HYDROLOGICAL PROCESSES
*Hydrol. Process.* **16**, 3543–3558 (2002)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.1228

# Prediction of seasonal snow accumulation in cold climate forests

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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. *Formirovanie Snezhnogo Pokrova i Metody Opredeleniya Snegozapasov*. Gidrometeoizdat: Leningrad) relationship between accumulation and canopy density derived from Russian observations, suggesting a good degree of transferability. Copyright © 2002 Crown in the right of Canada. Published by John Wiley & Sons, Ltd.

KEY WORDS 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 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 (1981). 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

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*Received 11 June 2002*
*Accepted 3 September 2002*

imposed a man-made 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 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 realize 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, whereas 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 that 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 (kilometre scale) and a small (100 m scale) clearing. This was a relatively cold and low wind speed environment compared with the montane forests of Alberta and Colorado. The practice 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;
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

$$S_f = S_c(1 - 0{\cdot}37C_c) \tag{1}$$

This expression has a useful simplicity, but, while widely referred to, it has not been extensively tested in North America. The authors do not know the theoretical basis of Equation (1). The following is an attempt to relate the possible theoretical basis of Equation (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

$$p_c - p_f = i \tag{2}$$

where $p_f$ is the sub-canopy snowfall for some event. The interception term defined in Equation (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

$$i = cI^*(1 - e^{-C_c p_c/I^*}) \quad \text{where } I^* = S_p \,\mathrm{LAI}' \left(0{\cdot}27 + \frac{46}{\rho}\right) \tag{3}$$

$c$ 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 $\rho$. Further generalizing the components of Equation (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

$$i = 3{\cdot}94 \text{ LAI}'(1 - e^{-C_c p_c/(5{\cdot}8 \text{ LAI}')}) \tag{4}$$

where units are millimetres 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 Equations (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 1 week in late winter, up to 1 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 Equation (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 of a clearing and sub-canopy respectively), $U$ is unloading and $D$ drip; 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, Equation (6) may then be expressed as

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

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 Equation (4) is valid; for example:

$$\left(\frac{\sum i}{P_c}\right)_{\text{Seasonal}} \cong \left(\frac{\overline{\sum i}}{P_c}\right)_{\text{Monthly}} \cong \left(\frac{\overline{\sum i}}{P_c}\right)_{\text{Weekly}} \cong \ldots \tag{8}$$

 

By summing event-based interception from intervals for which it can be assumed that the canopy has become initially snow-free, Equation (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, Equation (4) with its event-based (roughly weekly) time scale can be combined with Equation (7) to provide

$$S_f = S_c \left\{ 1 - e_s \left[ \frac{3{\cdot}94 \text{ LAI}'(1 - e^{-C_c p_{cj}/(5{\cdot}8 \text{ LAI}')})}{p_{cj}} \right] \right\} \tag{9}$$

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, Equation (7) is similar in form to Kuz'min's equation (Equation (1)), and comparison of the two equations suggests that his data give the product $e_s e_i = 0{\cdot}37 C_c$.

## 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 (PAMF), Saskatchewan, 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 Figure 1.

Stand characteristics are shown in Table I. Leaf area index and canopy density were estimated in low-sun periods in wintertime using an LI-COR LAI-2000 Plant Canopy Analyzer (Gower and Norman, 1991). The LAI-2000 was programmed to calculate average canopy statistics from records of ten 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° 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 $\text{LAI}' = \text{LAI}\Omega$, where $\Omega$ 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 that, 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 the LI-COR algorithms (LI-COR, 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.

### *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 km$^2$ area in the headwater region of the Yukon River. The forested area represents about 43 km$^2$ of total basin area with an

 


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

Table I. Seasonal (late winter maximum) snow accumulation derived from surveys of depth and density in the 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 |
| $C_c$ | 0·6–0·86 | 0·82 | 0·35 | 0·95 | 0·2 | 0 | 0 | 0·87 |
| Seasonal snow accumulation (mm) | | | | | | | | |
| 1994 | 52 | 34 | 61 | 34 | | 67 | 105 | 69 |
| 1995 | 74 | 54 | 90 | 48 | | 96 | 110 | 66 |
| 1996 | 44 | 49 | 57 | 28 | 70 | 83 | 100 | 68 |
| 1997 | 90 | 61 | 97 | 60 | 111 | 124 | 84 | 72 |
| 1998 | 42 | 35 | 47 | 33 | 62 | 48–65 | | |
| 1999 | | | | | | | 54 | 44 |
| 2002 | | | | | | | 65 | 45 |

 

elevation of 750 m 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 to 18 m in height. The snow course consisted of 25 depth points spaced approximately 5 m apart with a snow density every fifth 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.

