Physically Based Estimation of Seasonal Snow Accumulation in the Boreal Forest

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ABSTRACT

Accumulation of snow under forest canopies is known to decline with increasing canopy density and leaf area because of snow interception and sublimation in the canopy. Seasonal snow accumulation measurements collected over a decade from various forest stands in western Canada were used to test and develop methods to relate forest snow accumulation to stand properties and observations of either small clearing seasonal snow accumulation or seasonal snowfall. At sub-stand scales, the variability of seasonal snow accumulation was not well related to stand leaf area, seasonal interception or small clearing seasonal snow accumulation. At the stand-scale, physically-based snow interception equations predicted seasonal snow accumulation from the stand leaf area and the seasonal snow accumulation or snowfall in adjacent clearings. A simple parametric form of these equations showed the sensitivity of seasonal snow accumulation to leaf area at the forest stand scale and suggested a relationship to extrapolate snow accumulation or snowfall measurements from clearings to forests. These relationships, developed from Canadian boreal forest observations, are consistent with Kuz'min's (1960) relationship between accumulation and canopy density derived from Russian observations, suggesting a good degree of transferability.

Keywords: Snow accumulation; snow interception; snowfall; Boreal forest; forest hydrology; water resources prediction

INTRODUCTION

Snow accumulation varies at macroscales (10-1000 km) due to variation in snowfall as influenced by latitude, elevation, orography and water bodies; at mesoscales (100 m – 10 km) due to variation in terrain characteristics and vegetation cover; and at microscales (10-100 m) due to the influence of redistribution along airflow patterns and interception (McKay and Gray, 1981). It is well accepted that at mesoscales and microscales, snow accumulation differs substantially between forested and open environments because of processes of interception, sublimation and wind redistribution (e.g. Pomeroy and Gray, 1995). Interception, sublimation and redistribution processes operate at micro-scales or smaller (Pomeroy et al., 1998a) and yet result in characteristic

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snow accumulation patterns that are still evident at the stand scale (Pomeroy and Gray, 1995). In forested environments, the stand-scale corresponds to the extent of stands or clearings of some characteristic species mix, canopy density and leaf area characteristics and bridges the micro and meso scales noted by McKay and Gray. In natural forests, stand extent is often associated with aspect, moisture availability, soil type, hillslope location, wind exposure, drainage and forest fire history. Forest clearing and planting have imposed a manmade pattern on many forests, though there have been some recent attempts to mimic the spatial patterns of 'natural disturbance' in forest harvesting operations in western Canada.

Knowing the variation in seasonal (late winter maximum) snow accumulation amongst forest stand types and clearings is essential to predicting catchment-scale snow accumulation and melt, as most forested catchments are covered by a mosaic of clearings and stands of varying density. Point or small area measurements and estimates cannot be reliably extrapolated to areal estimates at the basin-scale without reference to the influence of the forest characteristics of the measurement site and of the larger basin on snow accumulation (Jeffrey, 1968). A primary problem for studies of snow accumulation in forested environments is: how do forest stand characteristics influence snow accumulation over a variety of scales? As more accurate and higher resolution maps of forest cover type, density and leaf area have become available, hydrologists with the answer to this question can take advantage of detailed basin landcover information to develop detailed snowcover information over space.

Two prominent practical problems in hydrology may find solutions through a better understanding of the relationship between snow accumulation observed in a small clearing and accumulation in adjacent forested environments. The first is that most meteorological stations recording snow depth and snowfall in forested environments are located in clearings, rather than the forest, the second is that snow remote sensing techniques become more uncertain as forest density increases and are most certain for open sites. Trees, especially evergreens, intercept, emit, and scatter visible, infrared, gamma and microwave radiation in complex manners. The result is that a dense coniferous stand can completely confound attempts by remote measures, to detect the presence or water equivalent of snow underneath it. Techniques that would relate snow accumulation in clearings to that in the more heterogeneous and complex forest landscape would help in extrapolating point observations and correcting remote sensing measurements to provide the areal representations of snow accumulation that are required by hydrologists.

Comparison of measured snow accumulation between natural coniferous forests and clearings demonstrates larger amounts of snow in clearings (Golding and Swanson, 1978), though the degree of difference is often related to the size of the cleared area. In southeastern British Columbia, Canada, Toews and Gluns (1986) report that snow accumulation in clear-cuts ranged from 4 to 118% more than that in adjacent coniferous forests, with a mean difference of 37%. In the foothills of southern Alberta, Canada, Golding and Swanson (1986) report snow accumulation increased from 20 to 45% from forest to clearing. It is important to realise that in windy environments, clearing size can have an important effect on snow accumulation. Very small clearings are sheltered from snowfall by the nearby forest canopy, while larger clearings can lose snow accumulation to wind transport via blowing snow erosion. Where mid-winter melts occur, larger clearings are more exposed to solar radiation and turbulent transfer, increasing the melt rate (Pomeroy and Granger, 1997) Troendle and Leaf (1980) demonstrated the effect of clearing size on snow accumulation in wind-swept mountain forests in Colorado; the largest snow accumulation occurred in clearings with dimensions five times the height of nearby trees. In the Alberta foothills, Swanson (1988) found the largest snow accumulation occurred in clearings with dimensions two to three times the height of surrounding forest. In the boreal forest of central Saskatchewan, Pomeroy et al. (1997), however, found no difference between snow accumulation (away from the edges) of a large (km scale) and a small (100 m scale) clearing. This was a relatively cold and low winter wind speed environment compared to the montane forests of Alberta and Colorado. The practise in Canadian boreal forest harvesting is to leave 'trash' from the treefelling and trimming operations on the clear-cut with the intention of retaining winter snowcover to insulate soils. The roughness created by this trash and the tall grasses and shrubs that quickly re-establish was sufficient to retain almost all of the seasonal snowfall as snow accumulation in forest clearings (Pomeroy et al., 1997). Melts in the clearings were earlier than forest stands, but did not occur until late March or April (Pomeroy and Granger, 1997). In such regions, the occurrence of a sufficiently rough surface to restrict blowing snow is more important than clearing size in determining snow accumulation.

Seasonal sublimation losses from intercepted snow as a percentage of seasonal snowfall in a boreal forest varied from 13% in aspen/spruce mixed-wood, to 31% in mature pine to 40% in a dense spruce stand (Pomeroy et al., 1998a). These losses resulted in a factor of two difference in accumulation between adjacent dense and sparse forest stands, found within scales of hundreds of metres. Pomeroy and Gray (1995) suggested that stratifying accumulation into classes by landscape type and then examining sub-landscape variability using statistical distributions could reasonably account for the hydrologically important variability in snow accumulation. Pomeroy et al. (1998b) and Faria et al. (2000) provided evidence of the lognormal distribution of snow accumulation mass within forests stands and typical coefficients of variation for various stand species types. They noted that taller vegetation dampens the variability of accumulation associated with landform (wind redistribution), but that there was greater variability in small-scale accumulation in evergreen forests than deciduous forests due to microscale effects of snow interception and unloading.

