Honor Paper Award

50TH EASTERN SNOW CONFERENCE
61ST WESTERN SNOW CONFERENCE
Quebec City 1993

The Use of Fractal Geometry in Modelling Intercepted Snow Accumulation and Sublimation

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ABSTRACT

In the boreal forest, interception of snow can store 60% of cumulative snowfall in mid-winter and sublimation of this snow can return over 30% of annual snowfall to the atmosphere as water vapour. A sublimation algorithm for a single ice sphere and an "exposure coefficient" which accounts for the difference in surface area to mass ratios between intercepted snow and the ice sphere permit calculation of the sublimation rate in coniferous canopies. Fractal geometry provides a tool to calculate this exposure coefficient from digitised photographs of snowcovered canopies. Intercepted snow is fractal and the irregularity of its shape depends on location in the canopy and age of the snow. The fractal shape of intercepted snow permits a relationship between snowcovered area in canopy photographs and interception load. The analysis shows the feasibility of a physically-based model of intercepted snow accumulation and sublimation that uses standard meteorological measurements and digitised photographs of the canopy.

INTRODUCTION

Interception of snow by vegetation strongly influences sub-canopy winter climate, snowcover chemical composition, snowcover physical characteristics and the snow hydrology of forested areas. In mid-winter, large proportions of the seasonal snowfall are stored as intercepted snow by coniferous canopies. Intercepted snow increases the albedo of coniferous forests, sublimates rapidly and undergoes relatively high dry deposition of atmospheric chemicals. Under snow-covered canopies the surface snowcover is relatively shallow throughout the winter and in continental cold climates produces roughly 1/3 less snowmelt water than adjacent small clearings or deciduous forests. Techniques to calculate the amount of snow intercepted in forest canopies and subsequently sublimated would greatly assist efforts to predict the environmental changes associated with changing climate logging, reforestation, fires and vegetation succession.

INTERCEPTION OF SNOW BY CONIFERS

Intercepted snow accumulation is controlled by the collection efficiency of the individual branches that comprise the canopy. The collection efficiency is the proportion of snowfall incident upon the horizontal projected area of a branch that is retained by the branch during a snow-storm. This efficiency decreases with increasing elastic rebound of snow crystals falling onto branches, increasing branch bending under a load of snow and decreasing strength of the intercepted snow structure (Schmidt and Gluns, 1991). These factors cause collection efficiency to increase with increasing size of falling snow crystals, horizontal cross-sectional area of branches and branch stiffness and to decrease with increasing snow-storm water equivalent, wind speed, temperature, and density of intercepted snow (Gubler and Rychetnik, 1991; Schmidt and Pomeroy, 1990; Schmidt and Gluns, 1991). Because of complex sequences of weather patterns over a winter and the heterogeneous nature of most forest canopies, modelling or predicting the interception storage as a function of snowfall and forest type has proven a complex task (McNay et al., 1988). It is also difficult to directly measure the mass of intercepted snow, hence interception storage is usually determined from comparisons of surface snowcover in forested and adjacent non-forested areas immediately after snowfall, with the assumption that melt, sublimation and redistribution are minimal between the time of snow fall and snow survey. An example of interception effects on snowcover under two coniferous forest stands in the southern boreal forest of central Saskatchewan, Canada, is the "residual snow" shown in Fig. 1. Residual snow is the difference in snowcover between the forest and a small adjacent clearing and represents the cumulative snowfall that is "missing": e.g. either intercepted by or sublimated from the forest canopy. The surveys were conducted over a cold, low sunlight period with no melt and very little loss of surface snow and show a maximum of 60% of cumulative snowfall (as measured in the small clearing) had been intercepted by the dense spruce canopy in early winter. As winter progressed, sublimation steadily reduced the storage of snow in the canopy. The decline from peak residual snow over December and January is due to unloading of intercepted snow which accelerated as the weather warmed in late January. By the end of January, all the intercepted snow had either sublimated or unloaded, hence the residual snow on 28 Jan 1993 indicates the loss of cumulative snowfall to sublimation of intercepted snow at that date.

