ACCUMULATION OF INTERCEPTED SNOW IN THE BOREAL FOREST: MEASUREMENTS AND MODELLING

N.R. Hedstrom[1,2] and J.W. Pomeroy[1]

ABSTRACT

A new snowfall interception model is introduced. The model incorporates physically-based processes to scale from the branch to canopy. Previous models of snow interception have neglected the persistence of intercepted snow load and the effects of temperature on maximum intercepted load and hence have only been applicable to climates where snow is regularly and quickly lost from the canopy. To investigate snow interception at the forest stand scale, measurements of above and sub-canopy snowfall, accumulation of snow on the ground and the load of snow intercepted by a suspended, full-size conifer were collected from boreal forest spruce and pine stands. These data show that interception increases with increasing snowfall, to a point when the intercepted load overcomes the strength of branches to support it. Hence, the interception efficiency decreases with snow load and amount of fresh snowfall. Leaf area index, tree species and initial snow load determine the maximum canopy snow storage. The maximum storage, canopy coverage and snowfall are used to calculate snow interception for a canopy, presuming exponential decay in incremental interception as the amount of snowfall increases. The sensitivity of the model to temperature, wind speed and other factors is examined. This method can be used to calculate snow interception over an entire winter period using relatively standard meteorological and forest inventory variables.

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 snowcover development varies with climatic region, local weather patterns, tree species and canopy density. Monitoring the sublimation of snow is particularly important because the spring snowcover 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). Quantification of the amount of snow intercepted in forest canopies and eventually sublimated is needed in order to 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) and Schmidt et al. (1988) have identified evaporation/sublimation as an important process affecting the amount of intercepted snow in forests. Conversely, Hoover and Leaf (1967) and Gary (1974) questioned the evaporation/sublimation process and emphasized the 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 snow-free branches inefficient at intercepting snow. Initial interception efficiency was low for relatively snow-free branches and for heavily loaded branches and high for moderately loaded branches. Strobel (1978) found that the canopy snow interception efficiency decreased with storm snowfall. His research was conducted in Swiss forests of varying crown density and measurements included large snowfall events. Harestad and Bunnell (1981) developed a relationship between canopy coverage and the snow on the forest floor to that in a cleared area (interception efficiency). They analysed the relationship between canopy cover and snow water equivalent (SWE) on the ground and found substantial differences between areas and years. The influence of canopy cover on maximum SWE decreases with an increase of precipitation.

[1]National Hydrology Research Institute Saskatoon, Saskatchewan, Canada S7N 3H5

[2]Division of Hydrology, University of Saskatchewan Saskatoon, Saskatchewan, Canada S7N 5A9

As the amount of snow accumulation increased, a smaller amount of snow was intercepted. Storm size determined how much snow would be caught by conifer crowns (Bunnell et al., 1985). McNay et al. (1988) expanded on Harestad and Bunnell's model using Strobel's technique, and conducted snow surveys on Vancouver Island, Canada before and after snowfall events. They found a linear increase of new snow depth under the forest canopy with new snow depth in open areas, with the rate of increase controlled by the canopy crown completeness. Calder (1990) defined a snow build-up function from snow events recorded at Aviemore, Scotland which related the rate of snow accumulation on the canopy to the rate of precipitation. This function displayed an asymptotic increase of canopy storage with total snowfall and predicts high initial interception efficiencies and lower efficiencies later in the event.

Snow interception in a cold boreal forest differs from interception in temperate forests. In cold boreal forests, intercepted snow may be retained in the canopy over periods from several days to a month. This limits the use of most snow interception models, which presume the complete loss of canopy snow shortly after each snowfall. Verseghy et al. (1993) use a snow interception algorithm in CLASS that allows for retention of snow by the canopy but accumulation is assumed linear up to an assigned value. This paper introduces a model of snow interception that accounts for effects of the persistence of intercepted snow load on subsequent interception efficiency. The interception efficiency of a canopy is defined as the ratio of snowfall interception to total snowfall. This efficiency is a synthesis of the collection efficiencies for individual branches that comprise the canopy. The mass of snowfall that accumulates on a branch depends on the horizontal plan area of the branch and the thickness of accumulating snow. The projected area of a branch varies with species and increases with a decrease in temperature (Schmidt and Pomeroy, 1990; Schmidt and Gluns, 1991). Schmidt and Pomeroy (1990) found that the resistance of a branch to bending increases with decreasing temperature below freezing. Colder branches are stiffer and provide a larger projected horizontal plan area. Therefore, they support more intercepted snow. Warming temperatures after a snowfall may increase the release of intercepted snow as the branch droops and the plan area is reduced. An increase in temperature increases cohesion but may also accelerate metamorphism and reduce the strength of accumulated snow (Kobayashi, 1987; Gubler and Rychetnik, 1991). The formation of snow bridges increase the collection area and the efficiency with which a branch accumulates snow; and additional snow is retained on the bridges by cohesion. Cohesion of snow crystals results from the formation of micro-scale ice-bonds between snow crystals shortly after contact. These bonds develop in response to movement of a thin, liquid-like layer surrounding the crystals or reformation of the crystals due to small-scale vaporization and condensation (Langham, 1981). Generally, the relationship between temperature and interception efficiency is ambiguous because of the counteracting effects of branch stiffness and cohesion. Low wind speed and snow density at low temperatures will promote the accumulation of snow (Wheeler, 1987; Bunnell et al., 1985; Schmidt and Gluns, 1991).

