

Variations in Snow Accumulation in the Southern Boreal Forest Preliminary Analysis of 1993–1994 and 1994–1995 Snow Measurements

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ABSTRACT

Snow measurements were made during the 1993–1994 and 1994–1995 snow cover seasons in the southern study areas of the Boreal Ecosystem Atmosphere Study (BOREAS) to examine spatial distribution and snow accumulation on the ground. Snow water equivalent (SWE) measured along snow courses in conifer stands was less than SWE measured in an open area and an aspen stand during the accumulation period, an indication of the effect of sublimation of intercepted snow. Differences increased with time to maximum accumulation. A weighted combination of snow course and under-crown measurements was used to estimate SWE for the stands. Differences in total accumulation between the two years were large; 1993–1994 had significantly less snow than 1994–1995. The black spruce stand had 36 mm water equivalent less than the open area in both years. The mature jack pine stand had 28 mm and 27 mm less than the open area in both years, while the young jack pine had 22 mm less the first year and 9 mm less the second. There was essentially no difference in accumulation between the open area and the snow course in the aspen stand in each of the two years.

Key Words: Snow cover; snow water equivalent; interception; canopy.

INTRODUCTION

Trees intercept falling snow and through sublimation of the intercepted load, unloading and melt, cause it to become unevenly distributed across the forest floor. Since Horton (1919), interception

potential has been thought to be proportional to canopy cover, but investigations on the disposition of intercepted snow have reached different conclusions depending on experimental conditions. As described by Lundberg and Halldin (1994), earlier studies stressed the importance of redistribution of snow from the canopy to the forest floor to explain differences between snow cover amounts in the forest compared with nearby clearings (Hoover and Leaf, 1965; Gary, 1974, e.g.). Later the differences were found to be due to sublimation of intercepted snow (Schmidt and Troendle, 1989). Conifers catch the falling snow in branches and needles where it has greater surface area exposed to the atmosphere and radiation so it may later be sublimated and never added to the forest snowpack (Pomeroy and Gray, 1995). Recent studies have focused on the problem of estimating sublimation from conifer canopies and found that it can account for area-averaged differences in snow water equivalent (SWE) between forest stands and clearings (Calder, 1985; Schmidt, 1991; Pomeroy et al., 1998).

BACKGROUND

The boreal region is a mix of forests, lakes, bogs and peatlands. The forests consist primarily of evergreen conifer species. Snow plays a major role in the annual water budget and can cover the land surface for more than half the year (Larsen, 1980). Interest in the boreal forest has increased due to evidence of feedback between boreal land surface biophysics, global weather and climate, and the global carbon cycle (e.g., Bonan et al., 1995). Recent reports show an increase in vegetation greening over the northern

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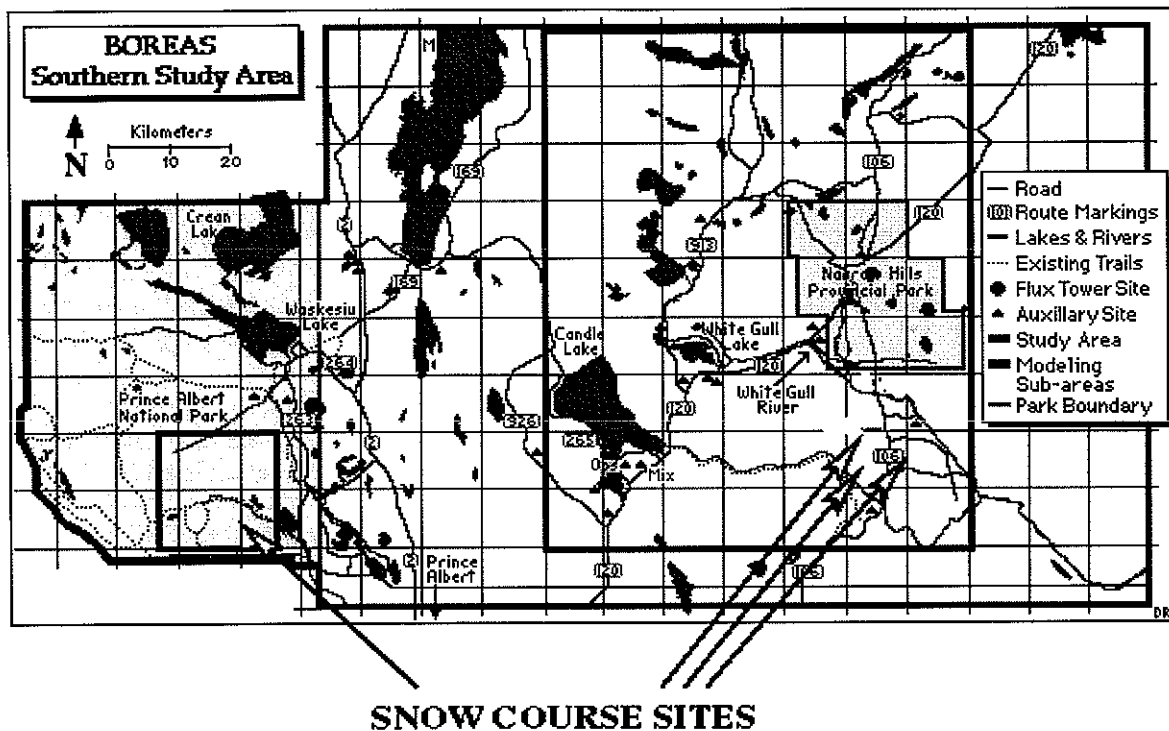