*PAMF*

Observations were made as part of Environment Canada's PAMF 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 snow water equivalent (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°52′N, 106°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. Owing 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°02′N 105°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 the 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 mm and 59 mm for clearing and forested landscapes respectively (Table I). 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 Figure 2a, and b. The ratio $S_f/S_c$ was negatively correlated to LAI′ and $C_c$, with coefficients of −0·69 and −0·72 respectively.

At the PAMF sites, the mean seasonal snowfall estimate of 78 mm was very similar to the mean accumulation in the clearings, i.e. 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 (CV) of the stand-scale means of SWE with respect to the PAMF mean for all PAMF sites were 16·4 mm and 0·28 respectively, averaged over 5 years of observation. At the microscale, within-stand standard deviations ranged from 4·7 to 20·0 mm and CVs from 0·05 to 0·37. As shown in Figure 3a–d, neither of the within-stand scale statistics 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 Figure 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 Figure 2a, as Figure 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 between canopy density and $S_f/S_c$ (Figure 2a and b) can be mainly explained by the strong association between leaf area index and canopy density measurements shown in Figure 4. A logarithmic form of a best-fit relationship between canopy density and LAI′ is:

$$C_c = 0{\cdot}29 \ln(\mathrm{LAI}') + 0{\cdot}55 \tag{10}$$

for which $R^2 = 0{\cdot}97$. Equation 10 suggests a possible comparison between Kuz'min's relationship and Equation (9). It also permits a simplification of Equation (9) to eliminate one of the canopy variables, which will be explored later in the paper.

 

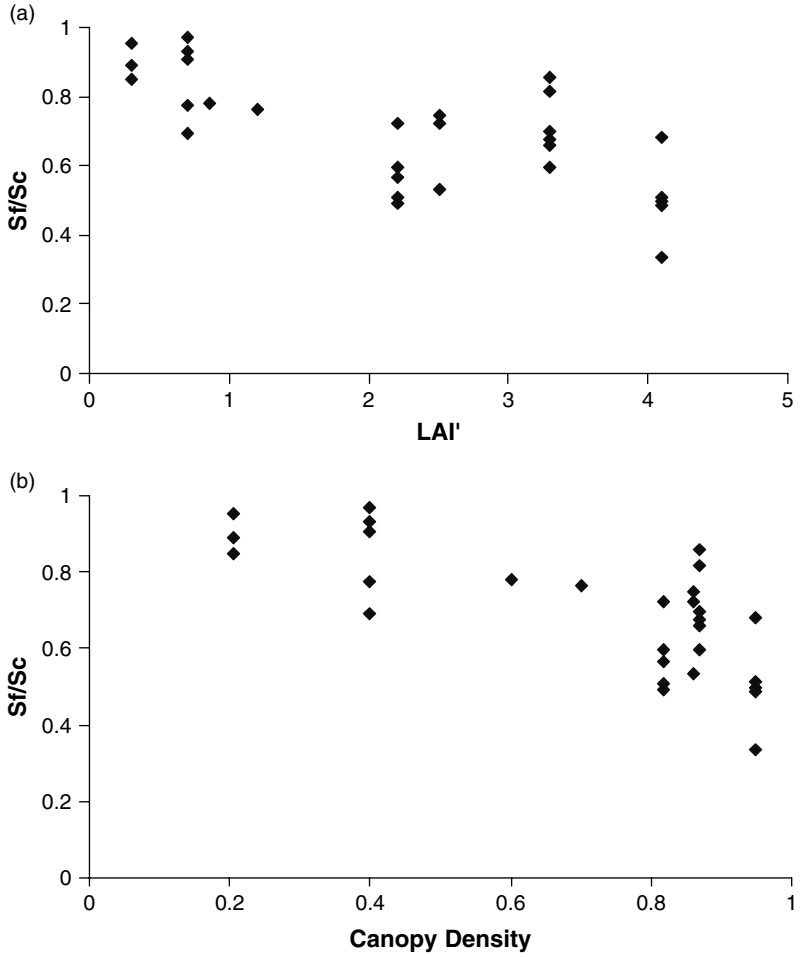


Figure 2. Ratio of forest to clearing snow accumulation as a function of stand characteristics: (a) leaf area index (effective winter); (b) canopy density (winter)

*Kuz'min's equation*

Kuz'min's (1960) relationship between mean seasonal snow accumulation in forest stands and clearing and canopy density was tested using the measurements and is shown in Figure 5. Considering that the relationship was developed from measurements on another continent, the fit is quite good, with $R^2 = 0{\cdot}77$, mean difference (measured − modelled) of $-4{\cdot}48$ 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

$$S_f = S_c(1 - 0{\cdot}43C_c) \tag{11}$$

with $R^2 = 0{\cdot}79$, mean difference (measured − modelled) of $-0{\cdot}87$ 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.

