ISSN 09189351

Research Report of IHAS

Proceedings of the GAME-MAGS International Workshop

MAGS Science Committee and
Japan National Committee for GAME

April 2000

No.7

Institute for Hydrospheric-Atmospheric Sciences
Nagoya University
Nagoya, Japan

Published by
Institute for Hydrospheric-Atmospheric Sciences
Nagoya University, Nagoya 464-8601, Japan

Printed by
Nagoya University COOP

Snow and Frozen Soil Process Studies in Northern and Western Canada

John Pomeroy and Don Gray
Division of Hydrology, University of Saskatchewan, Saskatoon, Saskatchewan S7N 0W0

Introduction

The objectives of this study are to examine and model processes important to the water and energy cycles of cold environments, namely, interception and sublimation of forest snow, blowing snow transport and sublimation, snowmelt energetics, ablation of snow-covered area, and coupled heat and mass transfer in snow and underlying ground. Modelling is accomplished by devising physically-based algorithms that describe these processes using field measurements in boreal, alpine and arctic environments.

Methodology

Field Measurements

Intensive measurements of snow accumulation, ablation and frozen soil infiltration were made at four locations:

a) Inuvik, Northwest Territories
b) Wolf Creek, Yukon Territory
c) Waskesiu, Saskatchewan
d) Kernen Farm, Saskatchewan

The measurements employed standard meteorological observations as well as direct observations of sensible and latent heat flux over snow surfaces, radiation, soil heat flux, blowing snow flux from an opto-electronic particle detector, intercepted snow mass measurements with a suspended, weighed full-size coniferous tree and infiltration to frozen soils using a twin-probe gamma attenuation device.

Modelling

Recently developed algorithms of the following cold regions hydrological processes have been examined with respect to their performance and have undergone enhancements where appropriate:

1) Infiltration to frozen soils – operational algorithm.
2) Boreal forest snow-cover - ablation.
3) Blowing snow model – sublimation
4) Complex terrain blowing snow model – snow accumulation
5) Intercepted Snow Accumulation/Unloading/Sublimation - sublimation

RESULTS

Ablation of Seasonal Snowcovers

The influence of forest canopy cover and variable melt energetics on depletion of snowcover was investigated in the boreal forest of central Saskatchewan following earlier work by Shook (1995) and Shook and Gray (1996) in open environments. The results can be distinguished between variability within the forest stand and that between forest stands. Within stands, Faria (1998) found the frequency distribution of SWE (snow water equivalent) under boreal canopies was found to fit a log-normal distribution, with the most dense stand displaying the most variable SWE prior to melt. Higher variability in SWE results in earlier exposure of ground under spatially uniform melt conditions (Shook and Gray, 1996), but within stands, snowmelt energy below the canopies was found to be spatially heterogeneous and inversely correlated to SWE (Fig. 1). The variability of melt energy within a stand decreased with overall stand density. Within-stand covariance between the spatial distributions of snow water equivalent and melt energy promoted an earlier depletion of snowcover than if melt energy were uniform. This covariance was largest for the most heterogeneous stands (usually medium density). Stand scale variability in mean SWE and mean melt energy resulted in more rapid SCA depletion for stands with lower leaf area. Because of the heterogeneity in the spatial distributions of SWE and melt energy in forest environments, it is necessary that these variations be included in calculations of snow covered area (SCA) depletion (Faria et al., in press). Comparisons of the measured depletion with simulated depletion showed improved fit for simulations that included covariance over those that neglect this feature (Faria et al., in press).

