fires and vegetation succession in this forest environment.

Wilm and Dunford (1945), Goodell (1959), Troendle and King (1985), Schmidt *et al.* (1988) and Lundberg and Halldin (1994) have identified interception and subsequent sublimation as important processes affecting the accumulation of snow in forests. Conversely, Hoover and Leaf (1967) and Gary (1974) questioned the evaporation/sublimation process and emphasized the unloading and wind redistribution of intercepted snow from the surrounding canopy. Interception models for individual storm events have been developed for temperate, 'high energy' forest environments (Satterlund and Haupt, 1967; Strobel, 1978; Harestad and Bunnell, 1981; McNay *et al.*, 1988; Calder, 1990). Satterlund and Haupt (1967) developed an interception model using single, small conifers (saplings) and found low interception efficiency (interception/snowfall) for lightly and heavily loaded branches, but high interception efficiency for moderately loaded branches. This result was confirmed at this scale by Schmidt and Gluns (1991) using measurements of interception on single conifer branches. Calder (1990) defined a snow interception function from forest stand-scale measurements in Scotland, which related the rate of snow interception to the precipitation rate and time. In contrast to the results of Satterlund and Haupt (1967) and Schmidt and Gluns (1991), interception efficiency decreased as snowfall increased. Strobel (1978) also found interception efficiency decreased with increasing snowfall. His research was conducted in Swiss forest stands of varying canopy density and included measurements of large snowfall events. Harestad and Bunnell (1981) developed a relationship from stand-scale field measurements that emphasized the effect of canopy coverage and snowfall on interception efficiency in coastal forests of British Columbia, Canada. Because interception efficiency was found to decrease with increasing snowfall, the influence of canopy cover on annual maximum snow accumulation under forest canopies also decreased with increasing snowfall (Bunnell *et al.*, 1985). McNay *et al.* (1988) estimated interception in a similar environment by taking the difference between increased snow depth in clearings and under forest canopies after snowfall events. Their model suggests that interception efficiency does not vary with snowfall but rather is solely controlled by canopy coverage (Pomeroy and Gray, 1995).

Snow interception in cold boreal forests differs from interception in more temperate forests. In cold boreal forests, intercepted snow may be retained in the canopy over periods from several days to a month (Pomeroy and Schmidt, 1993), whereas in all models discussed above, intercepted snow load is presumed to decline to zero between each snowfall event. Verseghy *et al.* (1993) use a snow interception algorithm in the Canadian land surface scheme (CLASS) that allows for retention of intercepted snow load over time (until depleted by sublimation or melt) but presumes the interception efficiency is controlled solely by canopy characteristics, up to a maximum intercepted load, which is always less than 0·8 mm.

Several physical factors may be hypothesized to influence interception efficiency. Interception efficiency is a synthesis of the collection efficiencies for individual branches that comprise the canopy, and the subsequent unloading of intercepted snow over a specified time. At branch scales, the physical processes that influence interception are more readily apparent. The collection efficiency of a branch depends on the collection area of the branch plus snow with respect to falling snowflakes, and therefore the horizontal plan area of the branch and the thickness of existing interception snow load (Schmidt and Gluns, 1991). The plan area of a branch varies with species and, for a given snow load, increases as the branch becomes less elastic with decreasing temperature (Schmidt and Pomeroy, 1990; Schmidt and Gluns, 1991). The formation of snow bridges with increasing snow load should increase the collection area and therefore the efficiency with which a branch accumulates snow.

Concomitant with snow interception in controlling interception efficiency is unloading of intercepted snow. Snow is retained in the canopy by cohesion of snow to the branch, the strength of intercepted snow masses and the support of branches. When any of these three factors fails, snow is unloaded. Cohesion of snow crystals to the branch results from rapidly forming micro-scale ice or liquid bonds between individual snow crystals and needles or stems. Snow strength is a result of bonding between snow crystals. The bonds grow or decay in response to equitemperature metamorphism, generally becoming stronger at cold temperatures and weaker as the melting point is approached (Langham, 1981). The relationship between temperature and unloading can be ambiguous because of the counteracting effects of branch stiffness, snow cohesion and strength (Pomeroy and Gray, 1995). At near-melting temperatures, branches are elastic and may not be able to support the mass of snow accumulated at colder temperatures, resulting in unloading (Schmidt and Pomeroy, 1990). An increase in snow wetness with increasing temperature increases the cohesion of snow to the branch but may also accelerate metamorphism and reduce the strength of accumulated snow (Kobayashi, 1987; Gubler and Rychetnik, 1991). Field observations show that low wind speed and low snow density are associated with cold temperatures and increased interception efficiency; the increased interception efficiency for these conditions is partly a result of reduced unloading (Bunnell *et al.*, 1985; Wheeler, 1987; Schmidt and Gluns, 1991). Conversely, warming temperatures after a snowfall increase snow unloading.

The problem that arises when extrapolating the results obtained by observing an interception process on a branch or single tree to the canopy, is that bulk properties of the canopy affecting interception may override the factors associated with interception by a branch or single tree (Pomeroy and Gray, 1995). The purpose of this paper is to develop a snow interception model that scales physically-based process descriptions from the branch to the canopy scale, assesses the effect of existing intercepted snow load on subsequent interception and describes the effect of canopy structure, snowfall size and unloading over time on interception efficiency. To this end, the paper introduces and evaluates such a model for conditions found in the southern boreal forest of western Canada.