Figure 1. Location of study area, sites of snow courses and snow measurements.

high latitudes over the last several years as measured by satellite sensors (Myneni et al., 1997). During a similar time period, annual snow covered area decreased by about 12 percent over land area in the Northern Hemisphere and by almost 20 percent during the spring time period (Groisman et al., 1994). There appear differences however between snow cover trends in Eurasia and North America, decreases being significantly greater in Eurasia (Brown, 1997). It was timely that the Boreal Ecosystem-Atmosphere Study (BOREAS) was already planned and initiated to focus on improving our understanding of energy, water and trace gas exchanges between the atmosphere and biosphere of the boreal forest (Sellers et al., 1995).

This study examined the accumulation in space and time of snow depth and water equivalent in the southern boreal forest of central Canada, as measured both by fixed snow survey lines and by specially designed surveys for field campaigns. These measurements and this study support development of improved physical and biophysical models of the land-atmosphere interaction and support algorithms for estimating snow and boreal forest properties from satellite measurements (Goodison et al., 1987; Chang et al., 1997, e.g.). The snow course data used in this

study were collected as part of the field program designed, implemented and support by the HYD-4 team of the BOREAS project.

Some distributed models of snow processes and melt have been initiated at the time of maximum snow accumulation, avoiding complexities due to redistribution of snow by wind or interception by vegetation (e.g., Davis et al. 1995; Harrington et al., 1995). This requires maps of initial snow cover properties and maps as melt progresses for model validation. This paper assessed the feasibility for constructing such maps from available spatial data and the snow survey measurements.

METHODS

Standard snow survey measurements and special under-tree snow measurements were made at regular time intervals throughout the winter season at the same locations in different forest types and an open area. The general test region is shown in Figure 1. The time series of measurements were compared according to land cover category, focusing on the snow accumulation period. In addition, intensive snow surveys carried out random measurements near peak accumulation to confirm the representativeness

of the standard snow survey measurements. All of these measurements allowed for some general conclusions to be made about the magnitude of the effects of forest canopy on interception loss.

Standard snow survey

Snow surveys were conducted at snow courses throughout the 1993–1994 and 1994–1995 snow seasons. The measurements provided a seasonal time series of snow depth and snow water equivalent in the BOREAS study areas. The snow courses were specifically established to sample snow accumulation and ablation in the important land cover types of the BOREAS Southern Study Area (SSA). Four snow courses were located on different land cover types in and near the White Gull River watershed in the BOREAS SSA, near Prince Albert, Saskatchewan, Canada (Fig. 1). A fifth snow course was located in a mature aspen stand. This site is about 120 km to the west-southwest of the other sites, but had similar snowfall. The snow course measurements were carried out on or near the first and fifteenth of each month throughout the winter season beginning with the first snow cover.

The SWE and snow depth were measured at each of five marked sampling points, located 100 m apart along each snow course. In addition, a graduated ruler was used to measure 10 depths with equal spacing between each sampling point resulting in 45 depth measurements along the snow course. Surveyors used the ESC30 metric snow sampler, a large diameter sampler (cutter area of 30 cm²), to measure SWE. The sampler consists of a single plastic tube approximately a metre in length with a stainless steel cutter. A complete description of the sampler along with plans, specifications and an assessment of errors and accuracy can be found in Farnes et al. (1982). The snow sampling procedure entails the surveyor driving the sampler to the ground, removing a core (usually with a plug of soil or moss), then weighing the net mass of the snow (read as SWE) using a specially designed spring scale for the ESC30. The soil or moss plug is removed before weighing. The density of the snow at each point is determined by dividing the SWE by the depth of the snow; mean density is obtained using the mean SWE and mean depth.

Snow depth and SWE measurements were also made under two randomly selected tree crowns during the conduct of each snow course. Snow depths were measured at 5 locations with equal spacing from the tree trunk and to the edge of the tree crown. Snow depth and SWE were measured using the ESC30

sampler midway between the tree trunk and crown edge. Typically the spacing of snow depth measurements under the canopy ranged from 25–45 cm in the aspen and jack pine and 15–25 cm under the narrower canopies of the black spruce.

Other snow measurements

Periodically, during the BOREAS focused field campaigns (FFC) snow on other land cover types was measured. The first FFC occurred during February, 1994. One set of these measurements were carried out in a mature jack pine stand about 20 km north of the snow course line in the mature jack pine stand. The mean vertical snow density was measured at incremental distance from tree trunks two ways: by using the ESC30 sampler and by measuring profiles of density from snow pits excavated radially away from tree trunks. In the snow pits density was measured using a small cutter with a 100cc volume. Samples were cut horizontally from the snow layers exposed by the pit wall in a vertical sequence. Each sample was vertically adjacent to the others. An electronic top loading balance was used to determine the net mass of the snow sample, which when divided by the volume provided the density. Hence, the average snow density determined from the pits used the average of a vertical series of measurements, while the ESC30 allows us to estimate an average density from the entire column of snow. Random measurements of snow depth were made with graduated rulers at several locations in each area. Depths from tree trunks to crown edges were also measured, in similar fashion to the standard snow surveys. These data were used for general comparison with the more regular measurements from the standard snow courses.