*Evaluation of Equation (9)*

To implement Equation (9), the magnitude of $p_{cj}$ must be found and the behaviour of the sublimation efficiency $e_s$ determined. It is proposed that, for the boreal forest, the recommendation of Hedstrom (1999)

 

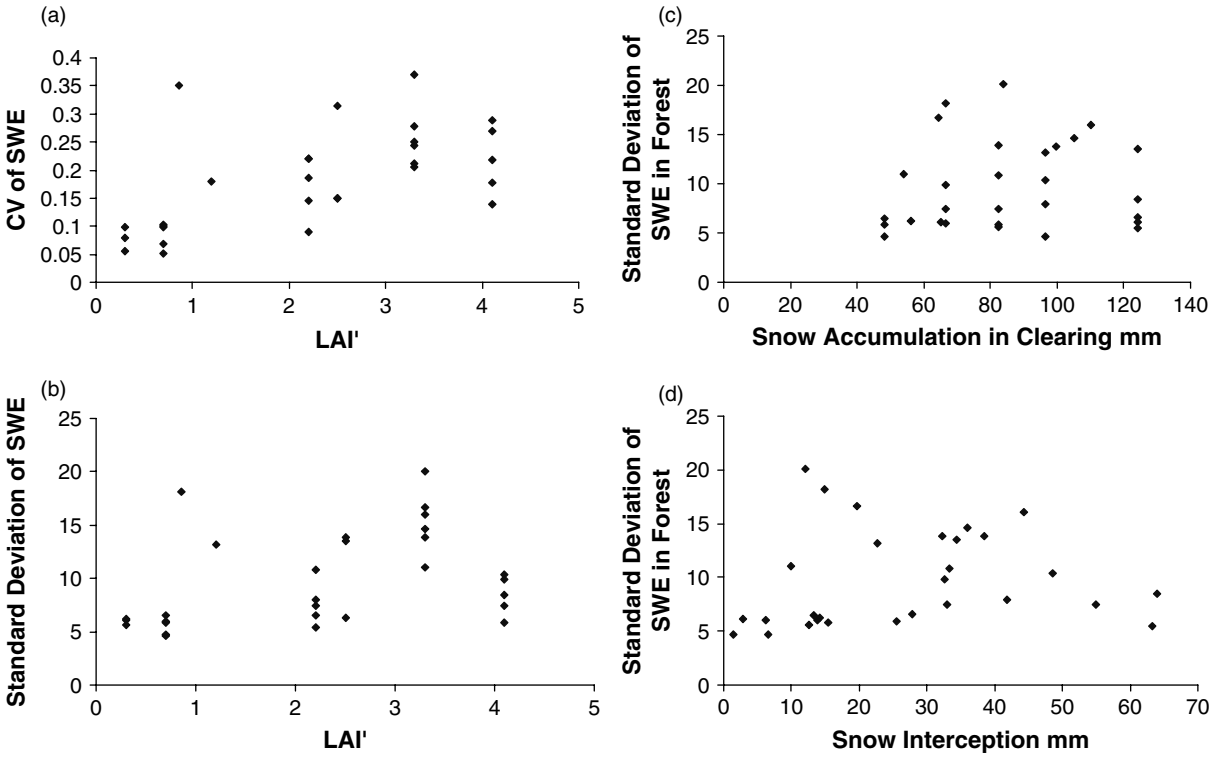


Figure 3. Influence of winter stand characteristics on within-stand variability of seasonal snow accumulation. (a) Leaf area index (effective winter) and the coefficient of variation of seasonal snow accumulation. (b) Leaf area index (effective winter) and standard deviation of seasonal snow accumulation. (c) Clearing seasonal snow accumulation and standard deviation of seasonal snow accumulation in adjacent forest stands. (d) Seasonal snow interception loss and standard deviation of snow accumulation in forest stands