The problem that arises when extrapolating the results of the interception process by a branch or single tree to a 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 uses physically-based processes to scale from the branch to canopy, permits snow load in the canopy to be greater than zero at the beginning of snowfall and is suitable for cold environments. An improved understanding of the amounts of snow intercepted by forest canopies and sublimation of this snow is necessary to predict the exchange of water and energy fluxes with the winter atmosphere and the amount of surface snow available for melt, infiltration and runoff.

EXPERIMENT

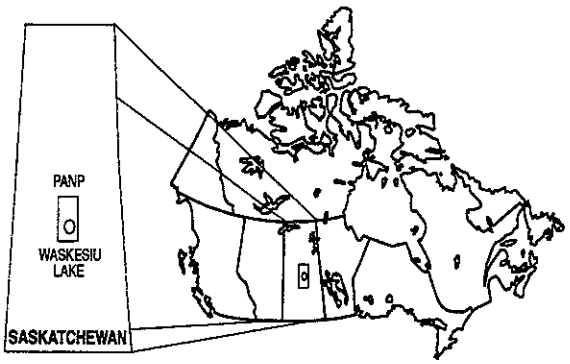
The experimental site is located in a mid-continental southern boreal forest (550 m above sea level) at about 54°N latitude and 106°W longitude near Waskesiu Lake, Saskatchewan, Canada in the Beartrap Creek GEWEX/Model Forest experimental basin of Prince Albert National Park (Fig. 1a). The region has a sub-humid 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. To describe the macro-structure of these stands, leaf area index and canopy coverage were determined in winter by a LICOR "Plant Canopy Analyser" which measures the light extinction by the canopy through several pathlengths. Canopy cover is represented as mean crown completeness or the percentage of sky occupied by canopy if looking up from below the canopy. Leaf

area index (LAI) is a dimensionless ratio of the layered area of vegetation leaf content (needles, branches and stems) occupying the space above the same area of ground cover. The LICOR, measures LAIΩ, the product of the leaf area index and a stem and leaf clumping factor, Ω (Nel and Wessman, 1993). The clumping factor can cause a significant error in estimates of true leaf area for conifer canopies. However, if the effect of clumping on radiation is roughly similar to its effect on snow interception, the LAIΩ (as measured by the LICOR) may be appropriate for this study.

The jack pine stand has mature trees 16-22 m in height, with a sparse understorey of deciduous bushes and mosses on sandy soils. 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 is 2.2 m^2 m^{-2} and canopy coverage of the sky in winter is 82%. Most of the canopy leaf area is concentrated in the top 5-7 m of canopy. The black spruce stand has densely spaced trees 10-12 metres tall, with an understorey of small bushes and mosses on organic overlying silt soils. 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 canopy coverage in the winter is 92%. The black spruce canopy leaf area is concentrated in the top 7-8 m of canopy.

Automated meteorological and hydrological data collection platforms exist at both sites, with Campbell Scientific 21X dataloggers controlling the instrumentation, retrieving and storing data (Fig. 1b). Temperature and wind speed sensors (Table 1) were installed within, above and below the canopy at four levels at the jack pine and three levels at the black spruce. Sensors at the jack pine site were located 5.0, 13.0, 20.0 and 25.0 m above ground. Sensors at the black spruce site were installed at 4.8, 8.8 and 15.0 m above ground. Opto-electronic snow particle detectors provided the falling snow particle flux above and below canopy but no direct measurement of snowfall rate. The weight of intercepted snowfall on a single tree was measured by cutting, sealing the cut end, and suspending a local tree from a cable with an in-line force transducer. A triangular tower equipped with an aluminum boom and davit system was used to suspend each cut tree within the canopy. The base of the weighed tree was stabilized by an aluminum frame attached near the bottom of the tower. The base was inserted in a collar with teflon rollers that allowed for vertical movement of the tree as snow accumulated on or ablated from the hanging tree branches. The datalogger performed a four-wire bridge measurement of the intercepted mass (g). The compensated temperature range of the force transducer was -17.8 to 65.6 °C. Tests of the repeatability of measurement of the transducer with the tree attached were better than 70 g. The experiment was operated in the black spruce forest for winter 1992-93 and then in the jack pine forest for winters 1993-94, 1994-95, 1995-96 and 1996-97.

a)



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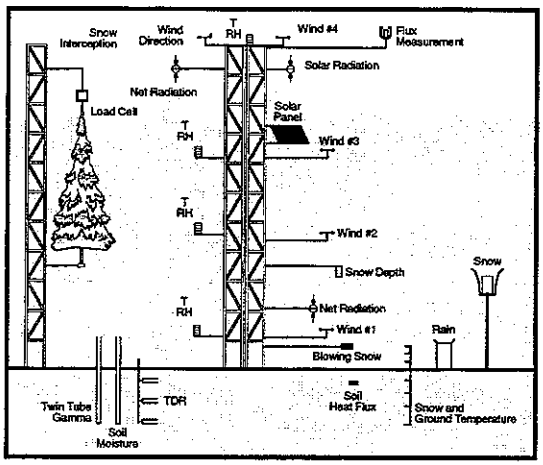

Figure 1. a) Experimental site location, b) Tower design and instrumentation. The schematic conceptualizes the basis for the towers used at the jack pine and black spruce sites.