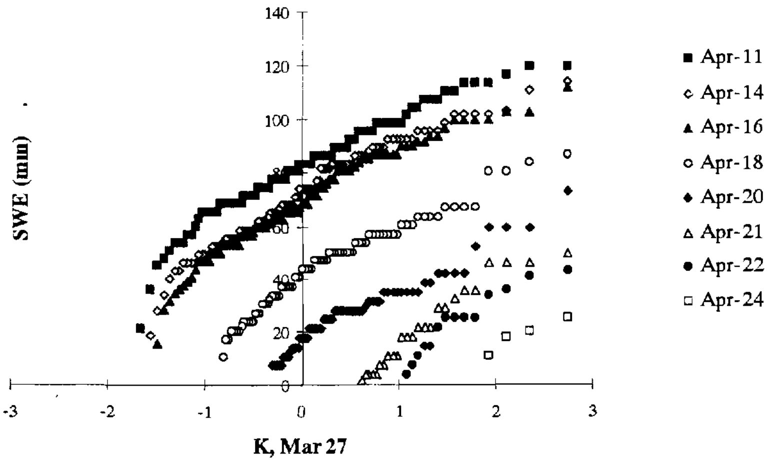

Figure 1. Sequential distributions of snow water equivalent (SWE) during melt in a Pine Stand. K is the frequency factor for the log-normal distribution of SWE), the K for SWE=0 reflects snow covered area. Note that melt is greater for smaller SWE (after Faria et al., in press).

Sublimation of Intercepted Snow

Physically-based equations describing snow interception (Hedstrom and Pomeroy, 1998) and sublimation processes (Pomeroy et al., 1998) were applied to canopy intercepted snow using a fractal scaling technique (Pomeroy and Schmidt, 1993) to provide a snow-covered forest boundary condition for a one-dimensional land surface scheme, CLASS (Verseghy et al., 1993). Substantial modification of CLASS's treatment of turbulent transfer and within-canopy ambient humidity were required to accommodate this nested control volume approach. Tests in late winter in a southern boreal forest against measured sublimation found that the coupled model provides good approximations of sublimation losses on half-hourly and event basis (Fig. 2). Cumulative errors in estimating canopy temperature, humidity, and intercepted snow load over 8 days of simulation were -0.7 °C, -4.2% of the average observed vapour pressure, and 0.04 kg/m^2, respectively. Testing of the model energy balance against eddy correlation measurements yielded reasonable estimates of latent and sensible heat fluxes during an overnight event, but poorer estimates during periods of large snow loads and sunlight. Further work to incorporate a radiation scaling correction, continuing improvements to heat storage terms, and within-canopy turbulent transfer are expected to improve coupled model performance.

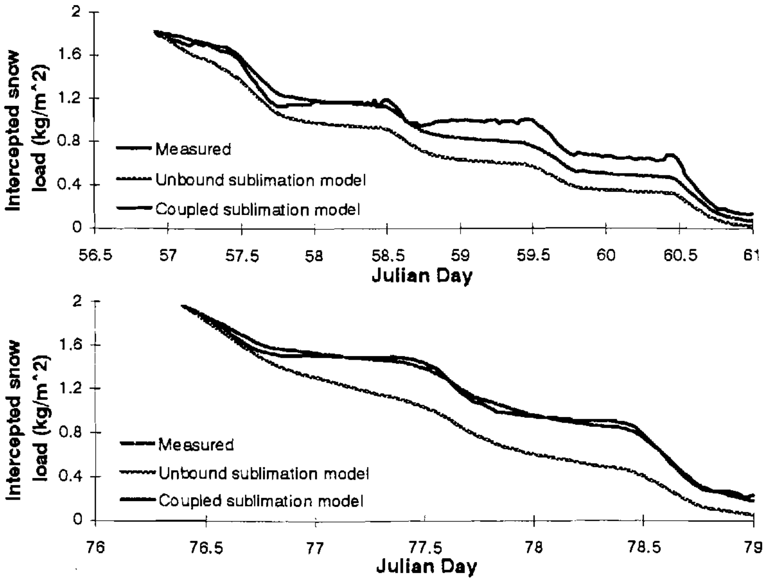

Figure 2. Measured intercepted snow load (from suspended pine tree), and unbounded sublimation model (Pomeroy et al., 1998) and coupled land surface scheme sublimation model calculated intercepted load.

Blowing Snow

Sublimation fluxes during blowing snow have been estimated to return 10-50% of seasonal snowfall to the atmosphere in North American prairie and arctic environments (Pomeroy and Gray, 1995; Pomeroy et al., 1997; Essery et al., 1999). These fluxes are calculated as part of blowing snow two-phase particle transport models with provision for phase change based upon a particle-scale energy balance. Blowing snow models have normally been evaluated based upon their ability to reproduce diagnostic mass flux gradient measurements and regional-scale snow redistribution patterns and snow mass, e.g. Pomeroy and Li, submitted; Essery et al. (1999). Direct evidence has been obtained that large latent heat fluxes (40-60 W m^{-2}) that result in sublimation rates of 0.05-0.075 mm snow water equivalent $hour^{-1}$, are associated with mid-winter, high-latitude blowing snow events (Fig. 3). For events with wind speeds above the threshold level for snow transport, these fluxes are in the range of those predicted by the Prairie Blowing Snow Model. The fluxes are well in excess of those found during spring snowmelt and which can be predicted by standard bulk aerodynamic transfer equations, suggesting that blowing snow physics will have to be incorporated in land surface schemes and hydrological models in order to properly represent snow surface mass and energy exchange during blowing snow events (Pomeroy and Essery, 1999).

