2.3 Biome Scale Representation of Snow Cover Development and Ablation in Boreal and Tundra Ecosystems

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1. Objectives

(1) Define mass and energy fluxes governed by the land surface processes of snow interception, redistribution, sublimation and ablation.
(2) Formulate process-based algorithms that represent snow cover development and ablation in boreal, alpine and arctic regions.
(3) Integrate these algorithms in distributed basin, continental-scale and global hydrometeorological models.

This study addresses MAGS objectives by identifying, quantifying and synthesizing at multiple scales the energy and mass fluxes associated with snow cover development and ablation in both forest and open land covers. Algorithms describing the processes are being incorporated in larger-scale models and these models are tested using field datasets. It is the only MAGS government study using both field observations and physically-based modelling to:

- develop and test hypotheses of the hydrological processes that lead to redistribution and sublimation of snow throughout the Mackenzie domain;
- examine the role of the forest canopy in modifying fluxes between the atmosphere and snow surface; and,
- verify model representations of snow redistribution, sublimation and subcanopy melt, and the associated mass and energy fluxes.

2. Progress and Collaborations

Field Work

Measurements of snow fluxes have been collected in recent campaigns conducted at four Canadian GEWEX "research basins" in the MAGS domain:

- Southern boreal forest: *Beartrap Creek*, Waskesiu, SK with pine, mixed-wood, burned, clear-cut and regenerating pine clear-cut sites - winter forest accumulation and spring ablation: turbulent and radiative energy fluxes from young jack pine, snow distribution, canopy temperature, intercepted snow load, melt rate, soil temperature, and heat flux during melt.

- Boreal-alpine transition: *Wolf Creek*, Whitehorse, Yukon with alpine, shrub-tundra, and spruce forest sites - winter alpine accumulation and spring ablation: intercepted snow load, blowing snow flux, snow drifts on alpine hillsides, snow distribution, melt rate on alpine hillsides, snow-covered area depletion in alpine, surface temperatures and heat flux during melt.

- Subarctic spruce forest-tundra: *Havikpak Creek*, Inuvik, NWT - winter subarctic accumulation: intercepted snow load, snow distribution.

- Arctic tundra: *Trail Valley Creek*, north of Inuvik, NWT sparse tundra – winter arctic accumulation: snow distribution, blowing snow flux.

An invited one-month visit to the *Cryospheric Environment Simulator* of the National Institute for Earth Science and Disaster Prevention, Japan Science and Technology Agency, Shinjo, Japan has provided a controlled snow environment for experiments designed to improve present theories on the physics of sensible heat advection to melting snow patches.

Modelling

The measurements have been complemented by modelling of blowing snow and intercepted snow processes and linkages with land-surface models, hydrological models, and GCMs.

- Coupled snow interception, unloading and sublimation model: A coupled model based on snow exposure, intercepted snow accumulation, unloading, and energy balance calculations has been developed and tested for determination of snow sublimation from coniferous canopies. Improvements have been proposed for CLASS calculation of snow interception.

- Winter energy balance of the boreal forest: The winter energy budget of boreal forest and lakes has been quantified, compared, and modelled in a regional atmospheric model (RAMS). Boreal forest albedo has been quantified and modelled, the improvements have contributed to improved ECMWF simulations of the boreal forest surface temperature in spring.

- Snowmelt dynamics in the boreal forest: The influence of the co-distribution of subcanopy energy flux and snow water equivalent on snowmelt rates in the boreal forest has been quantified and coded into an algorithm for snow-covered area depletion in boreal forests.

- Blowing snow model for GCMs: An existing blowing snow model (PBSM) has been substantially redeveloped so that it is suitable for coupling to GCMs.

- Blowing snow in a hydrological model: An existing large-scale hydrological model, SLURP, was recoded using blowing snow physics into *PBS-SLURP*, which calculates snow redistribution between landcover types within ASAs, sublimation loss within an ASA and then snowmelt infiltration into frozen soils. Initial testing of model performance was conducted.

- Blowing snow fluxes over complex terrain: PBSM was run with the MS3DJH/3R complex terrain wind flow model to calculate sublimation, transport, and accumulation of blowing snow over irregular arctic terrain. Results were compared to field measurements of snow distribution.

