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Evaluation of forest snow processes models (SnowMIP2)

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[1] Thirty-three snowpack models of varying complexity and purpose were evaluated across a wide range of hydrometeorological and forest canopy conditions at five Northern Hemisphere locations, for up to two winter snow seasons. Modeled estimates of snow water equivalent (SWE) or depth were compared to observations at forest and open sites at each location. Precipitation phase and duration of above-freezing air temperatures are shown to be major influences on divergence and convergence of modeled estimates of the subcanopy snowpack. When models are considered collectively at all locations, comparisons with observations show that it is harder to model SWE at forested sites than open sites. There is no universal ''best'' model for all sites or locations, but comparison of the consistency of individual model performances relative to one another at different sites

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shows that there is less consistency at forest sites than open sites, and even less consistency between forest and open sites in the same year. A good performance by a model at a forest site is therefore unlikely to mean a good model performance by the same model at an open site (and vice versa). Calibration of models at forest sites provides lower errors than uncalibrated models at three out of four locations. However, benefits of calibration do not translate to subsequent years, and benefits gained by models calibrated for forest snow processes are not translated to open conditions.

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1. Introduction

[2] In the past, forest snow processes in land-surface models have been poorly replicated or even neglected [*Essery*, 1998; *Pomeroy et al.*, 1998a], but recent development of more complex representations of forest canopies and snow processes as a result of experimental studies has led to the inclusion of more detailed considerations of forest snow processes in land-surface schemes [*Niu and Yang*, 2004; *Wang et al.*, 2007; *Yamazaki et al.*, 2007]. The purpose of this paper is to compare models that differ in their representation of forest snow processes, through comparison of model runs at paired forested and open sites, and to assess model performance in estimating snow water equivalent (SWE) or snow depth.

[3] Annual maximum snow extent covers ~47 million km^2 of the Northern Hemisphere each year [*Robinson and Frei*, 2000]. Although there are no direct estimates of the overlap between snow covered and forested areas, as boreal evergreen needleleaf forests (typical in subpolar boreal forest regions of the northern hemisphere) account for ~8.9 million km^2 [*Secretariat of the Convention on Biological Diversity*, 2001], a conservative estimate is that ~19% of Northern Hemisphere snow may overlap boreal forest. In nonpolar cold climate zones (Food and Agriculture Organization, Koeppen's climate classification map, 1977, http://www.scribd.com/doc/2164459/KoppenGeiger-World-Climate-Classification-Map), which again are typical of boreal forest regions, snow was estimated by *Güntner et al.* [2007] to account for 17% of terrestrial water storage. Consequently, it is important to obtain frequent, accurate estimates of forest SWE to: (1) evaluate Global Climate Models (GCM); (2) initialize hydrological forecast models; (3) estimate impacts on oceanic circulation of freshwater runoff from many large, poorly gauged catchments; and (4) to improve decision making in provision of drinking water, hydroelectric power, flood forecasting, agricultural irrigation and industrial uses in these environments. Uncertainty exists about the spatial distribution of boreal forests in the Northern Hemisphere under future climate scenarios. Although this uncertainty will be enhanced by fire and insect related disturbance [*Kurz et al.*, 2008; *McCullough et al.*, 1998], forest coverage is likely to spread north at the expense of tundra into seasonally snow covered areas [*Denman et al.*, 2007]. Consequently, forest snow processes are likely to become more, rather than less, important in the future.

[4] The magnitude of snow accumulation and the timing and rate of ablation are very different between forested and nonforested sites. *Hardy et al.* [1997] reported that areas beneath tree canopies accumulated only 60% as much snow as forest openings at the BERMS site in Canada, *Koivusalo and Kokkonen* [2002] found little difference between annual maximum SWE at clearing and forest sites in southern Finland, and *Appolov et al.* [1974] observed that ratios between annual maximum SWE at open and forest sites in Russia become greater in favor of forests when canopy density decreases and canopy type transitions from coniferous to broadleaf. Many complex and interacting processes account for these differences. Snow falling on a forest is partitioned into interception by the canopy and throughfall to the ground [*Hedstrom and Pomeroy*, 1998; *Storck et al.*, 2002]. Intercepted snow may sublimate [*Lundberg et al.*, 1998; *Lundberg and Halldin*, 1994; *Lundberg and Koivusalo*, 2003; *Molotch et al.*, 2007; *Montesi et al.*, 2004; *Pomeroy et al.*, 1998b; *Pomeroy and Schmidt*, 1993; *Schmidt*, 1991], unload [*MacKay and Bartlett*, 2006] or melt within the canopy. Intercepted snow in dense forest canopies has been shown to have little influence on albedo [*Pomeroy and Dion*, 1996], but the influence of subcanopy snow rapidly increases the overall albedo of the landscape as canopy density decreases [*Betts and Ball*, 1997; *Melloh et al.*, 2002; *Nakai et al.*, 1999a; *Ni and Woodcock*, 2000]. Subcanopy snow is sheltered from wind, thereby decreasing turbulent transport, and receives less solar radiation owing to extinction and reflection [*Hardy et al.*, 2004; *Pomeroy and Dion*, 1996; *Tribbeck et al.*, 2006]. However, this may be offset to a degree by increased thermal radiation emitted from the canopy [*Pomeroy et al.*, 2009; *Sicart et al.*, 2004]. Together, these processes above and below the canopy influence energy and mass fluxes at the snow surface [e.g., *Hardy et al.*, 1997, 1998; *Link and Marks*, 1999; *Niu and Yang*, 2004; *Ohta et al.*, 1999; *Suzuki and Nakai*, 2008]. The structure of the forest canopy, and its representation within a model, greatly influence estimates of accumulation [*Pomeroy et al.*, 2002] and rates of ablation [*Otterman et al.*, 1988; *Talbot et al.*, 2006]. By controlling the timing of snow cover depletion and the duration of melt, these influence the growing season and primary productivity of trees which depend on snowmelt infiltration water for thawing of frozen soils and for subsequent growth [*Vaganov et al.*, 1999], in addition to the biological response to increases in air temperature where soils are unfrozen [*Suni et al.*, 2003].

[5] Alternatives to numerical modeling to retrieve SWE in forests have not proven satisfactory. Globally, ground-based observations are sparse owing to problems of access in densely forested areas and lack of resources to maintain reliable observations. Remotely sensed observations are the only viable alternative to modeling SWE over such large areas, but forests are the most problematic land-cover classes for mapping snow covered area using optical sensors such as