Characterizing Local Scale Snow Cover Using Point Measurements During the Winter Season

N. N. Neumann*1, C. Derksen2, C. Smith1 and B. Goodison2

1Environment Canada, 11 Innovation Boulevard
Saskatoon SK S7N 3H5

2Environment Canada, 4905 Dufferin Street
Toronto ON M3H 5T4

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ABSTRACT
Snow cover is spatially heterogeneous at the local scale because of microclimatic, topographic and vegetative effects on snow accumulation, redistribution and ablation – processes which vary between different environments. Automated, fixed point snow depth measurements are the norm at research as well as operational sites, and the ability of these single point measurements to characterize snow depth for the surrounding area is an important issue. In this study, data for three winter seasons (2002–03, 2003–04, 2004–05) from ten Boreal Ecosystem Research and Monitoring Sites (BERMS) in northern Saskatchewan were used to assess the relationships between local scale snow depth variability, ascertained from snow survey transects, and single point measurements made with sonic depth sensors.

Analysis of the snow surveys showed a wide range of depths at each site, with increased variability as winter progressed. Single, fixed-point measures of snow depth did not statistically represent the average snow depth at a site, even for relatively uniform snow covers. Consistent over- or under-representation of the landscape mean allowed the development of a “scaling equation” for each point measurement, improving confidence in the use of these data for modelling and climate variability studies. Where manual snow surveys may not be practical, the use of multiple automated point depth measurements may be adopted, and for the BERMS sites it was found that the minimum number of point measurements required to represent the landscape mean within 25% ranged from 1 to 44, depending on the degree of variability in snow depth associated with the landscape type, and the magnitude of the site mean depth. The relationships between point snow depth measurements and mean areal snow depth are important to consider both when utilizing historical point observations for climatological and hydrological analysis, and for decision-making with regards to snow depth observing networks.

RÉSUMÉ

L’analyse des relevés nivométriques a montré, à chaque site, une large gamme d’épaisseurs dont la variabilité augmente à mesure que l’hiver progresse. Les mesures uniques d’épaisseur de neige à des points fixes ne se sont pas avérées statistiquement représentatives de l’épaisseur moyenne de la neige à un site, même pour des couvertures de neige assez uniformes. La constance de la sous-représentation ou de la surreprésentation de la moyenne du paysage a permis d’établir une « équation d’ajustement » pour chaque mesure ponctuelle et d’augmenter la confiance dans l’utilisation de ces données pour la modélisation et les études sur la variabilité climatique. Là où des relevés nivométriques sont difficilement réalisables, il est possible d’utiliser plusieurs mesures ponctuelles automatisées et on a trouvé, pour les sites du BERMS, que le nombre minimum de mesures ponctuelles nécessaires pour représenter la moyenne du paysage avec une précision de ±25 % variait de 1 à 44, selon le degré de variabilité de l’épaisseur de neige associé au type de terrain et selon la valeur de l’épaisseur moyenne au site. Il est important de prendre en considération les relations entre les mesures ponctuelles d’épaisseur de la neige et l’épaisseur moyenne dans la région avoisinante lorsqu’on utilise des observations ponctuelles historiques pour des analyses climatologiques et hydrologiques ainsi que pour planifier les réseaux d’observation d’épaisseur de la neige.

*Corresponding author’s e-mail: natasha.neumann@ubc.ca; current affiliation – Chemistry, Earth and Environmental Sciences, University of British Columbia – Okanagan, 3333 University Way, Kelowna BC V1V 1V7

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1 Introduction
The conventional snow depth observing network in Canada is comprised of point values from either manual ruler measurements or automated sonic ranging snow depth instruments. Although long snow surveys are required in many environments to represent snow distribution adequately, such surveys are labour intensive and expensive to conduct. As a result, few operational snow survey courses exist in Canada and the network has steadily eroded over the past twenty-five years. Given the relative paucity of operational snow course sites for snow water equivalent (SWE) measurement, the snow depth network provides the most comprehensive in situ perspective on terrestrial snow cover across Canada.