Forest cover characteristics

Forest species, tree height and canopy density classes were determined from data compiled by BOREAS staff at NASA Goddard Space Flight Center in Greenbelt, Maryland, as categorical data layers expressed as maps. These maps were derived from forest cover data from the Saskatchewan Environment and Resource Management, Forestry Branch—Resource Unit (Lindemas, 1985). Snow cover was measured in three different forest types in the eastern part of the test area (Fig. 1): 1) mature black spruce (*Picea mariana*); 2) mature jack pine (*Pinus banksiana*); and 3) young jack pine. The mature black spruce and mature jack pine stands had a canopy density class of 55–80 percent and tree height classes of 7.5–12.5 m and 12.5–17.5 m,

respectively. The young jack pine site was regenerated and thinned, with a canopy density class of 30–55 percent and a tree height class of 2.5–7.5 m. Saplings in the open area were less than 0.2 m high and widely spaced. A fifth course was located about 120 km to the west-southwest of the other sites near Namekus Lake in Prince Albert National Park (Fig. 1). Examination of the precipitation records of this site and one near the three conifer courses showed similar accumulated snowfall. The mature aspen (*Populus tremuloides*) stand had a tree height class 17.5–22.5 m and canopy density class 55–80 percent.

In the conifer stands we also measured canopy density along the snow survey courses using a forest densiometer (Strickler, 1959). The readings were corrected according to Ganey and Block (1994) to effective planimetric canopy density. The mean canopy density we measured along the snow course in the black spruce stand was 79 percent. In the mature jack pine, the mean of our measurements was 67 percent and in the young jack pine we measured a mean canopy density of 40 percent.

Data analysis

Along each snow course, means and standard deviations of 45 measurements of snow depth and 5 measurements of SWE were calculated. The mean SWE for a snow course was calculated from the average snow density from the marked points and the average of all snow depths. This calculation assumed that snow density was more spatially conservative than depth (Pomeroy and Gray, 1995). Measurements showed this is a valid assumption. Time series of snow depths and SWE from courses in forest stands were graphically compared with the open area, which was used as a standard of reference to compare relative accumulation and ablation rates. Measurements from under tree crowns were also averaged for each date: snow depths at given distances from the trunks of the two trees; and the SWE, measured midway between the trunk and crown edges. Measurements of snow depth under crowns were also graphically compared through time.

Least squares were used to fit linear functions through the means of measurements of snow depth and SWE for the purpose of comparing time-averaged trends at different sites. No transformation of variables was undertaken. The trend lines were used to interpret differences in snow accumulation before significant ablation occurred. That is, we fit trend lines to the measured means from the start of the snow measurements in each season up to the time

approximately corresponding to maximum accumulation for each land cover type. In cases where the time of maximum accumulation was different between sites, we chose to fit the data up to the earliest date of maximum accumulation.

The snow course SWE and under-crown SWE were used to estimate the average SWE in each conifer stand. We made two assumptions in estimating average, or stand-adjusted, SWE of the forest stands. First, we assumed that the SWE measurements under tree crowns (2 each survey in each stand) were representative of the mean SWE under crowns in general for that date. Second we assumed that the mean snow density under conifer crowns was similar to the mean density measured along the course. To estimate SWE for a forest stand we used the measured canopy density as the weight for SWE under tree crowns and added it to the mean snow course SWE weighted by one minus the canopy density. We then graphically compared the time series of the stand averaged SWE with the trend from the open area.

RESULTS

Overall, there were marked differences in accumulation of snow between the two snow seasons and between the different land cover classes. The greatest differences were observed between the open and various conifer forest categories. These are first addressed, with a comparison of the open area and the mature aspen stand to follow.

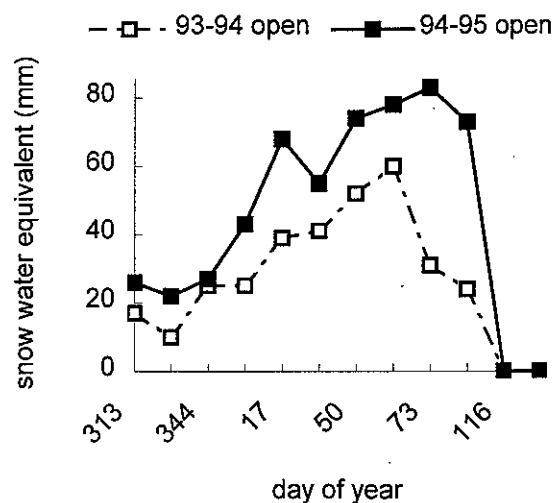


Figure 2. Snow course measurements of SWE from open area, 1993–1994 and 1994–1995.

**Between and within-year differences—
conifer forests**

There was significantly more snow during the 1994–1995 snow season than the 1993–1994 snow season. This was reflected in both the depths and SWE. The average snow depth at the peak of accumulation in 1994 was 33 cm and in 1995 it was 48 cm. At the individual snow courses in both years, there was less than 10 percent difference in snow depth from the mean up to maximum accumulation. At peak accumulation, there was approximately 38 percent more SWE on the ground in 1994–1995 in the open area compared with 1993–1994. Figure 2 shows the biweekly time series of SWE in the open during the two seasons.

