2.4 Hydrological Processes In Cold Regions

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1. Objectives

To study three processes important to the water and energy cycles of northern environments, namely:

1) ablation of seasonal snowcovers;
2) coupled heat and mass transfer in snow and underlying ground;
3) wind transport of snow; and,

to develop physically-based algorithms that describe these processes using field measurements in boreal, alpine and arctic environments.

2. Progress and Collaborations

<u>Field Work</u>

In anticipation of the CAGES field year, major field campaigns were conducted at:

1) Trail Valley Creek, Inuvik: Dec 1997 and March 1998 for blowing snow measurements.
2) Beartrap Creek, Waskesiu: Dec 1997-April 1998 for snowmelt infiltration measurements in boreal forest.
3) Wolf Creek, Whitehorse: March-May 1998 for snowmelt ablation, melt energetics, and infiltration to frozen soils in irregular alpine tundra and boreal forest.

<u>Modelling</u>

New algorithms of the following cold regions hydrological processes have been developed:

1) infiltration into frozen soils – operational algorithm;
2) ground heat flux during snowmelt infiltration into frozen soils;
3) boreal forest snow-covered area ablation;
4) coupled blowing snow – irregular terrain windflow;
5) intercepted snow accumulation/unloading/sublimation.

<u>Collaborations</u>

Collaborations in field work, modelling and analysis with GEWEX investigators: Pomeroy, Marsh, Granger and Pietroniro (NHRI); Woo (McMaster), with DIAND-Yukon, Whitehorse; Aurora College, Inuvik; Hadley Centre for Climate Prediction and Research.

3. Scientific Results

<u>Ablation of Seasonal Snowcovers</u>

Effect of Spatial Distribution of Snowmelt Energy on Ablation of Boreal Forest Snowcover: Previous research by Shook (1995) and Donald *et al.* (1995) has shown that the depletion of snow-covered area is affected by the distribution of snow water equivalent. For open environments, the distribution can be described by a log-normal distribution and modelled as a function of the mean and coefficient of variation of snow water equivalent (SWE) (Pomeroy, *et al.* 1998). Faria (1998) identified a co-distribution of melt energy and SWE for melting snowcovers in the boreal forest. The effect of the energy distribution is to increase energy inputs to shallower snow and, therefore, increase the rate of depletion of snow cover with respect to uniform or random energy conditions. Figure 1 shows the simulated depletion of snow-covered area as a function of the fraction of snowmelt for snowcovers with

(a) a constant initial coefficient of variation of SWE (CV=0.22) and (b) varying measured co-distributions of melt rate with SWE found in several common forest cover types. The less uniform the co-distribution of melt energy with SWE, the more rapid the depletion of snow covered area. Faria found for model runs with actual CV and melt energy distribution that the depletion of snow-covered area was underestimated by uniform melt models from 9% to 78%. Initial comparisons of model results with field data show improved predictions of snow cover depletion under boreal forest canopies.