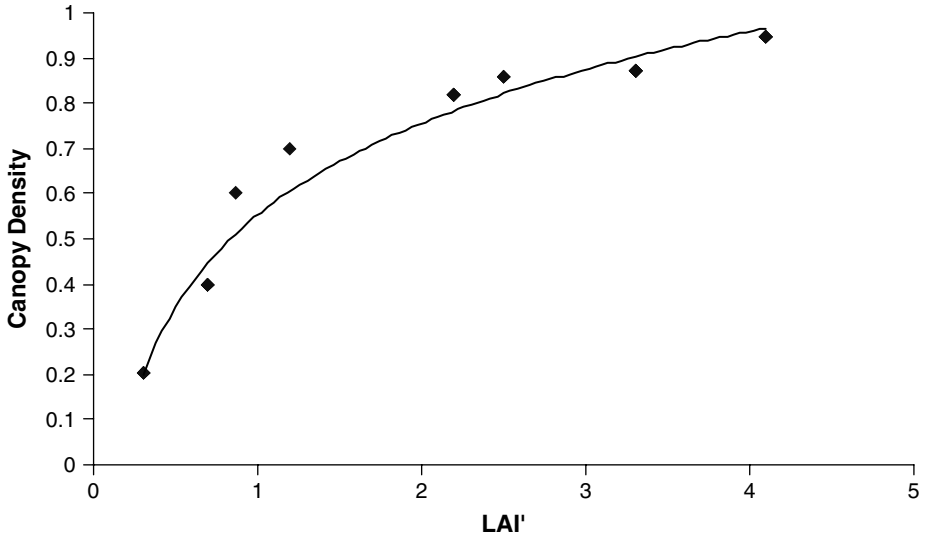


Figure 4. Canopy density and leaf area index (effective winter) measurements for all stands, points are measurements and line is Equation (10)

 

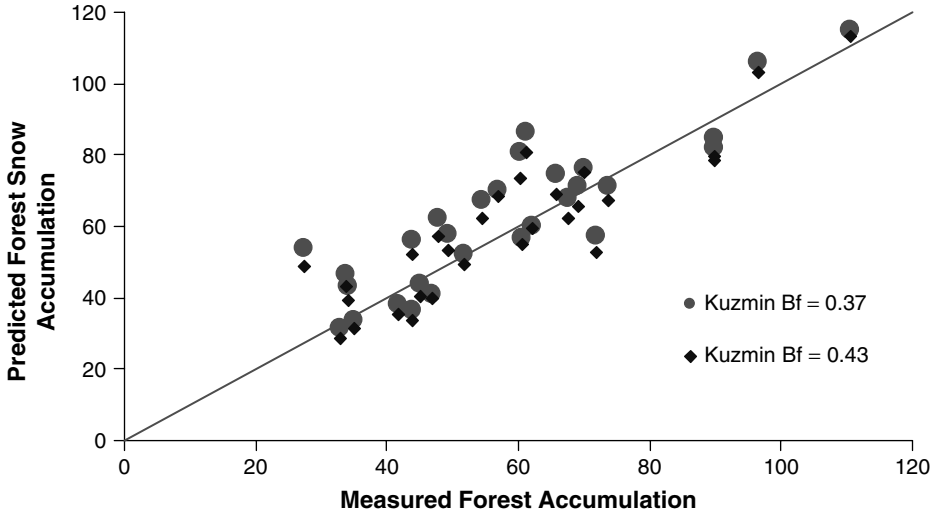


Figure 5. Measured and modelled forest stand seasonal snow accumulation using (mm) Kuz'min's (1960) relationship, Equation (1), and a modified form, Equation (11), along with a 1 : 1 line for reference