The purpose of this paper is to develop and evaluate simple techniques to

1. describe the between-stand variability of seasonal snow accumulation in forests,
2. describe the within-stand variability of seasonal snow accumulation in forests, and
3. relate forest snow accumulation to that in adjacent small clearings.

Where possible the techniques are based on popular physical measures of forest stands and retain a physical or theoretical basis. The study concentrates on cold, boreal forests where snow accumulation processes are not obscured by frequent or large mid-winter ablation events and defines seasonal snow accumulation as that accumulation at the time of maximum late-winter accumulation, just before ablation commences.

THEORY

Kuz'min (1960) suggested from extensive Russian measurements that the snow accumulation in a forest, S_f, and in a clearing, S_c, can be empirically related to forest winter canopy density, C_c (the ratio of canopy-covered area per unit area of ground), where,

$$S_f = S_c(1-0.37C_c) \qquad 1)$$

This expression has a useful simplicity, and while widely referred to, has not been extensively tested in North America. The authors do not know the theoretical basis of Eq. 1. The following is an attempt to relate the possible theoretical basis of Eq. 1 with more recent forest snow interception theories in order to develop practical equations for predicting snow accumulation in forests from accumulation in clearings.

Presuming horizontal redistribution is negligible, over a snowfall event (period of snowfall), interception, i, is defined as that snowfall which does not reach the ground. If the snowfall, p_c, into a clearing is the same as that to the top of a forest canopy, then

$$p_c - p_f = i \qquad 2)$$

where p_f is the sub-canopy snowfall for some event. The interception term defined in Eq. 2 was the subject of theoretical and observational study by Hedstrom and Pomeroy (1998). They discussed results in terms of interception efficiency, $i/p_c = e_i$, which was calculated from a physically based formulation. The snow interception formulation of Hedstrom and Pomeroy (1998) relates interception to leaf area index, tree species, canopy density, air temperature, wind speed and snowfall. For a *single snowfall event into a snow-free canopy,* Hedstrom and Pomeroy's algorithm can be simplified to its primary factors, as

$$i = c\,I^*\left(1-e^{\frac{-C_c p_c}{I^*}}\right), \quad where \qquad I^* = S_p LAI'\left(0.27+\frac{46}{\rho}\right) \qquad 3)$$

and c is an empirical unloading coefficient found equal to 0.68, p_c is above-canopy snowfall during the interception event, I* is interception capacity, found as a function of the species snow loading coefficient, S_p, effective winter leaf area index, LAI' (total horizontal area of stems, needles and leaves per unit area of ground) and density of fresh-fallen snow, ρ. Further generalising the components of Eq. 3 by assuming the density of fresh snow is 70 kg m^{-3}, presuming that snowfall into a clearing is equal to above-canopy snowfall and using an averaged species snow loading coefficient of 6.3 kg m^{-2} (range of measured values 5.9 to 6.6 kg m^{-2}) provides,

$$i = 3.94\, LAI' \left(1 - e^{\frac{-C_c p_c}{5.8 LAI'}} \right) \tag{4}$$

where units are mm for the coefficients 3.94 and 5.8, p_c and i; and LAI' and C_c are dimensionless. Hedstrom and Pomeroy's interception algorithm tracked snow load in the canopy; the simplifications shown as Eqs. 3 and 4 do not and hence are only valid for single snowfall events. Equations 3 and 4 lose their physical validity and accuracy when applied over longer periods of time with multiple snowfall events because elapsed time increases with precipitation. For every increment of p_c, these equations assume that *all* intercepted snow is retained as canopy snow load from the previous increment. The assumption that snow load is preserved over the time between snowfall increments is likely to be valid during individual snowfalls and for short periods after the snowfalls (up to one week in late winter, up to one month in mid-winter), but Pomeroy et al. (1998a) show that the canopy snow load for subsequent snowfall events is normally depleted by sublimation, melt or subsequent unloading between major snowfall events. In high sun periods of late spring this can take just a few hours. A consideration of the full suite of intercepted snow ablation processes and the time-scales of their operation is necessary to employ Eq. 4 in a meaningful way.

Intercepted snow eventually sublimates, unloads or drips to the ground. Over a winter season it may be presumed that this has occurred. Seasonal sublimation E may then be found as

$$P_c - P_f - U - D = E \tag{5}$$

where P denotes seasonal snowfall (subscripts c and f refer as before to that to a clearing and sub-canopy respectively), U, unloading and D, drip and the seasonal sum of interception, $\sum i = E + U + D$. Presuming that redistribution, surface melt and surface evaporation are negligible, the mass balance equations for the forest and clearing reduce to $S_c = P_c$ and $S_f = P_f - U - D$, resulting in

$$S_f = S_c - E \tag{6}$$

The sublimation term E was the subject of investigation by Pomeroy et al. (1998a) and requires the solution of coupled mass and energy balance equations. A sublimation efficiency term, e_s, may be defined as $E/\sum i$. This efficiency is expected to be lower in humid temperate winter environments where in-canopy melt and unloading of wet snow from the canopy are large (e.g. Lundberg et al., 1998; Storck and Lettenmaier, 1999) and higher in cold dry environments where sublimation processes may proceed with relatively little hindrance (Pomeroy et al., 1998a; Parviainen and Pomeroy, 2000). It is also expected to vary with several other factors such as snow age, amount of intercepted snow, branch elasticity, wind and radiation penetration into the canopy, and canopy structure.

