The Influence of Snow–Soil Moisture Flux on Snowpack Metamorphism in Late Winter and Early Spring

Y. C. CHUNG[1] AND A. W. ENGLAND[2]

ABSTRACT

The importance of land–atmosphere snow cover feedback in the climate system, water storage and release from snowpacks, and the large land areas covered by snow in the northern hemisphere, are reasons to accurately model late winter and early spring snow metamorphic processes. Snowpack models like SNTHERM predict snow behavior very well during the cold periods but do not adequately capture liquid and vapor transport between soil and snow conditions during the snowmelt period. To get a more realistic description of the dynamics between snowpack and soil, we developed a snow–soil–vegetation–atmosphere transfer (ssvat) model, which combines soil processes from our land surface processes (lsp) with the snowpack processes of SNTHERM.

We validated the model with data from the NASA cold land processes field experiment (CLPX) field experiment conducted in late winter and early spring near Fraser, Colorado, in 2003. We show an example where soil/snow fluxes increase the energy stored within the snowpack by as much as 17%. Thermal conduction was the predominant soil/snow energy flux. Other energy fluxes, those associated with air convection and vapor diffusion, were 10^{-7} smaller but do contribute to the formation of depth hoar and to grain size growth. Grain sizes in the upper snowpack are increased by soil/snow fluxes. Because radiobrightness scatter darkening at frequencies above 19 GHz increases with grain size, static snow water equivalent (swe) algorithms that use scatter darkening to estimate swe become less reliable when the soil/snow vapor fluxes are large as they would be when the soil is wet and unfrozen. Comparisons of SNTHERM and SSVAT with the CLPX data show that SSVAT provided better estimates of soil temperature by 1.4 K in the late winter and of snow temperature by 3.2 K in early spring. SSVAT also provides better moisture profiles in both snow and soil.

The combination of SSVAT and a new radiobrightness module will enable monitoring of water stored in snow over frozen or unfrozen soil during periods when the snowpack is experiencing thawing and refreezing. It will also contribute to the design of the NASA cold lands processes pathfinder (CLPP) field experiment planned for the arctic and help prepare the cold lands community to interpret the 1.4 GHz brightness observations from SMOS.

Keywords: snow processes; soil processes; vapor diffusion; water flow; free convection; depth hoar

INTRODUCTION

Snowmelt runoff in spring is a major source of hydroelectric and irrigation water at middle and high latitudes. Snow and ice also significantly increase the Earth's albedo, promoting cooling.

---

[1] Geosciences and Remote Sensing Graduate Program, University of Michigan, Ann Arbor, Michigan 48109-2143, USA.
[2] College of Engineering, University of Michigan, Ann Arbor, Michigan 48109-2102, USA.

Even small changes in climate influence these snow processes. The removal of the snow cover also initiates the melting of river and lake ice, the thawing of the active layer, and marks the beginning of the evaporation season. Meltwater increases soil moisture and initiates or increases streamflow. The decaying snowpack causes a major change in the surface energy balance of arctic regions.

A comprehensive search of the literature by the Snow Models Intercomparison Project (SNOWMIP) in 2001 identified more than 40 snow models motivated either by snow hazard investigation or as the lower boundary of an atmospheric model (Yang, 2004). Vapor transfer processes are treated in only 10% of the snow models. Most snow models are validated with field data but 10% are validated with remote sensing data. Effects of sub-grid-scale topography on distribution of precipitation, air temperature and snow depth are considered in 25% of the snow models (Jordan, 1991; Yang, 2004).

SNTHERM was chosen as the basis for our snow cover-soil model because it offers the high physical fidelity (Jordan, 1991; Jordan, 1999). SNTHERM considers retention/percolation, refreezing, vapor transfer, and heat transport by rainfall or snowfall for the snowpack. Snow parameters, such as density and heat capacity/conductivity evolve with the snowpack. SNTHERM predicts the temperature profiles within the frozen soil and the stratified snow with unlimited layers. SNTHERM has been verified with field data for several years from sites in Grayling, Michigan, and Hanover, New Hampshire. SNTHERM's weaknesses are that it ignores the liquid water and vapor transport in the soil and allows water to be artificially drained at the snow/soil interface.

Although soil processes have been combined in some models, these models were simplified in other ways that compromise overall performance. Among these models are SHAW, SNOWPACK, and ISBA-ES (Flerchinger and Hanson. 1989; Lehning et al., 1998; Boone and Etchevers, 2001). ISBA-ES and SNOWPACK only consider the soil processes on the surface or subsurface. In ISBA-ES, the subsurface soil column is divided into two subsurface soil moisture reservoirs consisting of a root-zone layer and a subroot-zone layer (Boone and Etchevers, 2001). The purpose of the ISBA scheme is to calculate the surface radiative heat, momentum, and moisture exchanges with the atmosphere and the components of the near-surface hydrological budget. SHAW considers similar soil processes to those of our LSP model but it has less detailed snow processes than SNTHERM. Neither precipitation nor litter fall are allowed and the interaction between snow grain and vapor diffusion are ignored. SHAW was developed for a continuous canopy cover.