EXPERIMENT

The experimental site is located in a mid-continental southern boreal forest (550 m above sea level, 54° N latitude and 106° W longitude) near Waskesiu Lake, Saskatchewan, Canada, in the Beartrap Creek basin of Prince Albert National Park (PANP) (Figure 1a) The region has a cool, subhumid continental climate, with 6–7 months of snow cover during a cold, dry winter. Two stands were examined, an older jack pine (*Pinus banksiana*) stand and a younger black spruce (*Picea mariana*) stand. The jack pine stand has mature trees 16–22 m tall, with a sparse understorey of deciduous bushes and mosses. The average distance between the jack pine trees measured on the ground is 2·04 m with an average tree diameter at breast height of 0·174 m. The winter leaf area index (LAI) is 2·2 $m^2 m^{-2}$ and canopy coverage of the sky in winter is 82%. Leaf area index is a dimensionless ratio (leaf area per unit ground area) of the layered area of vegetation leaf content (needles, branches and stems) occupying the space above the same area of ground cover (Nel and Wessman, 1993). Most of the canopy area is concentrated in the top 5–7 m of canopy. The black spruce stand has densely spaced trees 10–14 m tall, with an understorey of small bushes and mosses. The average distance between the black spruce trees measured on the ground is 1·01 m with an average tree diameter at breast height of 0·087 m. The winter leaf area index is 4·1 m^2 m^{-2} and the canopy coverage in winter is 92%. The black spruce canopy leaf area is concentrated in the top 7–8 m of canopy.

In order to describe the stand structure, leaf area index and canopy coverage were estimated using a LICOR LAI-2000 plant canopy analyser (Gower and Norman, 1991; LICOR, 1992). The LAI-2000 uses 'fish-eye' optics to project a hemispheric image of the canopy and/or sky on to five silicon detectors arranged in concentric rings. By comparing above- and below-canopy irradiance, the detectors measure visible radiation extinction at five angles through the canopy. Leaf area index and the fraction of sky visible from under the canopy are estimated from radiation extinction by the canopy (Gower and Norman, 1991). Canopy coverage is calculated as the fraction of sky not visible to the LAI-2000 from under the canopy. Because direct measurements of LAI are very difficult and laborious, the indirect measurement provided by the LAI-2000 is extremely useful (Gower and Norman, 1991; Nel and Wessman, 1993; Fassnacht *et al.*, 1994). LAI in conifer forests, as measured by the LAI-2000, may be underestimated somewhat owing to clumping of branches and needles; however, it is assumed that clumped branches will be as ineffective in intercepting snow as they are at extinguishing radiation and that the LAI as measured is the appropriate leaf area for snow interception studies.

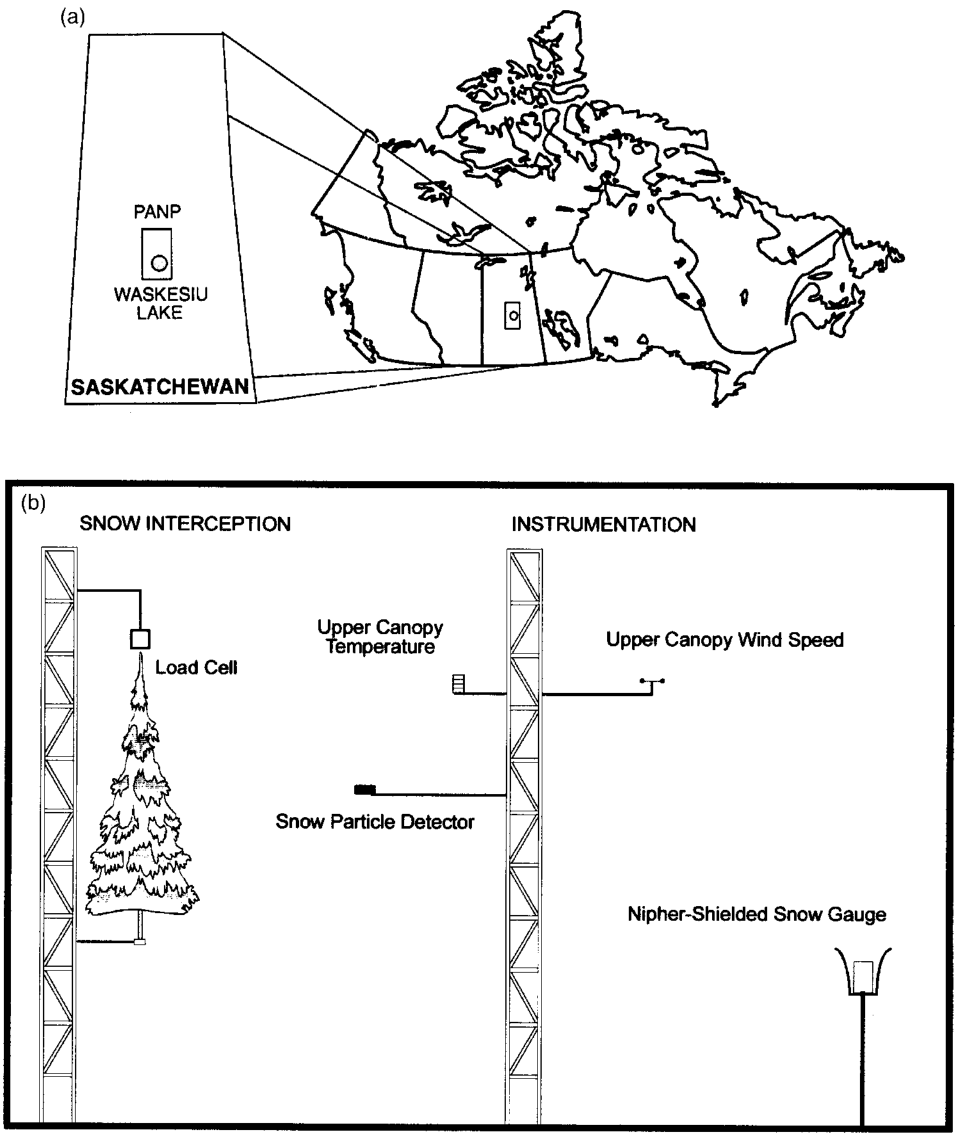


Figure 1. (a) Experimental site location. (b) Tower design and instrumentation. The schematic conceptualizes the basis for the towers used at the jack pine and black spruce sites