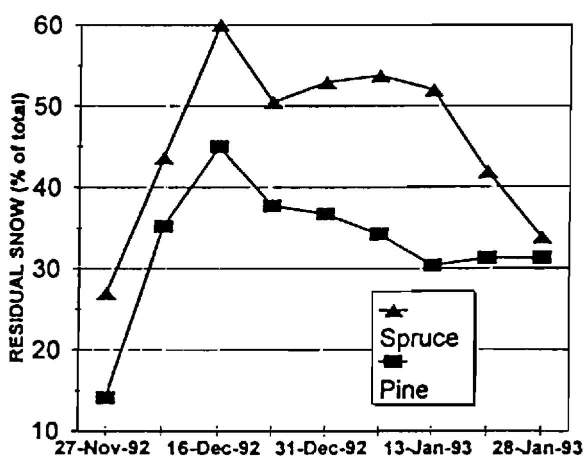


Figure 1. Residual snow (intercepted plus sublimated snow) is that missing from under canopies of black spruce and jack pine in Prince Albert National Park, Saskatchewan, Canada when compared to snow accumulation in an adjacent small clearing.

SUBLIMATION OF INTERCEPTED SNOW

Intercepted snow is subsequently unloaded, resuspended, redistributed, melted or sublimated as shown in Fig. 2. Resuspension and melt are usually insignificant, and redistribution is a small-scale effect, leaving unloading and sublimation of intercepted snow as the fundamental processes in the development of surface snowcovers in boreal and subalpine environments. The sublimation rate for snow intercepted in a single tree dI/dt is found from a sublimation rate coefficient v_s (s^{-1}), the mass of snow intercepted in the tree I (kg) and a dimensionless exposure coefficient, c_e, that indexes the effective exposure of snow in the tree to the atmosphere, where,

$$\frac{dI}{dt} = v_s \, c_e \, I \qquad (1)$$

The sublimation rate coefficient for a single snow particle is the change in mass per unit time divided by the particle mass, and can be determined using an energy balance calculation that matches turbulent transfer of heat to a snow particle and water vapour away from a snow particle with the incidence and reflectance of radiation by the particle (Schmidt, 1991). Sublimation rates increase rapidly with temperature and are quite sensitive to relative humidity. Over the course of several hours, significant amounts of snow can sublimate if the snow is well-exposed. However, snow in a forest canopy is not as well exposed to the atmosphere as is a single snow particle in that its ratio of surface area to mass is much smaller. Assuming that the difference in the sublimation rate coefficients for the intercepted snow mass and the single ice sphere is due entirely to the difference in ratio of surface area to mass between the two, then the exposure coefficient may be effectively defined as a geometric ratio:

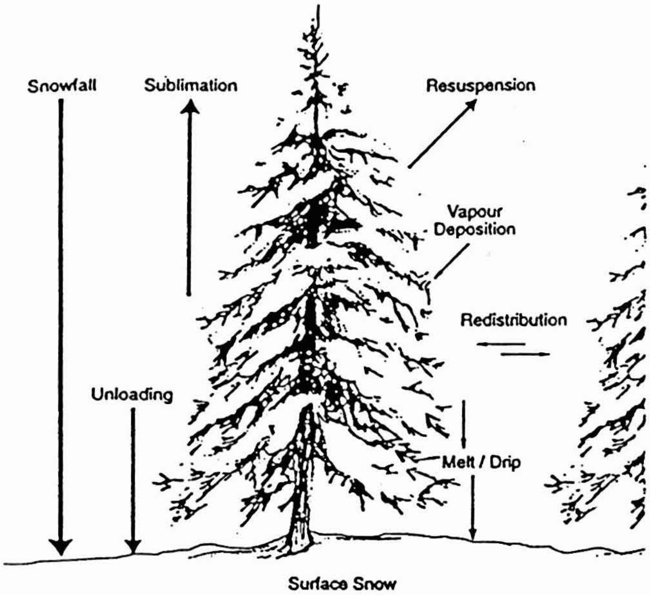


Figure 2. Disposition of winter snowfall in a boreal forest.

$$C_e = \frac{\frac{A_I}{I}}{\frac{A_m}{m}} \qquad (2)$$

where A_I is the surface area of intercepted snow in a tree, A_m is the surface area of a single ice sphere and m is the mass of a single sphere. Re-arranging Eq. 1, the exposure coefficient may be calculated from sublimation rates and intercepted snow loads as,

$$C_e \equiv \frac{m\frac{dI}{dt}}{I\frac{dm}{dt}} \qquad (3)$$

where m is the mass of a reference 1-mm diameter snow particle (roughly 0.5 mg) whose sublimation rate is dm/dt which may be estimated from air temperature, humidity and wind speed measurements using Schmidt's (1991) model. The exposure coefficient was calculated using Eq. 3 and experimental data which include simultaneous sublimation rate estimations for a 1-mm snow particle and measurements of sublimation rate using the rate of change of mass of snow intercepted by artificial conifer (1-m tall, 0.5-m wide Christmas tree), weighed electronically in the mountains of central Colorado (Schmidt et al., 1988; Schmidt 1991). For snow on the artificial conifer, the exposure coefficient is a function of the mass of intercepted snow on the tree and the age (structure) of snow on the tree as shown in Fig. 3 and fits,