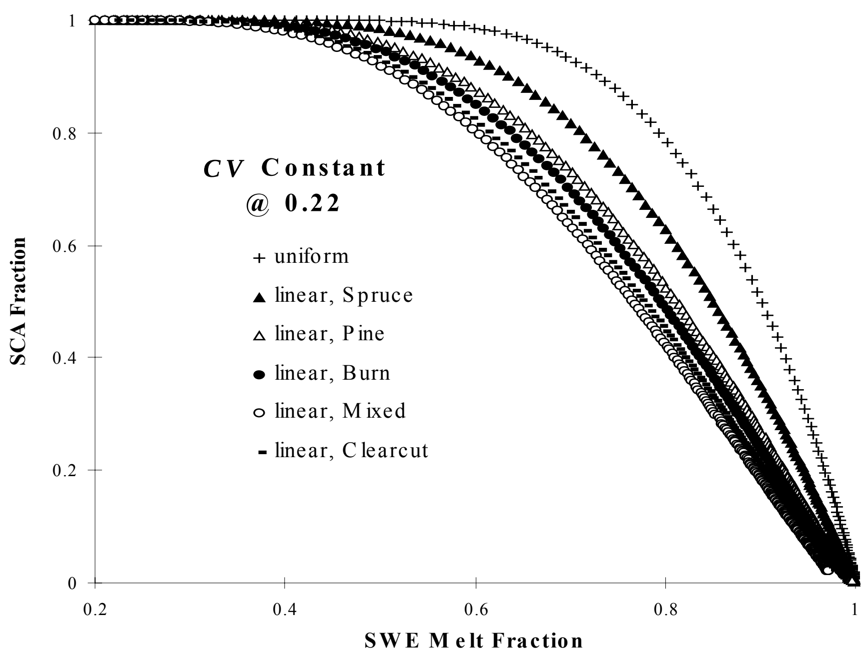

Figure 1 Output of boreal forest distributed snowmelt algorithm for uniform melt and five linear distributed-melt functions (initial *CV* is held constant at 0.22 for the six simulations).

Coupled Heat and Mass Flow in Frozen Ground

Infiltration: A general parametric correlation for estimating snowmelt infiltration into frozen soils was developed (Zhao and Gray 1997, 1998). 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:

$$INF = CS_o^{2.92}\left(1 - S_I\right)^{1.64}\left(\frac{273.15 - T_I}{273.15}\right)^{-0.45} t^{0.44}$$

in which C is a bulk coefficient that characterizes the effects on infiltration of differences between model and natural systems. Representative values of C for frozen sandy soils in a boreal forest and various fine-textured (sandy loam, loam, silty clay, and clay) frozen prairie soils were determined from field measurements made in the two ecosystems during snowmelt. These calibrations gave best-fit values of C=1.3 and C=2.05 for the boreal forest and Prairie sites, respectively. Estimates of cumulative infiltration with the appropriate value of C are compared against measured data in Figures 2a and 2b. The standard deviation of the difference among values for the boreal forest sites is 10 mm and the majority of the predicted values (75%) fall within the error band (Figure 2a). Similarly, the standard deviation of the difference among values for the prairie sites is 10 mm and the majority of the predicted values (88%) fall within the error band (Figure 2a). These results suggest that the correlation, with appropriate calibration, will provide acceptable estimates of the snowmelt infiltration into frozen mineral oils for use in operational hydrology schemes.

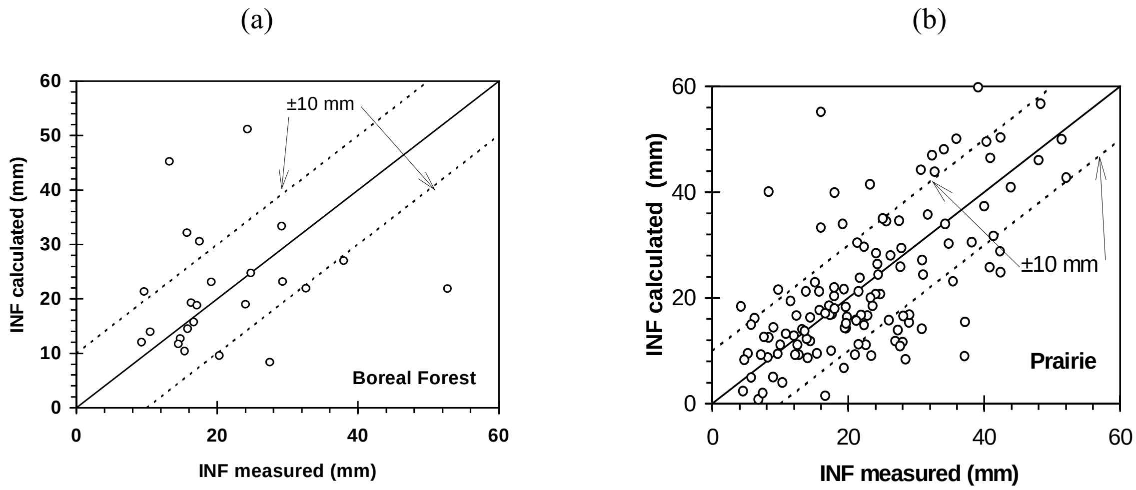

Figure 2 Comparison of calculated and measured cumulative infiltration for boreal forest (a) and prairie (b) sites.