Automated meteorological and hydrological data were collected at both sites, with Campbell Scientific 21X dataloggers controlling the instrumentation, and retrieving and storing data (Figure 1b). Thermometers and anemometers (Table I) were installed near the canopy top (20 m for pine and 15 m for spruce). Optoelectronic snow particle detectors above the canopy provided the occurrence of snowfall but no direct measurement of snowfall rate (Nipher gauges measured weekly snowfall). The weight of intercepted snow on a single, full-size tree in the canopy (one tree per season) was measured by cutting, sealing the cut end with tar, and freely suspending a local tree from a cable with an in-line force transducer (see review of these devices by Lundberg, 1993). A triangular tower equipped with an aluminium boom and davit system was used to support the cable. The base of the suspended tree was prevented from swaying or rotating but allowed to move vertically by an attached collar with Teflon rollers inserted in an aluminum frame linked to

Table I. Sensor type and specifications

Instrument	Parameter measured	Error
Vaisala HMP35CF hygrothermometer	Relative humidity and temperature	Temperature accuracy $\pm 0{\cdot}1\,^{\circ}$C (for 0 to $-45\,^{\circ}$C)
LICOR LAI-2000 canopy analyser	Leaf area index and canopy coverage	LAI within 10% of true leaf area
RM Young 05305 propellor anemometer	Wind direction and speed	Wind speed threshold 0·2 m s^{-1}
University of Saskatchewan snow particle detector	Snow particle flux	Only counts snow crystals larger than 20 μm diameter
T-Hydronics force transducer	Tree weight (load cell)	Details of error addressed in text of paper

the bottom of the tower. The datalogger performed a four-wire bridge measurement on the force transducer to determine the mass of the tree plus intercepted snow. The compensated temperature range of the force transducer is $-17{\cdot}8$ to $65{\cdot}6\,^{\circ}$C. However, over a temperature range from -10 to $-40\,^{\circ}$C, outdoor tests of the repeatability of measurement of the transducer with the tree attached were better than 70 g (Pomeroy and Schmidt, 1993). As the trees desiccated and lost needles over the winter, the tares were adjusted. The trees selected for both the pine and spruce were typical of mature trees found in each of these stands and were suspended such that the tree canopy height approximated the surrounding canopy height. The suspended jack pine trees tared from 38 to 90 kg and ranged from 7·0 to 15·0 m in cut length, while the black spruce had a 22·0 kg tare weight and 12·0 m cut length. Subtracting the tare from the force transducer measurement provided the mass of intercepted snow. The experiment was operated in the black spruce forest for winter 1992–1993 and then in the jack pine forest for winters 1993–1994, 1994–1995, 1995–1996 and 1996–1997.

DATA

The amount of snow intercepted by the canopy was estimated weekly using measurements of snowfall by twinned Nipher-shielded snow gauges (Atmospheric Environment Service standard); one beneath the canopy and the other without canopy, in a 500 m diameter clearing adjacent (200–2000 m) to the stand. As the local terrain is flat, the spatial variability of above-canopy snowfall between sites is negligible. Snowfall was measured weekly and hence as much as seven days after a snowfall event. Because of the weekly time-step, the snowfall measurement can be composed of several snowfall events. All subcanopy snowfall measurements were upscaled to the stand scale by multiplying by the ratio of mean increase in subcanopy snow accumulation to mean subcanopy snowfall. Snow accumulation was found in weeks for which no snowmelt occurred, along a 10-point (5 m apart) linear snow survey line adjacent to the tower. As some aerodynamic mixing of unloading or falling snow occurred between the canopy and ground, the correction ratio was typically close to 1·0. Canopy interception, I (mm), was estimated as the difference between snowfall in the clearing, P (mm), and that under the forest canopy, P_{FC} (mm). Interception on this time-scale is an accumulation of increases in canopy load, $\Sigma L\uparrow$, less any unloading to the ground, $\Sigma L\downarrow$, where,

$$I = P - P_{FC} = \Sigma L\uparrow - \Sigma L\downarrow \tag{1}$$

and all units are in mm snow water equivalent (SWE), i.e. mm per unit area. Note that sublimation losses during the week are not subtracted from I. Estimates of I using cumulative increases and unloading of canopy snow load can be in error when previously intercepted snow unloads in a week other that in which it accumulated or when intercepted snow melts and drips into the snowfall gauge. Such events were identified by frequent site visits, photographs of the canopy (daily) and examination of the meteorological record, and were found to be rare; those that did occur were not included in the data analysis.

To determine the initial canopy snow load for various snowfall events, the weight of snow on the suspended tree was used. To upscale this weight to the canopy, I was calculated from calm, cold weeks when snow fell late in the week and no unloading was observed (using canopy photography, examination of the surface snowpack for unloaded snow and visual observations). Extremely cold (< -30 °C), calm conditions appropriate for this measurement generally develop during several weeks each winter in the southern boreal forest. The scaling parameter, N, was defined as

$$N = \frac{\Sigma L\uparrow}{\Sigma M\uparrow} \tag{2}$$

where N (mm kg^{-1} m^{-2}) is the ratio of increased canopy intercepted load to increased tree intercepted load. $\Sigma M\uparrow$ was calculated for each accumulation period as the cumulative increase in snow weight, M (kg), on the tree and $\Sigma L\uparrow$ was estimated from I during the select periods. Note that, as a different tree was suspended each season, N values are specific to each season and varied according to the structure of the tree being suspended. Thirteen, one-week periods over four seasons (1993–1997) at the jack pine site and four, one-week periods from one season (1992–1993) at the black spruce site had no unloading and were suitable for calculating N. N was calculated for each season at the jack pine site at between 0·16 and 0·49 mm kg^{-1} m^{-2}. The N values for the black spruce ranged from 0·76 to 1·66 with a seasonal average value of 1·21 mm kg^{-1} m^{-2}.

With N determined for the season, the initial canopy snow load, L_0, was found from the weight of snow on the tree at the beginning of a snowfall period as,

$$L = N\,M \tag{3}$$

where M_0 is the weight of snow on the tree at the beginning of a snowfall period, and if $M = M_0$ then $L = L_0$. Because sublimation depletes snow load over time, L is not always equal to I, hence the suspended tree measurements were not used to calculate I in this study.