Our Prairie Land Surface Processes (LSP) model is a one-dimensional, high physical fidelity model with coupled heat and moisture transport for prairie soils (Liou, 1996; Judge, 1999). Figure 1 illustrates the processes in the Prairie LSP model, including interactions between the atmosphere, the canopy and the soil, and the effect of transpiration on moisture and energy fluxes within the root zone. To get a more realistic description of the snowpack–soil dynamics, we developed the Snow–Soil–Vegetation–Atmosphere Transfer (SSVAT) model, which combines soil processes from our Land Surface Processes (LSP) model with the snowpack processes of SNTHERM (Chung and England, 2005; Chung et al., 2006).

MODEL MODIFICATIONS

The coupled SSVAT model employs an index of layers in snow and soil in descending order from the top down as seen in Fig 1.

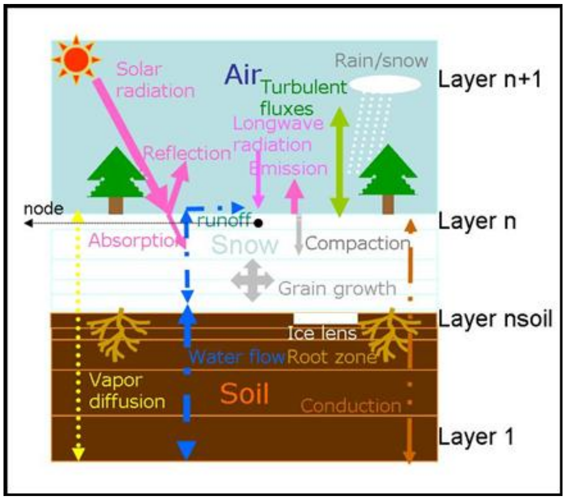

Figure 1. Layer 1 represents the soil base; nsoil represents the soil layer under the snow/soil interface; and n represents the top snow layer in the model structure (modified from Liou, 1996).

Water Flow

SNTHERM includes only gravity driven liquid water flow but liquid water is driven by both capillarity and gravity (Tao and Gray, 1994). Ignoring the capillary effect limits water flow to the downward direction. Particularly, the capillary effect should not be neglected under non-steady state conditions (Su et al, 1999; Waldner et al, 2004). Capillary forces can be neglected only for a stationary unsaturated water flow downwards. Water flow processes in SNTHERM have been modified in SSVAT to incorporate the capillary effect.

Heat convection due to liquid water flow is described by Eqn (1) in SNTHERM where c_w is specific heat of water per unit volume, U_w is the downward flow rate of liquid water, T^i is the temperature of the i^{th} layer, the superscripts (I ±1/2) refer to the interfaces at the top and bottom of layer i. The heat flux due to water flow across upper boundary into layer i is H_w^{i+1} and the heat flux across lower boundary out of layer i is H_w^i:

$$\begin{aligned} H_w^{i+1} &= c_w^{i+1} U_w^{i+\frac{1}{2}} T^{i+1} \\ H_w^{i} &= c_w^{i} U_w^{i-\frac{1}{2}} T^{i} \end{aligned} \tag{1}$$

Including water flow due to capillary requires consideration of the direction of water flow. For example, Eqn (2) describes flux out of the upper boundary of layer i if the water flow is upward due to capillary forces ($U_w^{i+\frac{1}{2}}$ <0) whereas Eqn (3) is used for the upper boundary if the water flow downward due to gravity forces ($U_w^{i+\frac{1}{2}}$ >0).

$$H_w^{i+1} = c_w^{i} U_w^{i+\frac{1}{2}} T^{i}, if \left(U_w^{i+\frac{1}{2}} < 0\right) \tag{2}$$

$$H_w^{i+1} = c_w^{i+1} U_w^{i+\frac{1}{2}} T^{i+1}, if \left(U_w^{i+\frac{1}{2}} > 0\right) \tag{3}$$

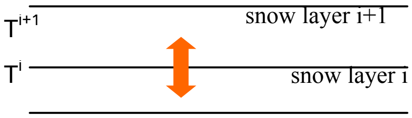

Figure 2. Red line shows the heat transport across upper boundary of the layer i.