Table 1. Sensor Type and Specifications

Instrument	Parameter Measured	Error
Vaisala HMP35CF	Relative humidity and temperature	Temperature accuracy ±0.2°C (full range)
LICOR LAI-2000 Canopy analyser	Leaf area index and canopy coverage	95% confidence with LAI mean within ±10% of true LA
RM Young 05305	Wind direction and speed	Wind speed threshold 0.2 metres/second (0-30 m/s)
T-Hydronics Force transducer	Tree weight (load cell)	<0.5% 22.9 m cable error, <0.5% change with temperature

DATA

Interception of snow 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 1000-m diameter clearing adjacent (500-1200 m) to the stand. Using a mass balance approach, measurements of snowfall in the twinned gauges can provide the increase in intercepted snow load by relating the change in this load to the "residual" or difference in snowfall accumulation between clearing and subcanopy snow gauges. The residual snow was measured weekly and hence as much as six days after the precipitation event. The measurement can be composed of several precipitation events and is an accumulation of increases in canopy load, $\Sigma L\uparrow$, where

$$R = P - P_{FC} = \Sigma L\uparrow \quad (1)$$

and R is residual snow, P is snowfall in the clearing, P_{FC} is snowfall under the forest canopy (throughfall) and all units are in mm snow water equivalent (SWE). Because snow intercepted in the canopy can unload after a snowfall and be released to the ground, $\Sigma L\uparrow$ estimated on a weekly basis from $P - P_{FC}$ can undermeasure that which would be found immediately after snowfall. In order to minimize such underestimates, calm, cold weeks were noted when snow accumulated on the canopy and there was no apparent branch unloading. Measurements of within-canopy snow particle flux, canopy temperature and intercepted snow weight on the suspended tree were used to identify such periods. To scale sub-canopy snowfall (P_{FC}) from point to stand, P_{FC} was compared to weekly changes in snow accumulation along a 10-point snow survey line. Using weeks when no melt occurred, a scaling correction ratio was developed and applied to all P_{FC} measurements from the nipher snow gauge.

The weight of intercepted snow on the suspended tree provides half-hourly estimates of interception that must be "scaled-up" to the canopy level in order to be useful for investigations of canopy snow interception. To provide a scaling parameter, only residual snow measurements from calm, cold conditions and corresponding snow weights from the suspended tree were used. The scaling parameter was then defined as,

$$N = \frac{\Sigma L\uparrow}{\Sigma M\uparrow} \quad (2)$$

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. Note that as a different tree was suspended each season, N values are specific to particular seasons.

There were twelve, one week periods over three seasons (1993-1996) at the jack pine site and four, one week periods from one season (1992-1993) at the black spruce site that had sufficiently small sublimation and transport losses to calculate N. Using three different suspended trees ranging from 38 to 90 kg tare weight, N was calculated for each season at the jack pine site at between 0.16 and 0.49. The jack pine trees that were suspended from the load cell ranged from 7.0 to 15.0 m in height. The N values for the black spruce (22.0 kg tare weight, 12.0 m height) ranged from 0.76 to 1.66 with a seasonal average value of 1.21.

With N determined for the season, the amount of snow intercepted by the canopy (I) during a snowfall of amount P, may be found as,

$$I = N(M_t - M_0) \quad (3)$$

where the subscripts t and 0 refer to time. The interception efficiency is defined as I/P, where P is snowfall over the period t. Figure 2 shows the seasonal progression of snow load, snowfall, interception efficiency and air temperature for 1992-1994 at the jack pine (Fig. 2a) and black spruce (Fig. 2b) stands. It is evident from Fig. 2 that increases in intercepted snow load always accompany snowfall events and that the rate of decrease in snow load after a snowfall varies strongly with air temperature. The dense black spruce stand sustains the highest intercepted snow load, a load maintained over one month. Interception efficiency varies from less than 0.1 to 1.0 (complete efficiency). I/P is sensitive to initial snow load and snowfall amount, but it is difficult to distinguish the effects from each other using only empirical data. The effect of temperature is also difficult to distinguish empirically because it is strongly related to snow load.