Typical winter sequences in measured values are provided in Figure 2, with the seasonal progression of mean daily snow load, weekly snowfall, interception efficiency and mean daily air temperature for part of 1994 at the jack pine stand (Figure 2a) and 1992–1993 at the black spruce stand (Figure 2b). The data indicate that increases in intercepted snow load always accompany snowfall events, and that high loads persist for a time after snowfall. More rapid rates of decrease in snow load after a snowfall occur when the air temperature is high. There is a slight trend for greater interception efficiency at higher temperatures. The dense black spruce stands sustains the highest intercepted snow load, a load maintained over one month. Interception efficiency varies from less than 0·1 to nearly 1·0. I/P is sensitive to initial snow load and snowfall amount, but it is difficult to distinguish the effect from each other when examined as a time-series. The effect of temperature is also difficult to distinguish empirically because it is strongly related to both unloading and sublimation, which deplete the snow load.

MODEL

The model is based on hypotheses developed from a review of the literature, observations in the field and an initial examination of the data in Figure 2. The hypotheses are that the interception efficiency decreases with canopy snow load and increases with canopy density, and that snow unloading increases with time. Formalizing these concepts requires the definition of some variables: C_p = maximum ratio to snow to leaf contact area per unit area of ground; and C_c = canopy coverage (plan area of continuous canopy per unit area of ground); L^* = maximum intercepted snow load that can be retained by the forest canopy given current canopy structure and temperature conditions (mm SWE); L_0 = intercepted snow load at the start of a snowfall event (mm SWE); U = unloading rate coefficient (s^{-1}); and I_1 = interception before unloading occurs (mm SWE).

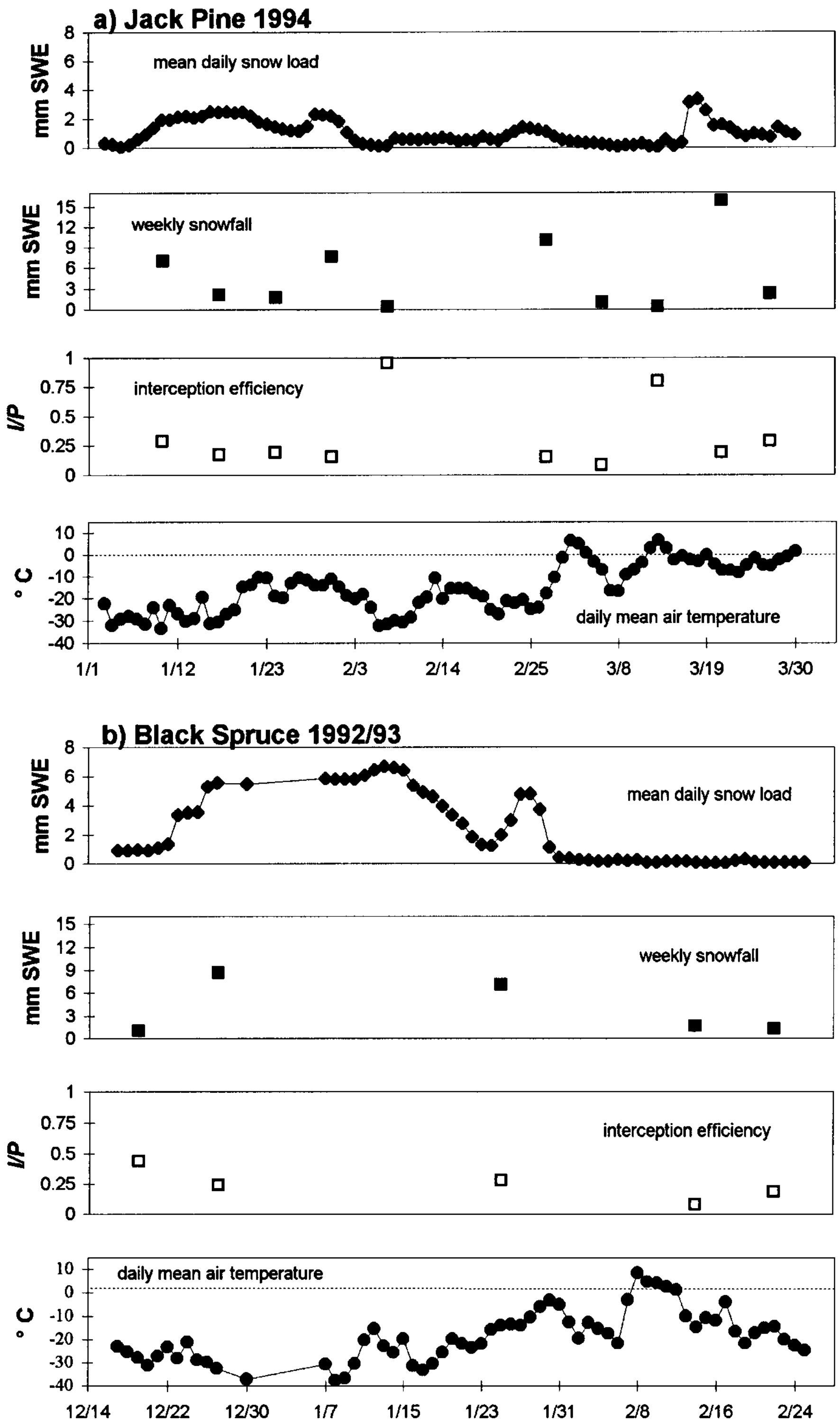


Figure 2. Variation of measured intercepted snow load, snowfall, interception efficiency and air temperature over a winter season: (a) jack pine, (b) black spruce

The rate of intercepted snow unloading from the canopy, dI/dt, is presumed to be proportional to an unloading rate coefficient, U, and the intercepted snow load, giving

$$\frac{dI}{dt} = -UI \tag{4}$$

and integrating provides an exponential decay in load over time, t,

$$I = I_1 \, e^{-Ut} \tag{5}$$

where I_1 is the intercepted snow load at the start of unloading.

