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Sublimation of snow intercepted by coniferous forest canopies in a climate model

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Abstract Using a tiled representation of land surfaces allows a direct estimation of how much snow sublimates from forest canopies in a climate model. Observations suggest that 25–45% of the annual snowfall can sublimate from coniferous canopies in cold, dry continental environments. A similar range of simulated sublimation fractions is found for the forested fractions of continental gridboxes, but the sublimation is likely to be overestimated in maritime environments due to the neglect of canopy snow unloading.

Key words boreal forest; climate simulation; mosaic; snow interception; sublimation

INTRODUCTION

Coniferous forest canopies have low albedos and large roughness lengths, even when snow covered (Pomeroy & Dion, 1996; Viterbo & Betts, 1999). Intercepted snow has a large surface area for sublimation, but snow on the ground below the canopy is sheltered from solar radiation and atmospheric turbulence. Increased branch bending and weakening of the snow structure accelerates unloading of snow from the canopy at higher temperatures. Mass balance studies (reviewed in Table 1) comparing snow accumulations beneath canopies and in clearings suggest that 25–45% of the cumulative annual snowfall can sublimate from forest canopies in cold, dry continental environments. Direct measurements of turbulent moisture fluxes using eddy-correlation techniques show that peak sublimation rates can exceed 0.2 mm of snow water equivalent (*SWE*) per hour (Harding & Pomeroy, 1996; Nakai *et al.*, 1999). Although high sublimation rates are possible in maritime environments, higher humidities will limit sublimation and more frequent unloading events will limit the time that snow is held in the canopy, so seasonal sublimation is likely to be less significant (Storck & Lettenmaier, 1999; Satterlund & Haupt, 1970).

Since coniferous forests cover a significant fraction of the Northern Hemisphere land surface, sublimation of intercepted snow could have an important influence on the climate simulated by general circulation models (GCMs). Northern landscapes are complex mosaics of forests, clearings and lakes not resolved by GCM horizontal grid scales, which are typically of the order of 200 km. Traditionally, GCM land surface

Table 1 Fraction of annual snowfall sublimated from coniferous forest canopies, estimated from mass-balance studies.

Study	Location	Tree species	% snowfall sublimated
Wilm & Dunford (1945)	Colorado	Lodgepole pine	32
Miner & Trappe (1957)	Eastern Oregon	Lodgepole pine	24
Pomeroy & Gray (1995)	Saskatchewan	Black spruce	36 (1992–1993)
		Jack pine	32 (1992–1993)
Pomeroy *et al.* (1998)	Saskatchewan	Black spruce	45 (1994–1995)
			38 (1995–1996)
		Jack pine	30 (1994–1995)
			32 (1995–1996)
Pomeroy *et al.* (1999)	Yukon	Spruce	39 (1993–1994)
			41 (1994–1995)
			38 (1995–1996)
			45 (1996–1997)
Storck & Lettenmaier (1999)	Western Oregon	Douglas fir	14
Satterlund & Haupt (1970)	Idaho	Douglas fir	4.5
		White pine	5.2

schemes have used effective surface parameters for entire gridboxes to calculate gridbox-average fluxes, so it has not been straightforward to estimate sublimation from different surfaces within a gridbox for comparison with small-scale measurements. The Met Office Surface Exchange Scheme (MOSES; Cox *et al.*, 1999) used in the Hadley Centre/Met Office GCM has recently been extended to introduce a tiled surface representation (Essery *et al.*, in preparation), allowing a more direct comparison. A gridbox may contain a mixture of eight surface types: broadleaf trees, needleleaf trees, C_3 (temperate) grass, C_4 (tropical) grass, urban development, inland water and bare soil. Separate albedos and roughness lengths are used in calculating separate surface temperatures, snow masses and energy balances for each surface type within a gridbox; tile fluxes are then averaged according to their fractional coverage to give gridbox-average fluxes of heat and moisture between the surface and the atmosphere.

MOSES simply assumes that any snow cover on forest tiles is held in the canopy; sublimation proceeds at the potential rate and the surface temperature is limited to be less than or equal to 0°C whenever snow is present. Using meteorological measurements made above a pine canopy to drive the surface model, Essery (1998) found this assumption to lead to excessive sublimation for periods when snow on the ground was erroneously assumed to be held in the canopy. Coupling the surface model to a single-column atmospheric model, however, moistening and cooling of air by sublimation provided a moderating negative feedback. In this paper, we consider sublimation from coniferous canopies in a global climate simulation.