Daily snow depth measurements began in Canada in 1941 at the principal meteorological observing stations of the Meteorological Service of Canada (MSC), with the stated purpose of collecting observations of the mean depth of snow on the ground in exposed areas (Potter, 1965). The majority of these sites were located near airports for easy site access and proximity to populated areas. The limitations of these single point measurements in adequately representing snow depth for the surrounding area have been questioned but not explored in detail (Brown and Braaten, 1998; Brown and Goodison, 1993, 1996; Schmidlin, 1989, 1990; Chang et al., 2005). The cost in terms of equipment, data management and personnel time required to expand the existing network to include regular snow surveys is prohibitive, and may not be necessary if a relationship can be found between the station point measurements and the mean snow depth of the surrounding landscape. Attempts have been made to estimate local snow conditions based on climatological station measurements of snowfall; the findings of McKay (1964) indicated that very exposed Prairie locations retained ~55% of the accumulated snow measured at nearby climatological stations, partly wooded areas retained ~65%, and forested areas could retain 100% or more (this was attributed to elevation differences relative to the station, but gauge undercatch or localized drifting where the surveys were close to the tree margin may also have contributed).

Snowcover measurement for research purposes faces similar challenges. Sometimes located in remote areas, these stations are automated and may only be visited occasionally for general servicing. Ten Boreal Ecosystem Research and Monitoring Sites (BERMS) in northern Saskatchewan (Fig. 1) are examples of relatively inaccessible stations which are visited irregularly. Fixed point measurements of snow depth are therefore relied upon to represent average snow conditions during accumulation, metamorphism and ablation in that landscape, and are an important component of the BERMS data archive. For application purposes, a need was identified for an assessment of the spatial variability in snow distribution within and among the different boreal landscapes represented in the BERMS study area, and an evaluation of the relationships between landscape means and existing fixed point measurements. This study will address these questions for the BERMS sites using snow survey records from the winter seasons of 2002–03, 2003–04 and 2004–05, and will also address questions about instrumentation – specifically, what would be the minimum number of fixed point measurements needed to represent the landscape mean at each research site adequately?

2 Data and site descriptions
The BERMS sites in northern Saskatchewan represent a broad spectrum of landscape types characteristic of the southern boreal forest (Amiro et al., 2005). Three mature (~100 yrs) forest stands of aspen (OA), black spruce (OBS) and jack pine (OJP) are included in the network of climatological stations, as well as a chronosequence of three jack pine stands that were harvested and scarified in 1975 (H75), 1994 (H94) and 2002 (H02), three mixed-wood stands regenerating after fires in 1977 (F77), 1989 (F89) and 1998 (F98), and a patterned fen (FEN) (see Fig. 1). These sites differ widely in stand composition, canopy characteristics, degree of exposure to wind, and ground cover (Table 1), but their close geographic proximity means that they are generally under the influence of the same synoptic regimes. BERMS is a particularly important component of the Fluxnet-Canada network, and meteorological measurements have been ongoing at the mature sites since the mid-1990s.