During snow accumulation the snow course measurements from the conifer forests showed consistent trends when compared with measurements from the open area. Figures 3 and 4 show mean SWE from the open area, from the black spruce and from under the black spruce crowns for 1993–1994 and 1994–1995 respectively. Figures 5 and 6 show mean SWE from the open area and mean SWE from the mature jack pine course for 1993–1994 and 1994–1995 respectively. The difference between mean SWE in the open area and mean SWE along the snow course in a conifer forest generally increased over time up to peak accumulation. The difference between the mean SWE measured under the conifer crowns and the mean SWE from conifer courses also generally increased over time. Young jack pine showed

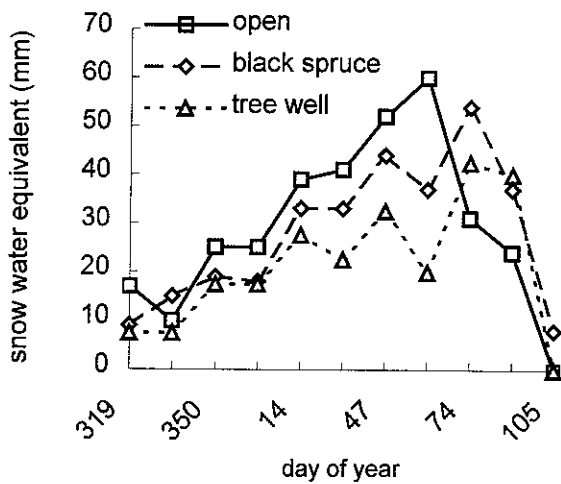


Figure 3. 1993–1994 snow course measurements from an open area and black spruce stand and from under black spruce crowns.

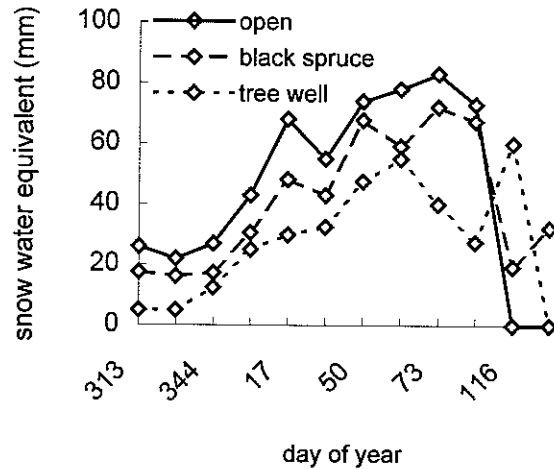


Figure 4. 1994–1995 snow course measurements from an open area and black spruce stand and from under black spruce crowns.

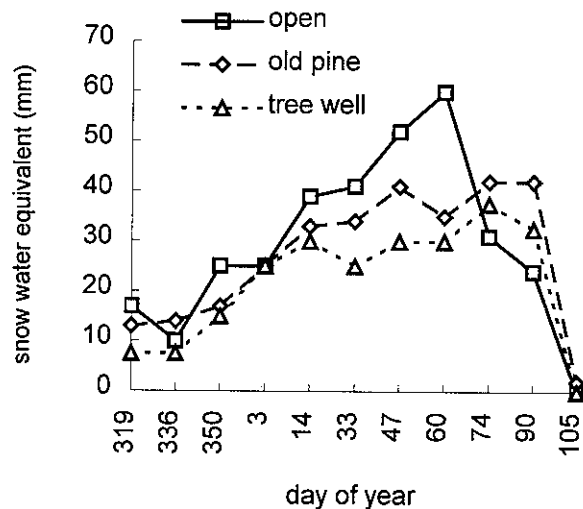


Figure 5. 1993–1994 snow course measurements from an open area and mature jack pine stand and from under the jack pine crowns.

similar trends comparing with the open area during the accumulation season.

The relative difference between SWE in the open area and SWE during accumulation in the conifer stands was greater during 1993–1994 than during 1994–1995. We examined the trends and the differences between the two years using least squares trend lines. The slopes of the regression lines show the relative differences using a linear model to smooth the differences over time. Figures 7 and 8 show the least squares line fit between mean SWE in the open area and mean SWE in the black spruce

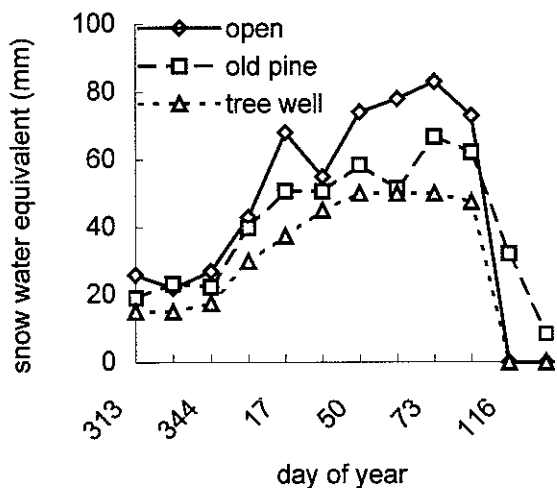


Figure 6. 1994–1995 snow course measurements from an open area and mature jack pine stand and from under the jack pine crowns.