Using the sublimation and interception efficiencies then Eq. 6 may be expressed as

$$S_f = S_c - S_c e_s e_i = S_c (1 - e_s \frac{i}{p_c}) \tag{7}$$

where the efficiencies $e_i = \sum i / S_c$ or $\sum i = e_i S_c$ and $e_s = E / \sum i$ or $E = e_s \sum i$, must be evaluated from the same data set and for the same time interval. It is assumed that the seasonal efficiencies can be approximated by the means of the ratios $\sum i / P_c$ (since $S_c \approx P_c$) and $E / \sum i$, for shorter time periods for which Eq. 4 is valid: for example:

$$\left(\frac{\sum i}{P_c}\right)_{Seasonal} \cong \left(\frac{\overline{\sum i}}{P_c}\right)_{Monthly} \cong \left(\frac{\overline{\sum i}}{P_c}\right)_{Weekly} \cong etc \qquad 8)$$

By summing event-based interception from intervals for which it can be assumed that the canopy has become initially snow-free, Eq. 4 can be employed. The interception efficiency term may be summed to seasonal terms (the seasonal value being the summation of event interception efficiencies) as $e_i = \sum i / S_c$. With this presumption, Eq. 4 with its event-based (roughly weekly) time scale can be combined with Eq. 7 to provide

$$S_f = S_c\left[1 - e_s\left(\frac{3.94LAI'\left(1 - e^{\frac{-C_c P_{cj}}{5.8LAI'}}\right)}{P_{cj}}\right)\right] \qquad 9)$$

where P_{cj} is the snowfall into a clearing over snowfall event time interval j. Equation 9 provides a means of calculating seasonal snow accumulation in a forest, based on accumulation in a clearing, the sublimation efficiency, the magnitude of individual snowfall events, canopy density and winter leaf area index. It is presumed that the canopy becomes snow-free over time interval j, therefore some estimate of snowfall amount over time interval j must be made. The expression uses two canopy parameters and can be further simplified by examining relationships between canopy density and leaf area index. For instance, Eq. 7 is similar in form to Kuz'min's equation (Eq. 1) and comparison of the two equations suggests that his data give the product $e_s\, e_i$ equal to $0.37C_c$.

FIELD OBSERVATIONS

Snow depth and density surveys were conducted during the snow season (usually October through April) in the Canadian boreal forest from 1993 through 2002, on a weekly basis in the Prince Albert Model Forest, Saskatchewan (PAMF) and a monthly basis at Wolf Creek Research Basin, Yukon. Timing of surveys was sometimes varied slightly to capture a snowfall event or anticipate a melt period, but was constrained by the operational requirements of the study programmes in the respective areas. The locations provide a northern and southern example of the western Canadian boreal forest as shown in Fig. 1.

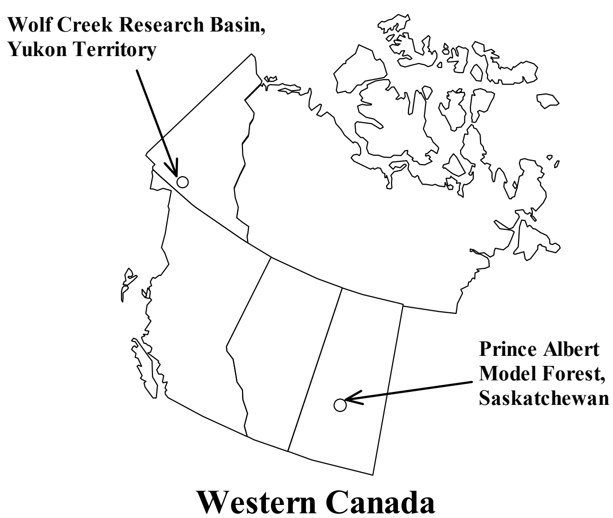


Figure 1. Map of study sites in Saskatchewan and Yukon, western Canada.

Stand characteristics are shown in Table 1. Leaf area index and canopy density were estimated in low-sun periods in wintertime using a LI-COR LAI-2000 Plant Canopy Analyzer (Gower and Norman, 1991). The LAI-2000 was programmed to calculate average canopy statistics from records of 10 samples of irradiance through the canopy, referenced to unobscured sky brightness. Samples were taken along snow survey transect lines. View angles were restricted to the 270^{o} of sky not including the operator or direction of sun. In some cases multiple sample sets were used to determine mean canopy characteristics. Where forest regrowth was noticed (young stands), stands were resampled to estimate canopy change over the course of this study.

Gower and Norman (1991) and Smith et al. (1993) noted that for needle-leaf canopies, the LAI-2000 measures the effective LAI' = LAIΩ, where Ω is the stand clumping index. Neglect of clumping can cause underestimation of LAI by 62%. Hedstrom and Pomeroy (1998) maintained that leaf area contained in clumps is ineffective in holding snow and therefore LAI', as measured by the LAI-2000, is more relevant for snow interception studies than the actual leaf area of the canopy. LAI' and the fraction of sky visible from under the canopy were estimated from radiation extinction by the canopy in various view paths as determined using LICOR algorithms (LICOR, 1990) described by Gower and Norman (1991). Canopy density was calculated as the fraction of sky not visible to the LAI-2000 from under the canopy.

Table 1. Seasonal (late winter maximum) snow accumulation (mm) derived from surveys of depth and density in the Prince Albert Model Forest (PAMF), near Waskesiu Lake, Saskatchewan and the Wolf Creek Research Basin, near Whitehorse, Yukon Territory

		Plantation Jack Pine	Mature Jack Pine	Mixed Aspen/ White Spruce	Black Spruce	Burned Black Spruce	Clearing	Clearing	White Spruce
Location		PAMF	PAMF	PAMF	PAMF	PAMF	PAMF	Wolf Creek	Wolf Creek
Winter LAI'		0.86-2.5	2.2	0.54	4.1	0.3	0.05	0.05	3.3
Cc		0.6-0.86	0.82	0.35	0.95	0.2	0	0	0.87
Seasonal Snow Accumulation	94	52	34	61	34		67	105	69
	95	74	54	90	48		96	110	66
	96	44	49	57	28	70	83	100	68
	97	90	61	97	60	111	124	84	72
	98	42	35	47	33	62	48-65		
	99							54	44
	02							65	45

Wolf Creek

Observations were made at Wolf Creek in the northern montane boreal forest of western Canada by Indian and Northern Affairs Canada as part of research basin operations in support of the Arctic Environmental Strategy and Mackenzie GEWEX (Global Energy and Water Cycle Experiment) Study. Wolf Creek Research Basin is located 15 km south of Whitehorse, Yukon Territory. The catchment occupies a 195-km² area in the headwater region of the Yukon River. The forested area represents about 43 km² of total basin area with an elevation of 750m at 60°36' N, 134°57' W. Surveys focused on a white spruce (*picea glauca)* forest stand, which was composed of mature trees ranging from 12-18m in height. The snow course consisted of 25-depth points spaced approximately 5 m apart with a snow density every 5th depth (25 m apart). The course direction was random and did not deflect from dense brush. Snow density was measured with a metric Mount Rose or an ESC-30 core sampler depending upon snow conditions (Pomeroy and Gray, 1995). Snowfall was recorded by a Nipher-shielded copper cylinder gauge in a nearby small (60 m wide) clearing. Clearing snow accumulation was measured along a short five-point transect in 1-m tall sparse brush near the snowfall gauge; the brush restrained wind transport. Unpublished surveys by Derek Faria (1999) and Susanne Hanson (2001) suggest that fine scale (1-m increment) measurements along this transect have the same statistical properties as the operational surveys.