Collaborations

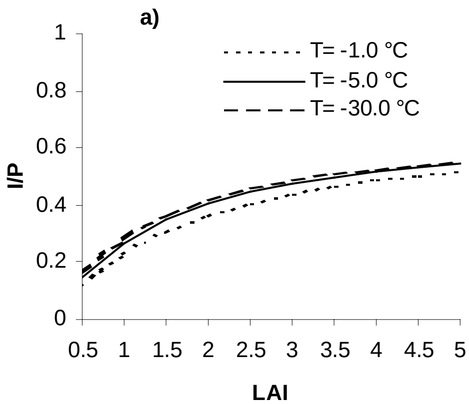
Strong collaborations were maintained at the research basins with Granger, Marsh, Woo, Gray, and Janowicz, and in the laboratory with Sato. The important collaboration with Gray has been strongly pursued, with co-supervision of graduate students, technicians, research officers, post-doctoral fellows, and common field and modelling strategies. Modelling was conducted in concert with Pietroniro, Marsh, Gray, Woo, Verseghy, Soulis, Kite, Harding, Yau, Essery, and Davies through algorithm/code exchange, data exchange, and planned co-development of modelling strategies.

3. Scientific Results

Recent results are highlighted by:

- Snow interception algorithm: field results show that leaf area, canopy closure, species type, time since snowfall, snowfall amount, and existing snow load control the efficiency by which snow is intercepted.. A physically-based algorithm (first of its kind and winner of two awards) describing these results has been field validated at Beartrap Creek and is being tested at Wolf Creek and Havikpak Creek (Figure 1). Results of this study have been presented at the *1997 CGU* and *CMOS*

Conferences, published in the *Proceedings of the Western Snow Conference* and *Hydrological Processes*. A thesis on this topic by Mr. N. Hedstrom under my supervision is being finalized. Initial examination of CLASS supports a recommendation that CLASS and other land surface schemes, incorporate the Snow Interception Algorithm to correct an order of magnitude underprediction of intercepted snow.



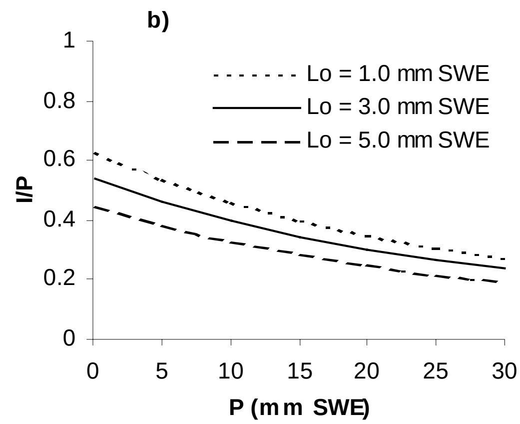


Figure 1 Modelled interception efficiency (snow interception/snowfall) as a function of a) winter leaf area index and air temperature, b) snowfall and initial canopy snow load (L_o).

- Exposure parameterization of intercepted snow: fractal geometry indexes the exposure of intercepted snow in the forest canopy, an important parameter for sublimation rate calculations and for calculating the "resistance" of intercepted snow to sublimation. The relationship between fractal dimension of snow and canopy resistance for evaporation calculations is being examined. The fractal geometries of intercepted snow in forests of the research basins can be measured by digitized canopy photographs, and modelled for input to sublimation algorithms as described below.

- Coupled snow interception, unloading, and sublimation algorithm: a coupled model of snow interception, unloading and sublimation, based on snow exposure, intercepted snow accumulation and energy balance calculations can determine snow sublimation from coniferous canopies. Sublimation losses are 30 to 45% of annual snowfall for conifers in the southern and montane boreal forest. Initial tests of the coupled model at Beartrap Creek are highly successful and have been presented at the *1997 CMOS Congress*, as invited lectures to Quebec & Japan and to user groups in northern Saskatchewan. A paper describing the model has been published in *Hydrological Processes*.