<u>Ground Heat Flux</u>

Infiltration into frozen ground involves simultaneous coupled heat and mass transfers with phase changes. Therefore, the presence of infiltrating water affects heat transfer into the ground and the soil temperature regime. Field measurements (Kane and Stein 1983) and model simulations (Zhao *et al.* 1997) demonstrate that both the infiltration rate and the surface heat transfer rate (conduction) in a frozen soil decrease with time following the application of meltwater to the surface (Figure 3). Zhao *et al.* (1997) separate these variations into two regimes, a transient regime and a quasi-steady state regime. The transient regime follows immediately the application of water on the surface and during this period the infiltration rate and the heat transfer rate decrease rapidly. The quasi-steady state regime occurs where the changes in the infiltration rate and the heat transfer rate with time are relatively small. The duration of the transient period is usually short (a few hours) and the energy used to increase the soil temperature is largely supplied by heat conduction at the surface (high heat transfer rate at the surface). In the quasi-steady state regime, the energy used to increase the soil temperature at depth is supplied by latent heat released by the refreezing of percolating meltwater in the soil layers above (low heat transfer rate at the surface. Zhao *et al.* (1997) estimate that as much as 90% of the latent heat (say 90%) released by the refreezing of meltwater is conducted deeper in the soil where it used for melting and increasing the soil temperature.

Most simulations of ground heat in land process models are based on heat transfer by conduction using the temperature gradient approach and simulated soil temperatures at 3 or 4 levels in a soil profile that extends to the rooting depth of the crop or below. The application of this approach for estimating the ground heat flux in frozen soils during snowmelt infiltration is not straightforward. The difficulty arises because the most important heat and mass transfer processes affecting the flux occur in the surface layers of the soil. Consequently, the temperature gradient at the soil surface is determined by soil temperature profile near the surface (top 10 cm) and the temperature gradient at depth (below) is established by the downward conduction of latent heat released by the freezing of percolating water. Therefore, the processes of heat and mass transfers into frozen soils during infiltration can only be described properly by a mult-ilayered model having a reasonably small grid spacing. For those models with only a few soil layers, the ground heat flux should not be calculated by estimating the temperature gradient. Instead, it is likely that the assumption of a very small value for ground heat or the use of parametric or empirical correlations for estimates of both the ground heat and infiltration will give better results.

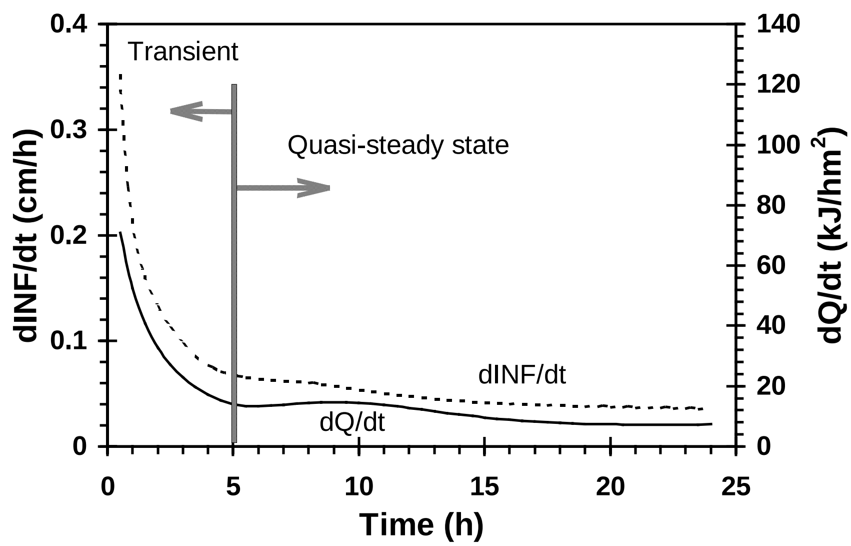

Figure 3 Variations in infiltration rate, dINF/dt, and surface heat flux rate, dQ/dt, with time during snowmelt infiltration into a frozen silty clay soil.