Prince Albert Model Forest

Observations were made as part of Environment Canada's Prince Albert Model Forest study and the Mackenzie GEWEX Study in a mid-continental southern boreal forest in western Canada. Three mature forest stands and a grassy small clearing (550 m above sea level) near Waskesiu Lake, Saskatchewan, Canada in the Beartrap Creek basin of Prince Albert National Park. The Park provided an undisturbed, 'natural' environment. Two disturbed forests and a large clearing were located to the north and northwest of the Park in a commercial forest zone managed by the provincial government. Snow surveys in forest stands and clearings were taken along ten-point, randomly located depth and density transects of approximately 100 m in length. Densities were measured at four of the depth locations using an ESC-30 core sampler and weight scale (Pomeroy and Gray, 1995). The snow survey protocol was tested by Faria (1999) who showed that sample lengths were sufficient to estimate mean areal SWE and that finer resolution (1-m increment) samples had similar statistical properties to the operational surveys. Areas of dense brush were not avoided. Snowfall was collected using a Nipher-shielded copper cylinder in the clearings.

Mature Jack Pine Site: this pine site is within the Beartrap Creek catchment in Prince Albert National Park, at 53^{o}52' N, 106^{o}08' W. The jack pine (*Pinus banksiana*) stand has mature trees (50-70 years old) 16-22 m tall, with a sparse understory of deciduous shrubs and mosses. Jack pine trees are sparsely branched and variable in form. The needles of the jack pine are long (2-4 cm) and grow in slightly twisted clusters. Due to the age of this stand, the trees are covered in lichens 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 (DBH) of 0.174 m. Most of the canopy leaf area is concentrated in the top 5-7 m of canopy.

Black Spruce Site: this spruce site is within the Beartrap Creek catchment in Prince Albert National Park at 53°53' N, 106°07' W. The black spruce (*Picea mariana*) stand has densely spaced trees (50-90 years old) 10-14 m tall, with an understory of small bushes and mosses on a thick organic forest floor cover. Black spruce trees are slender and straight in form with sagging branches. Needles are short, very sharp and four-sided. The average distance between the black spruce trees measured on the ground is 1.01 m with an average DBH of 0.087 m. The black spruce canopy leaf area is concentrated in the top 7-8 m of canopy.

Mixed-wood (Aspen/White Spruce) Site: this mixed-wood site is within the Beartrap Creek catchment in Prince Albert National Park, at 53°54' N, 106°07' W. Forest vegetation in this mature stand is a mixture of aspen (*Populus tremuloides*) and white spruce (*Picea glauca*) with an understory of grasses and kinnikinnick (bearberry). Approximately 75% of the trees are aspen 15-26 m tall, the remainder being white spruce with heights up to 15 m.

Burned Black Spruce Site: this recent burn site is at 54^{o}02' N 105^{o}27' W in a cutting exclusion zone managed by the provincial government. The site was previously covered with black spruce up to 10-m tall, and burned completely in the "Monday Fire" of June, 1995. The fire left a 'canopy' of standing charred trunks, with few branches, no surviving vegetation and little organic soil. In the years after the fire, regrowth of a deciduous understory vegetation occurred, and standing trunks began to fall.

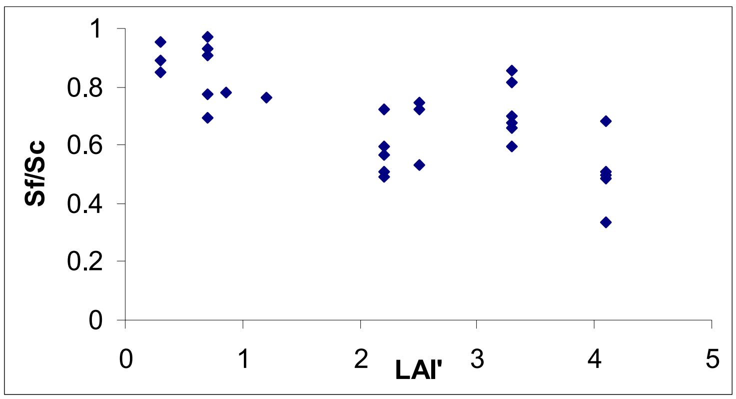
Jack Pine Plantation Site: this regenerating clear-cut is in the Waskesiu River catchment near Ehman Lake, at 54°02' N, 105°55' W. The site was logged, trenched and replanted to jack pine (*Pinus banksiana*) in 1983. At the time of survey the vegetation was dominated by jack pine tree heights up to about 4 m but normally less than 3 m tall.

Bittern Creek Clear-cut Site: this cleared site is in the Bittern Creek catchment on land managed by the provincial government and subject to commercial logging, and is located at 53°59' N, 105°55' W. The initial forest of spruce with some aspen was logged after the summer of 1990, trenched and replanted to white spruce in 1992. During the surveys, grass bushes and small aspen trees dominated the vegetation with heights up to 1.5 m but typically less than 1 m tall. Much of the soil surface was exposed between very small spruce trees, 0.3-1.0 m tall, growing in sheltered furrows. The aspen at this site were thinned as part of a stand management practice in mid-June, 1996.

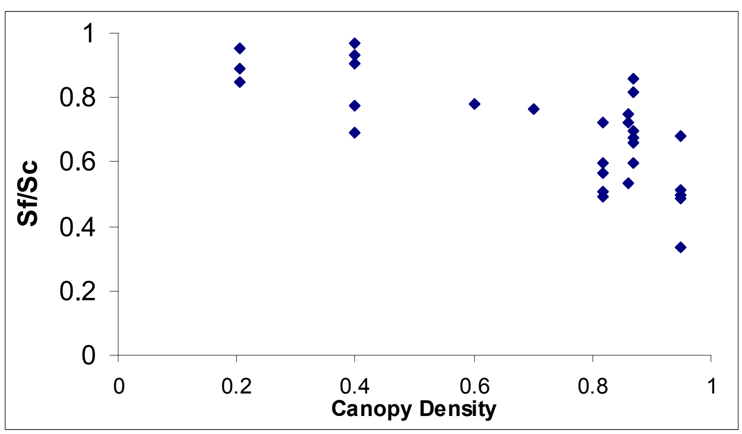
RESULTS

Statistical Properties of Snow and Canopy

Over all stands, seasonal clearing snow accumulation varied from 54 to 124 mm and stand-scale seasonal forest snow accumulation varied from 28 to 110 mm water equivalent with means of 86 and 59 mm for clearing and forested landscapes respectively (Table 1). The ratio of forest to clearing snow accumulation S_f/S_c declined from values near 1.0 to near 0.5 as leaf area index, LAI' and canopy density, C_c, rose from 0.2 to 4.1 and 0.95 respectively as shown in Fig. 2(a, b). The ratio S_f/S_c was negatively correlated to LAI' and C_c with coefficients of -0.69 and -0.72 respectively.