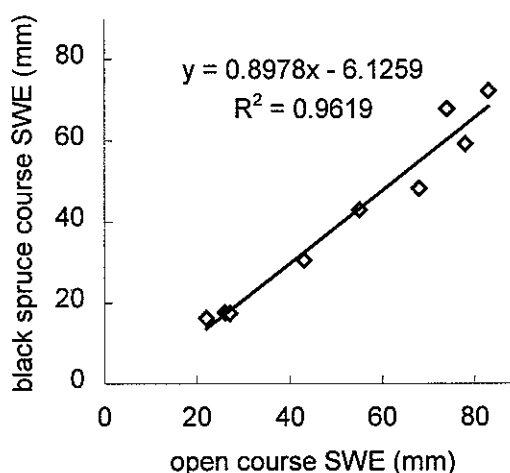


Figure 8. Least squares linear fit to accumulation measurements 1994–1995.

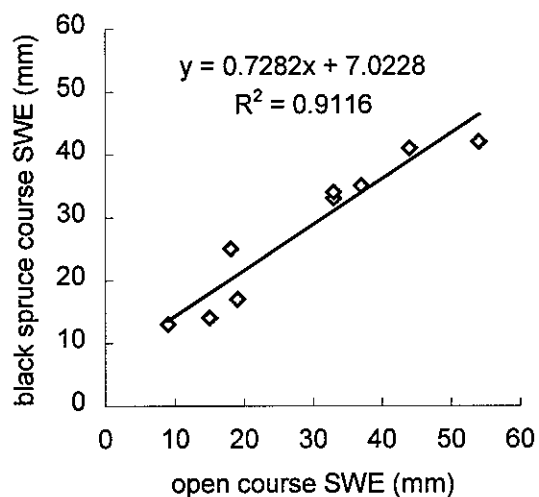


Figure 7. Least squares linear fit to accumulation measurements 1993–1994.

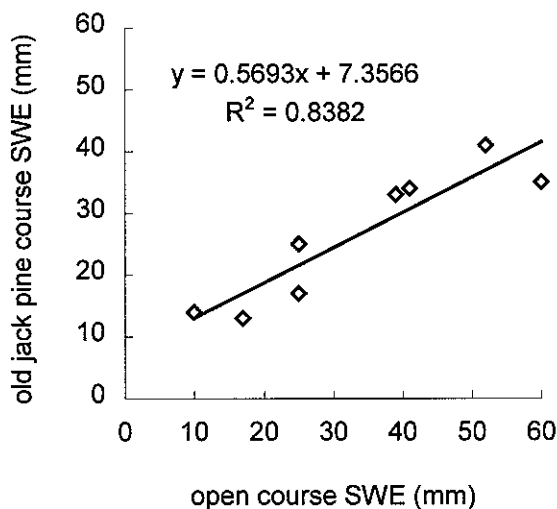


Figure 9. Least squares linear fit to accumulation measurements 1993–1994.

stand during 1993–1994 and 1994–1995, respectively. Figures 9 and 10 show a similar comparison for the mature jack pine and open area. Again young jack pine showed similar trend between the two seasons.

The greatest difference in both years between the conifer forest and open area was associated with the mature jack pine (Fig. 9 and 10). The slopes of the trend lines fit to the comparison of the SWE from the open area and SWE from jack pine were less in

both years than the slopes from trend lines fit to scatter plots of SWE in black spruce and SWE in the open area. It is interesting to note that the change in trend line slopes from 1993–1994 to 1994–1995 for SWE in each of the forest types compared with SWE in the open area was almost the same, about 1.20. The relative difference between the two years also showed from the SWE measurements under the conifer crowns; there was less SWE under the various conifer crowns relative to the open area in

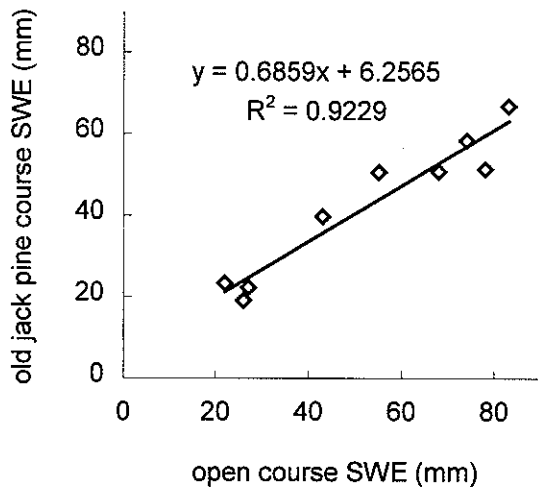


Figure 10. Least squares linear fit to accumulation measurements 1994-1995.

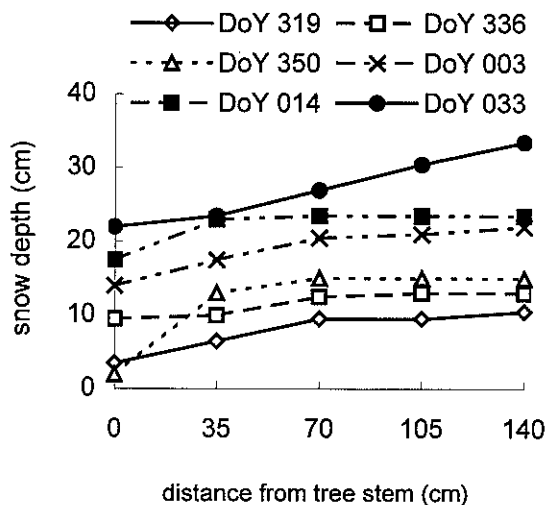


Figure 11. Snow depth measured under jack pine crowns during snow accumulation period 1993-1994.