<u>Wind Transport of Snow</u>

Blowing Snow Fluxes over Complex Terrain: PBSM was simplified, spatially-distributed and driven using a terrain windflow model MS3DJH/3R over the complex arctic terrain of Trail Valley Creek on an hourly time step (Essery *et al.,* 1998). Topography was permitted to vary according to measurements contained in a geographic information system (digital elevation model). Probability of blowing snow occurrence algorithms in the simplified PBSM were sensitive to vegetation type and burial of vegetation by snow, and used to index the effect of variable vegetation roughness on blowing snow. The simulation was run for Trail Valley Creek over the winter of 1996-97 on an hourly time step with a spatial resolution of 80 m. Mean SWE and CV of SWE are within a standard deviation of measured values at the end of the winter season. A simulation with suppressed sublimation provided much greater predicted snow accumulation than that observed. Several new open terrain landscape classes were identified based on windflow regimes: windswept, windward, divergent, neutral, and convergent. The mean SWE and CV of SWE are notably different amongst these regimes. Figure 4 shows predicted frequency distributions for end of season SWE in various terrain types. The differences are the result of wind redistribution.

Normal distributions of SWE, fitted to the frequency histograms predicted by the complex terrain blowing snow model (Figure 4) can be used to initialize models of snow-covered area depletion. The distributions are also the first physically-modelled estimates of the variability of SWE over complex tundra terrain and are critical to "scaling up" snowcover estimates for the Mackenzie Basin.