None of the mature forest stands represented by the BERMS network was considered a closed canopy; snow fell unobstructed through gaps in the canopy at all three sites (OA, OJP and OBS). Canopy interception, causing wells adjacent to tree trunks, was significant at the OBS site, was a minor process at the OJP site, and was not observed at the OA site. The oldest sites had the tallest and largest diameter trees, with mean tree heights of 8, 13 and 21 m at the OBS, OJP and OA sites, respectively. The mixed woods forests at F77 and F89 had mean tree heights of 6 and 4 m, respectively, and were considered open stands where the view of the sky was somewhat obscured by the forest canopy. The monoculture stand of jack pine at H75 was also considered an open canopy, with mean tree height and diameter similar to the older fire sites of F77 and F89. The relatively young sites of H94 and F98 had sparse tree stands, with the gap between trees being greater than the mean tree heights of 2.5 and 1 m, respectively. Ground cover varied between sites and was largely determined by soil type. The effect of ground cover on snow accumulation processes was only relevant at the open sites affected by drifting, H02 and FEN, but even at these sites the groundcover influence was largely overshadowed by local surface roughness elements. At H02, the horizontal scale of elevation change was greater than 100 m, resulting in limited drifting, but the presence of slag debris at this site created a very rough surface. A ridge and swale pattern gave the FEN site a horizontal elevation change at the microscale, which in combination with the presence of shrubs on the ridges resulted in a very rough surface and considerable drifting. At the H94 site the surface roughness was increased by the sparsely distributed young jack pine trees. Tree wells were also observed at the H94 site.
Fig. 1 Location of BERMS research sites (indicated by stars) in the southern portion of the boreal forest, Saskatchewan, Canada (see Table 1 for site names and descriptions). The shaded region in the overview map indicates the extent of the southern boreal forest.
Standard in the suite of climatological measurements at the BERMS sites is a minimum of one fixed point snow depth, measured using a Campbell Scientific sonic ranging instrument (model SR50). The SR50 uses the return speed of an ultrasonic pulse to determine the distance to a reflecting surface (corrected for air temperature), and common applications are monitoring changes in snow depth and surface water levels (Campbell Scientific, 2003). The accuracy of measurements using the SR50 depends on the sturdiness of the mounting system and the accuracy of the associated temperature measurement; under proper operating conditions the sensor accuracy is ±1 cm or 0.4% of total distance to target, whichever is greater, at a resolution of 0.1 mm (Campbell Scientific, 2003). Thus, measurement error increases with greater distance from the reflecting surface (that is, when the instrument height increases), and an optimal distance of approximately 0.5 m from the reflecting surface is recommended. Measurements are also affected by environmental conditions, the most important being false echoes from blowing or falling snow and from vegetation extruding from the snowpack. False readings due to snow crystals are generally transient and can be filtered out using standard data assessment procedures, while the effects of vegetation are removed through proper site management. Periodic independent manual measurements of snow depth beneath the sensors are essential for calibration and correction procedures.

At both the OA and OJP sites, two SR50s were installed to monitor changes in snow depth in a clearing and under the canopy (Table 2), while at the OBS site one clearing and three subcanopy SR50s were installed (the clearing SR50 was decommissioned in 2002). At the remaining sites, single sensors were installed in locations typical of that landscape. At the H94 site a temporary grid of nine sensors was also established for the 2002–03 winter season (covering an area of approximately 10 m × 10 m), to study the effects of drifting in this sparse stand. Automated snow depth measurements were averaged over 30-min intervals and archived for all sites, and these data were used to determine a daily median snow depth value for each site.

In order to gain information on the spatial and temporal variability of snow distribution in these boreal landscapes, monthly snow depth and water equivalent surveys were conducted along fixed transects during the winters of 2002–03, 2003–04 and 2004–05. The snowfall normal for the Prince Albert airport (located in the southern portion of the study area, Fig. 1) is 111.3 cm. Slightly lower than normal snowfall was measured during 2002–03 (92 cm), with slightly greater than normal snowfall during 2004–05 (139 cm) and near-normal snowfall during 2003–04 (111 cm). The study period thus represents a range of natural snowfall conditions.

Transects approximately 100 m in length, were established at all sites. Five SWE sampling points were evenly distributed along the length of these transects and marked with stakes. Between each SWE measurement ten depth measurements were made, which when combined with the five depth measurements at the SWE stakes provided forty-five depth samples. Surveys were conducted at mid-month during the accumulation period. The data reported on in this paper cover the accumulation period only (that is, beginning in November or December and ending with the mid-March surveys).
3 Results

a Snow Distribution

Shook (1995) found that the minimum length of a snow survey transect could be determined by assessing the change in the coefficient of variation of snow depth with increasing transect length (the coefficient of variation is a measure of the spread of data relative to its mean, calculated as the standard deviation divided by the mean). For Prairie environments, Shook (1995) found that snow surveys had to be between 50 and 100 m to represent the local variability adequately. At all the BERMS sites, there was little change in the coefficient of variation of the surveyed snow depth as the transects approached 75 to 90 m, indicating that the 100 m snow survey transects were of sufficient length to represent the variability in snow depth for each landcover type (see insets of Figs 4–6 for examples from the H02, OBS and OA sites).