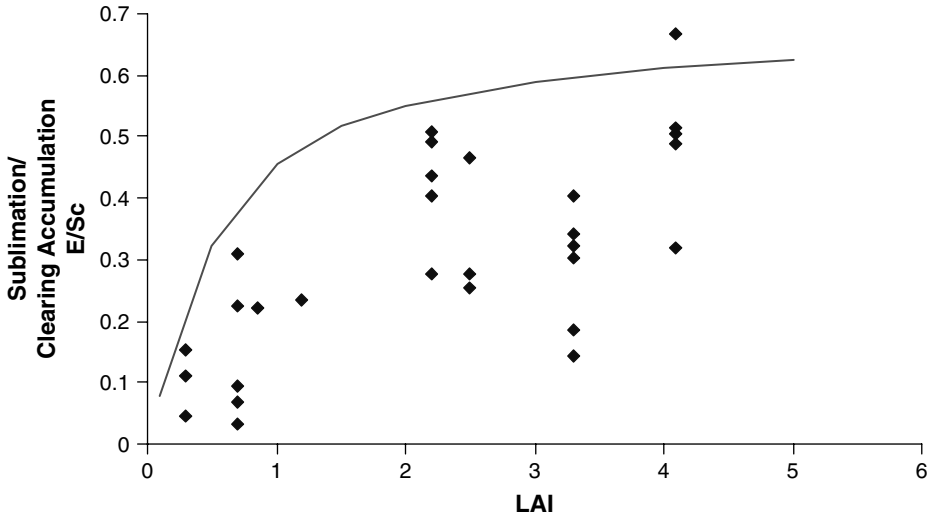


Figure 6. The measured ratio of seasonal intercepted snow sublimation from forest to clearing seasonal snow accumulation, $E/S_c$, versus the leaf area index (effective winter), shown as points, and the modelled values of the interception efficiency $e_i$, presuming snowfall event size $p_c = 5$ mm shown as a 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

is followed and that weekly snowfall be used to estimate $p_{cj}$. Over three seasons (1994–96) 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 (1994–97), providing a weekly mean of 4·8 mm. A value for $p_{cj}$ of 5 mm was therefore adopted for subsequent analysis. An initial inspection of the data (Figure 6) shows that the ratio of sublimation to clearing accumulation $E/S_c$ is not well

 

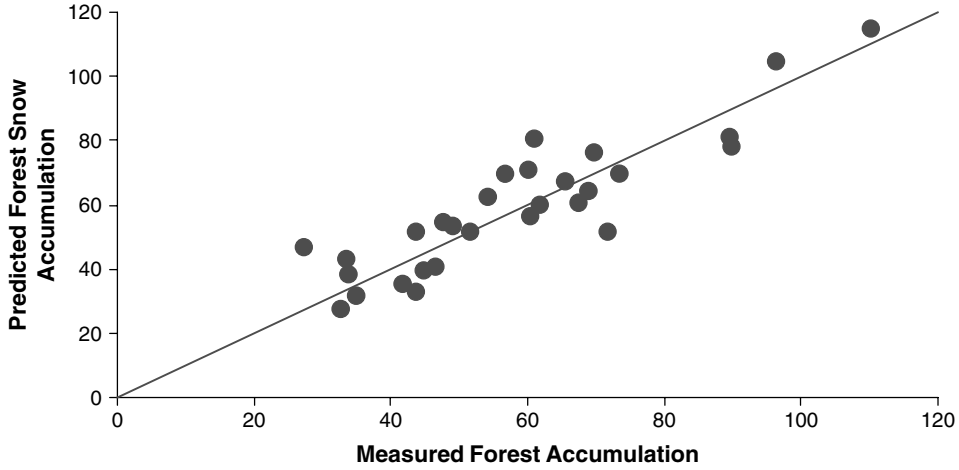


Figure 7. Points indicating measured seasonal forest snow accumulation and that predicted using Equation (9) using snowfall event size $p_c = 5$ mm and sublimation efficiency $e_s = 0{\cdot}72$, with a 1 : 1 line for reference

predicted by the interception efficiency $e_i = i/p_{cj}$ where

$$e_i = 3{\cdot}94\frac{\mathrm{LAI}'}{p_{cj}}\left(1 - e^{-C_c p_{cj}/(5{\cdot}8\mathrm{LAI}')}\right)$$

and suggests that the sublimation efficiency $e_s$ is less than one. Solving for $e_s$ from Equation (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.

A comparison of Equation (9) using $p_{cj} = 5$ and $e_s = 0{\cdot}72$ with measurements is given in Figure 7, with $R^2 = 0{\cdot}80$, mean difference (measured − modelled) of −0·48 mm and a standard deviation of differences of 9·4 mm. The comparison of Equation (9) with measurements is similar to that of the calibrated Kuz'min relationship (Equation (11)), the goodness of fit due to the use of a experimentally derived value for sublimation efficiency.