To find I_1, the interception efficiency for a small increment of snowfall, dI_1/dP, is assumed to be proportional to the maximum snow load, L^*, less the initial snow load, L_0, less current interception, I_1,

$$\frac{dI_1}{dP} = k(L^* - L_0 - I_1) \tag{6}$$

where k is a proportionality factor. Integrating Equation (6) provides,

$$I_1 = (L^* - L_0)(1 - e^{-kP}) \tag{7}$$

the exponential form of which is similar to expressions used to describe the interception of rainfall (Linsley *et al.*, 1949).

To evaluate k, consider the case of a closed canopy, empty of intercepted snowfall and snow load ($I_1 = 0$, $L_0 = 0$) where incremental snow interception is completely efficient, $dI_1/dP = 1$. Following Equation (6) then

$$k = \frac{1}{L^*} \tag{8}$$

However, even for this condition, not all snowfall crystals may contact the canopy in the boreal forest because the canopy is porous and partially open, so completely efficient interception may not always occur. In this case the maximum interception efficiency, dI_1/dP, is equal to C_p, the maximum plan area of the snow–leaf contact per unit area of ground. For canopies that are partly open, Equation (8) becomes

$$k = \frac{C_p}{L^*} \tag{9}$$

Should snow fall vertically, it may be presumed that $C_p \approx C_c$, i.e. that over the course of a snowfall, the snow–leaf contact area ratio is approximately equal to the canopy coverage. This presumes that all points on the canopy at some time are intersected by the path of vertically falling snowflakes. However, consider a snowflake with horizontal velocity, u, equal to the wind speed and vertical velocity, w, equal to the negative of the particle terminal fall velocity, falling through a gap in the canopy x m wide (downwind) with canopy height being H m tall (Figure 3). The horizontal distance travelled by the particle whilst falling through the canopy gap, from canopy top to ground, is $(uH)/w$. For extremely conservative wind speed and typical mature canopy conditions of mean wind speed $u = 0{\cdot}5$ m s^{-1}, canopy height $H = 10$ m and vertical velocity $w = 0{\cdot}8$ m s^{-1} (taken from Isyumov, 1971), this represents a horizontal distance of 6·25 m travelled by the snowflake falling through the gap. This distance is larger than the diameter of gaps found in the stands in this experiment but smaller than that of gaps found in sparse or open coniferous canopies. If we estimate canopy coverage and snow–leaf contact area ratio as functions of the mean canopy gap downwind width, x, then the

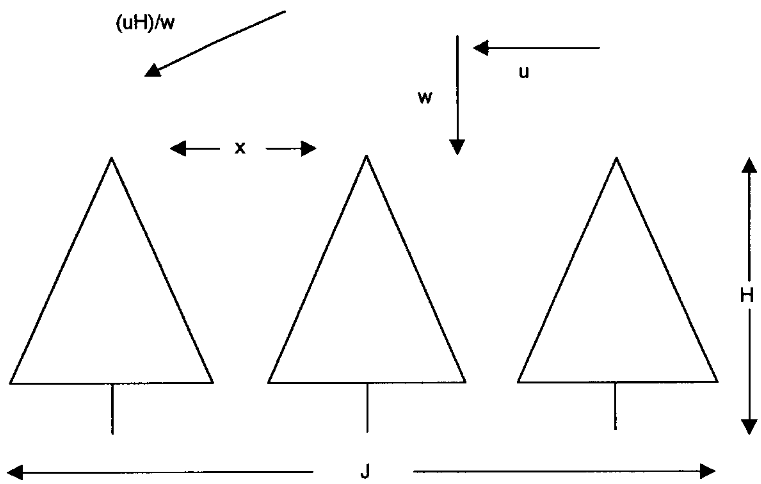


Figure 3. Representation of falling snow particle velocity components and canopy geometry. w is the snow particle vertical velocity (fall velocity), u is the horizontal velocity (wind speed), x is the canopy gap diameter, H is canopy height, J is the forested downwind distance. As is evident from the diagram, a deviation of particle trajectory from the vertical will cause the particle to intercept canopy even when it falls within a canopy gap

mean forested canopy downwind distance, J, and the downwind particle travel distance, then, for $(uH)/w \leqslant x$

$$C_c = \frac{J}{J + x} \quad \text{and} \quad C_p = \frac{J}{J + x - \dfrac{uH}{w}}\ .$$

Hence

$$C_p = \frac{C_c}{1 - \dfrac{C_c uH}{wJ}} \tag{10}$$

Equation (10) suggests that the snow–leaf contact area ratio will be greater than canopy coverage where downwind snowflake travel distance in the canopy gaps is large or forested downwind distance becomes small. Hence for many open boreal conifer canopies, $1 > C_p > C_c$. However, for mature conifer canopies and typical wind speeds of greater than 1 m s^{-1} during snowfall, C_c can be approximated as 1.

The maximum canopy load L^* can be calculated as a function of the leaf area index, LAI, and the maximum snow load per unit branch area S (kg m^{-2})

$$L^* = S \cdot LAI \tag{11}$$

where S is composed of a mean species value corrected by a function that fluctuates with snow density, as proposed by Schmidt and Gluns (1991)

$$S = \bar{S}\left(0{\cdot}27 + \frac{46}{\rho_s}\right). \tag{12}$$

The units for fresh snow density (ρ_s) are kg m^{-3}. Schmidt and Gluns (1991) made extensive measurements that suggest values of $\bar{S} = 6{\cdot}6$ and $5{\cdot}9$ kg m^{-2} for pine and spruce, respectively. As fresh snow density is not normally available in the meteorological record, an empirical relationship developed from the data of

Schmidt and Gluns (1991) and the US Army Corps of Engineers (1956) is used to relate ρ_s to air temperature (Figure 4). The relationship is

$$\rho_s = 67{\cdot}92 + 51{\cdot}25\ \mathrm{e}^{(T_a/2{\cdot}59)} \tag{13}$$

where T_a is ambient air temperature (°C). This relationship has a coefficient of determination of $r^2 = 0{\cdot}84$ and a standard error of estimate of 9·31 kg m^{-3}.