1993-1994 than 1994-1995, again showed by the slopes of the trend lines.

Tree wells under conifer crowns were generally more pronounced during the early and late season. As seen in the previous figures, SWE under conifer crowns was usually less than the mean snow course SWE. There were periods when they had similar values, for example the late December to early January time frame, as seen in Figures 3-6. This was also evident in the depth measurements. For example, Figure 11 shows snow depths measured under jack pine crowns during the accumulation period of 1993-1994. Figure 11 also shows that the position midway

between the trunk and the crown, where SWE was measured, represents a reasonable average of snow depth under the crowns. The proximity to tree trunks appeared to have little effect on mean snow density. Densities were measured from snow pits at four trees and showed no appreciable variation of mean density with distance from the tree trunk. Generally the densities measured under tree crowns were found within the range of mean densities measured along the snow courses.

The stand averaged SWE in the conifer stands was compared in February 1994 with intensive measurements in a mature jack pine stand 20 km to the north (Fig. 1). Using the mean density from 21 measurements in jack pine on 2 and 16 February 1994, we calculated the stand averaged SWE from 137 depth measurements. The mean measured canopy density in this stand was 76 percent, and the estimated SWE was 33 mm. This compares with

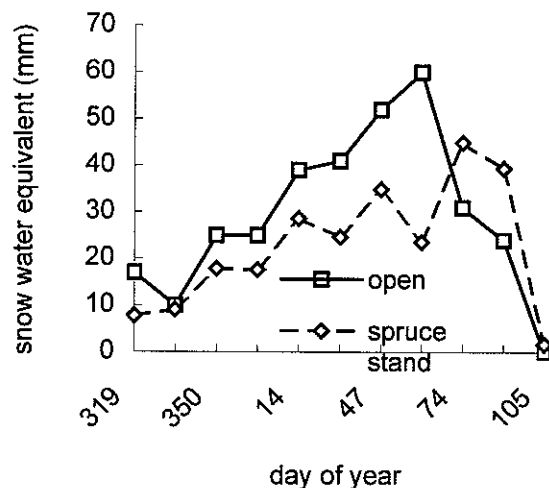


Figure 12. Adjusted SWE for the black spruce stand and the open area SWE 1993-1994.

SWE of 28 mm to 33 mm during the same period in the stand where the jack pine course was located, and SWE of 25 mm to 35 mm in black spruce.

As expected, the stand averaged SWE showed large differences from the SWE in the open area for both types of mature conifer forest. For example, Figures 12 and 13 show the time series of stand-averaged SWE for black spruce and jack pine, respectively, plotted with time series SWE from the open area during 1993-1994. Although the relative difference between the stand averaged SWE in conifers and open area SWE ranged greatly between the two years, the absolute difference did not vary much.

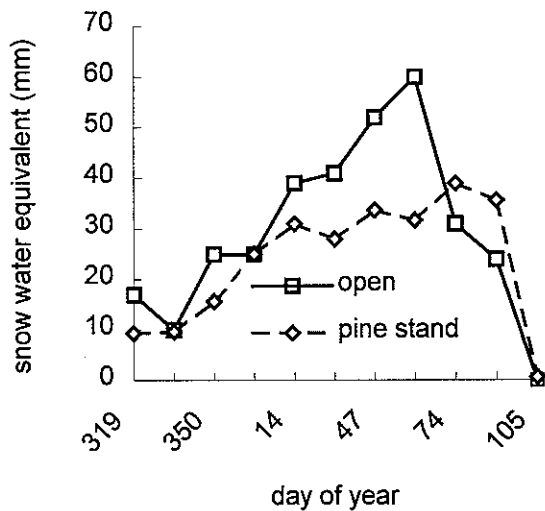


Figure 13. Adjusted SWE for jack pine stand and open area SWE 1993–1994.

In 1993–1994 the SWE of the black spruce stand was 46 percent of the SWE in the open area at maximum accumulation. In 1994–1995 SWE in the black spruce stand was 64 percent of the SWE in the open area at maximum accumulation. Between the two years and at maximum accumulation, the SWE in the mature jack pine stand ranged between 53 and 67 percent of the SWE in the open area. In the young jack pine the values were 63 and 84 percent.

On the other hand, the absolute difference at maximum accumulation in stand averaged SWE between the black spruce stand and the open area was the same for 1994 and 1995: 36 mm. Similarly, there was only a 1 mm change in the difference at maximum accumulation between the stand averaged SWE in the mature jack pine and the open area in 1994 and 1995, from 28 mm to 27 mm. Only the stand averaged SWE from the young jack pine stand showed much change from one year to the next. In 1994 the difference between the SWE in the young jack pine stand and the open area was 22 mm and in 1995 it was 9 mm.