a) Leaf area index (effective winter)



b) Canopy density (winter)

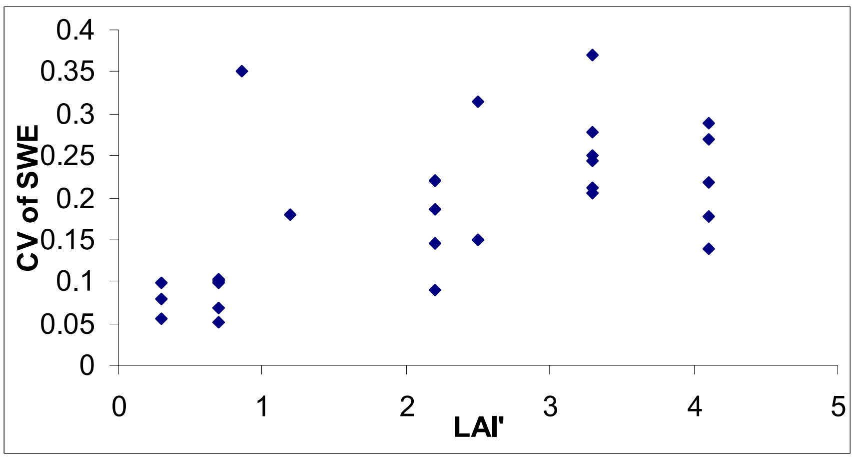
Figure 2. Ratio of forest to clearing snow accumulation as a function of stand characteristics.

At the PAMF sites, the mean seasonal snowfall estimate of 78 mm was very similar to the mean accumulation in the clearings, 85 mm, (difference 8.2%) suggesting that the assumption $P_c \approx S_c$ is acceptable for many purposes. The mesoscale standard deviation and coefficient of variation of the stand-scale means of SWE with respect to the PAMF mean for all PAMF sites were 16.4 mm and 0.28, averaged over five years of observation. At the micro scale, within-stand standard deviations ranged from 4.7 to 20.0 mm and coefficients of variation from 0.05 to 0.37 respectively. As shown in Fig. 3(a-d), neither within-stand scale statistic associated strongly with LAI', clearing snow accumulation or seasonal snow interception. The increase of CV with forest stand density noted by Pomeroy et al. (1998b) is not clearly evident in Fig. 3a. Any trend between CV for snow and leaf area would be due to the decrease in the mean snow accumulation with increasing leaf area as shown in Fig. 2a, as Fig. 3b shows that there is no association between standard deviation of SWE and stand LAI'.

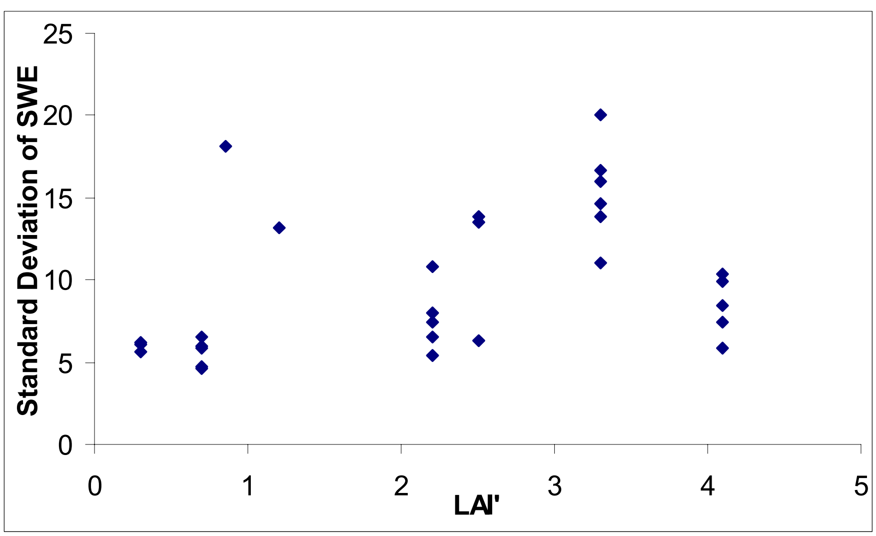
The similarity in relationships between leaf area and S_f/S_c and canopy density and S_f/S_c (Fig. 2 a, b) can be mainly explained by the strong association between leaf area index and canopy density measurements shown in Fig. 4. A logarithmic form of a best-fit relationship between canopy density and LAI' is:

$$C_c = 0.29\ln(LAI') + 0.55 \qquad 10)$$

for which the R^2 is 0.97. Equation 10 suggests a possibly comparison between Kuz'min's relationship and Eq. 9. It also permits a simplification of Eq. 9 to eliminate one of the canopy variables, which will be explored later in the paper.

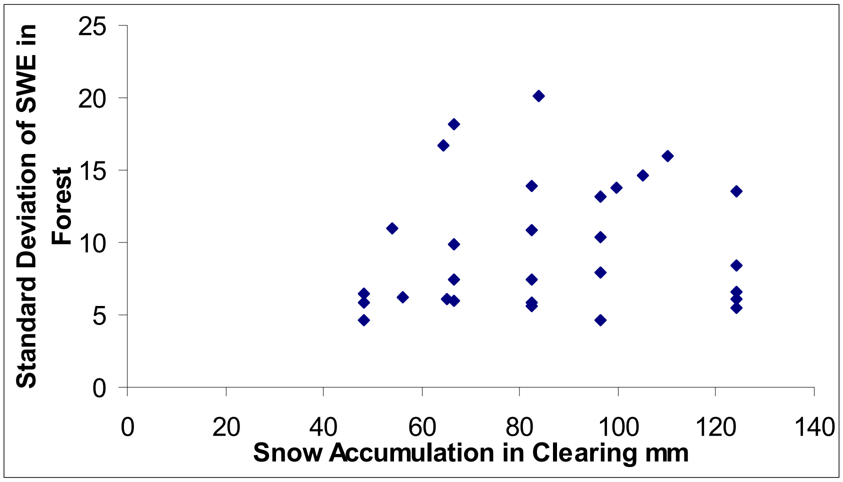


a) Leaf area index (effective winter) and the coefficient of variation of seasonal snow accumulation