The unloading rate coefficient, U, and time since snowfall, t, are not known in this experiment since U is difficult to measure directly and t is difficult to define when the snowfall frequency is greater than that of measurement. For this weekly application a dimensionless unloading coefficient, c was defined as

$$c = \mathrm{e}^{-Ut} \tag{14}$$

and determined from measured I and modelled I_1 in the pine and spruce canopies. For time after snowfall of between zero and seven days, a mean value of $c = 0{\cdot}678$ was found from 59 estimates, with a standard error of estimate of 0·0248. No relationship in individual values of c was found for forest species, snowfall amount or other variable measured, although at low air temperatures the range of c was limited to its lower end.

To calculate weekly snow interception, I, using this model, the input variables are: (i) initial snow load, L_0; (ii) leaf area index, LAI; (iii) air temperature, T_a; (iv) wind speed, u; (v) canopy coverage, C_c; (vi) canopy height, H; (vii) mean snowflake fall velocity, w; (viii) mean forested fetch length, J; (ix) snowfall over the period, P; and (x) dimensionless unloading coefficient, c.

Parameters (ii), (v), (vi) and (viii) are properties of the forest stand; parameters (iii), (iv) and (ix) are standard meteorological measurements; and parameter (vii) is estimated from the temperature and time of year. The dimensionless unloading coefficient varies (x) with time. Initial snow load (i) is determined from the previous iteration of the model, less sublimation and unloading, or set to zero at the beginning of the season. In the model runs shown in this paper, L_0 is determined from the weight of snow on the suspended tree.

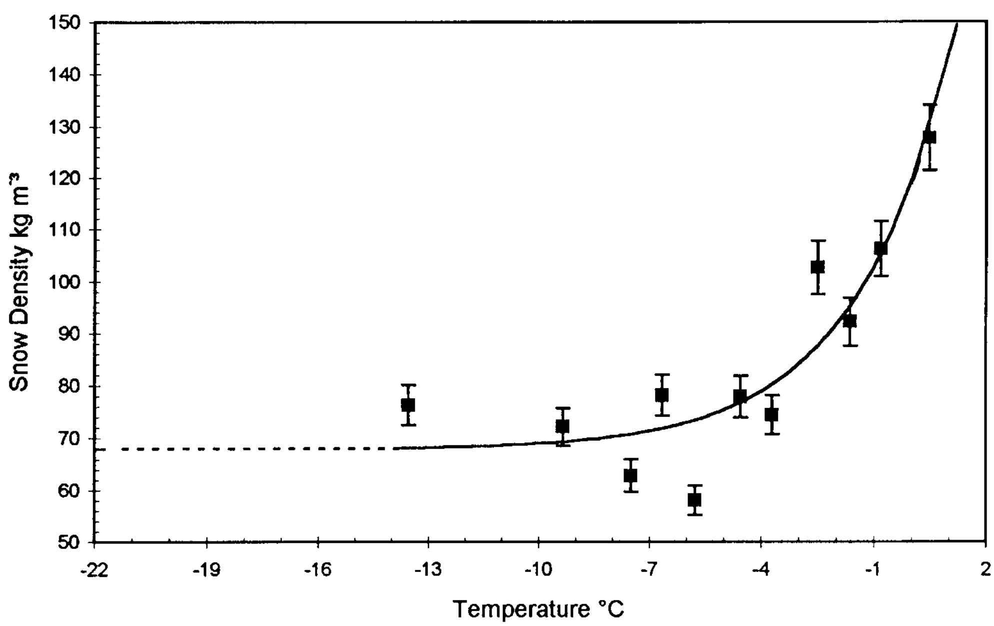


Figure 4. Relationship between new fallen snow density and temperature compilation of data reported by the US Army Corps of Engineers (1956) and Schmidt and Gluns (1991). 95% confidence intervals are shown, along with means

PERFORMANCE

To examine the behaviour of the model under varying input conditions, a sensitivity analysis was conducted and graphed. Figure 5 shows the influence of varying input variables on the modelled interception efficiency, I/P. Unless otherwise indicated in the caption or figure, $L_o = 0$ mm, $C_p = 1$, $L^* = 15$ mm, $c = 0{\cdot}678$, $S(\text{mean}) = 5{\cdot}0$ kg m^{-2}, $T = -15\,^\circ$C and $P = 10$ mm for the simulations. Figure 5a shows the effect of maximum canopy load on interception efficiency for varying snowfall amounts. As maximum canopy load increases, there is an increase in the interception efficiency that levels off at higher L^* values. Maximum canopy load has relatively little effect on I/P for small snowfall amounts. Figure 5b shows the effect of varying leaf area and temperature on interception efficiency. There is a declining rate of increase in interception