Between and within-year similarities—mature aspen stand

Few of the trends in SWE accumulation observed by comparing conifer stands and the open area were evident in comparing the aspen stand with the open area. Figures 14 and 15 show plots of the SWE in the open area with SWE along the snow course in the aspen stand and under the aspen crowns, for 1993–1994 and 1994–1995 respectively. In the first year, the difference between the tree well SWE and the

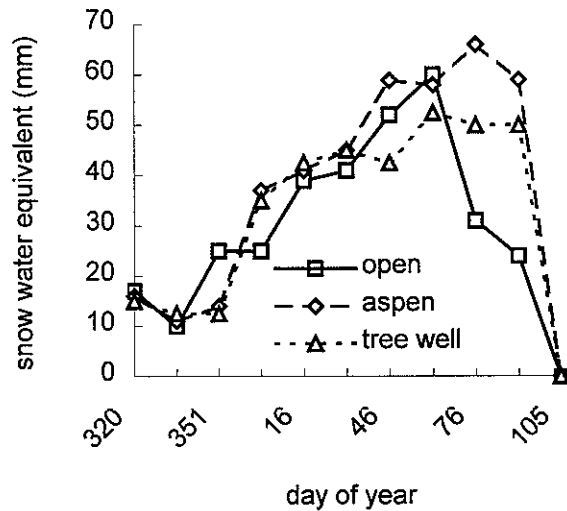


Figure 14. 1993–1994 SWE from an open area, aspen pine stand and from under the aspen crowns.

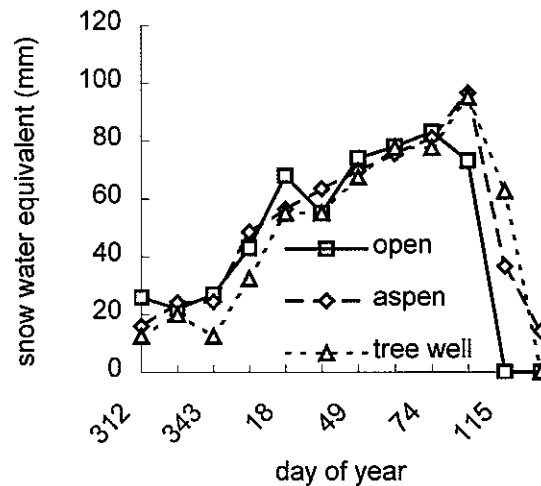


Figure 15. 1994–1995 SWE from an open area, aspen pine stand and from under the aspen crowns

two other time series increased in the middle to late parts of the period (Fig. 14), but this trend was absent in the 1994–1995 measurements (Fig. 15). There was little apparent difference between mean SWE in the aspen stand and the open area despite the 120 km difference in location. Figures 16 and 17 show the least squares line fit to the SWE from the open and aspen courses for 1993–1994 and 1994–1995, respectively. The slopes for both years are not significantly different from 1, and the intercepts are small. Measurements of depth under the crowns showed little evidence of a tree well, except late in the season. Figure 18 shows the accumulation and

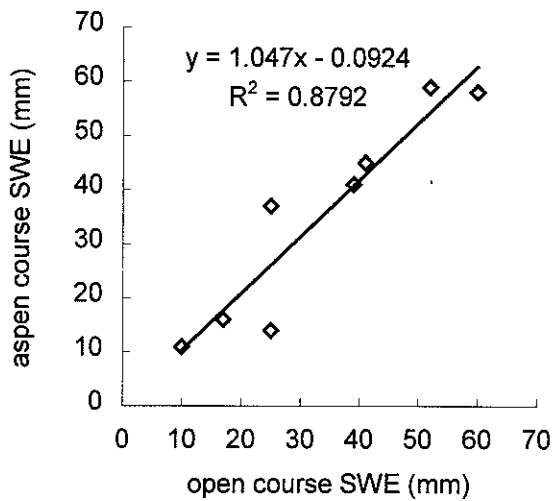


Figure 16. Least squares linear fit to accumulation measurements 1993-1994.

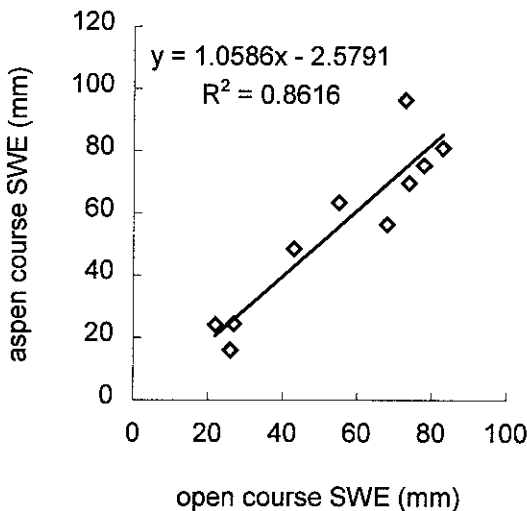


Figure 17. Least squares linear fit to accumulation measurements 1994-1995.

ablation periods, respectively, for the under-tree aspen measurements during 1994-1995.