- Winter energy balance of the boreal forest: the latent heat flux in winter was found to be large and variable, its direction governed by conifer coverage and the load of intercepted snow. Shortwave radiation is extinguished and longwave emitted by conifer canopies, the downward longwave flux found to be controlled by the angle of incoming shortwave. A canopy radiation model based on these observations describes this phenomenon and its implications for sublimation and snowmelt. The implications are important; high net radiation in the canopy provides energy for mid-winter sublimation and radiation attenuation by dense canopies lengthens the snowmelt period 3-fold compared to open areas. Frozen lakes were found to have energy fluxes of differing magnitude, direction, and diurnal pattern from forests. Aggregation of fluxes from frozen lake and boreal forest surfaces was found to be complicated by local-scale advection of energy between lake and forest. The local-scale advection was described using a regional atmospheric model (RAMS) and shown to involve complex patterns of divergent or convergent "snow breezes" between small lakes and adjoining forest. The implications are that aggregation of fluxes from such differing surfaces may not necessarily be successfully accomplished by tiling or blending height techniques without further improvements in scaling techniques. Papers describing this were published in the *Journal of Geophysical Research, Journal of Climate, Hydrological Processes,* and *International Association of Hydrological Sciences Publ. No. 240.*

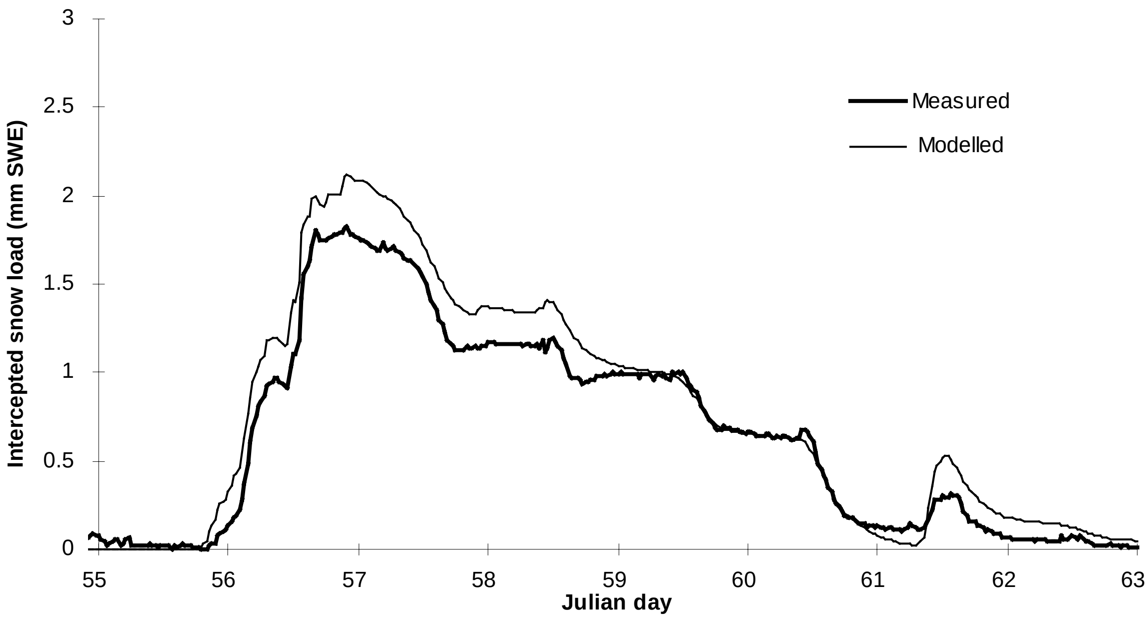


Figure 2 Modelled and simulated intercepted snow load in a pine forest: change in intercepted snow load is due to precipitation, unloading, and sublimation. Measured snow load is derived from the mass of snow weighed on a suspended pine tree, scaled to areal snow water equivalent by comparative measurements of above canopy snowfall and below canopy snow accumulation. (after Pomeroy, Parviainen, Hedstrom, and Gray 1998)

- Snowmelt dynamics in the boreal forest: a coupling between subcanopy energetics and snow water equivalent has been detected, and provides the basis for a snowmelt scaling algorithm that scales processes operating at the individual tree level up to canopy or regional scale snowcover depletion curves. The co-distribution of sub-canopy snowmelt energy and SWE (smaller SWE is associated with higher energy) significantly accelerates the depletion of snow-covered area during melt - results were presented at the *1997 CMOS Congress* and the *International Union of Geodesy and Geophysics Congress* - *Morocco* and are being finalized in a thesis under my supervision "Distributed Snowmelt Energetics in the Boreal Forest" by Mr. D. Faria.