Depth Hoar

Depth hoar, which is unique to SSVAT, can change the insulating effect of the seasonal snow cover significantly during ablation periods because of the lower density and thermal conductivity of depth hoar. The growth of depth hoar is favored when the difference between soil and air temperatures is greater and when vegetation buried within the snow results in a high porosity of snow cover near the snow–soil interface (Zhang et al., 1997). Natural convection of air in snow can occur to form depth hoar if a critical temperature gradient is exceeded. The convective flux can be determined from the relationship between the thickness of the snow cover and the temperature gradient (Fig 44 of Akitaya, 1974).

Snow/Soil Interface

Mass and energy transfer at the snow/soil interface in SSVAT are based on the algorithms from LSP (Liou, 1996). The infiltration model for soil can be estimated using a quasi-analytic solution to Richard's equation for vertical infiltration in a homogeneous soil (Liou, 1996; Judge, 1999). To precisely capture mass and energy transfer at the soil/snow interface, snow and soil layers at the soil/snow interface should be thin.

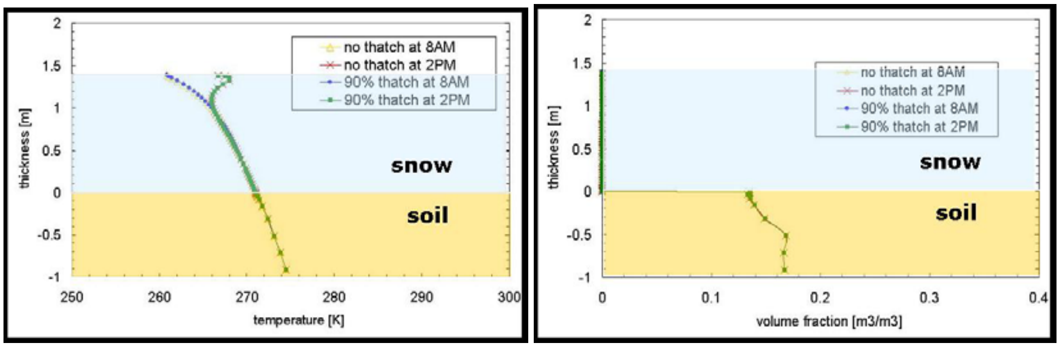

Figure 3. Simulations of temperature and liquid water content for a thatch layer(modified from Chung et al., 2006)

Heat transfer at the snow/soil interface can be affected by vegetation. A thatch layer in LSP was defined as a 2cm layer of organic matter at the base of the grass canopy that is subject to the heat exchange with the atmosphere, the canopy and the underlying soil (Liou, 1996). To see if this thatch layer buried within the snow is important for heat exchanges in SSVAT, a simulation was run for two weeks using a forcing data from Feburary 23, 2003 in CLPX (Chung et al., 2006). Our results showed that a thatch layer did not affect moisture and temperature profiles of either snow or soil when the thatch fraction varied (Fig 3). SSVAT thus ignores thatch at the snow/soil interface.

RESULTS

Study Area

Fig 4 shows the study area at the Local Scale Observation Site (LSOS) of the NASA Cold Land Processes Field Experiment (CLPX). SSVAT requires temperature, moisture and grain size profiles for initialization, which were taken from the Micrometeorological Data and Snow Measurements (Cline et al., 2002; England, 2003). SSVAT also requires precipitation data, which were taken from Ground Based Passive Microwave Radiometer Data (Graf et al, 2003). Data for model validation came from snow pit measurements of density and grain size profiles and sub-canopy meteorological observations for late winter and early spring (Cline et al., 2002; Hardy et al., 2002).

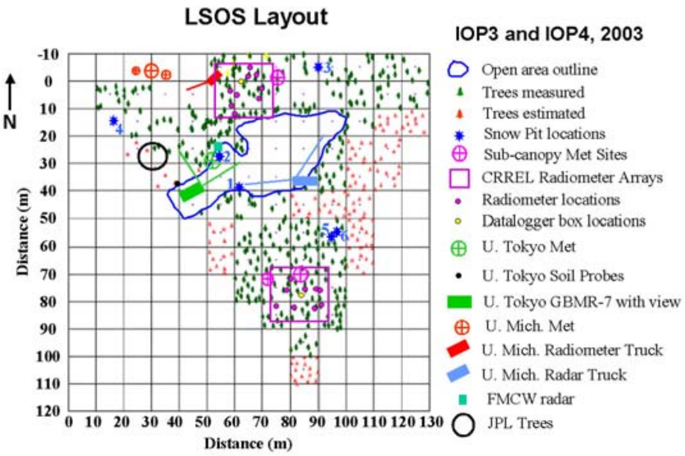

Figure 4. The general layout of the LSOS during IOP3 and IOP4 (England, 2003).

The soil type in the study area is sandy loam, whose dry substance consists of 52% quartz, 7% clay, and residual for silt (Cline et al., 2001). Trees in the study area are of mixed species (predominantly lodgepole pine with some Englemann Spruce and Subalpine Fir) with an average tree height of 7.8 m (standard deviation = 4.8 m; n = 88) and heterogeneous spacing between trees (Hardy et al., 2002).