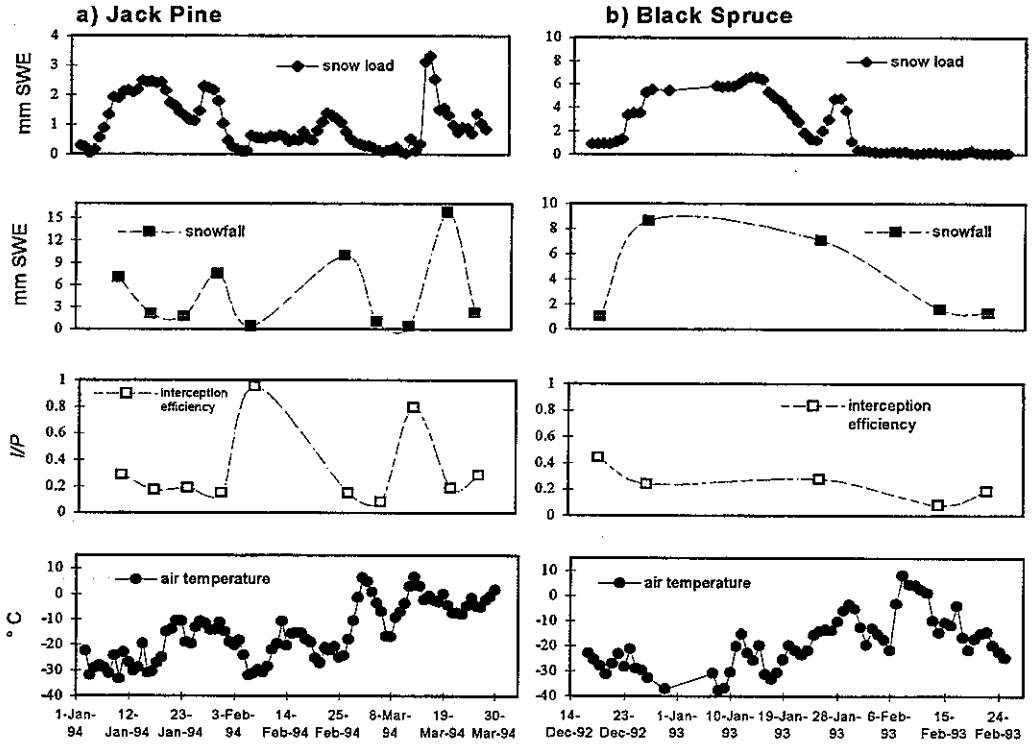

Figure 2. Variation of measured intercepted snow load, snowfall, interception efficiency and air temperature over a winter season, a) jack pine, b) black spruce.

MODEL

The development of the model is based upon the observed behaviour of snow interception efficiency in Fig. 2; that snow interception efficiency decreases with canopy snow load and increases with canopy density. Formalizing these concepts requires the definition of some useful variables:

C_p = maximum snow-leaf contact area (ratio) per unit area of ground during snowfall,
C_c = canopy coverage (plan area of continuous canopy per unit area of ground),
L^* = maximum intercepted snow capacity (load) that can be retained by the forest canopy under current canopy structure and temperature conditions (mm SWE),
L_0 = intercepted snow load at the start of a snowfall event (mm SWE), and
I_p = canopy snow storage capacity (for intercepted snow) (mm SWE).

The interception efficiency for a small increment of snowfall dI/dP is assumed to be proportional to canopy snow storage capacity less current interception, I,

$$\frac{dI}{dP} = k(I_p - I) \tag{4}$$

where k is a proportionality factor. The snow storage capacity is equal to the maximum snow storage capacity L^*, less the load at the beginning of the incremental interception L_0,

$$I_p = L^* - L_0 . \tag{5}$$

In this sense I_p can be seen as a potential for further interception and as a parameter that can be found from the present snow load and some canopy characteristic that governs L^*. Integrating Eq. 4 provides,

$$I = I_p(1-e^{-kP}) \tag{6}$$

which is similar to expressions used for interception of rainfall (Linsley et al., 1949).

To evaluate k, consider the case of a closed canopy, empty of intercepted snowfall ($I \approx 0$) where incremental snow interception is completely efficient, $dI/dP = 1$. Following Eq. 4 then

$$k = \frac{1}{I_p} . \tag{7}$$

However, not all snowfall crystals contact the canopy in the boreal forest because the canopy is porous and partially-open, and completely efficient interception cannot occur. In this case the maximum interception efficiency is equal to C_p, the maximum plan area of snow-leaf contact per unit area of ground. For true canopies which are never completely closed,

$$k = \frac{C_p}{I_p} . \tag{8}$$

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 terminal fall velocity, ω falling through a gap in the canopy x m wide (downwind) with canopy height being H m tall. The horizontal distance travelled by the particle whilst falling through the canopy gap from canopy top to ground is $(uH)/\omega$. For extremely conservative conditions of mean wind speed $u = 0.5$ m s^{-1}, canopy height $H = 10$ m and fall velocity $\omega = 0.8$ m s^{-1}, this leaves a horizontal distance travelled of 6.25 m as the snowflake falls 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 certain 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, the mean forested canopy downwind distance, J, and the downwind particle travel distance then, for $(uH)/\omega \le x$,

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

$$Hence \quad C_p = \frac{C_c}{1 - \frac{C_c u H}{\omega J}} \tag{9}$$

and, the canopy coverage will be reduced as downwind snowflake travel distance in canopy gaps increases or forested downwind distance decreases. Equation 9 suggests that for many open boreal conifer canopies, $1 > C_p > C_c$. However, for mature conifer canopies and mean wind speed of greater than 1 m s^{-1} during snowfall, C_p can be approximated as 1.