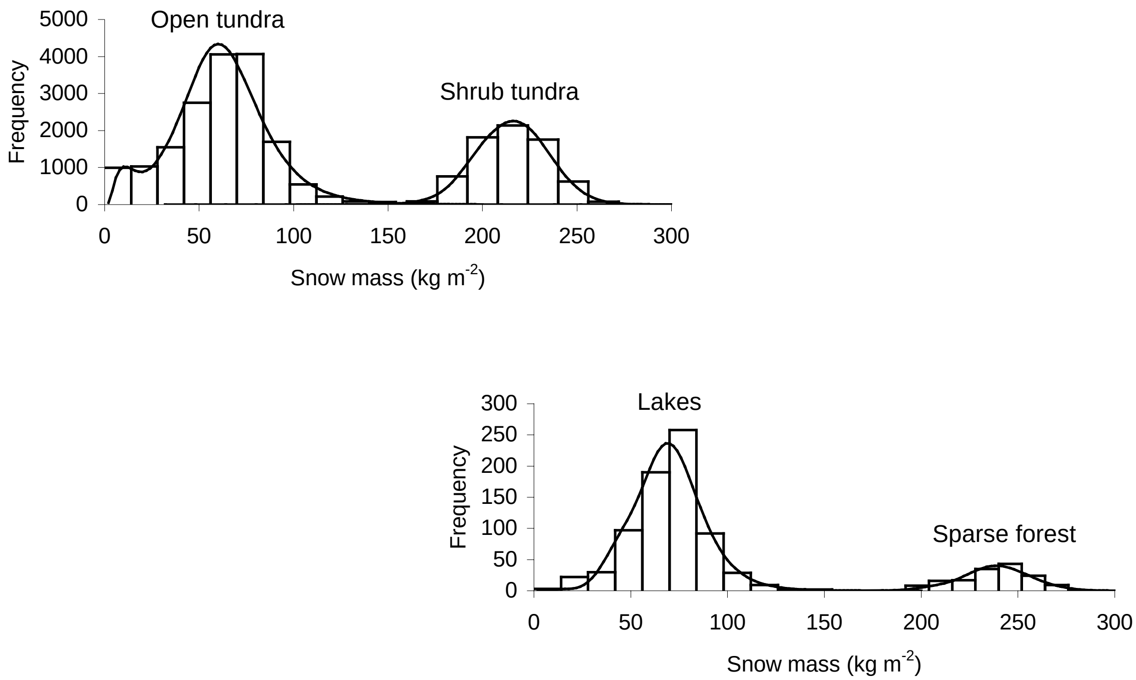

Figure 4 Histograms showing modelled snow water equivalent (expressed as mass) frequency compared to summed lognormal distributions for terrain types of varied vegetation and topographic placement in Trail Valley Creek, spring 1997.

Coupled Interception-Sublimation Model

A series of process-based algorithms has been developed to describe the accumulation, unloading and sublimation of intercepted snow in forest canopies (Pomeroy *et al.*, 1998). These algorithms are unique in that they scale-up the physics of interception and sublimation from small-scales, where they are well understood, to forest stand-scale calculations of intercepted snow sublimation. The interception algorithms are based on that of Hedstrom and Pomeroy (1998). The sublimation algorithm is that used in the blowing snow model PBSM, with modifications to account for exposure of snow in a forest canopy (Pomeroy and Schmidt, 1993). Figure 5 shows measured and modelled daily sublimation from intercepted snow, using the model and measurements of snow mass and mass loss from a suspended, weighed tree. It indicates that a reasonable estimation of sublimation fluxes can be achieved. Evaluation of results from the set of algorithms against measured interception and sublimation in a southern boreal forest jack pine stand during late winter, found the coupled model provides reasonable approximations of both interception and sublimation losses on half-hourly, daily, and event basis. Cumulative errors in estimate of intercepted snow load over 23 days of test were 0.06 mm SWE with a standard deviation of 0.46 mm SWE. Sublimation losses during the evaluation were high, approximately two-thirds of snowfall within this period. Seasonal intercepted snow sublimation as a portion of annual snowfall at the model test site was lower than sublimation during the tests, ranging from 13% for a mixed spruce-aspen, 31% for the mature pine and 40% for a mature spruce stand. The results indicate that sublimation can be a significant abstraction of water from mature evergreen stands in northern forests and that the losses can be calculated by application of process-based algorithms.

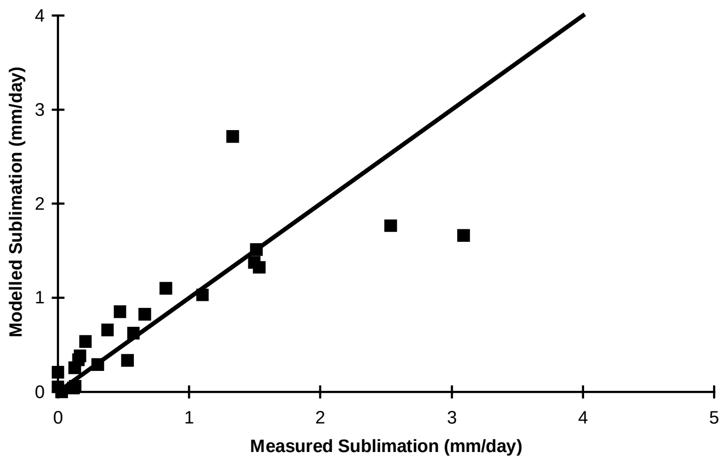

Figure 5 Daily measured sublimation fluxes, calculated from the loss of snow mass from a weighed pine tree versus modelled sublimation.

4. Summary

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 and in developing operational algorithms for some of the processes. 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.

5. Literature Cited

Donald, J.R., E.D. Soulis, N. Kouwen, and A. Pietroniro, 1995. A land cover-based snow cover representation for distributed hydrological models. *Water Resources Research*, **31**(4): 995-1009.