Energy Stored within the Snowpack

SSVAT and SNTHERM were forced by downwelling radiance and observed meteorology for the periods of IOP3 (2/19~2/24) and IOP4 (3/25~3/29). The results were compared with observations. Figure 5 shows the model-derived heat contents stored in the snowpack over the study period. The simulations show an average increase for SSVAT relative to SNTHERM of 0.54 W/m^2 for late winter and 1.87 W/m^2 for early spring. That is, SSVAT stored heat contents were increased by soil/snow fluxes. Exceptions occurred on some afternoons (e.g. DOY 86~87 and DOY 51~52) when the snowpack became warmer in the late afternoon transporting heat to its underlying frozen soil. In general, SSVAT predicted a warmer snowpack. Soil processes increased energy stored in the snowpack by as much as 17%.

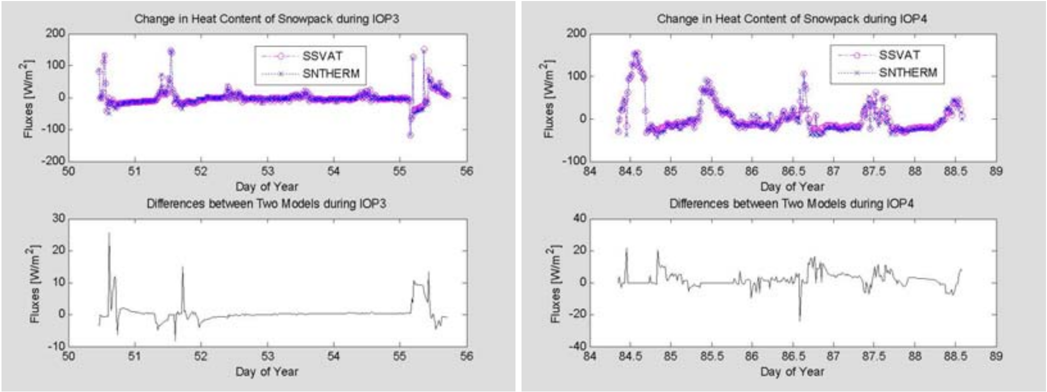

Figure 5. Heat content stored in the snowpack predicted by two models and the model differences over the study period.

Thermal Conduction

Heat fluxes at the snow/soil interface include thermal conduction, vapor diffusion, and convection from free air and flow water (Chung et al., 2006). Figure 6 shows the thermal conduction fluxes, with an average difference between two models of 1.43 W/m^2 for late winter (IOP3) and 0.06 W/m^2 for early spring (IOP4). The daily oscillation was less dramatic in early spring than in late winter since the temperature differences at the interface was less significant in early spring (soil and snow both thawed). This suggests that soil conduction is predominant in the soil heat contribution to the snowpack.

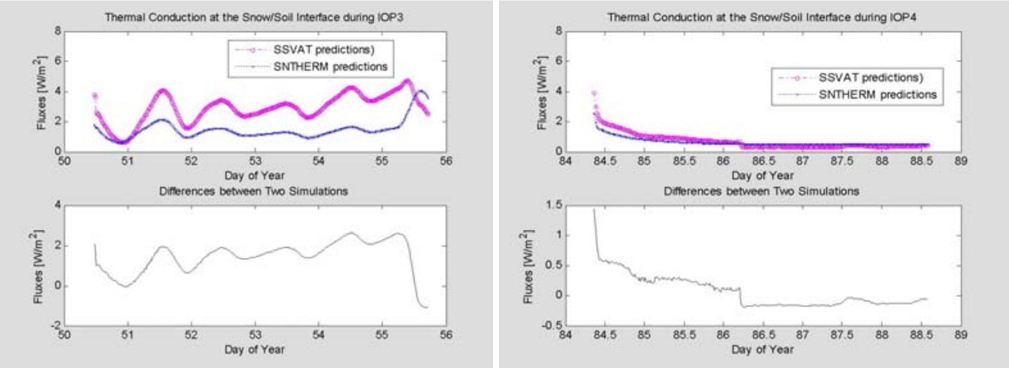

Figure 6. Simulated soil heat fluxes at the snow/soil interface over the study period.

Diffusion and Convection

SNTHERM only considers thermal conduction from the soil. Vapor diffusion from the soil and natural convection of free air in snow are unique to SSVAT. On average, vapor diffusion and natural convection were 10^{-7} times smaller than thermal conduction at the interface (Fig 7). Vapor diffusion displayed a diurnal cycle in late winter because it was affected by the diurnal temperature cycle. Natural convection of free air in snow was significant in early spring, especially on DOY 87–88. Comparing Fig 5 with Fig 7, air convection may be responsible for the increasing variability of the heat content in snow on DOY 87–89. This suggests the importance of convection in snow may exceed that of vapor diffusion or the thermal conduction.