Goodison (1981) found that the differences in snow depth and water content between land use classes in southern Ontario increased as the season progressed, and he attributed this to location-specific processes of accumulation and retention. Similar results were found at the BERMS sites (Fig. 2). For 2002–03 and 2003–04, all sites showed similar mean depths in mid-November, but began to diverge by the December survey (there were no November snow surveys during the 2004–05 season). During 2002–03, the two open sites, H02 and FEN, showed decreases in depth in the earliest part of the season while there were increases at other sites, attributable to wind removal and melt events which were either less likely to occur or had a smaller impact at the vegetated sites. Of the three mature sites, the largest accumulations occurred at the OBS site, especially before February, while the shallowest depths occurred at the OA site; however, by mid-March there was little difference between the three mature sites during 2002–03 and 2003–04. Differences between the mature sites were maintained throughout the 2004–05 season. During 2003–04 there was a general decline in mean depth at most sites after the February survey, indicating settling of the pack as temperatures began to rise in the region. This pattern was repeated at most sites during 2004–05.

The shallowest depths occurring during the three study periods were measured at the H02 site where consistent winter winds and a rough surface resulted in considerable drifting; the end-of-season snowpack in 2003 was extremely dense, so the shallow depths did not indicate low snow water content. Deeper snow depths were measured at the other post-harvest sites throughout the year relative to the recent clearcut. During 2002–03, the youngest fire-disturbed site, F98, had larger mean depths than at the older site, F89, where there was greater interception by the mixed-wood canopy, but during 2003–04 and 2004–05 the mean snowpacks in these two stands were similar and the deepest snow was measured at the F77 site. The most snow accumulated at the FEN site by the end of the 2002–03 winter season despite having one of the shallowest mean depths in December, while during 2003–04, the F77 site had a slightly greater accumulation. As mentioned previously, the FEN site is a patterned wetland with considerable microtopography and low-lying vegetation, which creates a very rough surface and allows for the accumulation of redistributed snow. During 2004–05, however, there was standing water in the FEN site which effectively reduced the surface roughness and resulted in one of the shallowest snowpacks at the end of the year.

Snow distribution patterns in any landscape are determined by precipitation inputs, interception by overlying vegetation, wind exposure, microtopography, proximity to vegetation and vegetation characteristics. Even in open low-wind environments there can be considerable local variability in snow depth and water content. Goodison (1979) showed that amongst various agricultural land uses in southern Ontario, the most variable snow cover was found in areas with short grass vegetation. At airport sites in New York and Ohio which are relatively free of drifting snow, Schmidlin et al. (1995) found that while the variability in SWE measurements

<table>
<thead>
<tr>
<th>Site</th>
<th>Sensor Location</th>
<th>Correlation Coefficient (r)</th>
<th>Scaling Equation</th>
<th>RMS Error (cm)</th>
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<tr>
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<td>0.83</td>
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<tr>
<td>OJP</td>
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<td>0.84</td>
<td>1.95</td>
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<tr>
<td></td>
<td>Subcanopy</td>
<td></td>
<td>1.12</td>
<td>3.35</td>
</tr>
<tr>
<td>OBS</td>
<td>Clearing</td>
<td>0.46</td>
<td>0.24</td>
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<td></td>
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<td>0.85</td>
<td>2.05</td>
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<td>0.95</td>
<td>7.62</td>
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</table>

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increased with mean SWE, the standard deviation generally increased in proportion, and that the natural microscale variability in SWE was within approximately 25% of the mean. The coefficient of variation was approximately constant and near 0.125. (Goodison (1981) also reported consistent values for different land use classes.) In Prairie landscapes of fallow, stubble and pasture fields, Pomeroy et al. (1998) reported coefficients of variation of 0.3 to 0.5 SWE, while in the boreal forest, values between 0.07 and 0.14 were reported. At the vegetated BERMS sites, the coefficient of variation for the measured snow depths ranged from 0.12 to 0.22, while at both open sites the coefficient of variation was 0.17. The best fit line through all data followed a value of 0.16 for the coefficient of variation (Fig. 3); as expected the fit was not as good as that shown by Schmidlin et al. (1995), who used SWE measurements in environments which experienced low rates of drifting. The coefficient of variation for snow depth may be a useful statistic for representing subgrid-scale variability in snowmelt models. As noted by Liston (1999), while mean depths are expected to change from year to year, the patterns of snow distribution are generally controlled by climate (e.g., prevailing winds, predominant synoptic patterns), topography.