MODEL RESULTS

Results were analysed from the last 10 years of a 15-year run of MOSES coupled to the HadAM3 version of the GCM (Pope *et al.*, 2000) with a resolution of 2.5° latitude by 3.75° longitude and 19 levels in the atmosphere. Vegetation maps for MOSES were derived from the University of Maryland AVHRR 1-km global land cover classification (DeFries *et al.*, 1999). Figure 1 shows the average sublimation from "needleleaf

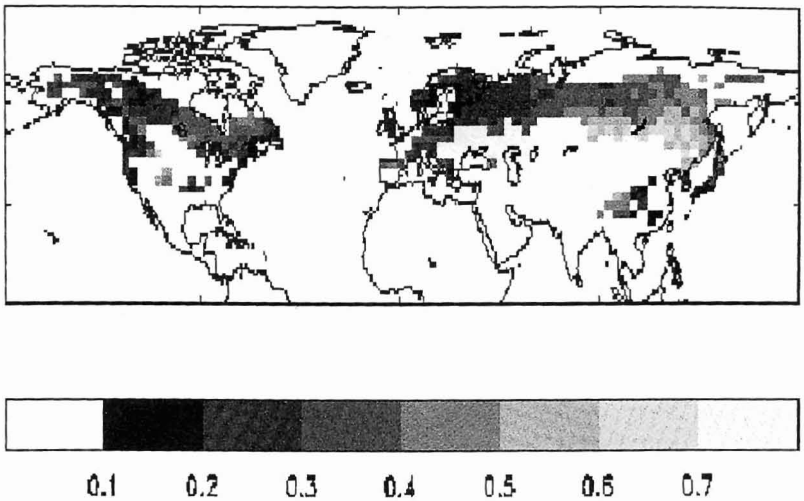

Fig. 1 Fraction of annual snowfall sublimated from "needleleaf tree" fractions of GCM gridboxes.

tree" fractions of Northern Hemisphere gridboxes divided by the average snowfall. The sublimated fraction shows an eastward increase over the continents (large values exceeding 70% in four gridboxes around Lake Baikal reflect low snowfall rather than large sublimation rates). A histogram of sublimation fractions (Fig. 2) for forested gridboxes with an average annual snowfall of at least 10 mm is peaked around 30%, with 74% of gridboxes falling in the range 20–50%.

Cumulative snowfall, sublimation and melt are shown in Fig. 3 for continental and coastal gridboxes centred on 55°N, 105°W (Saskatchewan) and 47.5°N, 123.75°W (Washington). Precipitation for the Saskatchewan gridbox has a minimum in winter; monthly average air temperatures are below 0°C between November and March in both the GCM simulation and the CRU climatology (New *et al.*, 1999), with a minimum monthly average below –15°C in January. Some of the snowfall early in the

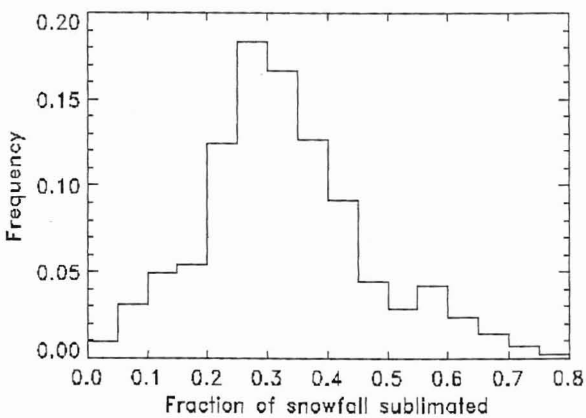

Fig. 2 Histogram of sublimation fractions in Fig. 1.

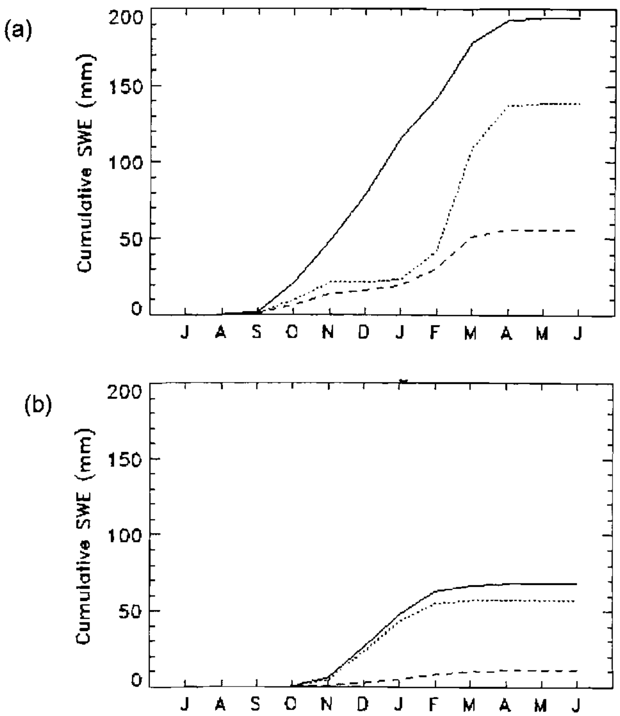

Fig. 3 Cumulative snowfall (——), melt (·····) and sublimation (– – –) for gridboxes (a) in Saskatchewan and (b) in Washington.

winter melts and there is a rapid spring snowmelt, but sublimation continues throughout the winter, removing 29% of the annual snowfall. Only 2% sublimates from the open fraction of the average, but it should be noted that sublimation of wind-blown snow, which can remove large amounts of snow in open environments (Pomeroy & Li, 2000), is not represented in MOSES. For the Washington gridbox, the precipitation shows a winter maximum, but only a small fraction of this falls as snow; there is no month of the year for which the average air temperature is below 0°C. Frequent melt events throughout the winter limit the snow available for sublimation to 14% of the snowfall. This is likely to be an overestimate, as midwinter melting would encourage unloading of snow from the canopy.