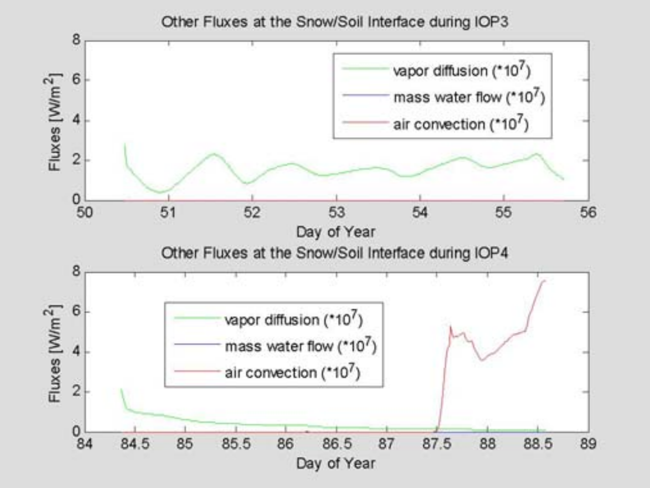

Figure 7. Simulated heat fluxes at the snow/soil interface over the study period.

Air Convection

Fig 8 shows the occurrence of air convection in a snowpack in late winter (IOP3) and early spring (IOP4). Red color and black color represented the occurrence of the air convection whereas blue color represented no convection. Air convection was predicted to occur more frequently in the upper snowpack, especially in early spring. This may reflect on the snow and soil characteristics, such as temperature, moisture and grain size.

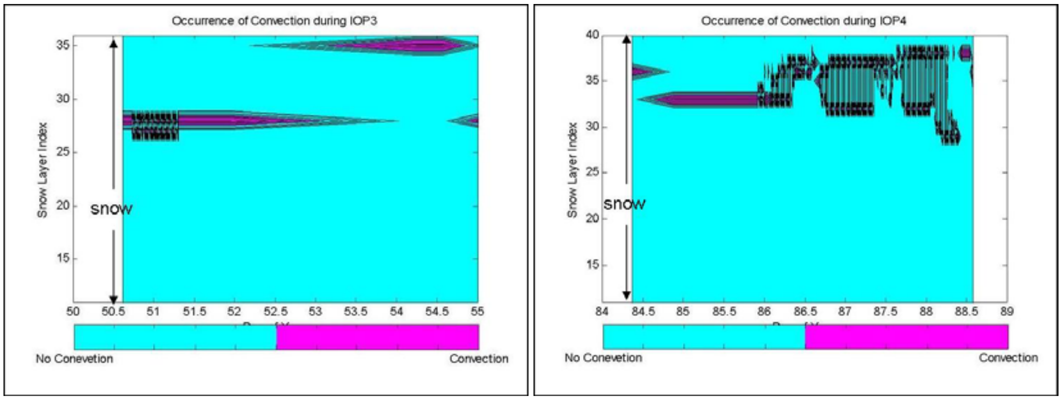

Figure 8. Air convection simulated over the study period.

Temperature Profiles

Figure 9 compares the temperature profiles predicted by the two models with observations. The maximum difference between SSVAT and observation of 0.3 K was observed in soil temperature in late winter scenario, better then that of SNTHERM (1.7 K). The maximum difference of 2.8 K was observed by SSVAT in snow temperature, better than 6 K by SNTHERM in early spring scenario. As expected, the bigger improvement was displayed in early spring once the snowpack started melting. It also reflected on the simulated flux in the figures above. The temperature in the upper snowpack can be affected by the soil processes even when the soil and lower snowpack temperature predictions by two models are similar (Fig 7 and 8). This suggests that SSVAT better estimates temperature during the variable climate of late winter and early spring, and that the soil processes cannot be ignored for predicting the evolution of the snowpack.