$$C_e = k_1 \left(\frac{I}{I*}\right)^{-F} \qquad (4)$$

where I* is the maximum intercepted load for the conifer (5.5 kg in this case), k_1 is a coefficient indexing the age/structure of snow on the conifer (k_1 = 0.0001099 for fresh snow and 0.0000545 for old snow) and F is an exponent defining the log-log slope of the relationship and is equal to 0.3 for the conifer. Equation 4 is developed from data collected from an artificial conifer that is much smaller and somewhat different in form from natural conifers, though it describes the probable form of a C_e vs I relationship for natural forests, its extrapolation to a natural coniferous forest is not valid without a method to quantify the mass of intercepted snow and the surface area of this snow in natural canopies in order to test the values of k_1 and F.

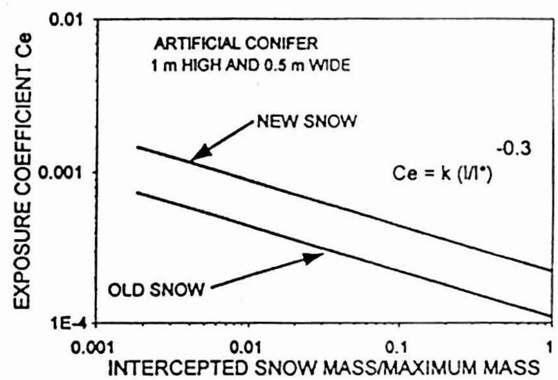


Figure 3. The exposure coefficient is the surface area to mass ratio for snow intercepted by a conifer to that ratio for a single ice sphere. It is shown as a function of the intercepted snow mass for Schmidt's (1991) artificial spruce and is calculated from atmospheric measurements and direct measurements of sublimation rate from the artificial spruce.

THE FRACTAL GEOMETRY OF INTERCEPTED SNOW

Fractal geometry is a mathematical tool that, amongst other uses, describes manifestations of the natural environment that are chaotic but not random in form. Fractal objects are complex, convoluted and irregular but have certain intrinsic patterns that govern their form (Mandlebrot, 1983). They also have no characteristic spatial scale, in that their degree of roughness is independent of the scale of measurement. Natural objects can often be described by fractal geometry over a range of scales for which they "behave" as fractals; examples are cloud formations, turbulent flow patterns, porous media properties, time series of river discharges, forest canopy shapes and melting snow patches (Barnsley, 1988; Broomhead and Jones, 1989; Lenormand, 1989; Mandlebrot, 1989; Shook, 1993; Shook et al., 1993). Simple recursive fractal algorithms can create objects that strongly resemble a conifer and a snow crystal. These suggest that fractal geometry may be able to mathematically describe the volume and surface area of snow on trees in a manner suitable for use in an interception/sublimation model.

One measure commonly used in fractal mathematics to evaluate the degree of irregularity of an object is its dimension D. For classical Euclidean objects this dimension is an integer, for instance the perimeter of a circle or square has a dimension of 1, the surface area of a sphere or cube has a dimension of 2. The more convoluted an object is, however, the greater its dimension is in excess of the Euclidean dimension. Shook et al. (1993) have shown that melting snow patch perimeters are fractal, with dimensions ranging from 1.45 to 1.6. For fractal objects the dimension can be shown to be composed of a fractal and an Euclidean component. For instance, to find the dimension of a fractal perimeter D we add the Euclidean (integer) component (D_e) = 1 to the fractal (non-integer) component (D_f),

$$D = D_e + D_f \qquad (5)$$

and if the object is self-similar in all directions (same degree of convolution in all dimensions) then we can find the dimension of a fractal surface area by setting $D_e = 2$ and adding the same D_f. The dimension, D, of a collection of perimeters, P, of objects that are fractal, can be found empirically from their individual areas, A, by the expression (Mandlebrot, 1983),

$$P = k A^{\frac{D}{2}} \qquad (6)$$

where k is a coefficient whose magnitude depends upon the scale of measurement of P and A. Hence if snow on trees is fractal and self-similar in all directions then the perimeter and cross-sectional area of intercepted snow, measured by photographic or other means, should be useful in determining the dimension of the surface area of intercepted snow and hence the relationship between snow surface area and volume (and therefore mass).