DISCUSSION

Studies of forested watersheds have found that increased canopy cover results in decreased snow water equivalent of snowpack, and that differences between dense stands and clearings range 25-45 percent, which may be attributed to interception and loss (e.g., Hardy and Hansen-Bristow, 1990; Pomeroy

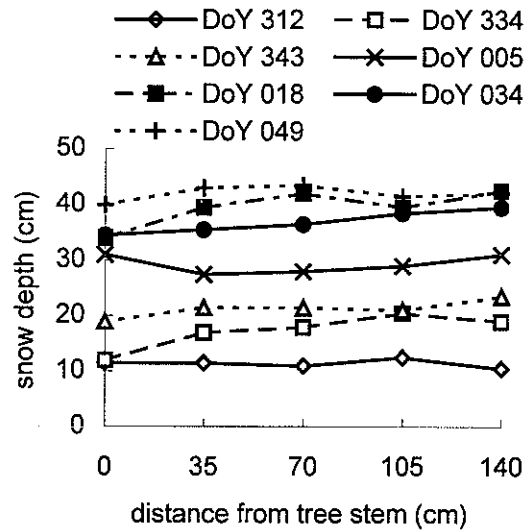


Figure 18. Snow depth measured under aspen crowns during snow accumulation period 1994-1995.

and Gray, 1995; Moore and McCaughey, 1997). Our findings concur with this reported range, and since the differences could be traced through time to maximum accumulation, they are almost certainly due to sublimation of intercepted snow. Energy for sublimation at the forest floor in these and similar stands are low during accumulation (Harding and Pomeroy, 1996; Hardy et al., 1997; 1998, e.g.) so cannot account for much sublimation from the snow on the ground.

The effects of interception and subsequent sublimation of intercepted snow were apparent from measurements in gaps along snow courses through the conifer stands and under crowns. Snow depth variations around conifers held no consistent pattern throughout the season in any of the stands in either of the two years. Moreover, the ratio of SWE under crowns to SWE along the courses in the conifers was different in time and at maximum accumulation between the two years. On the other hand, measurements of depth and SWE midway between the trunk and crown edge appeared to be fairly representative of under-crown means. We combined under-crown and along-course measurements to estimate stand averaged SWE for three conifer stands. Independent estimates of SWE for a jack pine stand had a value intermediate to SWE in stands with greater and lesser canopy density. The relative differences at maximum accumulation between stand averaged SWE in conifers and SWE in the open area (or in the aspen stand) varied from one year to the next depending on the total snowfall. However, the absolute loss, estimated at maximum accumulation in both years was similar.

Pomeroy and Gray (1995) suggest that intercepted snow in a canopy can reach a maximum value. If this was the case for both mature conifer stands in 1993–1994 and 1994–1995, then it might explain the similarity in absolute SWE loss between the two years. Further analysis is required to examine this more closely, since 1994–1995 exhibited some mid-winter melt periods.

These measurements suggested the possibility that SWE estimates could be extrapolated across the area based on canopy density or other stand properties. Snow accumulation during each of the two years appeared in the open area and in the mature aspen stand 120 km to the west. Preliminary evaluation of precipitation gage records nears the two test areas also shows similar accumulated snowfall. In the BOREAS test area, forest stands with similar canopy density class to the black spruce and mature jack pine stands in this study occupy 48 percent of the total forest cover, according to the standard forest inventory map. Stands with similar canopy density class to the young jack pine occupy 11 percent according to the same source. Thus it may seem that the measurements reported here may be extrapolated to a considerable portion of the forested area using forest maps. However, 28 percent of the forest in the BOREAS southern test area are shown as treed muskeg, for which there are no reported canopy density or tree height. Moreover, forest harvesting and fire require that the maps would have to be constantly updated.

Remote sensing products of forest cover should be incorporated in the estimation of the spatial distribution of SWE. Spectral unmixing techniques show promise for estimating canopy density when snow provides a high contrast background. We used canopy density as a weighting term to estimate stand averaged SWE, and thus showed some sensitivity to canopy density. However, this analysis was based on having measurements under crowns of the different conifers, and these measurements varied between the conifer types. Schmidt and Gluns (1991) developed a procedure to estimate the maximum canopy snow load using winter leaf area index (LAI). Hedstrom and Pomeroy (1998) and Pomeroy et al. (in press) used this procedure to couple physical models of interception and sublimation. LAI is used in modeling biophysical processes and methods have been developed to derive maps from remote sensing measurements (e.g., Chen et al., 1997).

Future directions

The goal of extending this work will be to generate maps of SWE across the BOREAS test region. This work represented a first step in this

direction. As described above, more detailed analyses of the SWE data will be important, involving tests for covariance of depth and SWE (e.g., Shook and Gray, 1994), a mass balance approach using precipitation records and potentially a snow energy and mass flux model to assess mid-winter melting episodes. (e.g., Hardy et al., 1997; 1998). Moreover, we plan to compare the SWE loss due to sublimation of intercepted snow with LAI (e.g., Hedstrom and Pomeroy, 1998).

CONCLUSIONS

Time series of measurements of SWE along snow courses and under conifer crowns demonstrate the effects of interception and sublimation of intercepted snowfall in the southern boreal forest. SWE under conifer crowns and along snow courses was less than at a nearby open area, and this difference increased up to maximum accumulation in the open area. Snow density was more spatially conservative than snow depth, which allowed us to make more robust estimates of SWE. SWE sampled from midway between the trunk and crown edge of randomly selected trees appeared to provide a reasonable estimate of SWE under crowns in stands with similar attributes. We assumed this was correct to allow estimation of stand averaged SWE in each of the conifer forest types. The effects of sublimation of intercepted snow, relative to the maximum accumulation each year, were different and depended on the difference in total snow accumulation in each year. On the other hand, the SWE losses were similar between years in absolute terms, suggesting the possibility that the forest canopies reached load saturation during the snow seasons, limiting total sublimation loss.

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