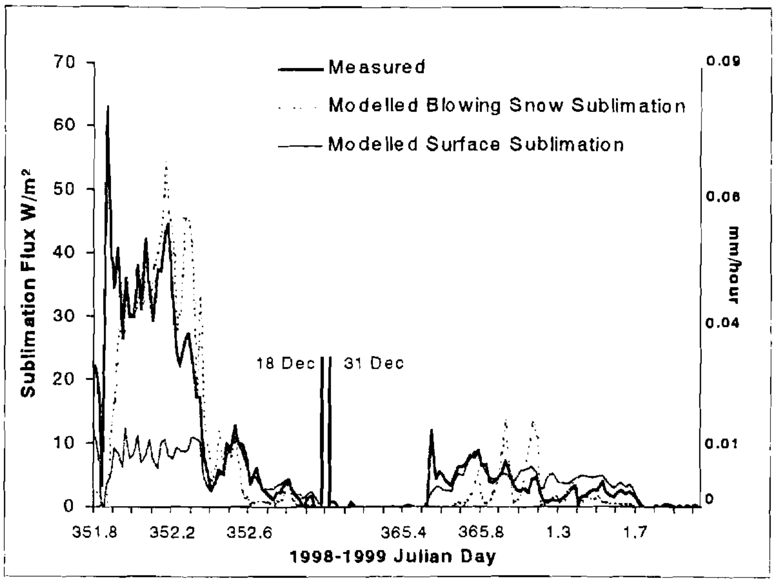

Figure 3. Measured sublimation flux, modelled blowing snow sublimation (PBSM) and modelled surface sublimation (bulk transfer) measured at over a level Prairie surface (after Pomeroy and Essery, 1999).

Infiltration to Frozen Soils

Previous studies (Zhao and Gray, 1997, 1998, 1999) have reported the development and testing of a general parametric correlation for estimating snowmelt infiltration into frozen soils. The expression relates cumulative infiltration, INF, to the soil surface saturation during melting, S_o, the total soil moisture saturation (water + ice), S_I, and temperature, T_I, at the start of snow ablation, and the infiltration opportunity time - the time that meltwater is available at the soil surface for infiltration, t, as:

$$\mathrm{INF} = C S_o^{2.92} \left(1 - S_I\right)^{1.64} \left(\frac{273.15 - T_I}{273.15}\right)^{-0.45} t^{0.44}, \qquad (1)$$

in which C is a bulk coefficient that characterizes the effects on infiltration of differences between model and natural systems.

Up to now, the parametric expression (Eq. 1) has been tested against field measurements of seasonal infiltration. During snow ablation in 1999, a series of field measurements were conducted at sites in the Prince Albert National Park near Waskesiu, SK and on the Kernen Research Farm at Saskatoon SK to obtain data to verify estimates of infiltration by the expression over short time periods. The textures of the soils at the two sites are distinctly different; a sandy loam (43.0% sand, 11.0 clay) at Waskesiu and silty clay (4.4% sand, 49.0% clay) at Saskatoon. The sites were instrumented to provide information on air, snow and soil temperatures, net radiation, soil heat flux and profiles of changes in soil moisture (water + ice) over consecutive measurement dates. These data were used to derive estimates of snowmelt infiltration and infiltration time and to establish the initial and boundary conditions for the physically-based numerical model, HAWTS (Heat And Water Transport in Frozen Soils) Zhao *et al.* 1997. This simulation was used to derive the parametric equation (Zhao and Gray, 1999).

Figure 4 compares modeled and measured profiles of soil moisture (water + ice) at different infiltration opportunity times, showing reasonable agreement (likely within measurement accuracy) between measured and modeled values in the sandy loam soil at Waskesiu. Similarly, there is good agreement among measured and modeled cumulative infiltration with a maximum difference of about 3.5 mm. These results suggest that the parametric expression (Eq. 1) will give reasonable estimates of snowmelt infiltration.

