1.5 Biome-scale Representation of Snow Cover Development and Ablation in Boreal and Tundra Ecosystems

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ABSTRACT

The objectives of this study were to:

- Define mass and energy fluxes governed by the land surface processes of snow interception, redistribution, sublimation and ablation;
- Formulate process-based algorithms that represent snow cover development and ablation in boreal, alpine and arctic regions; and
- Integrate these algorithms in hydro-meteorological models.

Substantial progress has been made in defining the mass and energy fluxes governed by snow interception, redistribution, sublimation and ablation processes over both complex and uniform terrain. Estimates of sublimation losses from blowing snow range up to 50% of seasonal snowfall and have been verified by mass balance techniques. The existence of such large sublimation fluxes is supported by eddy correlation water vapour flux measurements in excess of 60 W m^{-2} during blowing snow. Estimates of sublimation from snow intercepted by conifers range up to 45% of seasonal snowfall and have been verified at small and medium scales by mass balance techniques and eddy correlation water vapour flux measurements. Snowmelt under evergreen forest canopies is retarded up to 3 fold relative to that in open areas due to reduced sub-canopy radiation and turbulent transfer. The inverse spatial association between snow accumulation and melt energy under forest canopies; however, acts to accelerate snow cover depletion under forest canopies relative to conditions without such associations.

The effects of spatial variability have been incorporated in algorithms describing these processes for arctic, alpine and boreal forest environments. Integration of the algorithms in GCM land surface schemes and large-scale hydrological models has shown that substantial problems can develop with the stability of such models when physically based descriptions are introduced. However, it is felt that the next generation of model will be able to take advantage of such process improvements.

Introduction

Snow cover accumulation and ablation were poorly understood processes in the Mackenzie Basin at the start of MAGS. This study initially focused on identifying the major accumulation and ablation processes that operated in the primary land covers of the Mackenzie. It followed the identification of processes by detailed description of their rates and energetics, interaction with atmosphere and surface and by descriptions suitable for inclusion in several popular modelling platforms. The objectives of this study were to:

- Define mass and energy fluxes governed by the land surface processes of snow interception, redistribution, sublimation and ablation;

- Formulate process-based algorithms that represent snow cover development and ablation in boreal, alpine and arctic regions; and
- Integrate these algorithms in hydrometeorological models.

This study identified, quantified and synthesized at multiple-scales the energy and mass fluxes associated with snow cover development and ablation in both forest and open land covers. Particular attention was paid to the problem of upscaling process representations from point to basin scales. Algorithms describing the upscale processes were incorporated in larger scale models. The study used 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 representations of snow redistribution, sublimation and sub-canopy melt and the associated mass and energy fluxes.

It is felt that physically based descriptions of processes and field verification of hypotheses have represented strengths of this study and that as a result the conclusions can be applied with confidence to the Mackenzie Basin and other high latitude environments.

Methodology

Field Work

Measurements of snow fluxes have been collected in recent campaigns conducted at four Canadian GEWEX "research basins" in the MAGS domain and one prairie land use test site:

<u>Southern Boreal Forest:</u>

Beartrap Creek, Waskesiu, Saskatchewan - 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.

<u>Boreal-Alpine Transition</u>:

Wolf Creek, Whitehorse, Yukon - 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.

<u>Subarctic Spruce Forest-Tundra:</u>

Havikpak Creek, Inuvik, NWT - winter subarctic accumulation: intercepted snow load, snow distribution

<u>Arctic Tundra:</u>

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

<u>Prairie</u>:

Kernan Farm, east of Saskatoon, Saskatchewan - open environment blowing snow sublimation fluxes and snowmelt energetics.

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. The full interception-sublimation model has been coded into a coupled model with existing CLASS subroutines.

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 (reduced snow-covered albedo for conifers) have contributed to significantly improved ECMWF simulations of the boreal forest surface temperature in spring.

Snowmelt Dynamics in the Boreal Forest:

The influence of the spatial association 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. This model has been field validated with direct eddy flux measurements of sublimation as well as surface snow mass balance methods for transport and sublimation quantities.

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, showing dramatic improvement for open environments.

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. The model can also predict snow water equivalent distributions for various land cover types – an important input for snow covered area depletion calculations. Results were compared to spatially distributed measurements of snow distribution and provided an indirect confirmation of the sublimation and transport calculations over complex terrain.

Results

Snow Interception Algorithm

Field results show that leaf area, canopy closure, species type, time since snowfall, snowfall amount and existing snow load controls 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 co-supervision, was successfully defended in November 1998. 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.

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 geometry 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.