CONCLUSIONS

Despite the simplicity of its representation of canopy snow processes, the MOSES land surface scheme coupled to the Hadley Centre/Met Office GCM simulates sublimation fractions that are broadly in line with observations from continental environments. Because unloading is neglected, sublimation in maritime environments is likely to be overestimated, and warming of the atmosphere at temperatures above 0°C due to absorption of solar radiation by snow-free canopies over snow-covered ground is neglected (Douville & Royer, 1997). We are adapting physically-based models of snow interception (Hedstrom & Pomeroy, 1998) and sublimation (Pomeroy *et al.*, 1998) for implementation in MOSES to assess the influence of forest snow processes on climate.

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REFERENCES

Cox, P. M., Betts, R. A., Bunton, C. B., Essery, R. L. H., Rowntree, P. R. & Smith, J. (1999) The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Clim. Dyn.* **15**, 183–203.

DeFries, R. S., Townshend, J. R. G. & Hansen, M. C. (1999) Continuous fields of vegetation characteristics at the global scale at 1-km resolution. *J. Geophys. Res.* **104**(D14), 16911–16923.

Douville, H. & Royer, J.-F. (1997) Influence of the temperate and boreal forests on the Northern Hemisphere climate in the Météo-France climate model. *Clim. Dyn.* **13**, 57–74.

Essery, R. (1998) Boreal forests and snow in climate models. *Hydrol. Processes* **12**, 1561–1567.

Harding, R. J. & Pomeroy, J. W. (1996) The energy balance of the winter boreal landscape. *J. Climate* **9**, 2778–2787.

Hedstrom, N. R. & Pomeroy, J. W. (1998) Accumulation of intercepted snow in the boreal forest: measurements and modelling. *Hydrol. Processes* **12**, 1611–1625.

Miner, N. H. & Trappe, J. M. (1957) Snow interception, accumulation and melt in lodgepole pine forests in the Blue Mountains of Eastern Oregon. *USDA Forest and Range Experimental Station Research Note no. 143.*

Nakai, Y., Sakamoto, T., Terajima, T., Kitamura, K. & Shirai, T. (1999) The effect of canopy snow on the energy balance above a coniferous forest. *Hydrol. Processes* **13**, 2371–2383.

New, M., Hulme, M. & Jones, P. (1999) Representing twentieth-century space-time climate variability. Part I. Development of a 1961–90 mean monthly terrestrial climatology. *J. Climate* **12**, 829–856.

Pomeroy, J. W. & Dion, K. (1996) Winter radiation extinction and reflection in a boreal pine canopy: measurements and modelling. *Hydrol. Processes* **10**, 1591–1608.

Pomeroy, J. W. & Gray, D. M. (1995) Snowcover accumulation, relocation and Management. *NHRI Science Report no. 7. National Hydrology Research Institute, Saskatoon, Canada.*

Pomeroy, J. W. & Li, L. (2000) Prairie and arctic areal snow cover mass balance using a blowing snow model. *J. Geophys. Res.* **105**(D21), 26619–26634.

Pomeroy, J. W., Parviainen, J., Hedstrom, N. & Gray, D. M. (1998) Coupled modelling of forest snow interception and sublimation. *Hydrol. Processes* **12**, 2317–2337.

Pomeroy, J. W., Hedstrom, N. & Parviainen, J. (1999) The snow mass balance of Wolf Creek. In: *Wolf Creek Research Basin: Hydrology, Ecology, Environment* (ed. by J. Pomeroy & R. Granger). National Water Research Institute, Environment Canada, Saskatoon.

Pope, V. D., Gallani, M. L., Rowntree, P. R. & Stratton, R. A. (2000) The impact of new physical parameterisations in the Hadley Centre climate model: HadAM3. *Clim. Dyn.* **16**, 123–146.

Satterlund, D. R. & Haupt, H. F. (1970) The disposition of snow caught by conifer crowns. *Wat. Resour. Res.* **6**, 649–652.

Storck, P. & Lettenmaier, D. P. (1999) Predicting the effect of a forest canopy on ground snow pack accumulation and ablation in maritime climates. In: *Proc. 67th Western Snow Conference* (Lake Tahoe, California) (ed. by C. Troendle & K. Elder), 1–12.

Viterbo, P. & Betts, A. K. (1999) Impact on ECMWF forecasts of changes to the albedo of the boreal forests in the presence of snow. *J. Geophys. Res.* **104**(D16), 27803–27810.

Wilm, H. G. & Dunford, E. F. (1945) Effect of timber cutting on water available for streamflow from a lodgepole pine forest. *US Dept Agric. Tech. Bull. no. 965.* US Dept of Agriculture, Washington DC, USA.