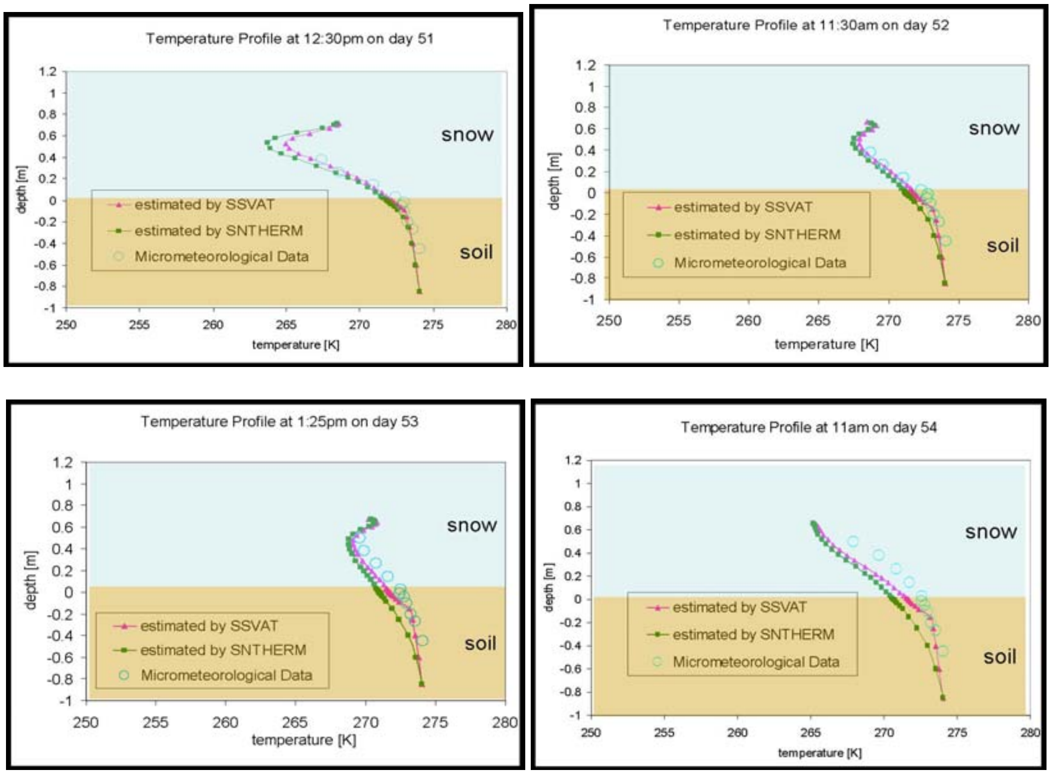

Figure 9(a). Simulated temperature profiles in late winter.

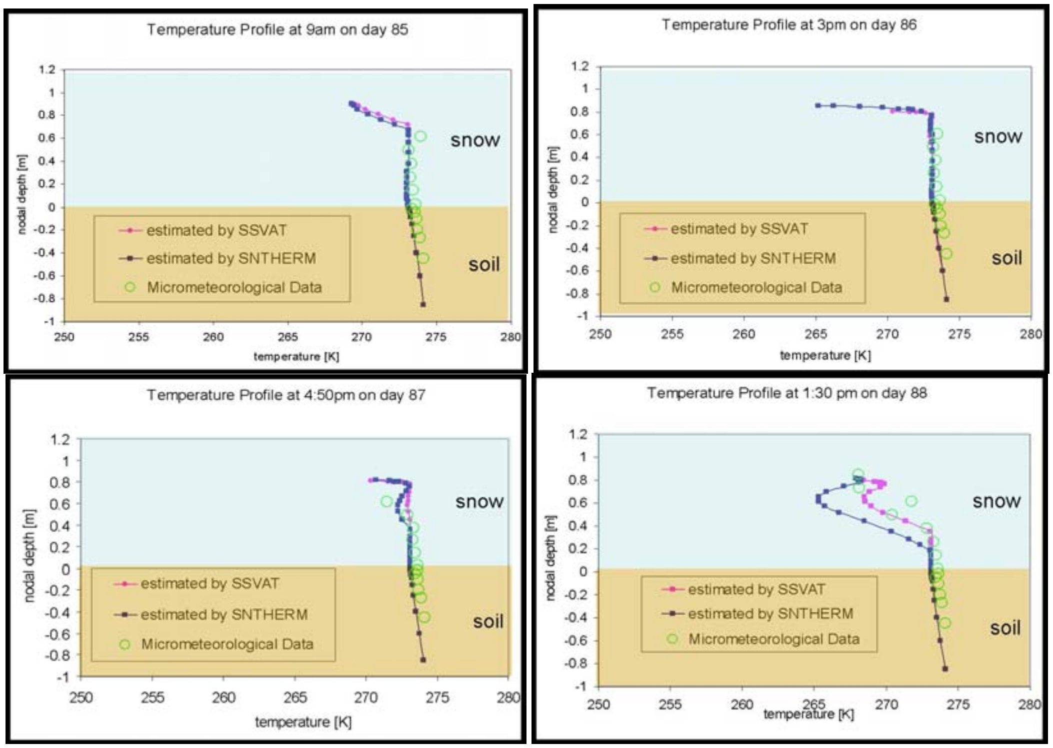

Figure 9(b). Simulated temperature profiles in early spring.