## DISCUSSION

At the stand scale, both Kuz'min's relationship and Equation (9) have a physical basis and make use of fitted coefficients. Equation 9, though linked to interception theory, is relatively complex for scaling 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 Equations (4) and (10) as

$$e_i = \frac{3{\cdot}94}{p_{cj}}\mathrm{LAI}'\left(1 - \exp\left\{\frac{-1[0{\cdot}29\ln(\mathrm{LAI}') + 0{\cdot}55]p_{cj}}{5{\cdot}8\mathrm{LAI}'}\right\}\right) \tag{12}$$

and as the fitted logarithmic form

$$e_i = 0{\cdot}1984\ln(\mathrm{LAI}') + 0{\cdot}309 \tag{13}$$

which has $R^2 = 0{\cdot}99$ when compared with Equation (12). From Equations (7) and (13), a parametric equation to predict snow accumulation in forests based on that in clearings and leaf area index is

$$S_f = S_c\{1 - e_s[0{\cdot}2\ln(\mathrm{LAI}') + 0{\cdot}31]\} \tag{14}$$

 

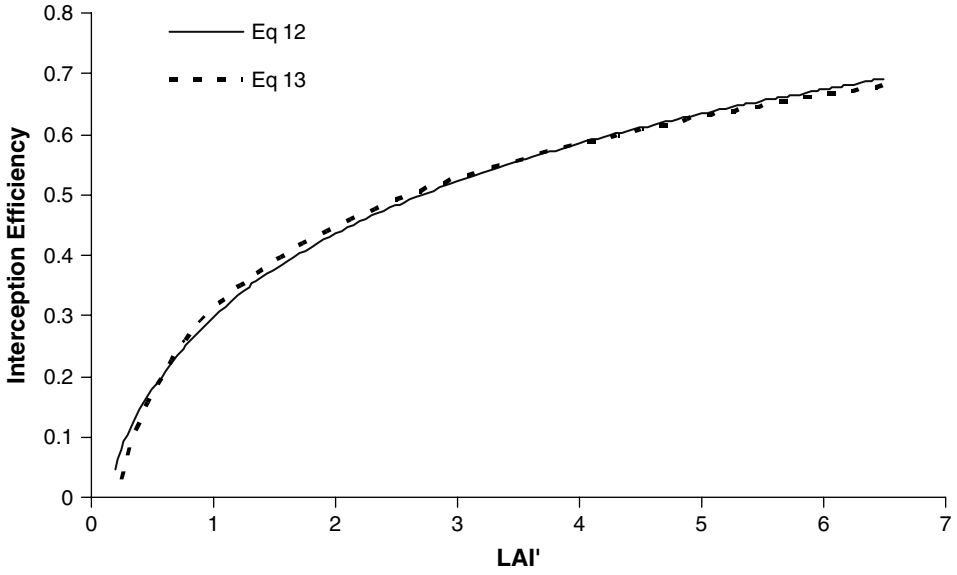


Figure 8. Modelled interception efficiency from the physically based calculation (Equation (12)) and the parametric calculation (Equation (13)) against leaf area index (winter effective)

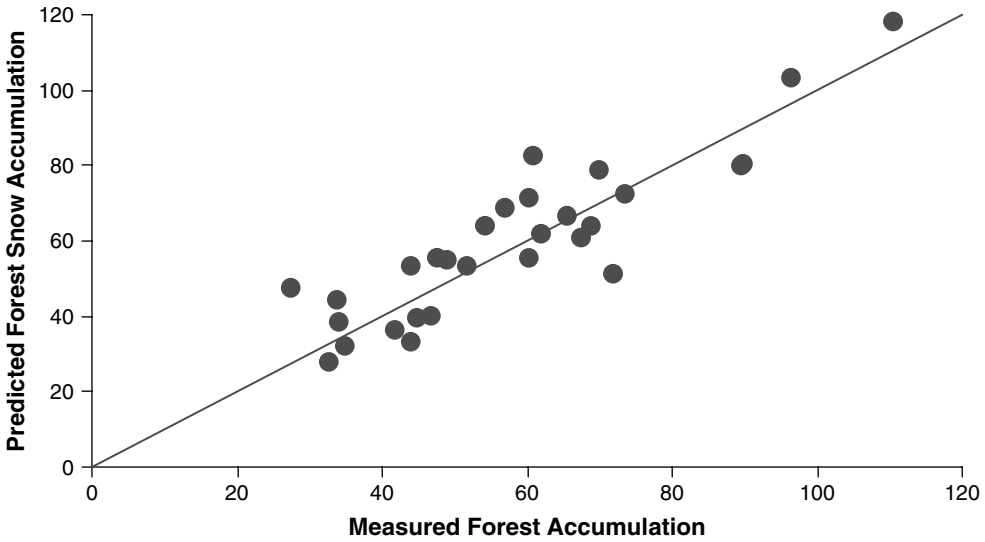


Figure 9. Performance of the parametric forest snow accumulation equation (Equations (14) and (15)), presuming that sublimation efficiency is 0·72; measured and modelled as points with a 1 : 1 line for comparison