Conclusions

The results listed above demonstrate that cold regions hydrological processes can have profound and previously undocumented impacts on the calculation of surface water and energy fluxes in the Mackenzie Basin. Progress has been made in describing many of the processes in a physical manner, evaluating the process descriptions and in developing operational algorithms for some of the processes. Some coupling, and/or comparison of process algorithms with standard land surface scheme calculations has been demonstrated. The observed multi-scale operation and horizontal interaction of some of these processes means that phenomena operating at very small scales can affect large-scale water and energy balances. The relative success in transposing hydrological process descriptions from one environment to another can be attributed to the strong physical basis of the descriptions.

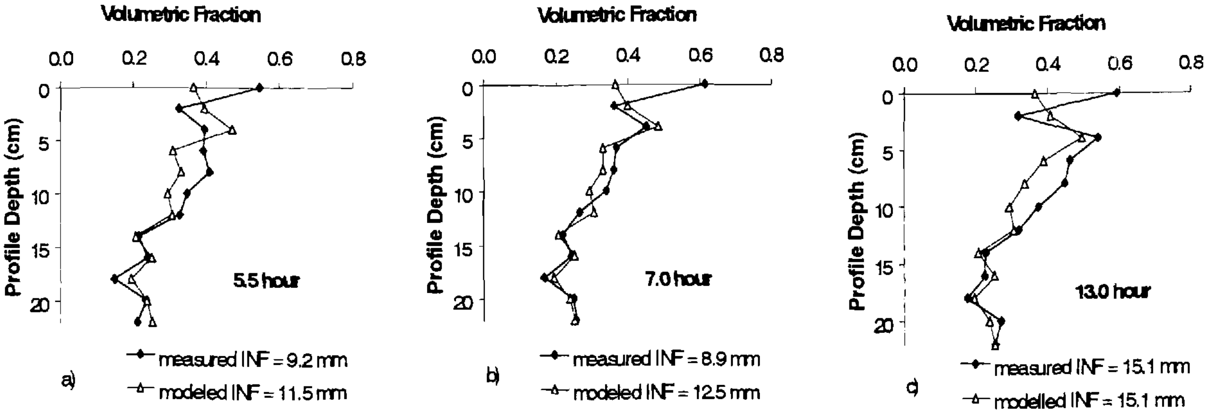

Fig. 4. Comparison of modeled and measured profiles of soil moisture (water + ice) into a frozen sandy loam soil at the Prince Albert Model Forest after 5.5 h (Fig. 4a), 7.0 h (Fig. 4b) and 13.0 h (Fig.4c) of snowmelt infiltration. Simulation initiated at 1200 h March 25/99 and compared to measurements of soil moisture (water + ice) at: a) 1730 h March 25/99, b) 0900 h March 26/99 and c) 1800 h March 26/99.

Recent References

Buttle, J., I. Creed and J.W. Pomeroy. 1999. Advances in Canadian Forest hydrology, 1995-1998. *Hydrological Processes*, in press.

Elliott, J.A., B.M. Toth, R.J. Granger and J.W. Pomeroy, 1998. Soil moisture storage in mature and replanted sub-humid boreal forest stands. Canadian Journal of Soil Science, 78, 17-27.

Essery, R., L. Li and J.W. Pomeroy. 1999. Blowing snow fluxes over complex terrain. Hydrological Processes, 13, 2423-2438.

Faria, D.A., J.W. Pomeroy and R.L.H. Essery. 1999. Forest canopy influences on snowcover depletion. *Hydrological Processes*, in press.

Faria, D.A. 1998. Distributed Energetics of Boreal Forest Snowmelt. M.Sc. Thesis. Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Saskatoon. 140 p.

Granger, R.J. and J.W. Pomeroy, 1997: Sustainability of the western Canadian boreal forest under changing hydrological conditions - 2- summer energy and water use. In: Sustainability of Water Resources under Increasing Uncertainty. (Eds. D. Rosjberg, N. Boutayeb, A. Gustard, Z. Kundzewicz and P. Rasmussen). International Association Hydrological Sciences Publ. No. 240. IAHS Press, Wallingford, UK. pp.243-250.