C*oupled 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 30-45% 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. Paper describing the model has been published in *Hydrological Processes* and *Proceedings of the Eastern Snow Conference*. The coupled model has been coded into CLASS forest canopy subroutines with the complete coupled model the subject of a thesis completed by Mr. Jason Parviainen, under my supervision.

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 Publication No. 240.*

Snowmelt Dynamics in the Boreal Forest

A correlation between subcanopy energetics and snow water equivalent has been detected, and provides the basis for a snowmelt scaling algorithm that scales the variation in melt energy at the individual tree level up to the canopy or regional scale to provide improved snow-cover depletion curves. The correlation 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.* Results were published as a thesis entitled, "Distributed Snowmelt Energetics in the Boreal Forest" by Mr. D. Faria, under my supervision. Mr. Faria successfully defended in November 1998.

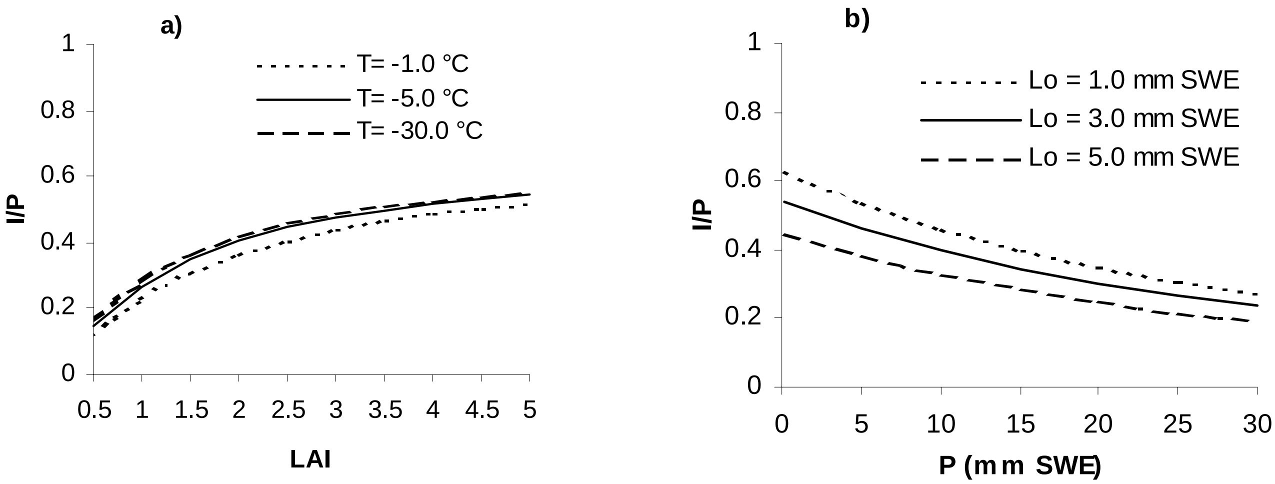

Figure 1 **Modelled interception efficiency (snow interception/snowfall) as a function of a) winter leaf area index and air temperature, b) snowfall and initial canopy snow load (L_o).**