Equation (14) has a mean difference with measurements of $-1{\cdot}24$ mm, standard deviation of difference of $9{\cdot}72$ mm and $R^2 = 0{\cdot}79$ (Fig. 9). Interestingly, assuming the sublimation efficiency is 0·72, then this equation and the modified Kuz'min equation (Equation (11)) are almost identical when Kuz'min's equation is placed in terms of LAI′ using the relationship between LAI′ and $C_c$ (Equation (10)). The two forms, parametric and modified Kuz'min, are then

$$S_f = S_c\{1 - [0{\cdot}144 \ln(\mathrm{LAI}') + 0{\cdot}223]\} \tag{15}$$

 

and

$$S_f = S_c\{1 - [0{\cdot}125 \ln(\mathrm{LAI}') + 0{\cdot}237]\} \tag{16}$$

respectively. 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 Equation (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 PAMF and of Kuz'min's (1960) recommendation from Russian experience suggest that if accumulation data are unavailable, then cumulative snowfall could be substituted in the previous analysis.

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, Equation (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 (Equations. (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.

To see if the stand-scale mean SWE predictive relationship can help describe within-stand variability, the average of the individual standard deviations for all stands StDev($\overline{\mathrm{SWE}}$) was taken and found to be 9·758 mm. The CV for an individual stand CV(SWE) was then estimated using Equation (15) as

$$\mathrm{CV(SWE)} = \frac{\mathrm{StDev}(\overline{\mathrm{SWE}})}{S_c\{1 - [0{\cdot}144 \ln(\mathrm{LAI}') + 0{\cdot}223]\}} \tag{17}$$

and is shown in Figure 10. The mean difference between measured and modelled CVs 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 predict accurately the statistical characteristics of snow accumulation within a specific stand.

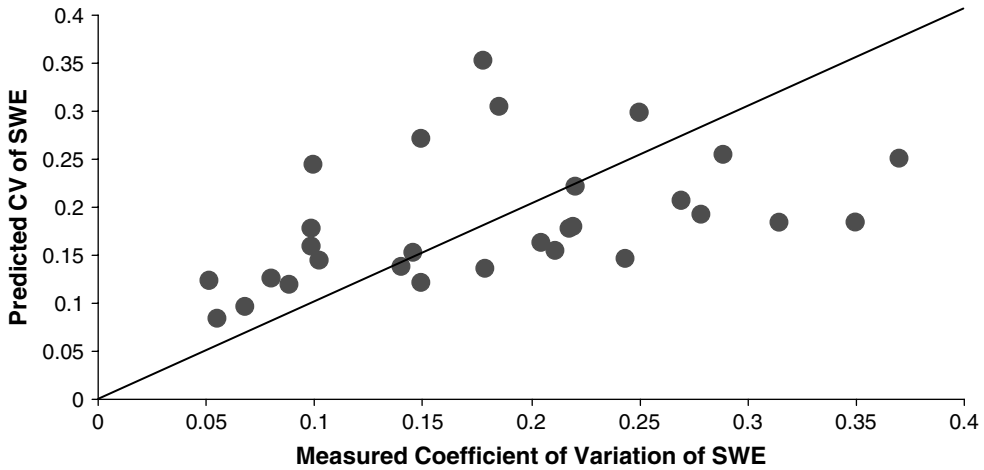


Figure 10. Predicted coefficient of variation of forest snow accumulation (Equation (17)) and measured values shown as points; the 1 : 1 line is for reference

 

## CONCLUSIONS

The within-stand variation of snow accumulation in a forest as described by the standard deviation of SWE is not associated with seasonal maximum snow accumulation in small clearings, seasonal snow interception or leaf area index. The CV 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 CV 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.

### REFERENCES

Faria DA. 1999. *Distributed energetics of boreal forest snowmelt*. Masters of Science Thesis, Division of Hydrology, Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Saskatoon, Canada.

Faria DA, Pomeroy JW, Essery RLH. 2000. Effect of covariance between ablation and snow water equivalent on depletion of snow-covered area in a forest. *Hydrological Processes* **14**: 2683–2695.