A combination of dimensional analysis and fractal mathematics may be used to evaluate C_e from its definition in Eq. 2. Assuming that the ice sphere is Euclidian ($D = D_e$) in its volume and surface area and the canopy snow is similarly fractal ($D = D_e + D_f$) in all dimensions of its volume and surface area (not self-affine), then cancelling out redundant terms leaves C_e having dimensions of a Euclidian length over a fractal length, and therefore dimensions of $-D_f$ where,

$$C_e = \frac{\dfrac{A_f}{V_f \rho}}{\dfrac{A_e}{V_e \rho}} = \frac{L_e}{L_f} = \frac{L^1}{L^{1+D_f}} = L^{-D_f} \qquad (7)$$

and A represents area, V represents volume, ρ represents density and the subscripts f and e refer to fractal and Euclidian respectively. As I/I^* and k in Eq. 4 are truly dimensionless, then $D_f \equiv F$. D_f can be found empirically from Eq. 6 as D-1.

MEASUREMENTS OF THE FRACTAL DIMENSION OF SNOW

To test the fractal geometry of intercepted snow we took 81 photographs of 30 individual snow-covered branches of white spruce *Picea glauca* and jack pine *Pinus banksiana* in the southern boreal forest of Prince Albert National Park near Waskesiu Lake, Saskatchewan, Canada from December 1992 to January 1993. The photographs were taken from at least two angles (side view and end view) with some branches photographed from 10 angles (various side, top and end angles). Branch photographs have a black velvet background to exclude all but the branch of interest and include a ruler for scale. After photography the snow was shaken from the branch into a plastic bag which was later weighed to determine the mass of intercepted snow on the branch. Cold temperatures during this phase of the experiment (-47 to -33 °C) were an advantage, ensuring that branches and snow remained stiff during our photography so that no snow was disturbed until it could be bagged. Examples of the photography method and resulting photographs are shown in Fig. 4a and 4b. The images were digitised into the TIFF image format (256 level gray scale) from the photographs projected as slides, using a video camera and a frame-grabber card. The TIFF files were input to a *MOCHA* image analysis programme (Jandel Scientific, 1993). Using the *MOCHA* software, threshold gray scale ranges were set to distinguish intercepted snow from branches, reflections and sky and a spatial scale was calibrated against the photographed ruler. The perimeters and areas of identified snow "clumps" were then measured by *MOCHA*. Perimeters and area of snow clumps from the same branch were assembled and entered to a spread sheet, graphed on a log-log plot and fitted to Eq. 6 using a regression model. As each branch was photographed from different angles this exposed any differences in the perimeter/cross-sectional area relationship with view angle. Typical examples of the perimeter-area relationship for snow on spruce and pine are shown in Fig. 5a and 5b. Correlation coefficients for the regression fits were above 0.98 and there is no indication of any variation in the perimeter/area relationship with view angle (Fig 5a includes measurements from 10 different view angles). This presents strong evidence that intercepted snow is self-similar rather than self-affine: its dimension and therefore its degree of irregularity are constant in all directions. The dimensions of intercepted snow clump perimeter determined by regression analysis range from 1.22 to 1.36 with an average of 1.29, indicating that snow on individual natural branches is fractal and that for this snow, $F = 0.29$ in Eq. 4. Figure 6 shows the dimension of intercepted snow and the cumulative intercepted snow mass on each branch. In general, lower dimensions are associated with smaller masses but no statistically significant relationship is evident between intercepted snow mass and dimension for individual branches. Figure 7 shows the cross-sectional area of intercepted snow as measured from the end view of a branch and the mass of snow on the branch. There is some evidence here for an increase in cross-sectional area with snow mass, however the r^2 for a linear increase is only 0.51 with a standard error of estimate of snow mass of 66 g.

Figure 4a.

Figure 4. Photographing single snow-laden branches in Prince Albert National Park, December, 1992.
a) A black velvet background isolated the branch of interest and a ruler provided scale, photographs were taken from a variety of angles.