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

$$L^* = S\ LAI\ \Omega_s \tag{10}$$

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),

$$S = \overline{S}\ (0.27 + \frac{46}{\rho_s})\ . \tag{11}$$

The units for fresh snow density (ρ_s) are kg m^{-3}. Schmidt and Gluns suggested values of S(mean) = 6.6 and 5.9 kg m^{-2} for pine and spruce respectively. As fresh snow density is a parameter not normally available in the meteorological record an empirical relationship is used to relate ρ_s to air temperature (Fig. 3). The relationship is,

$$\rho_s = 67.92 + 51.25\ e^{(T_a / 2.59)} \tag{12}$$

where T_a is ambient air temperature (°C). This relationship has a coefficient of determination $r^2 = 0.84$ and a standard error of estimate of 9.31 kg m^{-3}.

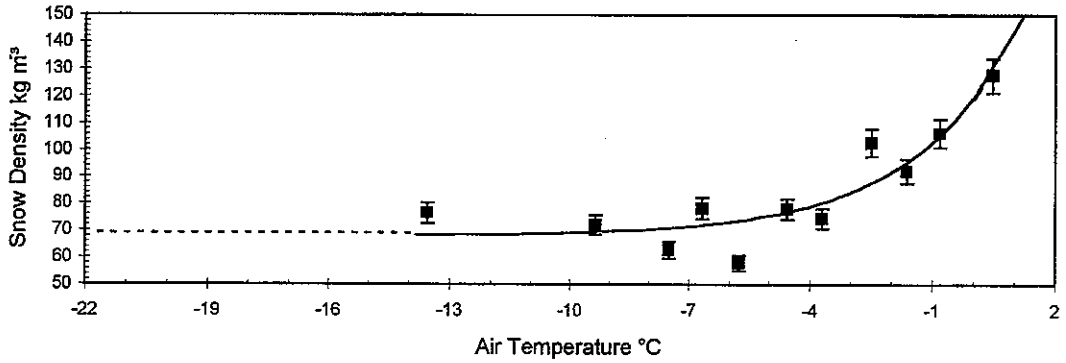

Figure 3. Relationship between new-fallen snow density and temperature (compilation of data reported by the US Army Corps of Engineers (1956) and Schmidt and Gluns (1991)). 95% confidence intervals shown along with means.

It is possible that $\Omega_s<1$ for a variety of reasons:
1) not all winter surfaces will intercept snow (e.g. vertical stems, twigs),
2) for small snowfalls, very little snowfall may penetrate to the lower canopy and be available for interception, and
3) conifer branches often clump together; when one branch lies directly under another it will not be able to intercept snow. A clumping factor for light Ω is used to correct measurements of LAI made with light extinction devices. What is measured by such devices is $LAI\Omega$ where $\Omega \leq 1$ but is not independently measured. $LAI\Omega_s$ is therefore found empirically as a function of $LAI\Omega$ from measurements as

$$LAI\ \Omega_s = c\ LAI\ \Omega \tag{13}$$

where c is a proportionality factor between Ω for light and for snow. A relationship between the amount of snowfall, P and c was determined by calculating c using Eq.1 to estimate I from residual values, Eqs. 5,6,8,9,10,11,12,13 and measured $LAI\Omega$ values. The following relationships,

$$\begin{array}{lll} \textit{pine} & c = 0.0296\ P + 0.132\ , \text{ and} \\ \textit{spruce} & c = 0.0390\ P + 0.033 \end{array} \tag{14}$$

can be used to determine the proportionality factor based on snowfall for each forest type (Fig. 4). The pine (Fig. 4a) relationship has a coefficient of determination $r^2 = 0.62$ with a standard error of estimate of

0.13. The spruce (Fig. 4b) relationship has a coefficient of determination $r^2 = 0.85$ with a standard error of estimate of 0.06.

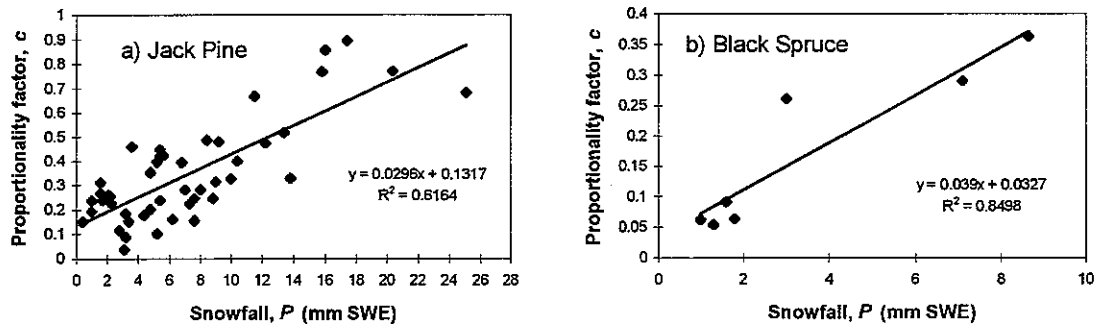

Figure 4. Proportionality factor for snow to light interception as a function of snowfall, a) jack pine, b) black spruce.