Fig. 2 Evolution of mean snow depth from BERMS snow surveys, winters of 2002–03, 2003–04 and 2004–05 (measurements were not made at F77 during 2002–03, nor at any site during November 2004).
(e.g., orography, drift patterns) and local vegetation (e.g., interception patterns) and thus are often consistent interannually.

b Scaling From Point Measurements to Landscape Means
One goal of this study was to relate the fixed point snow depth measurements at a site to the average snow depth of a larger area. The field approach was to perform landcover-stratified snow surveys, that is, surveys in parcels of land of relatively homogeneous vegetation and topographic structure (here called a landscape). Within a landscape, the transect was laid out relatively randomly, except where ecological integrity and the presence of other instrumentation limited access. The transects themselves represented a cross-section approximately 100 m in length, while the landscapes might be much larger. The spatial scale of the landscape data used in this study was therefore at least the length of a transect, though in reality somewhat larger. Most importantly, both the point and the transect measurements were affected by the same snow accumulation controls, including both local scale processes such as redistribution and interception, and regional processes such as precipitation.

The advantages of summarizing snow surveys as in Fig. 2 are the identification of general trends and the ability to compare the snowpack evolution between sites. To provide a different perspective for interpreting these average values, histograms of snow depth frequency were used to show the range of snow depth values at a site and how snow distribution changed over time. Plotting the frequency histograms of each snow depth transect with the SR50 point measurements also demonstrated consistent over- or under-representation of the survey mean by the fixed point measurements (selected sites for 2003–04 shown in Figs 4–6). Under-representation generally occurred at the H02 and H94 sites, although the SR50 over-represented the mean at H02 by the end of the accumulation season in both 2003 and 2004 (Fig. 4). This may be due to preferential and early melt along the snow
transect relative to the sensor location. During the winter of 2001–02 an experimental $3 \times 3$ grid of SR50s was established at the H94 site, approximately 75 m from the station SR50 in a more open and uneven area of the same stand. Like the main site sensor, the SR50 grid average consistently underestimated the survey mean, and only some of the deepest grid points fell within the snow survey histogram. The fixed point snow depth measurements reasonably represented the mean survey depth at the H75 site, though showing increased deviation with increased snow depth. At the OJP site, point snow depth measurements made in a clearing generally fell in the right-hand tail of the histogram, especially late in the season, while subcanopy measurements were always shallower and fell in the left-hand tail. The subcanopy depth was not represented in the histogram for January 2002. At the OBS site the three subcanopy fixed point measurements showed a wide range of depths, surrounding the mean (Fig. 5). One clearing SR50 (Subcanopy A) consistently underestimated the survey mean and occasionally did not fall in the histogram. An SR50 placed in a clearing was the original source of depth measurements at this site, and it was decommissioned in 2002. At the OA site, the depth measurements from the clearing and subcanopy sensors generally fell on opposite sides of the histogram means (Fig. 6), suggesting that the mean of the two sensors would provide an adequate estimate of the mean snow depth in this aspen stand. The fixed point depth measurements at the F98 and F89 sites slightly underestimated the landscape average. At the F77 site, where measurements commenced in summer 2003, the SR50 represented the snow survey mean quite well. Fixed point depth measurements for the FEN site were unavailable until November 2003; the fixed point depth measurements at this site drastically underestimated the mean survey depth.