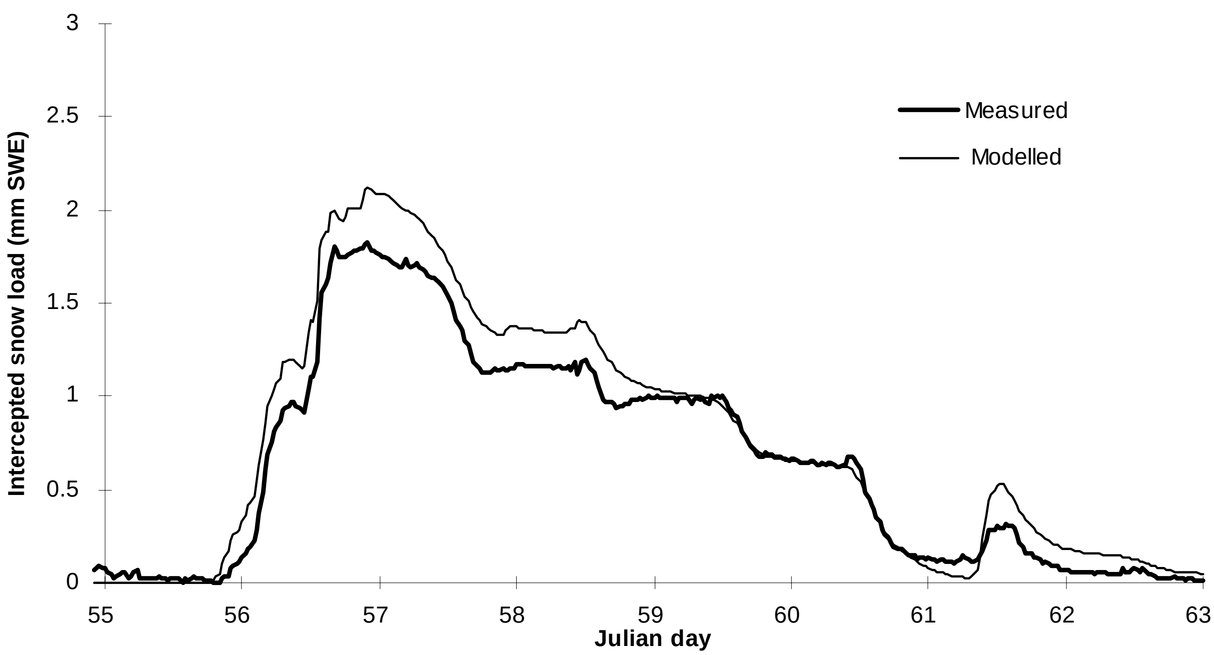

Figure 2 **Modelled and simulated intercepted snow load in a pine forest: change in intercepted snow load is due to precipitation, unloading and sublimation. Measured snow load is derived from the mass of snow weighed on a suspended pine tree, scaled to areal snow water equivalent by comparative measurements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

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*.

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 was subjected to a test along with a typical GCM bulk water vapour transfer routine (UKMO) against direct eddy correlation measurements of latent heat flux during a blowing snowstorm and during lower wind speed periods on a prairie outside of Saskatoon.

As shown in Figure 5, the blowing snow model calculates latent heat fluxes to a much greater accuracy than can a GCM land surface routine for high wind speed events. 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 recently in *Journal of Geophysical Research*.

Snow Accumulation and Ablation Process Recommendations for Land Surface Schemes

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 was presented and published at the IUGG in 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.

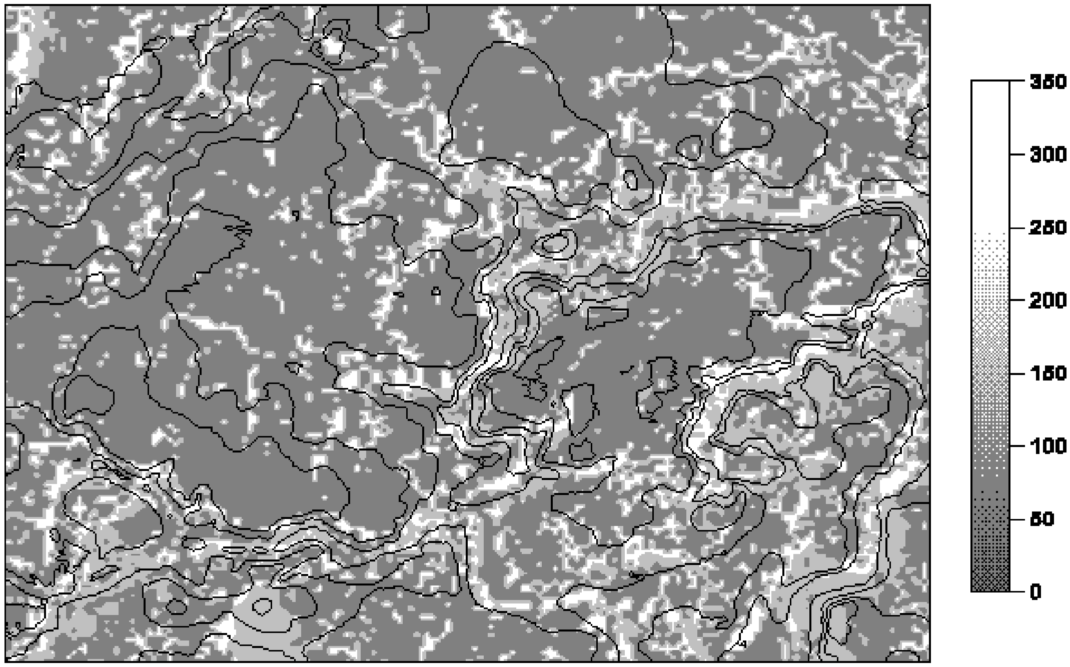

Figure 3 **Mapped distribution of late winter snow accumulation (mm SWE) in the Trail Valley Creek domain, simulation produced with a version of PBSM coupled to the Walmsley/Salmon/Taylor MS3DJH/3R complex terrain boundary-layer model.** (after Essery, Li and Pomeroy 1998).