- Distributed blowing snow model (DBSM): Landscape classifications, an irregular windflow model, snowmelt, and blowing snow process routines can be used to determine blowing snow fluxes over complex land surfaces. Initial tests with a DBSM represented the distribution of snow water equivalent in test basins and matched basin snow accumulation within 6%. Sublimation losses were small for the subarctic basin, about 21% over the arctic basin and 30% from tundra surfaces. Subsequent tests with a more physically-based DBSM show that arctic tundra is composed of a variety of blowing snow flow zones, largely controlled by vegetation cover. Results with suppressed sublimation (Taylor's hypothesis) produced snow accumulation in vegetation that was much greater than that observed, whilst results that included sublimation produced snow accumulation distributions near to values measured. An example of the mapped snow water equivalent distribution for an arctic domain is shown in Figure 3. The results were published in *Hydrological Processes* and *Applications of Remote Sensing in Hydrology* and presented at the *International Conference on Snow Hydrology*.

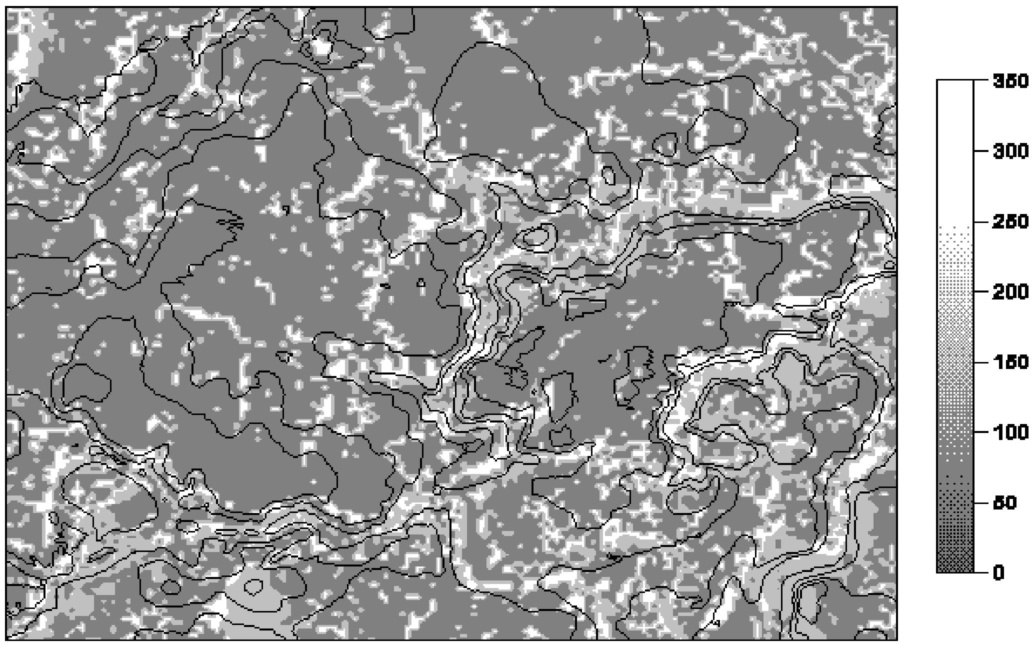


Figure 3 Mapped distribution of late winter snow accumulation (mm SWE) in the Trail Valley Creek domain, simulation produced with a version of PBSM coupled to the Walmsley/Salmon/Taylor MS3DJH/3R complex terrain boundary-layer model. (after Essery, Li, and Pomeroy 1998)

- Blowing snow model for GCMs and hydrological models: the probability of occurrence of blowing snow over time or space (for uniform terrain) follows a cumulative normal distribution, which is controlled by snow temperature, snow age, vegetation exposure, and occurrence of melt or rain. An algorithm describing blowing snow probability provides a means to scale blowing snow fluxes from point to large areal averages in a computationally simple manner. An example of the model operation for tundra surfaces at Trail Valley Creek is shown in Figure 4. The model has been revised for potential coupling to land surface schemes and, as a demonstration, has been coded along with a frozen soil infiltration scheme into the SLURP hydrological model as PBS-SLURP. Tests of PBS-SLURP in a prairie catchment were extremely promising in that the snowmelt runoff hydrograph was correctly simulated without the calibration that is normally necessary with SLURP. The revised model is described in *Journal of Geophysical Research*, *Journal of Applied Meteorology*, a NWRI Report, a paper given to *1997 CMOS Conference,* published in the *Proceedings of the Western Snow Conference* and in two manuscripts submitted to *Journal of Geophysical Research*.