The fixed point snow depth measurements, then, had a limited capability to represent the landscape mean (as estimated from the snow depth transect), but there were indications of consistent under- or over-representation by each instrument. High correlation coefficient values (0.86–0.99) were found when a simple linear relationship was applied between the fixed point and landscape mean depths (Table 2). The exception was the clearing SR50 at the OBS site, where shallow depth samples were unavailable and no relationship could be found for the heavily clustered dataset. The strong relationships were expected, since the processes of winter snow accumulation affect the entire landscape. Even where a sensor significantly under- or over-represented the landscape mean (e.g., the OBS Subcanopy A), the fixed point measurement was still strongly related to the survey mean because the
direction of bias was consistent. The linear relationships between the point and landscape mean depths can be used to scale the point depth measurements to the landscape level (Fig. 7, Table 2). These “scaling equations” were developed using multi-year data from a range of sub-, near- and above normal snowfall seasons, so the scaling factors are expected to be relatively temporally stable. The root mean square (RMS) errors ranged from 1.6 to 7.3 cm (excluding the OBS Clearing SR50), representing between 3 and 14% of the peak depth measured at the BERMS sites.

c Sample Size Requirements
For many locations in the Canadian snow depth network, and for most remote field sites, snow surveys are not conducted in a regular fashion, are not in representative landcover types, or are not of sufficient length to provide an adequate dataset for the calculation of scaling factors. Regular personnel visits may be impractical, and snow surveys are relatively labour intensive. A choice may be made to increase the number of automated snow depth sensors to estimate the landscape mean snow depth better. Given the importance of local vegetation and microtopographical variability, how many instruments would be required to represent mean snow depth in a given landscape? Logistical considerations generally limit the number of fixed-point sensors that can be practically installed at a site, such as logger and power requirements and data storage and transmission capabilities, so an assessment of the efficacy of multiple point depth measurements is required to make informed management decisions. It is important to note that this assessment will vary by location, or at least by landscape type; the following analysis was performed for the landscape types represented by the BERMS network, and are thus only applicable to these types of biogeoclimatic zones.

The snow surveys were assumed to represent the landscape mean depth, and the minimum sample sizes needed to represent this mean within 10 to 50% were calculated for each site. The Type I error ($\alpha$) which described the risk of concluding that a difference existed between datasets when one did not occur, was set to 0.05, while the Type II error ($\beta$) which described the failure to conclude that a difference existed when one actually did was set to 0.10 (Hicks, 1973). These confidence limits were considered to be quite stringent (95%). The calculated minimum sample size ($n$) is based on both the mean ($\bar{\chi}$) and the standard deviation ($\sigma$) of the snow surveys following

$$n = \left( \frac{2.927\sigma}{\bar{\chi}V} \right)^2$$  (1)
where V is the accepted variability (0.10–0.50) (Hicks, 1973). Because the ranges in snow depth were generally smaller during November and December than later in the winter at most sites (histograms for selected sites shown in Figs 4–6), the dataset was separated to reflect these differences; an early accumulation season (November and December) was distinguished from the peak period (January to March). As expected, the results showed that using more than one sample point would improve estimates of the landscape mean, but that the actual number varied between sites (Fig. 8). The minimum number of fixed point sensors required to represent the mean within 25% ranged from 1 to 44, though for most sites during peak snow accumulation five would have adequately represented the mean within 25%. During the early accumulation season, more samples would be necessary for confidence that the depths being measured represented the landscape average. Single fixed point snow depth measurements during the early part of the season, when snow is the shallowest, therefore have the most potential error. At most sites, the curves in Fig. 8 shifted toward smaller sample sizes later in the season, but at the F98 and F89 sites the opposite was true, though the shift was small. The early season curves for these sites were based on a few available snow surveys, and the addition of more samples in the future would improve the relationships for the early winter period. From Eq. (1), the coefficient of variation at a site can be used to estimate the minimum sample size required for the desired confidence level (Fig. 8 inset). While there is some natural variation from the best-fit lines, the high $R^2$ value (0.94) of the theoretical lines suggests that these curves can be used in other landscapes with similar snow accumulation processes.