To operate the model to calculate snow interception *I* for a snowfall event, the input variables are:

i) initial snow load L_0,
ii) effective winter leaf area index $LAI\Omega$,
iii) proportionality factor c for snow to light interception,
iv) air temperature T_a,
v) wind speed u,
vi) canopy coverage C_c,
vii) canopy height H,
viii) mean snowflake fall velocity ω,
ix) mean forested fetch length J, and
x) snowfall over the period P.

Parameters ii, iii, vi, vii and ix are properties of the forest stand; parameters iv, v and x are standard meteorological measurements; and parameter viii is estimated from the temperature and time of year. Initial snow load is determined from the previous iteration of the model, less sublimation and unloading, or set to zero at the beginning of the season.

PERFORMANCE

Figure 5 shows the influence of variation in input variables on the modelled interception efficiency, *I/P*. In Fig. 5a as storage capacity increases there is a dramatic increase in the interception efficiency that eventually levels off at higher I_p values. Storage capacity has relatively little effect on *I/P* for small snowfall amounts. For high I_p values, varying snowfall amounts have less influence on *I/P*. In Fig. 5b there is a strong but declining increase in interception efficiency as the leaf area index increases. *I/P* has a linear increase with snow-leaf contact area (Fig. 5c). Figure 5d shows that interception efficiency declines only slightly as temperature increases. Increasing snowfall results in decreasing interception efficiency, irrespective of initial snow load as shown in Fig. 5e. However, Fig. 5f shows interception efficiency decreasing as the snow load increases. This trend is more pronounced with higher snowfall amounts.

Figure 6 shows weekly interception (mm SWE) calculated using the model, and measured using the difference between open and sub-canopy snowfall for jack pine (Fig. 6a) and black spruce (Fig. 6b) forests against the corresponding open snowfall. The application of the model with weekly measurements corresponds well with measured interception with a mean underestimation of 0.23 mm SWE for the black spruce and a mean overestimation of 0.51 mm SWE for the jack pine. Due to the limited amount of snowfall at these sites it is not completely evident from the pattern of modelled points in Fig. 6 that exponential decay in interception with snowfall is occurring. However, for the pine site in Fig. 6a the pattern of modelled values would start to level off at 30.0 mm snowfall just slightly above the maximum on the graph. The black spruce modelled interception in Fig. 6b will start to level off at 45.0 mm snowfall.