Total Density of Water Profiles

The total density profile includes both liquid and solid (ice) phases. Regression coefficients of the density predicted by two models with observations in the soil can be seen in Table 1. It shows that SSVAT predicted soil moisture well whereas SNTHERM were poor for soil moisture profiles. SNTHERM artificially draining the water at the snow/soil interface so cannot accurately predict the soil moisture in late winter.

Table 1. Regression coefficients of the model predictions and observations.

	SSVAT	SNTHERM
1.5 cm*	0.99	0.69
4.5 cm*	0.89	0.68
10 cm*	0.96	**
27 cm*	0.98	**
45 cm*	0.91	**

*means the depth beneath the ground (snow/soil interface).

** SNTHERM failed to capture the variation of the water density.

Fig 10 represents that simulated density of water profiles in late winter and early spring. It also shows that SSVAT predicted density profiles well. The differences between two model predictions were not significant in early spring since the model initialization in early spring was more realistic than that in late winter. Others may consider liquid water fractions to be significantly different. However, we do not have observations of liquid water content to compare. This suggests that the SSVAT provides a realistic representation of moisture profiles in snow and soil even under an less realistic initialization.

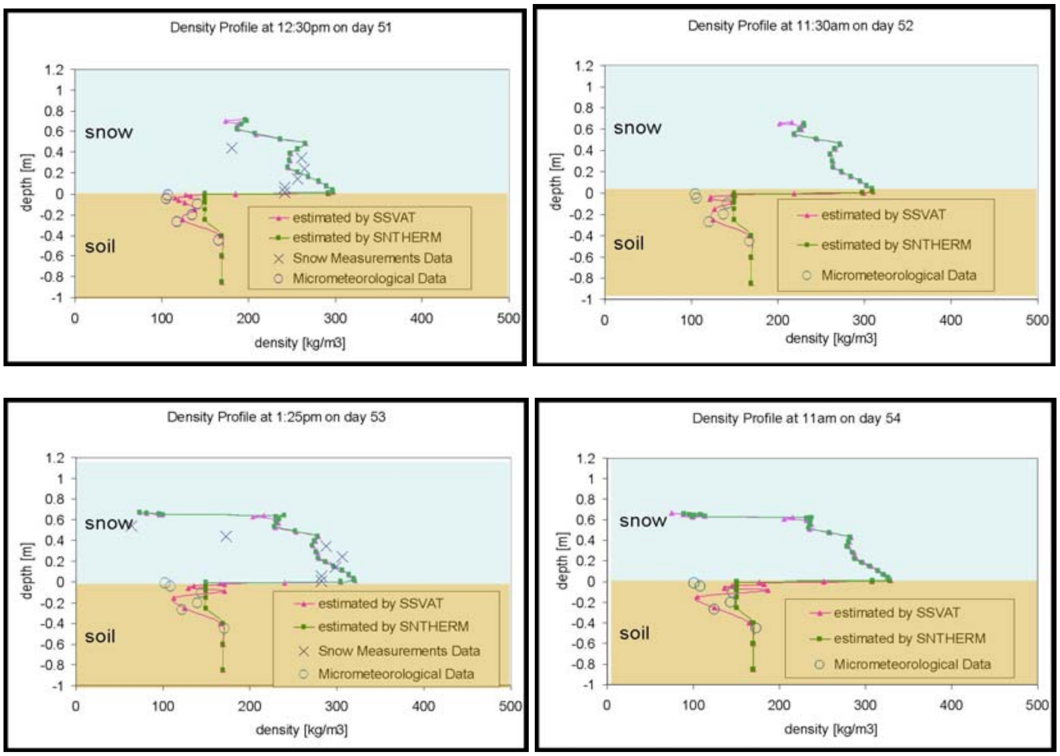

Figure 10(a). Simulated density of water profiles in late winter.