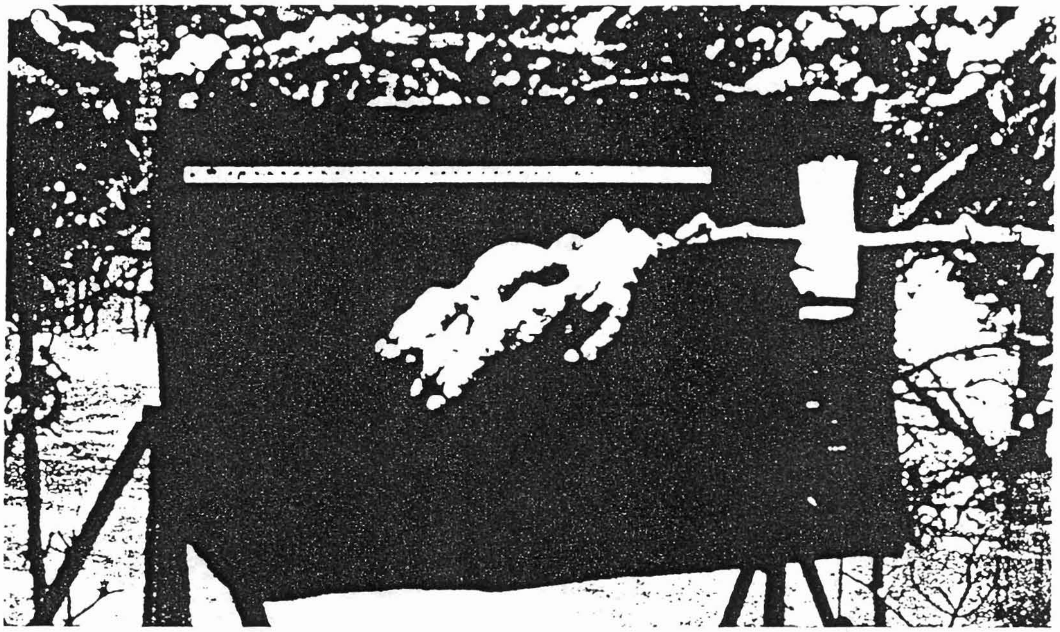


Figure 4b.

b) The resulting photographs clearly show that the shape of intercepted snow is complex and the perimeter difficult to determine with traditional geometry.

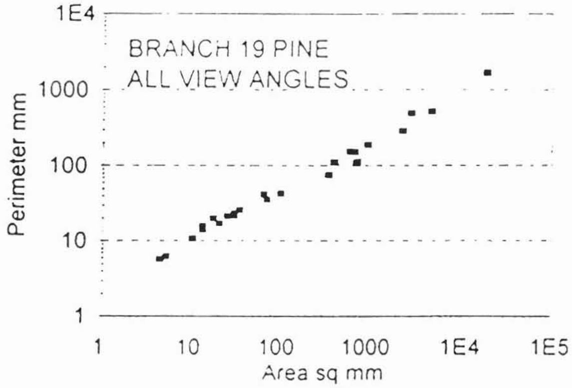


Figure 5a.

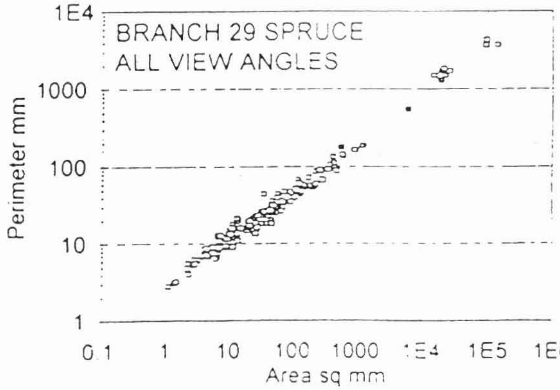


Figure 5b.

Figure 5. The perimeters and areas of snow on single branches of a) jack pine and b) white spruce. The data include measurements from a variety of angles and suggest that the same perimeter-area relationship works for all angles of view. The relatively straight lines and high perimeter to area ratios indicate that this snow is fractal.

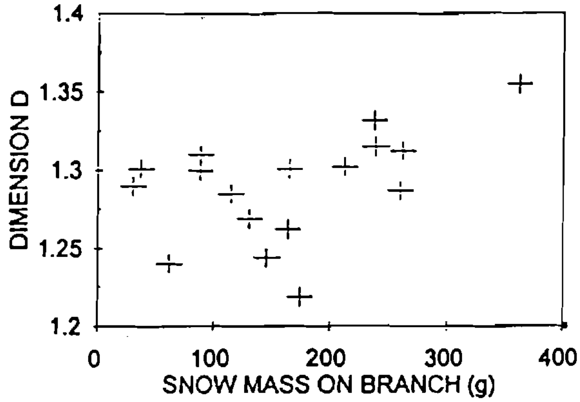


Figure 6. The dimension (which being greater than 1 is fractal) of the perimeter of snow intercepted on individual branches of spruce and pine and the mass of snow on each branch. There is no clear relationship evident.