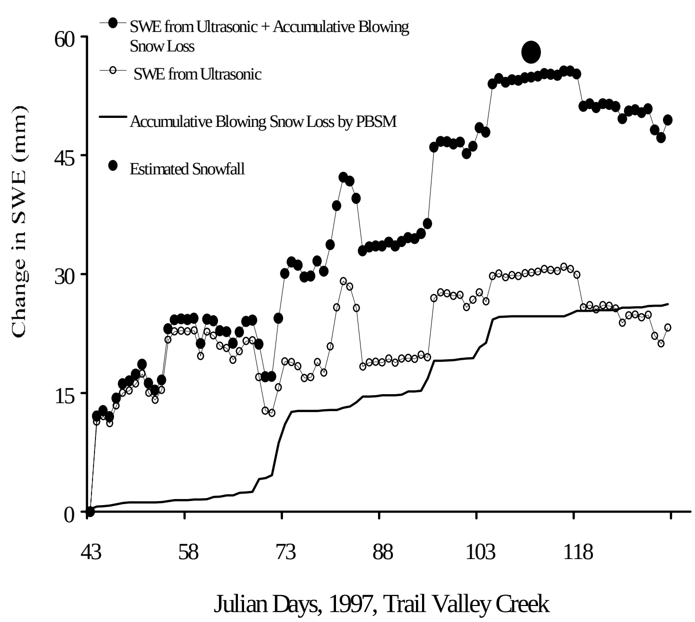

Figure 4 **Modelled PBSM single-column spatially scaled results for Trail Valley Creek open tundra site. Accumulated blowing snow loss is due to transport and sublimation of blowing snow, snow water equivalent is estimated based on measured snow depth and density, corrected to areal snow surveys, the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

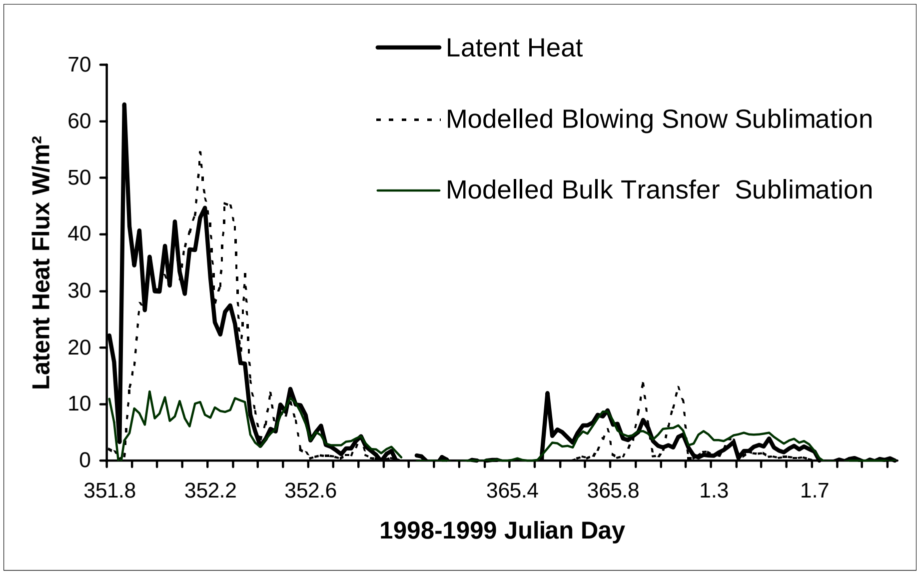

Figure 5 Measured latent heat (sublimation) flux, sublimation calculated using the blowing snow model, sublimation calculated using a standard bulk transfer model. Strong blowing snow Day 351.9-352.6; intermittent blowing snow Day 365.5-1.7.

Discussion, Conclusions, Recommendations

Substantial progress has been made in defining the mass and energy fluxes governed by snow interception, redistribution, sublimation and ablation processes over both complex and uniform terrain. Sublimation losses from blowing snow range up to 50% of seasonal snowfall and have been verified by mass balance techniques. The existence of such large sublimation fluxes is supported by eddy correlation water vapour flux measurements in excess of 60 W m^{-2} during blowing snow. Sublimation of intercepted snow in conifers can return up to 45% of seasonal snowfall to the atmosphere before melt and has been verified by mass balance techniques and eddy correlation water vapour flux measurements. Snowmelt under evergreen forest canopies is retarded up to 3-fold relative to that in open areas due to reduced sub-canopy radiation and turbulent transfer. The inverse spatial association between snow accumulation and melt energy under forest canopies however acts to accelerate snow cover depletion under forest canopies relative to conditions without such associations.

Algorithms have been devised to describe these processes, the state of developed ranges from verified to provisional. Substantial progress on spatial variability and scaling has been made for the arctic, alpine and boreal forest environments. 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 with the stability of land surface schemes when enhanced physically-based descriptions are introduced. Critical multiple-scale horizontal fluxes of mass and energy have been detected near the surface for nearly all of 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.

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