Hedstrom, N.R. and J.W. Pomeroy, 1997: Accumulation of intercepted snow in the boreal forest. Proc. 65th Annual West. Snow Conf., pp. 130-141.

Hedstrom, N.R. and J.W. Pomeroy, 1998. Measurements and modelling of snow interception in the boreal forest. Hydrological Processes, 12, 1611-1625.

Hedstrom, N.R. 1998. Development and Evaluation of a Cold Regions Snow Interception Model. M.Sc. Thesis. Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Saskatoon. 102 p.

Janowicz, J.R., Gray, D.M. and J.W. Pomeroy, 1997. Snowmelt and runoff in a subarctic mountain basin. In, *Proceedings of the Hydro-ecology Workshop on the Arctic Environmental Strategy.* NHRI Symposium No. 16, 303-320.

Li, L and J.W. Pomeroy, 1997. Estimates of threshold wind speeds for snow transport using meteorological data. Journal of Applied Meteorology. 36(3). 205-213.

Li, L. and J.W. Pomeroy. 1997: Probability of Blowing snow occurrence by wind. Journal of Geophysical Research. 102, D18, 21,955-21,964.

Marsh, P. and J.W. Pomeroy 1999. Spatial and temporal variations in snowmelt runoff chemistry, Northwest Territories, Canada. Water Resources Research, 35(5), 1559-1567.

Marsh, P., N. Neumann, R. Essery and J.W. Pomeroy, 1999. Model estimates of local advection of sensible heat over a patchy snow cover. In, (ed. M. Tranter) Interactions between the Cryosphere, Climate and Greenhouse Gases. IAHS Publ. No. 256. IAHS Press, Wallingford, UK. 103-110.

Marsh, P., J.W. Pomeroy and N. Neumann. 1997: Sensible heat flux and local advection over a heterogeneous at an arctic tundra site during snowmelt. Annals of Glaciology, 25, 132-136.

Maxfield, A.W., P. Marsh, J.W. Pomeroy and W.L. Quinton, 1997: Arctic snow and soil observations by radar satellite. In: Applications of Remote Sensing in Hydrology. (Eds. G.W. Kite, A. Pietroniro and T.J. Pultz). NHRI Symposium No. 17, National Hydrology Research Institute, Saskatoon, SK, pp. 199-210.

Parviainen, J. and J.W. Pomeroy, 1999. Multiple-scale modelling of forest snow sublimation: initial findings. *Hydrological Processes,* in press.

Pomeroy, J.W. and L. Li., 1997: Development of the Prairie Blowing Snow Model for application in climatological and hydrological models. Proc. 65th Annual West. Snow Conf., pp. 186-197.

Pomeroy, J.W. and P. Marsh, 1997: The application of remote sensing and a blowing snow model to determine snow water equivalent over northern basins. In: Applications of Remote Sensing in Hydrology. (Eds. G.W. Kite, A. Pietroniro and T.J. Pultz). NHRI Symposium No. 17, National Hydrology Research Institute, Saskatoon, SK, pp. 253-270.

Pomeroy, J.W. and R.J. Granger. 1997: Sustainability of the western Canadian boreal forest under changing hydrological conditions - I- snow accumulation and ablation. In: Sustainability of Water Resources under Increasing Uncertainty. (Eds. D. Rosjberg, N. Boutayeb, A. Gustard, Z. Kundzewicz and P. Rasmussen). International Association Hydrological Sciences Publ. No. 240. IAHS Press, Wallingford, UK. pp. 237-242.

Pomeroy, J.W. and L. Li. 1999. Prairie and arctic areal snow cover mass balance using a blowing snow model. *Journal of Geophysical Research*, submitted.

Pomeroy, J.W. and R. Essery. 1999. Turbulent fluxes during blowing snow: field tests of model sublimation predictions. *Hydrological Processes*, 13, in press.

Pomeroy, J.W., R. Essery, D.M. Gray, K.R. Shook, B. Toth and P. Marsh, 1999. Modelling snow-atmosphere interactions in cold continental environments. In, (ed. M. Tranter et al.) Interactions between the Cryosphere, Climate and Greenhouse Gases. IAHS Publ. No. 256. IAHS Press, Wallingford, UK. 91-102.