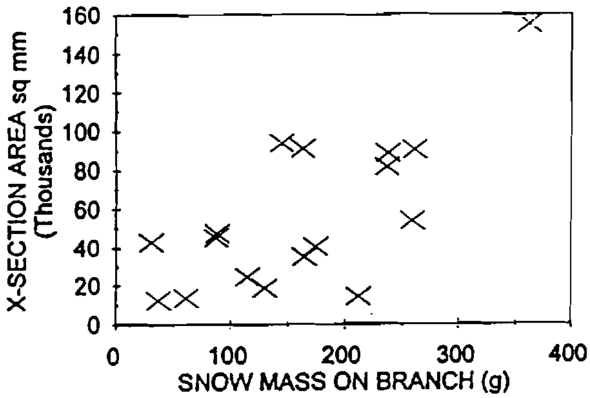


Figure 7. The cross-sectional area of snow intercepted on individual branches of white spruce and jack pine and the mass of snow on each branch. There appears to be an increase in area with mass, though the exact form of the relationship is not evident.

To examine and demonstrate how these findings might be extrapolated to the forest level we suspended a full-size (9-m tall) black spruce tree, *Picea mariana*, from a cable attached to a tower in a dense black spruce forest (Leaf Area Index = 4, Maximum Canopy Height = 12 m) in Prince Albert National Park near to our individual branch measurements. An electronic force transducer, in-line on the cable, weighed the tree every 10 sec. and a Campbell CR-10 datalogger provided 15 min average, maximum and minimum weights as well as the transducer temperature. A series of extensive tests of the weighing mechanism showed little temperature drift and excellent repeatability. Given the cumulative effects of wind gusts, tower flexure, temperature effect on the full-bridge electrical measurement, resolution limits and hysteresis in the transducer we estimate the error in measurement to be no more than +/- 70 g out of a tree tare (bare of snow) of about 21000 g. The tree accumulated snow much like nearby living trees from its installation on 16 Dec 1992, and lost less than 100 g of its own mass over the six week intensive measurement period. An adjacent 16-m mast held three levels of anemometers, temperature and humidity gauges, opto-electronic snow particle detectors and sensors for a complete radiation balance. The mast also permitted us to climb and take oblique photographs of the canopy at heights of 3, 4.5, 6.5, 8.5 and 11.5 m. These photographs were taken with a *Logitech Fotoman* digital camera which takes electronic images and stores them as black and white TIFF files which may be directly downloaded to a computer. At least two images were taken at each level, having consistent view angles and view composition and using the forest canopy as background. Good sets of images with corresponding measurements of intercepted snow load on the hanging spruce were obtained for 7, 12, 19 and 28 January 1993. The procedure for image analysis and regression fit to Eq. 6 using these canopy images matched that for the individual branch images. An absolute pixel scale was impossible to establish for the canopy photographs, as each photograph included a range of distances from the camera. Hence, the percentage of the canopy cross-sectional area in a photograph covered with "snow pixels" was calculated rather than the horizontal area of snow-covered canopy in m^2. Examples of an oblique spruce canopy image taken from 11-m height and the corresponding perimeter and cross-sectional area of intercepted snow in the image are shown in Fig. 8. High r^2 values (> 0.97) were obtained in fitting the perimeter and area measurements from the canopy photographs to Eq. 6, indicating that intercepted snow in a spruce canopy is fractal.

The results of the analysis may be briefly discussed here to illustrate the application of the fractal dimension. Two parameters were estimated from the photographs: F, the exponent in Eq. 4 and I, the intercepted snow mass are estimated from the fractal dimension and the snow-covered area respectively. The dimension of intercepted snow perimeters for the canopy clustered around 1.3, very similar to the individual branch measurements. The dimension is plotted against height of observation in Fig. 9 and shows an increasing deviation from 1.3 as height increases.

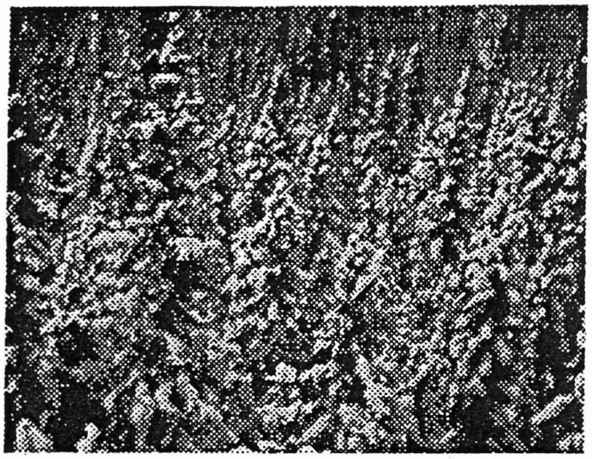
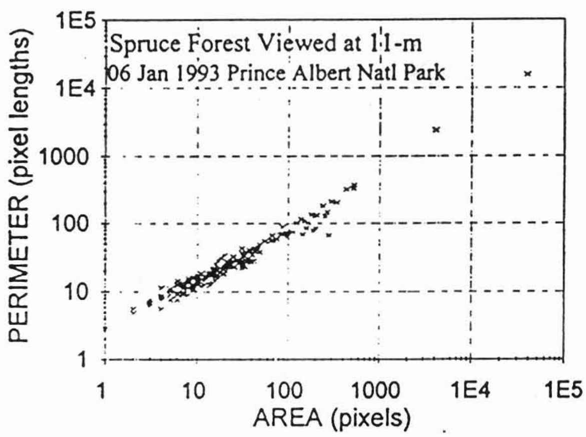