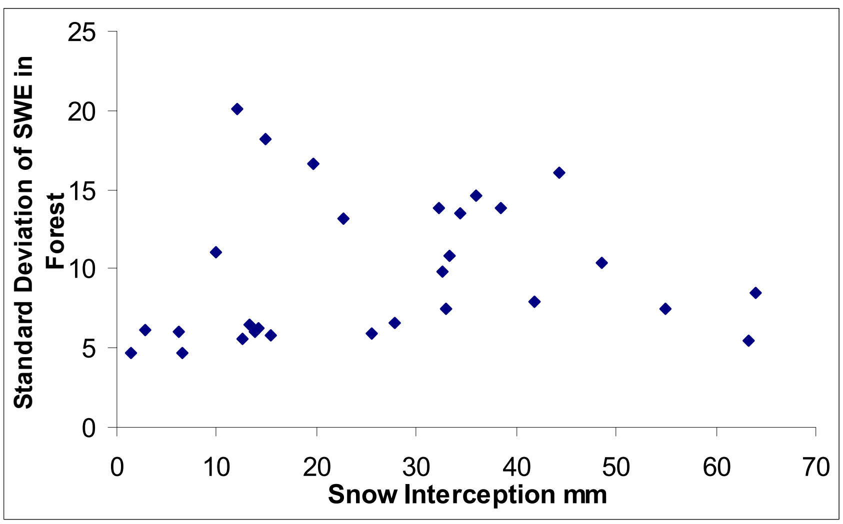


b) Leaf area index (effective winter) and standard deviation (mm) of seasonal snow accumulation.

Figure 3 Influence of winter stand characteristics on within-stand variability of seasonal snow accumulation.



c) Clearing seasonal snow accumulation and standard deviation (mm) of seasonal snow accumulation in adjacent forest stands.



d) Seasonal snow interception loss and standard deviation (mm) of snow accumulation in forest stands.

Figure 3 Influence of winter stand characteristics on within-stand variability of seasonal snow accumulation (continued)

Kuz'min's Equation

Kuz'min's relationship between mean seasonal snow accumulation in forest stands and clearing and canopy density was tested using the measurements and is shown in Fig. 5. Considering that the relationship was developed from measurements on another continent, the fit is quite good, with an R^2 of 0.77, mean difference (measured – modelled) of –4.48 mm suggesting a systematic overestimate, and standard deviation of the differences of 10.1 mm. Fitting the form of the relationship to the Canadian data gives:

$$S_f = S_c(1 - 0.43C_c) \qquad 11)$$

with a R^2 of 0.79, mean difference (measured – modelled) of –0.87 mm and a standard deviation of differences of 9.5 mm. This fitting improves the overall overestimation, but provides a similar level of error in estimation.

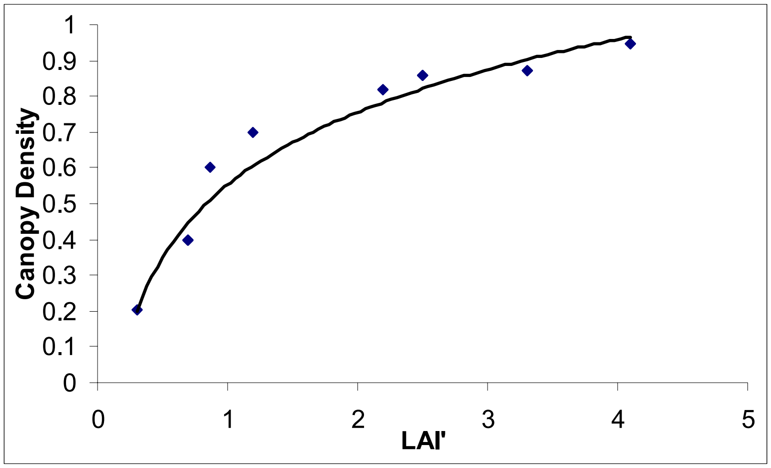


Figure 4. Canopy density and leaf area index (effective winter) measurements for all stands, points are measurements and line is Eq. 10.

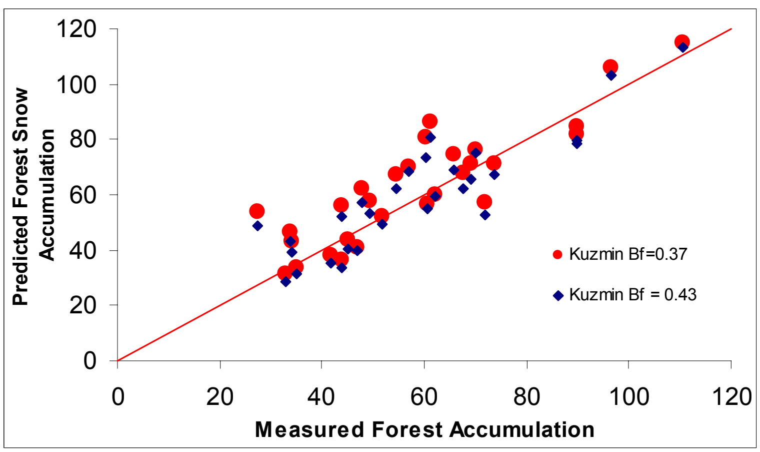


Figure 5. Measured and modelled forest stand seasonal snow accumulation (mm) using Kuz'min's (1960) relationship, Eq. 1, and a modified form, Eq. 11, along with a 1:1 line for reference.

Evaluation of Equation 9

To implement Eq. 9 the magnitude of pc must be found and the behaviour of the sublimation efficiency, es, determined. It is proposed that for the boreal forest, the recommendation of Hedstrom (1998) is followed and that weekly snowfall be used to estimate pc. Over three seasons (94-96) at PAMF for which weekly data quality is highest, the mean weekly winter period snowfall into a clearing was 5.1 mm. Mean monthly winter period snowfall at Whitehorse was 20.4 mm over four seasons (94-97) providing a weekly mean of 4.8 mm. A value for pc of 5 mm was therefore adopted for subsequent analysis. An initial inspection of the data (Fig. 6) shows that the ratio of sublimation to clearing accumulation, E/Sc, is not well predicted by the interception efficiency, e_i, where

$$e_i = i / p_{c_j} \qquad 12)$$

and

$$e_i = 3.94\,\frac{LAI'}{p_{c_j}}\left(1 - e^{\frac{-C_c p_{c_j}}{5.8LAI'}}\right) \qquad 13)$$

and suggests that the sublimation efficiency, e_s, is less than one. Solving for e_s from Eq. 9 and measurements provides a mean e_s of 0.72 with a standard deviation of 0.32. There were no trends of e_s with leaf area index or clearing snow accumulation.