Faria, D., 1998. *The Energetics of Boreal Forest Snowmelt.* Unpublished M.Sc. Thesis, University of Saskatchewan, Saskatoon, SK, 158 p.

Kane, D.L. and J. Stein, 1983. Water movement into seasonally frozen soils. *Water Resources Res.* **19**(6):1547-1557.

Shook, K., 1995. *Simulation of the Ablation of Prairie Snowcovers.* Ph.D. Thesis. University of Saskatchewan, Saskatoon, SK, pp. 1-189.

6. Recent Publications and Presentations

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, 1998. Blowing snow fluxes over complex terrain, 1, distributed modelling. *J. Hydrol. Processes*. (submitted)

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: D. Rosjberg, N. Boutayeb, A. Gustard, Z. Kundzewicz, and P. Rasmussen (Eds.), *Sustainability of Water Resources under Increasing Uncertainty*, International Association Hydrological Sciences Publ. No. 240, IAHS Press, Wallingford, UK, pp. 243-250.

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

Hedstrom, N.R. and J.W. Pomeroy, 1997. "Accumulation of intercepted snow in the boreal forest." In: *Proceedings, 65th Annual Western Snow Conference*, pp. 130-141.

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

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:. G.W. Kite, A. Pietroniro and T.J. Pultz (Eds.), *Applications of Remote Sensing in Hydrology*, NHRI Symposium No. 17, National Hydrology Research Institute, Saskatoon, SK, pp. 199-210.

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: D. Rosjberg, N. Boutayeb, A. Gustard, Z. Kundzewicz, and P. Rasmussen (Eds.), *Sustainability of Water Resources under Increasing Uncertainty*, International Association Hydrological Sciences Publ. No. 240, IAHS Press, Wallingford, UK, pp. 237-242.

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. *J. Hydrological Processes* (in press). Also, presented at the Eastern Snow Conference, In: *Proceedings Eastern Snow Conference*, **55** (in press).

Pomeroy, J.W. and L. Li., 1997. "Development of the Prairie Blowing Snow Model for application in climatological and hydrological models." In: *Proceedings, 65th Annual Western Snow Conference*, 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: G.W. Kite, A. Pietroniro, and T.J. Pultz (Eds.), *Applications of Remote Sensing in Hydrology*, NHRI Symposium No. 17, National Hydrology Research Institute, Saskatoon, SK, pp. 253-270.

Pomeroy, J.W., J. Parviainen, N. Hedstrom, and D.M. Gray, 1998. Coupled modelling of forest snow interception and sublimation. *J. Hydrological_Processes* (in press). Also, presented at the Eastern Snow Conference, In: *Proceedings, Eastern Snow Conference*, **55** (in press).

Shook, K. and D.M. Gray, 1997. "Ablation of shallow seasonal snowcovers." In: .I.K. Iskandar, E.A. Wright, B.S. Sharratt, P.H. Groenvelt, and L. Hinzman (Eds.), *International Symposium on Physics, Chemistry and Ecology of Seasonally-frozen Soils*, June 10-12, 1997, Fairbanks, Alaska, 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. *J. Geophysical Res*., D18, 103, 23,087-23,103.

Zhao, L. and D.M. Gray, 1998. Estimating snowmelt infiltration into frozen soils. *J. Hydrol. Processes*. (in press)

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: I.K. Iskandar, E.A. Wright, B.S. Sharratt, P.H. Groenvelt, and L. Hinzman (Eds.), *International Symposium on Physics, Chemistry and Ecology of Seasonally-frozen Soils*, June 10-12, 1997, Fairbanks, Alaska, Special Rept. 97-10, US Army Cold Regions Research and Engineering Lab., Hanoever, NH, pp. 287-293.

- N.D. Plenary presentation to Eastern Snow Conference.
- N.D. Invited talk to Universitiy of East Anglia, Norwich, UK.
- N.D. Numerous other presentations (>25) in Ontario, Qu0bec, New Hampshire, Vermont, Norway, Japan, England, Saskatchewan, Alberta, Yukon.

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