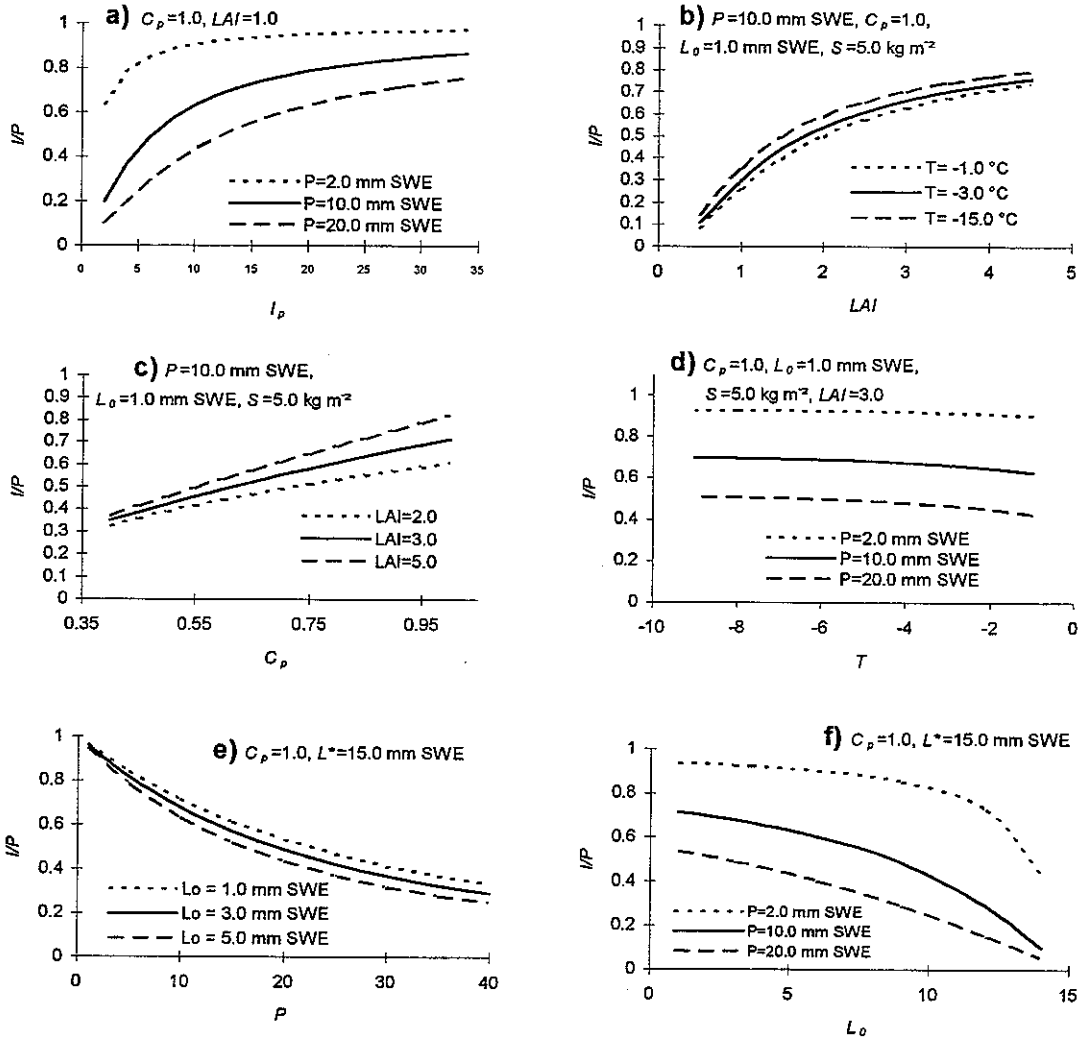

Figure 5. Sensitivity of modelled interception efficiency to input variables, a) storage capacity, b) leaf area index, c) canopy coverage, d) temperature, e) snowfall, and f) initial canopy snow load.

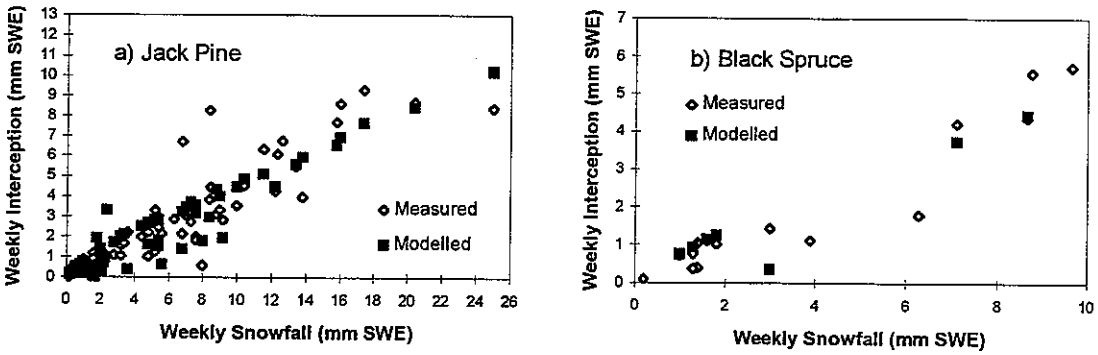

Figure 6. Comparison of modelled and measured weekly interception, a) jack pine, b) black spruce.

DISCUSSION

The development of a new snow interception model has permitted the calculation of snow interception over entire winters in a cold environment. The model incorporates physically-based processes in scaling from branch to canopy, including the effects of incremental increases in canopy storage while accounting for previously intercepted snow. Leaf area index proves to be the most useful of the forest stand parameters for calculating interception. Leaf area index is dampened by a proportionality factor with the reasoning that not all leaf area contributes to the snow collection area. The influence of wind on effective canopy coverage has proven negligible especially for denser canopies and higher wind speed. Temperature is related to the density of snow with more of an affect on interception at warmer temperatures than at colder.

Based on weekly measurements, 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 Fig. 7 provides initial validation of the model. The new model fulfills all known physical considerations of snow accumulation by coniferous canopies. These considerations have not been incorporated in previous snow interception algorithms. McNay et al. (1988) show a constant interception efficiency while Verseghy et al. (1993) have an arbitrary maximum interception load. Strobel's (1978) method of calculating interception depends on an empirical coefficient for which no means of calculation is provided. The new model relies on standard forest inventory and meteorological variables making its use quite suitable for hydrological modelling and research applications.

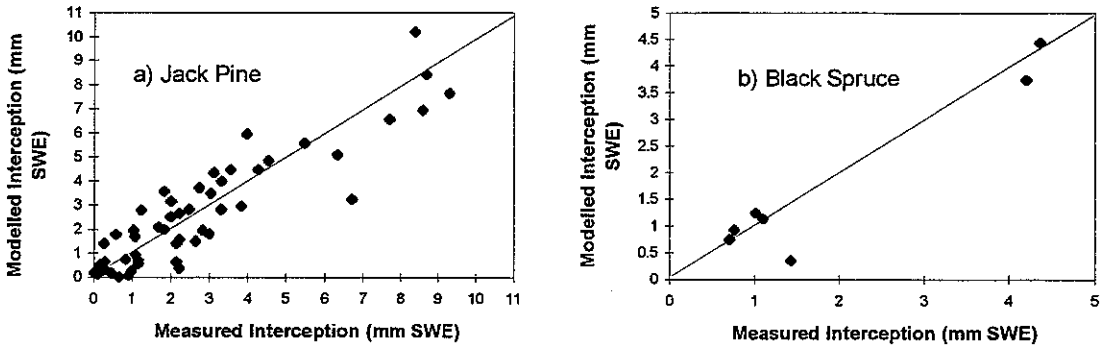

Figure 7. Modelled versus measured interception, a) jack pine coefficient of determination $r^2 = 0.82$ and standard error of estimate = 1.01, b) black spruce coefficient of determination $r^2 = 0.92$ and standard error of estimate = 0.51.