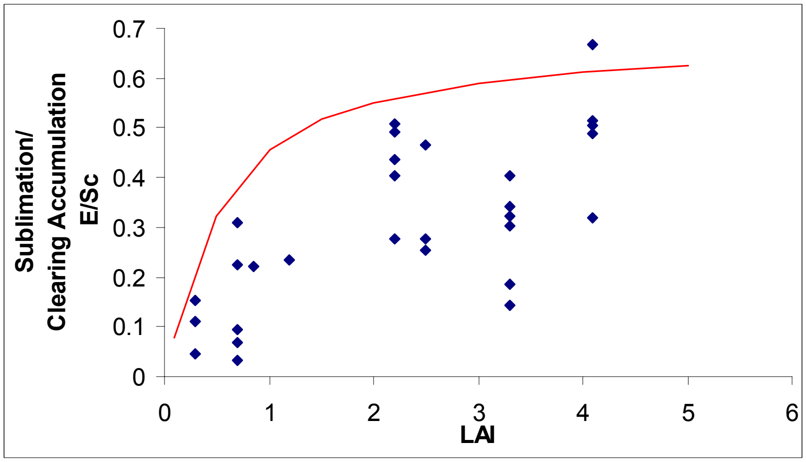


Figure 6. The measured ratio of seasonal intercepted snow sublimation to clearing seasonal accumulation, E/S_c, versus the effective leaf area index shown as points, and modelled values of the interception efficiency, e_i, presuming snowfall event size, p_c, = 5 mm shown as line. It is evident that the interception efficiency overestimates the ratio E/S_c suggesting that the sublimation efficiency must be less than 1.0.

A comparison of Eq. 9 using $p_c = 5$ and $e_s = 0.72$ with measurements is given in Fig.7, with a R^2 of 0.80, mean difference (measured – modelled) of –0.48 mm and a standard deviation of differences of 9.4 mm. The comparison of Eq. 9 to measurements is similar to that of the calibrated Kuz'min relationship (Eq. 11), the goodness of fit due to the use of a 'calibrated' value for sublimation efficiency.

DISCUSSION

At the stand-scale, both Kuz'min's relationship and Eq. 9 have a physical basis and make use of fitted coefficients. Equation 9, though linked to interception theory, is relatively complex for prediction and upscaling purposes. Its use of LAI' is desirable however, as this parameter is direct linked to interception efficiency and is becoming widely available for forests from remote sensing products and allometric relationships. An examination of the sensitivity of interception efficiency e_i to LAI' can provide a simpler form. Figure 8 shows the interception efficiency calculated from Eqs. 4 and 10 as

$$e_i = \frac{3.94}{p_{c_j}} LAI'\left[1 - e^{\frac{-1(0.29\ln(LAI')+0.55)\,p_{c_j}}{5.8LAI'}}\right] \qquad 14)$$

and as the fitted logarithmic form

$$e_i = 0.1984\ln(LAI') + 0.309 \qquad 15)$$

which has a R^2 of 0.99 when compared to Eq. 14.

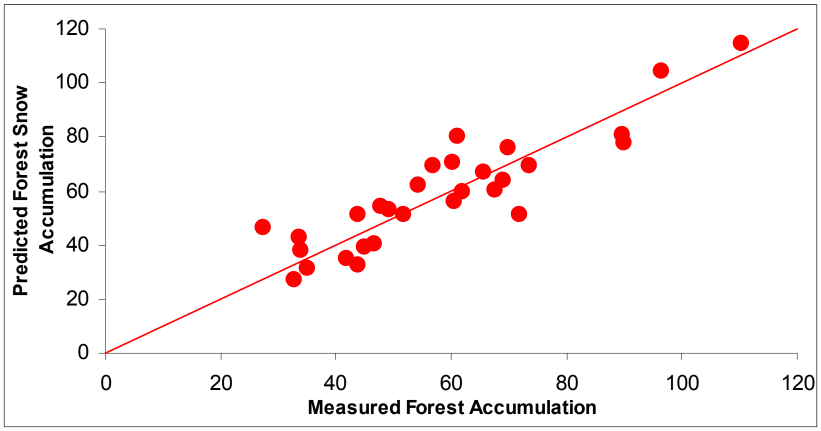


Figure 7. Points indicating measured seasonal forest snow accumulation (mm) and that predicted using Eq. 9 using snowfall event size, p_c,,of 5 mm and sublimation efficiency, e_s, of 0.72 and a 1:1 line for reference.

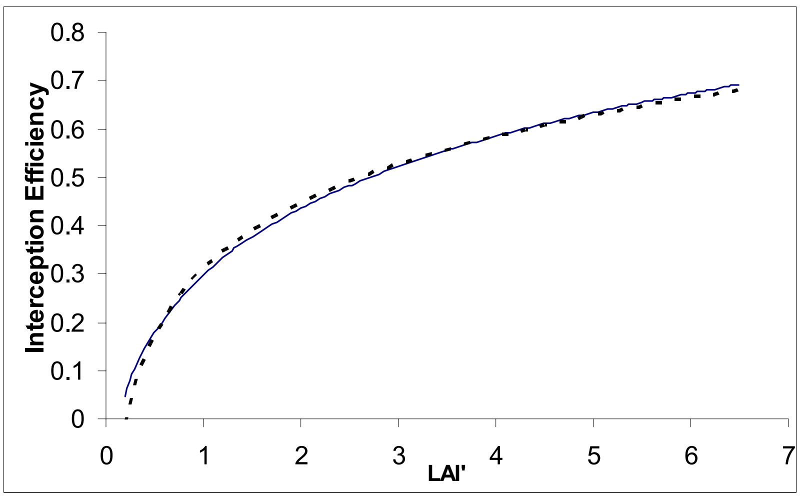


Figure 8. Modelled interception efficiency from the physically based calculation (Eq. 14) solid line and the parametric calculation (Eq. 15) dashed line against leaf area index (winter effective).

From Eqs. 7 and 15 a parametric equation to predict snow accumulation in forests based on that in clearings and leaf area index is:

$$S_f = S_c(1 - e_s(0.2\ln(LAI') + 0.31)) \qquad 16)$$

Equation 16 has a mean difference with measurements of –1.24 mm, standard deviation of differences of 9.72 and a R^2 of 0.79 (Fig. 9). Interestingly, assuming the sublimation efficiency is 0.72, then this equation and the modified Kuz'min equation (Eq. 11) are almost identical when Kuz'min's equation is placed in terms of LAI' using the relationship between LAI' and C_c (Eq. 10). The two forms (parametric, modified Kuz'min) are then:

$$S_f = S_c[1 - (0.144\ln(LAI') + 0.223)] \quad \text{parametric Canada} \qquad 17)$$

and

$$S_f = S_c[1 - (0.125\ln(LAI') + 0.237)] \text{ modified Kuz'min} \qquad 18)$$

Both forms provide a good fit to measurements and can be easily used to predict forest snow accumulation from LAI' and clearing snow accumulation. Using Eq. 10 they could also be stated in terms of canopy density if that is the forest descriptor available for an application. The similarity of the modified Kuz'min equation from his original equation derived from Russian data suggests that these forms may be applicable to the cold climate forests of both western Canada and Russia. The similarity of P_c and S_c values from the Prince Albert Model Forest, and Kuz'min's (1960) recommendation from Russian experience, suggest that if accumulation data is unavailable, then cumulative snowfall could be substituted in the previous analysis.