4 Discussion and conclusions

This study demonstrated the valuable information on snow distribution patterns in the boreal landscape that can be obtained from simple snow depth surveys, and the importance of placing fixed-point measurements in the context of the local landscape variability.

Mean snow depth values at the BERMS sites for the winters of 2002–03, 2003–04 and 2004–05 were compared and, as expected, the shallowest depths were measured at the most open, windblown site (H02). Somewhat surprisingly, the deepest snow depths were measured at the other open site, FEN, and also at the mixed-wood F77 site, except in 2004–05 when standing water at the FEN site reduced the effective surface roughness. The ranges in snow depth from snow survey transects were smaller during the early part of the accumulation season but began to increase by January (the range in depths became greater as the mean depth increased). All histograms showed similarities to normal distributions, although bi- and multi-modal curves also developed depending on the accumulation processes occurring at each site. Further analysis showed that the standard deviation in depth increased in proportion to the mean, with an estimated coefficient of
variation of 0.16 (range of 0.12 to 0.22) for all BERMS landscapes.

Where snow survey data may be unavailable or impractical to acquire, multiple sensors may be used to improve the representation of the landscape mean. There is a need, however, for proper assessment of the benefits of using multiple depth sensors at a single site. Even at the topographically and vegetatively uniform BERMS sites the minimum number of sensors required to estimate the landscape mean within 25% ranged from 1 to 44, with an average of 5. A greater number of sensors were required early in the accumulation season, when mean depths were small but there was considerable spatial variability locally (also found by Chang et al. (2005)). The sample size requirements for locations with more topographic variability or in different biogeoclimatic zones would be expected to be considerably different from those in northern Saskatchewan. In a study of different forest management units in the southern interior of British Columbia, Spittlehouse and Winkler (1996) found that even 100 samples were not adequate to detect a 10% difference in SWE between two forest stands. They found that ten samples were sufficient to detect differences greater than 60 mm water equivalent between sites. In the high snowfall region of their study this represented 30 to 50% of the peak accumulated snow. In the northern Great Plains region of the United States, Chang et al. (2005) concluded that more than ten point measurements of snow depth would be needed within a passive microwave grid cell of 25 km × 25 km in order to attain an accuracy of 5 cm (10 to >50% depending on annual mean depth). The larger number of samples required in this area of relatively uniform snowfields is not unexpected since the 625 km² grid cells can cover a broad range of landcover types and their interfaces, including different crops (and their winter stubble), rangeland, ditches and gullies. Passive microwave sensors have limited application in areas of deep snowpacks (where depth exceeds ~1 m), and the impact of small but possibly widespread linear features of deep snow such as gullies and drifts on the passive microwave signal is unknown.
At many of the BERMS research sites in northern Saskatchewan the arbitrarily located, fixed point snow depth measurements did not approximate the average landscape depth as determined from the snow surveys. There were strong relationships between the point measurements and the survey means, indicating a systematic bias in the point measurements (Chang et al., 2005), and location-specific scaling equations were determined. These factors should be
employed in order to take full advantage of the BERMS point depth record in future hydrological and surface processes modelling, and snow distribution studies. More generally, this analysis stressed the importance of assessing fixed point measurements in the context of landscape level snow distribution patterns. Users of the national snow depth archive in Canada, be it for modelling purposes or for comparison with satellite-derived products, should consider the efficacy of these points in representing a larger area or landscape. The archive provides an important historical resource on the condition of the terrestrial snow pack in Canada, and informed use of the dataset is important. The results from the BERMS dataset have provided a perspective on snow depth variability in the southern boreal forest of Saskatchewan.

Scaling of fixed point snow depth data will allow for better use of historical automated depth measurements in comparisons with airborne or satellite-derived measurements. Proper care in siting and ground preparation is essential for quality automated ground-based measurements, but there must also be an understanding of the spatial context for proper application of these data. Satellite-derived data provide a perspective on snow cover across vast high latitude regions where conventional measurements are sparse or non-existent, but surface observations are also required to validate the satellite-retrieval algorithms in the same areas. There is a need for historical data to improve this manuscript.

References


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