Figure 8a.

Figure 8. Intercepted snow in a canopy of black spruce at 11-m height on 6 January, 1993 in Prince Albert National Park, Saskatchewan, Canada.

a) Image of snow-laden canopy from 11-m height, taken with the digital camera



b) Perimeter and cross-sectional area measured from the image. The relatively straight line on the graph and high ratio of perimeter to cross-sectional area indicate that this snow is fractal.

At the 11.5-m height, the dimension ranges from 1.39 to 1.44 except for that measured on 12 January when it dropped to 1.26. These results suggest that the dimension within the lower canopy can be approximated by 1.3, confirming for this portion of the spruce canopy that $F \approx 0.3$ as determined from Schmidt's (1991) measurements using the artificial tree. In the upper canopy the dimension ranges widely depending upon the age of the snow and the degree to which it has sublimated, the outlier value of 1.26 at 11.5-m height corresponded to a day of maximum snow load and fresh snowfall. In the upper canopy it appears that F ranges from 0.26 to 0.44 and is sensitive to snow load and "freshness". The percentage of snow-covered area

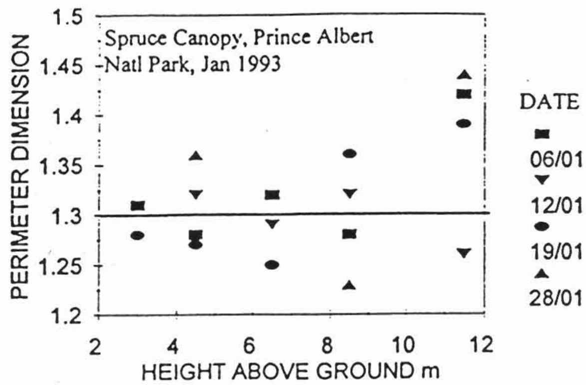


Figure 9. Dimension (greater than 1 and therefore fractal) of the perimeter of intercepted snow in a black spruce canopy, Prince Albert National Park, on four dates in January, 1993 graphed against the height of the measurement. The dimension centres on 1.3 lower in the canopy but for fresh snow (6-19 January) rises to above 1.4 in the upper canopy.

in the canopy is graphed for various observation heights against the total snow mass intercepted on the suspended spruce, I, in Fig. 10. The snow mass on the spruce is anticipated to be strongly related to interception storage in the whole spruce canopy, and for the purpose of this comparison indexes canopy snow storage.. The snow-covered area increases with height and with the mass of intercepted snow. There appear to be two families of curves. The lower-canopy curve for the 3 and 4.5 m height increases from about 0% snow-covered at 2.5 kg interception to about 23% snowcovered at 5.5 kg. The upper-canopy curve for the 6.5 to 11.5 m height increases from about 16% snow-covered at 2.5 kg interception to about 48% snowcovered at 5.5 kg. The curves suggest that unique, linear relationships between canopy snowcovered area at a height and intercepted snow load may be developed if the height of observation is accounted for. Further work is needed to determine if this dependence on height is an intrinsic property of canopy geometry, snow interception process or measurement technique.

The intent of this analysis is to advance techniques for aid the estimation of the exposure coefficient (Eq. 4) and the sublimation rate for the canopy (Eq. 1). The preceding illustrations provide evidence that the exponent, F, and intercepted snow load, I, can be deduced from canopy photographs. Further analysis, comparing the ratio of sublimation rates from snow on the weighed-tree to the sublimation rate coefficient calculated from the tower meteorological