CONCLUSIONS

Based on an extensive series of measurements and a new physically-based model of snow interception, the following conclusions can be made for 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 standard meteorological data and forest inventory variables to calculate snowfall interception.

2) Interception efficiency is much greater for lower snowfall.

3) Interception efficiency increases with leaf area index and canopy coverage, and decreases with temperature.

4) At high wind speed the effective canopy coverage becomes unity.

5) 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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REFERENCES

Bunnell, F.L., R.S. McNay and C.C. Shank. 1985. *Trees and snow: the deposition of snow on the ground-a review and quantitative synthesis,* Research Branch, Ministries of Environment and Forests, IWIFR-17. Victoria, B.C., Canada, p. 449.

Calder, I.R. 1990. *Evaporation in the Uplands*, Wiley, Chichester, p. 144.

Gary, H.L. 1974. 'Snow accumulation and snowmelt as influenced by a small clearing in lodge pole pine forest', *Water Resources Research,* **10**, 348-353.

Goodell, B.C. 1959. 'Management of forest stands in western United States to influence the flow of snow-fed streams', In *Symposium of Hannoversch-Munden Water and Woodlands* Vol. 1, IAHS Publication, No. 48, IAHS Press Gentbrugge, Belgium, 49-58.

Gubler, H. and J. Rychetnik. 1991. 'Effects of forests near the timberline on avalanche research'. In *Snow, Hydrology and Forests in High Alpine Areas*, IAHS Publication No.205, IAHS Press, Wallingford, UK. 19-38.

Harestad, A.S. and F.L. Bunnell. 1981. Prediction of snow-water equivalents in coniferous forests. *Canadian Journal of Forest Research,* **11**, 854-857.

Hoover, M.D. and C.F. Leaf. 1967. 'Process and significance of interception in Colorado subalpine forest'. In: *Forest Hydrology,* edited by W.E. Sopper, and H.W. Lull. Pergamon Press, New York, 213-223.

Kobayashi, D. 1987. 'Snow accumulation on a narrow board', *Cold Regions Science and Technology,* **13(3)**, 239-245.

Langham, E.J. 1981. 'Physics and properties of snowcover'. In: *Handbook of Snow, Principles, Processes, Management and Use*, edited by D.M. Gray and D.H. Male. Pergamon Press, Toronto, 275-337.

Linsley, R.K., Kohler, M.A. and J.L.H. Paulhus. 1949. *Applied Hydrology*, McGraw-Hill Book Co., New York, N.Y., p. 689.

McNay, R.S., L.D. Petersen and J.B. Nyberg. 1988. 'The influence of forest stand characteristics on snow interception in the coastal forests of British Columbia', *Canadian Journal of Forest Research,* **18**, 566-573.

Nel, E.M. and C.A. Wessman. 1993. 'Canopy transmittance models for estimating leaf area index', *Canadian Journal of Forest Research*, **23**, 2579-2586.

Pomeroy, J.W. and D.M. Gray. 1995. *Snowcover Accumulation, Relocation and Management*, National Hydrology Research Institute, Science Report No.7, Saskatoon, Environment Canada, p. 144.

Pomeroy, J.W. and R.A. Schmidt. 1993. 'The use of fractal geometry in modelling intercepted snow accumulation and sublimation', *Proceedings of the Eastern Snow Conference*, **50**, 1-10.

Satterlund, D.R. and H.F. Haupt. 1967. 'Snow catch by conifer crowns', *Water Resources Research*, **3**, 1035-1039.

Schmidt, R.A. and D.R. Gluns. 1991. 'Snowfall interception on branches of three conifer species', *Canadian Journal of Forest Research,* **21**, 1262-1269.

Schmidt, R.A., R.L. Jairell and J.W. Pomeroy. 1988. 'Measuring snow interception and loss from an artificial conifer', *Proceedings of the Western Snow Conference*, **56**, 166-169.

Schmidt, R.A. and J.W. Pomeroy. 1990. 'Bending of a conifer branch at subfreezing temperatures: implications for snow interception', *Canadian Journal of Forest Research*, **20**, 1250-1253.

Strobel, T. 1978.' Schneeinterzeption in Fichten-Bestaenden in den Voralapen des Kantons Schwyz', In *Proceedings, IUFRO Seminar on Mountain, Forests and Avalanches.* Davos, Switzerland, 63-79.

Troendle, C.A. and R.M. King. 1985. 'The effect of timber harvest on the Fool Creek watershed: 30 years later', *Water Resources Research,* **21**, 1915-1922.

Verseghy, D.L., N.A. McFarlane and M.Lazare. 1993. 'CLASS-A Canadian Land Surface Scheme for GCMS, II. Vegetation model and coupled runs', *International Journal of Climatology*, **13**, 347-370.

Wheeler, K. 1987.' Interception and redistribution of snow in a subalpine forest on a storm by storm basis', *Proceedings of the Western Snow Conference*, **55**, 78-87.

Wilm, H.G. and E.G. Dunford. 1945. 'Effect of timber cutting on water available for stream flow from a lodge pole pine forest', *Technical Bulletin 965 U.S. Department of Agriculture,* Washington, D.C., p. 43.