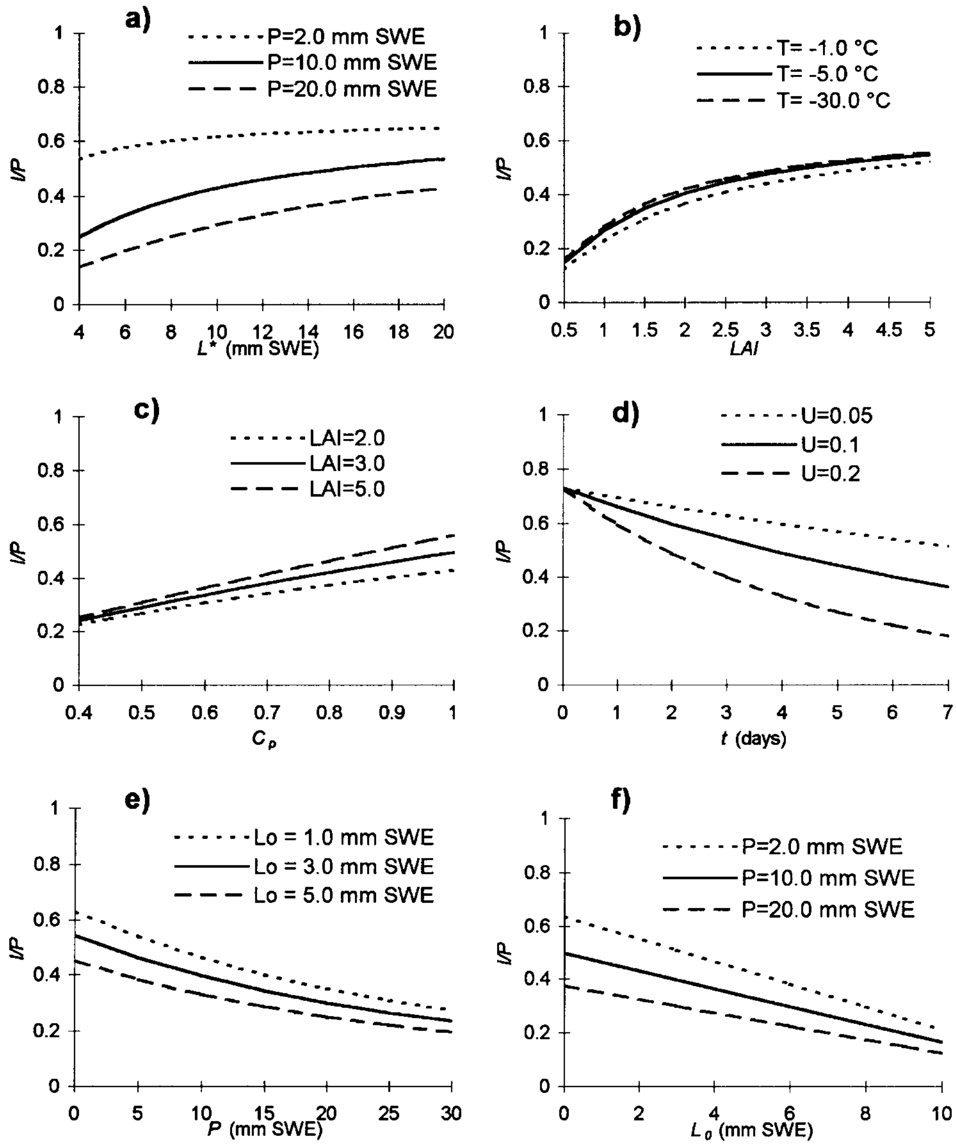
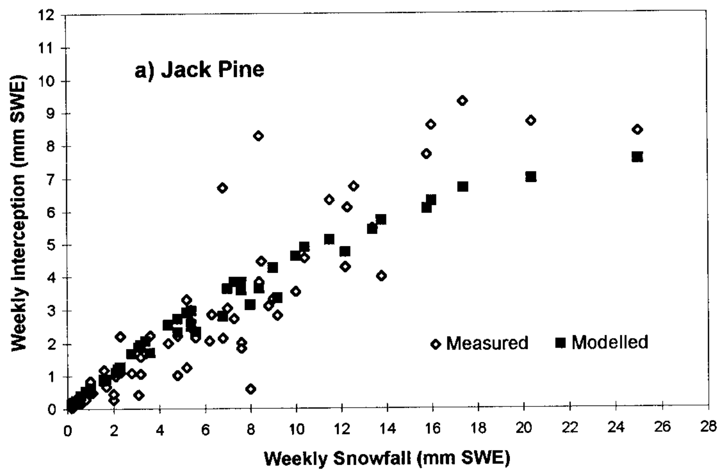


Figure 5. Sensitivity of modelled interception efficiency to input variables. Fixed variable are: $L_0 = 0$ mm, $C_p = 1$, $L^* = 15$ mm, $c = 0{\cdot}678$, $S(\text{mean}) = 5{\cdot}0$ kg m^{-2}, $T = -15\,^\circ$C and $P = 10$ mm unless noted on the figure. (a) Storage capacity; (b) leaf area index; (c) canopy coverage; (d) time; (e) snowfall; and (f) initial canopy snow load



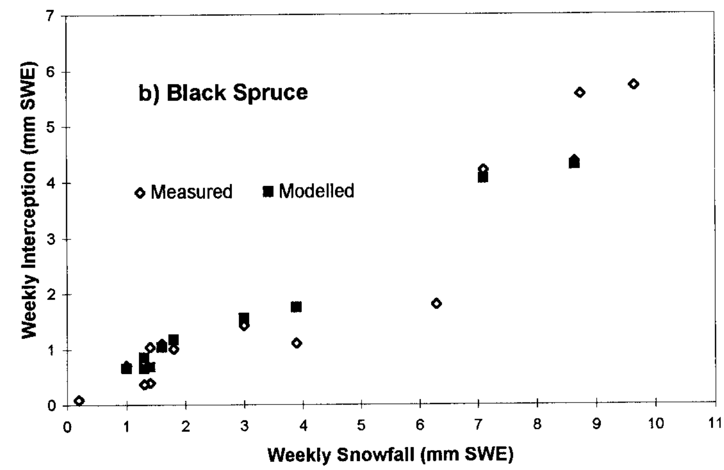


Figure 6. Modelled and measured weekly interception and measured weekly snowfall: (a) jack pine, (b) black spruce

efficiency with increasing leaf area index and very little effect of air temperature on I/P. Figure 5c shows the effect of snow–leaf contact area (controlled by canopy coverage, canopy structure and wind speed) on interception efficiency, indicating a directly proportional relationship. The influence of leaf area on this relationship increases with increasing C_p, only becoming strong for $C_p > 0{\cdot}7$. Figure 5d shows the exponential effect of time on unloading and hence interception efficiency. Small changes in U can cause dramatic changes in I/P. Increasing snowfall results in decreasing interception efficiency, as shown in Figure 5e. The effect of varying initial snow load on I/P diminishes as snowfall becomes large. Figure 5f shows the effect of initial snow load on interception efficiency. I/P decreases strongly as the snow load increases. This trend is most pronounced with higher snowfall amounts.