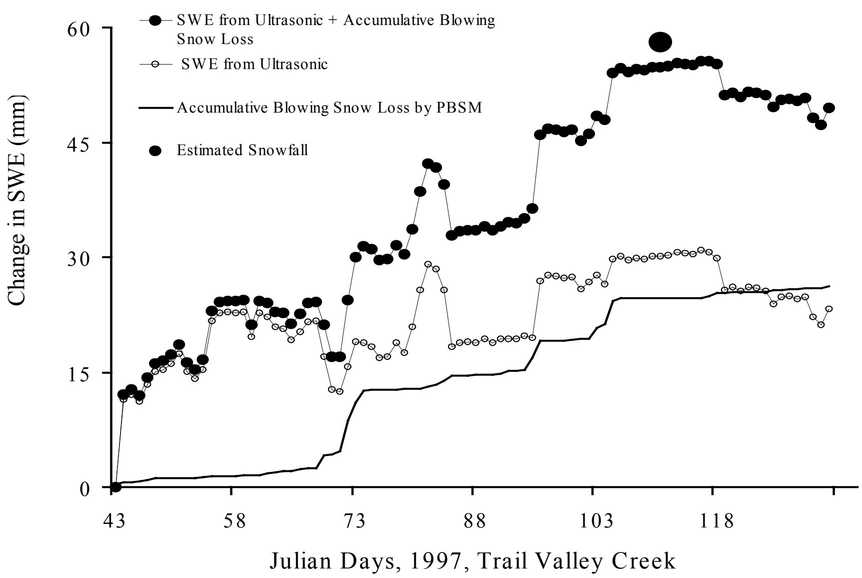


Figure 4 Modelled PBSM single-column spatially-scaled results for Trail Valley Creek open tundra site. (after Pomeroy and Li 1998). Accumulated blowing snow loss is due to transport and sublimation of blowing snow, snow water equivalent is estimated based on measured snow depth and density, corrected to areal snow surveys, the sum of snow water equivalent, and blowing snow losses should equal snowfall if the modelled and estimated values are correct.

- <u>Snow accumulation and ablation process recommendations for land surface schemes</u>: a major review paper detailing a series of recommendations on appropriate modelling strategies for snow accumulation and ablation processes in land surface schemes was presented as the *Plenary Talk* to the *Eastern Snow Conference, 1998*, an invited lecture to the University of East Anglia, England, published in the *Proceedings of the Eastern Snow Conference* and in *Hydrological Processes*. A subsequent paper is being prepared for presentation and publication in an IAHS symposium in the IUGG 1999.

These results apply to MAGS objectives by providing an identification and understanding of snow redistribution, sublimation, and melt in the MAGS area - demonstrating the incorporation of this understanding in multi-scale representations that are linked to large-scale models and providing a means of verifying large-scale models in the MAGS domain.

4. Summary

Substantial progress has been made in defining the mass and energy fluxes governed by snow interception, redistribution, sublimation, and ablation processes. Algorithms have been devised to describe these processes, the state of developed ranges from verified to provisional. Substantial progress has been made for the arctic and boreal forest environment, with the effort now to be concentrated on the more complex alpine environment. Initial progress has been made to integrate the algorithms in GCM land surface schemes, regional atmospheric models, and large-scale hydrological models; however, substantial problems have also been identified. Critical multiple-scale horizontal fluxes of mass and energy have been detected near the surface for all the processes examined. The scaling of these horizontal fluxes to provide larger-scale representations of vertical fluxes is not trivial and will require a large effort in the future.

5. Publications and Presentations for MAGS

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- 1998. Invited Talk to University of East Anglia, Norwich, UK.
- N.D. Numerous other presentations in Ontario, Quebec, New Hampshire, Vermont, Norway, Japan, England, Saskatchewan, Alberta, Yukon.

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