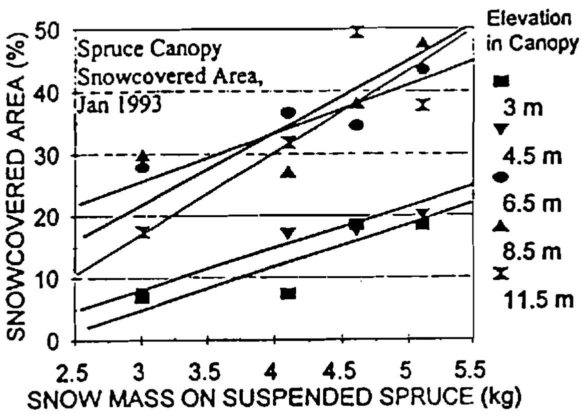


Figure 10. The cross-sectional area of intercepted snow in a black spruce canopy, Prince Albert National Park and the intercepted snow mass measured on one typical spruce tree in the canopy. The snowcovered area increases more sharply with intercepted mass for snow in the upper canopy than with that in the lower canopy.

instruments with other geometric parameters of digitised photographs should allow determination of the coefficient k_1. This will then allow a complete solution for the exposure coefficient and the canopy snow sublimation rate from measurements of digitised canopy snowcover, some measure of canopy branch density, air temperature, humidity, wind speed and radiation.

CONCLUSIONS

1) An exposure coefficient that is the ratio of surface area to mass of intercepted snow divided by the ratio of surface area to mass of a single ice sphere permits calculation of the sublimation rate of intercepted snow if the interception storage and sublimation rate for a single ice sphere is known.
2) This exposure coefficient decreases exponentially with interception load and decreases with the degree to which intercepted snow has sublimated. The slope of the decrease in exposure coefficient with interception load is controlled by the fractal dimension of intercepted snow.
3) Intercepted snow on individual branches of white spruce and jack pine and for complete canopies of black spruce behaves as a fractal.
4) The fractal dimension of intercepted snow perimeters on individual branches and in the lower-canopy centres on 1.3 and is found to vary from 1.22 to 1.36. This suggests an exponent, F, in the exposure coefficient - intercepted snow mass relationship equal to 0.3, identical to that found by Schmidt (1991) for an artificial conifer.
5) The fractal dimension of intercepted snow perimeters in the upper-canopy is found to vary from 1.26 to 1.44, usually remaining well above 1.37 . This suggests that F varies from 0.26 to 0.44, and can not be approximated by 0.3 as in the lower-canopy
6) Snowcovered area from oblique photographs of spruce canopies increases with the mass of intercepted snow.

Acknowledgements

Funding for this experiment was provided by the Canadian GEWEX Programme (Green Plan), Environment Canada and the United States Forest Service. The expert installation and maintenance of the experimental site and towers in Prince Albert National Park by Newell Hedstrom, Cuyler Onclin, Tom Carter and Darren Schill of NHRI was critical to the success and ease of this experiment. The cooperation, interest and assistance provided by the Wardens of Prince Albert National Park contributed substantially to our work. Finally, we must thank the staff of the Hawood Inn, Waskesiu: Don Cyr and Linda and Lisa Archer for their gracious, warm hospitality and encouragement in the depths of a cold Saskatchewan winter.

REFERENCES

Barnsley, M., 1988. Fractals Everywhere. Academic Press Inc., San Diego, CA.

Broomhead, D.S. and R. Jones, 1989. Time series analysis. Proceedings of the Royal Society of London, vol. 423, no. 1864. 103-122.

Gubler, H. and J. Rychetnik, 1991. Effects of forests near the timberline on avalanche formation. In, Snow, Hydrology and Forests in High Alpine Areas (Proceedings of the Vienna Symposium, August, 1991). IAHS Publ. No. 205. IAHS Press, Wallingford, UK. 19-38.

Jandel Scientific, 1993. Mocha Image Analysis Software for Windows User's Manual. Jandel Scientific, San Raphael, CA.

Lenormand, R. 1989. Flow through porous media: limits of fractal patterns. Proceedings of the Royal Society of London, vol. 423, no. 1864. 159-168.

Mandlebrot, B.B. 1983. The Fractal Geometry of Nature. W.H. Freeman and Co., New York.

Mandlebrot, B. B. 1989. Fractal geometry: what is it and what does it do? Proceedings of the Royal Society of London, vol. 423, no. 1864. 3-15.

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

Schmidt, R.A. 1991. Sublimation of snow intercepted by an artificial conifer. Agricultural and Forest Meteorology, vol. 54. 1-27.

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

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

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

Shook, K. 1993. Fractal Geometry of Snowpacks During Ablation. Unpublished M.Sc. Thesis. University of Saskatchewan, Saskatoon. 178 pp.

Shook, K., D.M. Gray and J.W. Pomeroy, 1993. Temporal variation in snowcover area during melt in Prairie and Alpine environments. Nordic Hydrology, 24. 183-198.