The sensitivity analysis shows that certain variables, such as temperature, are relatively unimportant to the modelled interception efficiency, while others, such as snowfall, snow load, leaf area and time since snowfall, are quite important. In natural settings, some variables such as canopy coverage and leaf area index may be related to each other, causing mature, dense canopies to have characteristically higher interception than young, open canopies.

To compare model output with measurements, Figure 6 shows weekly interception (mm SWE) calculated using the model ($c = 0{\cdot}678$), with measured inputs, and weekly measured interception for jack pine

(Figure 6a) and black spruce (Figure 6b) forests against the corresponding snowfall. Both model and measurements show a declining rate of increase in interception with snowfall, and there is no consistent deviation between the model and measurement as snowfall increases. The application of the model with weekly measurements corresponds well with measured interception, with a mean overestimation of 0·13 mm SWE for the black spruce, and 0·18 mm SWE for the jack pine. The scatter in measured points may well be due to varying times between snowfall and interception measurement and varying values of the unloading rate coefficient, though this could not be verified.

DISCUSSION

The development of a new snow interception model has permitted the calculation of snow interception over entire winters in a cold environment, but requires specialized measurements of canopy snow load in order to operate. Based on a comparison with weekly measurements, however, the new model is well suited for calculating interception in cold environments. The strong correspondence of modelled and measured values to a 1:1 relationship evident in Figure 7 provides initial validation of the model. The r^2 value between

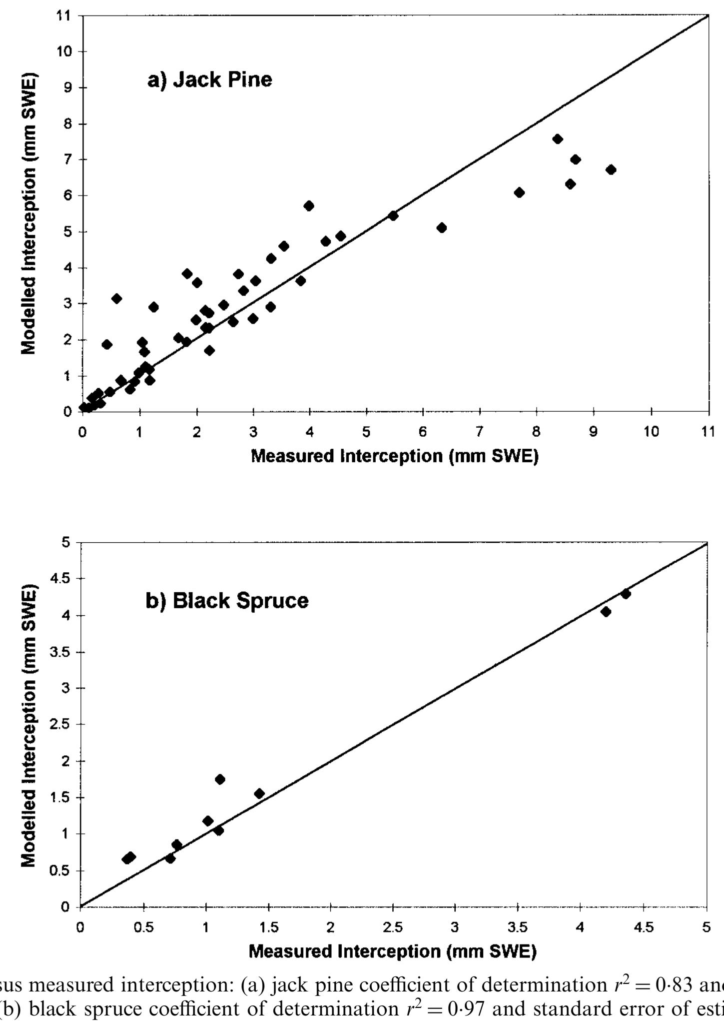


Figure 7. Modelled versus measured interception: (a) jack pine coefficient of determination $r^2 = 0{\cdot}83$ and standard error of estimate = 1·00; (b) black spruce coefficient of determination $r^2 = 0{\cdot}97$ and standard error of estimate = 0·27

measured and modelled for the jack pine is 0·83 and for the black spruce is 0·97, with standard errors of estimate of 1·00 and 0·27 mm SWE, respectively. The new model considers a number of physical processes that influence snow interception by coniferous canopies, processes that have not been completely incorporated in previous snow interception algorithms. Snow interception modelling would be improved by the addition of intercepted snow sublimation and melt routines, however. Sublimation and melt routines will permit the use of modelled rather than measured values of initial canopy snow load and permit a shortening of the time-step. When coupled to intercepted snow sublimation and melt routines in the future, the interception routines presented here will allow modelling of snow interception and loss from coniferous canopies using more readily available measurements or outputs from energy balance land surface models.

CONCLUSIONS

Based on an extensive series of measurements and a physically-based model of snow interception, the following conclusions can be made regarding the accumulation of intercepted snow in the boreal forest.

1. Scaling of interception processes from branch to canopy has permitted the development of a physically based model that allows the researcher to use meteorological data and forest inventory variables to calculate snowfall interception.
2. Interception efficiency decreases with increasing snowfall, time since snowfall, initial canopy snow load and temperature.
3. Interception efficiency increases with increasing leaf area index and canopy coverage.
4. At high wind speeds the effective canopy coverage becomes unity.
5. For heavy snowfalls, the effect of initial snow load on interception becomes small.
6. Initial validation of the new model in a cold boreal environment has proven promising, but further improvement and verification in other environments should be examined. A larger data set should be obtained for further testing and development.

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