Golding DL, Swanson RH. 1978. Snow accumulation and melt in small forest openings in Alberta. *Canadian Journal of Forest Research* **8**: 380–388.

Golding DL, Swanson RH. 1986. Snow distribution patterns in clearings and adjacent forest. *Water Resources Research* **22**(13): 1931–1940.

Gower ST, Norman JM. 1991. Rapid estimation of leaf area index in conifer and broad-leaf plantations. *Ecology* **72**(5): 1896–1900.

Hedstrom NR. 1999. *Development and evaluation of a cold regions snow interception model*. Masters of Science Thesis, Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Saskatoon, Canada.

Hedstrom NR, Pomeroy JW. 1998. Measurements and modelling of snow interception in the boreal forest. *Hydrological Processes* **12**: 1611–1625.

Jeffrey WW. 1968. Snow hydrology in the forest environment. In *Snow Hydrology, Proceedings of a Workshop Seminar*. Canadian National Committee for the International Hydrological Decade. Queen's Printer: Ottawa; 1–19.

Kuz'min PP. 1960. *Formirovanie Snezhnogo Pokrova i Metody Opredeleniya Snegozapasov*. Gidrometeoizdat: Leningrad. (Published 1963 as *Snow Cover and Snow Reserves*. [English Translation by Israel Program for Scientific Translation, Jerusalem]. National Science Foundation: Washington, DC).

LI-COR Inc., 1990. LAI-2000 plant canopy analyser, technical information. LI-COR Inc.: Lincoln, NE.

Lundberg A, Calder I, Harding R. 1998. Evaporation of intercepted snow: measurements and modelling. *Journal of Hydrology* **206**: 151–163.

McKay GA, Gray DM. 1981. The distribution of snowcover. In *Handbook of Snow: Principles, Processes, Management and Use*, Gray DM, Male DH (eds). Pergamon Press: Toronto; 153–190.

Parviainen J, Pomeroy JW. 2000. Multiple-scale modelling of forest snow sublimation: initial findings. *Hydrological Processes* **14**: 2669–2681.

 

Pomeroy JW, Granger RJ. 1997. Sustainability of the western Canadian boreal forest under changing hydrological conditions—I—snow accumulation and ablation. In *Sustainability of Water Resources under Increasing Uncertainty*, Rosjberg D, Boutayeb N, Gustard A, Kundzewicz Z, Rasmussen P (eds). IAHS Publication No. 240. IAHS Press: Wallingford, UK; 237–242.

Pomeroy JW, Gray DM. 1995. *Snowcover accumulation, relocation and management*. National Hydrology Research Institute, Science Report No. 7, Saskatoon, Environment Canada; 144.

Pomeroy JW, Granger RJ, Pietroniro A, Elliot J, Toth B, Hedstrom NR. 1997. *Hydrological Pathways in the Prince Albert Model Forest*. NHRI Contribution Series No. CS-97004. National Hydrology Research Institute, Environment Canada: Saskatoon; 154.

Pomeroy JW, Parviainen J, Hedstrom NR, Gray DM. 1998a. Coupled modelling of forest snow interception and sublimation. *Hydrological Processes* **12**: 2317–2337.

Pomeroy JW, Gray DM, Shook KR, Toth B, Essery RLH, Pietroniro A, Hedstrom N. 1998b. An evaluation of snow accumulation and ablation processes for land surface modelling. *Hydrological Processes* **13**: 2339–2367.

Smith NJ, Chen JM, Black TA. 1993. Effects of clumping on estimates of stand leaf area index using the LI-COR LAI-2000. *Canadian Journal of Forest Research* **23**: 1940–1943.

Storck P, Lettenmaier DP. 1999. Predicting the effect of forest canopy on ground snow pack accumulation and ablation in maritime climates. *Proceedings of the Western Snow Conference* **67**: 1–12.

Swanson RH. 1988. The effect of *in situ* evaporation on perceived snow distribution in partially clear-cut forests. *Proceedings of the Western Snow Conference* **56**: 87–92.

Toews DA, Gluns DR. 1986. Snow accumulation and ablation on adjacent forested and clearcut sites in southeastern British Columbia. *Proceedings of the Western Snow Conference* **54**: 101–111.

Troendle CA, Leaf CF. 1980. *Hydrology. An approach to water resources evaluation of non-point silviculture sources*. US Environmental Protection Agency, Athens, GA; 1–173.

 