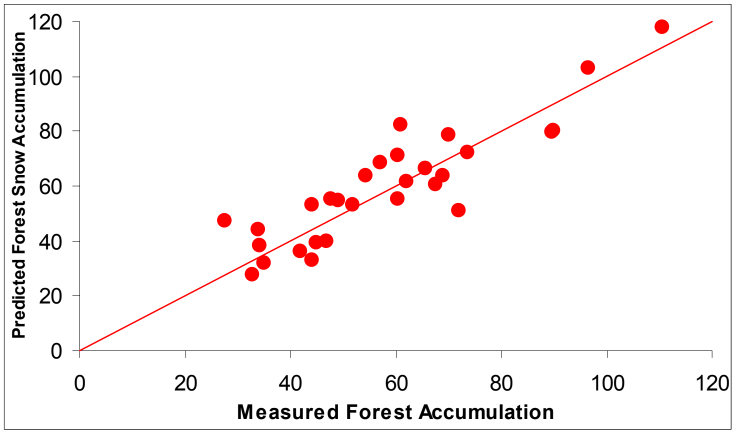


Figure 9. Performance of the parametric forest snow accumulation equation (Eq. 16) presuming that sublimation efficiency is 0.72; measured and modeled accumulation (mm) as points with a 1:1 line for comparison.

At the within-stand scale, the lack of association between the standard deviation of SWE and the leaf area index (and by inference canopy density, Eq.10), snow accumulation in clearings (and by inference seasonal snowfall) or snow interception in canopy is instructive. These parameters are fundamental to canopy interception processes and therefore snow accumulation under the canopy (Eqs. 7 and 9). Other factors that influence the nature of unloading of snow from the canopy, for instance snow wetness, branch temperature, and degree of wind redistribution vary from season to season and with geographical location in the boreal forest and may play important roles in the ultimate distribution of snow under the canopy (Pomeroy and Gray, 1995). The within-stand spatial variability of LAI' may also be an important factor; however the measurements needed to assess this variability were not collected in this study.

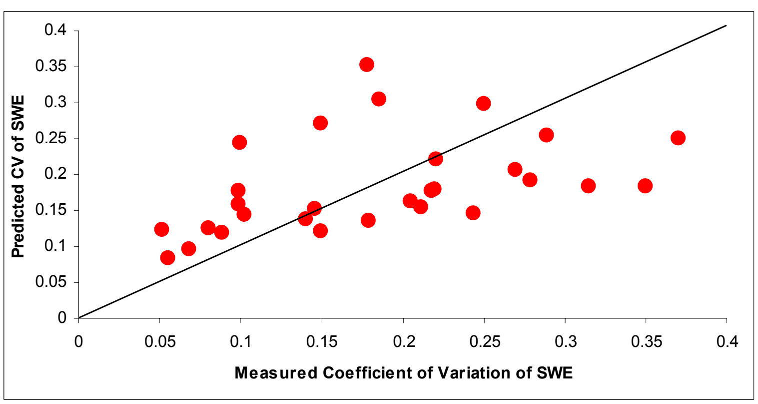


Figure 10. Predicted coefficient of variation of forest snow accumulation (Eq. 19) and measured values shown as points; the 1:1 line is for reference.

To see if the stand-scale mean SWE predictive relationship can help describe within stand variability, the average of the individual standard deviation for all stands $StDev(\overline{SWE})$ was taken and found as 9.76 mm. The coefficient of variation for an individual stand CV(SWE) was then estimated using Eq 17 as,

$$CV(SWE) = \frac{StDev(\overline{SWE})}{S_c(1-(0.144\ln(LAI')+0.223))} \tag{19}$$

and is shown in Fig. 10. The mean difference between measured and modelled CV is –0.0009 and the standard deviation of difference is 0.0836, whilst the R^2 of modelled and measured values is 0.20 suggesting a poor predictive power. The low correlation suggests that a bulk standard deviation from all stands and estimates of snowfall and canopy characteristics for a specific stand cannot be used to accurately predict the statistical characteristics of snow accumulation within a specific stand.

CONCLUSIONS

The within-stand variation of snow accumulation in a forest as described by the standard deviation of snow water equivalent is not associated with seasonal maximum snow accumulation in small clearings, seasonal snow interception or leaf area index. The coefficient of variation of snow accumulation is not well associated with mean stand leaf area index. Standard deviations have a large variation (4-21 mm) about their mean, such that even if the mean snow accumulation can be estimated for a stand, the coefficient of variation cannot be reliably estimated from snowfall and stand characteristics.

Seasonal snow accumulation in forests at the stand scale is shown to scale with leaf area index following the interception theory of Hedstrom and Pomeroy (1998); the function is one of declining accumulation with increasing leaf area. It is anticipated that the assumptions underlying this relationship are valid where mid-winter melts, wind redistribution and surface evaporation are infrequent or small. The relationship between snow accumulation and leaf area is consistent with Kuz'min's (1960) relationship between forest snow accumulation and canopy density, as leaf area and canopy density are strongly related in boreal forests. Knowledge of the distribution of leaf area index can therefore provide the distribution of snow accumulation at medium to large scales. Very similar relationships between forest stand parameters and forest snow accumulation occur between western Canada and Russia, suggesting the transferability of the results between North America, eastern Europe and Siberia.

ACKNOWLEDGEMENTS

The authors wish to note the high quality of snow surveys conducted by Dell Bayne, Glenn Ford, Kerry Paslawski, Glen Carpenter, Cuyler Onclin, Derek Faria, Brenda Toth, Jason Parviainen, Steve McCartney, John Bastien and others over a decade of study. Funding was provided by the Prince Albert Model Forest Association, Arctic Environmental Strategy, Mackenzie GEWEX Study, National Science and Engineering Research Council of Canada, Indian and Northern Affairs Canada, Environment Canada, Canadian Forestry Service, Natural Environment Research Council (UK), British Council (Canada) and the Scientific Affairs Division of NATO.

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