Pomeroy, J.W., N. Hedstrom and J. Parviainen. 1999. The snow mass balance of Wolf Creek. In, (eds. J. Pomeroy and R. Granger) Wolf Creek Research Basin: Hydrology, Ecology, Environment. National Water Research Institute. Minister of Environment: Saskatoon. 15-30.

Pomeroy, J.W., T.D. Davies, H.G. Jones, P. Marsh, N.E. Peters and M. Tranter. 1999. Transformations of snow chemistry in the boreal forest: accumulation and volatilisation. Hydrological Processes, 13, 2257-2273.

Pomeroy, J.W., R. Granger, A. Pietroniro, J. Elliott, B. Toth and N. Hedstrom. 1999. Classification of the boreal forest for hydrological processes. In, (ed. Severin Woxholtt) Proceedings, the Ninth International Boreal Forest Research Association Conference, Oslo, September 21-23, 1998. *Aktuelt fra skogforskningen, 4/99, Norsk institutt for skogforskning.* Norwegian Forest Research Institute, Oslo. 49-59.

Pomeroy, J.W., J. Parviainen, N. Hedstrom and D.M. Gray. 1998. Coupled modelling of forest snow interception and sublimation. Hydrological Processes, 12, 2317-2337.

Pomeroy, J.W., D.M. Gray, K.R. Shook, B. Toth, R.L.H. Essery, A. Pietroniro and N. Hedstrom. 1998. An evaluation of snow accumulation and ablation processes for land surface modelling. Hydrological Processes, 12, 2339-2367..

Pomeroy, J.W., J. Parviainen, N. Hedstrom and D.M. Gray. 1998. Coupled modelling of forest snow interception and sublimation. Proceedings of the Eastern Snow Conference, 55, 101-114.

Pomeroy, J.W., D.M. Gray, K.R. Shook, B. Toth, R.L.H. Essery, A. Pietroniro and N. Hedstrom. 1998. An evaluation of snow processes for land surface modelling. Proceedings of the Eastern Snow Conference, 55, 57-80.

Pomeroy, J.W., P. Marsh and D.M. Gray, 1997. Application of a distributed blowing snow model to the Arctic. Hydrological Processes 11, 1451-1464.

Quinton, W.L., D.M. Gray and P. Marsh. 1999. Sub-surface drainage from hummock-covered hillslopes in the Arctic tundra. *Journal of Hydrology*, in press.

Shook, K. and D.M. Gray, 1997. Synthesizing shallow seasonal snowcovers. Water Resources Research 33 (3):419 - 426.

Shook, K. and D.M. Gray, 1997: Ablation of shallow seasonal snowcovers. In: International Symposium on Physics, Chemistry and Ecology of Seasonally-frozen Soils. Fairbanks, Alaska, June 10-12, 1997. Eds. I.K. Iskandar, E.A. Wright, B.S. Sharratt, P.H. Groenvelt and L. Hinzman. Special Rept. 97-10, US Army Cold Regions Research and Engineering Lab., Hanoever, NH, pp.280-286.

Shook, K. and D.M. Gray, 1997: The role of advection in melting shallow snowcovers. J. Hydrol. Processes, 11, 1725-1736.

Taylor, C.M., R.J. Harding, R.A. Pielke, J.W. Pomeroy, P.L. Vidale and R.L. Walko. 1998. Snow breezes in the boreal forest. Journal of Geophysical Research D18, 103, 23,087-23,103.

Woo, M.K., P. Marsh and J.W. Pomeroy. 1999. Snow, frozen soils and permafrost hydrology in Canada, 1993-98. *Hydrological Processes*, in press.

Zhao, L. and D.M. Gray. 1999. Estimating snowmelt infiltration into frozen soils. *Hydrological Processes*, 13, 1827-1842.

Zhao, L. and D.M. Gray, 1997: A parametric expression for estimating infiltration into frozen soils. J. Hydrol. Processes, 11, 1761-1775.

Zhao, L. and D.M. Gray, 1997. Estimating snowmelt infiltration into medium and fine-textured, frozen soils. In: International Symposium on Physics, Chemistry and Ecology of Seasonally-frozen Soils. Fairbanks, Alaska, June 10-12, 1997. Eds. I.K. Iskandar, E.A. Wright, B.S. Sharratt, P.H. Groenvelt and L. Hinzman. Special Rept. 97-10, US Army Cold Regions Research and Engineering Lab., Hanoever, NH, pp.287-293.