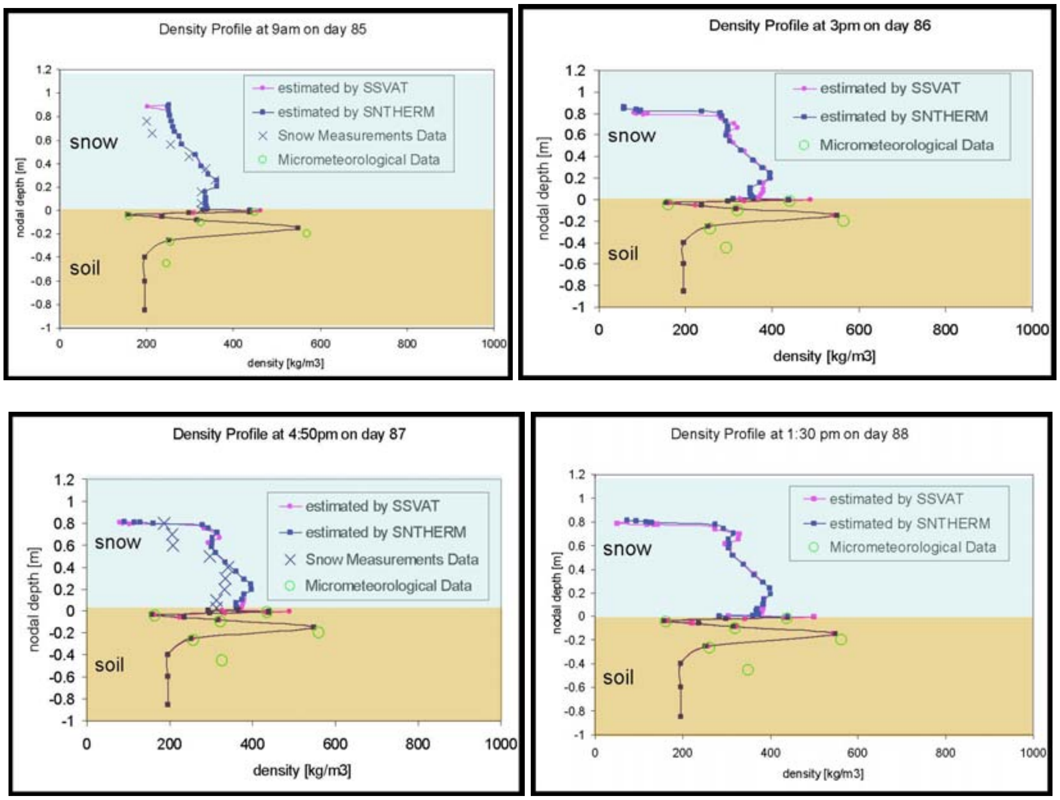

Figure 10(b). Simulated density of water profiles in early spring.

Snow Grain Size Profiles

Comparisons show that snow grain size was predicted larger by SSVAT in response to vapor diffusion contribution from the soil that can grow the grain size more (Fig 11). This contribution accumulates when transporting through the snowpack, making the model difference more obvious near the snow surface. These differences might significantly affect the radiobrightness.

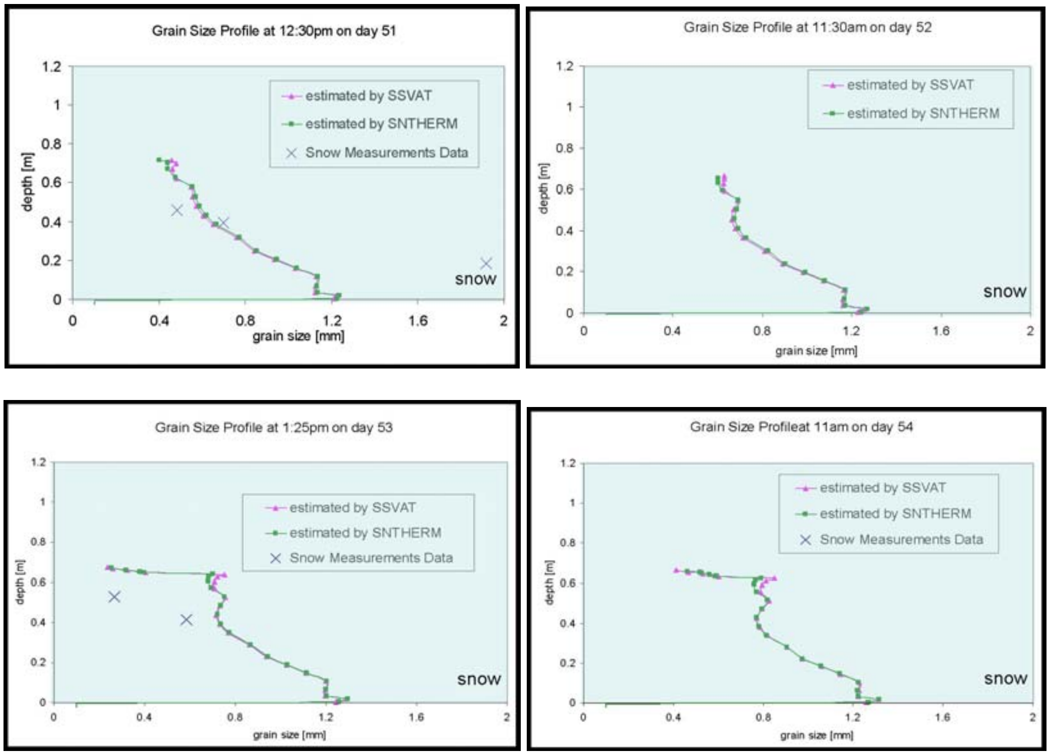

Figure 11(a). Simulated snow grain size profiles in late winter

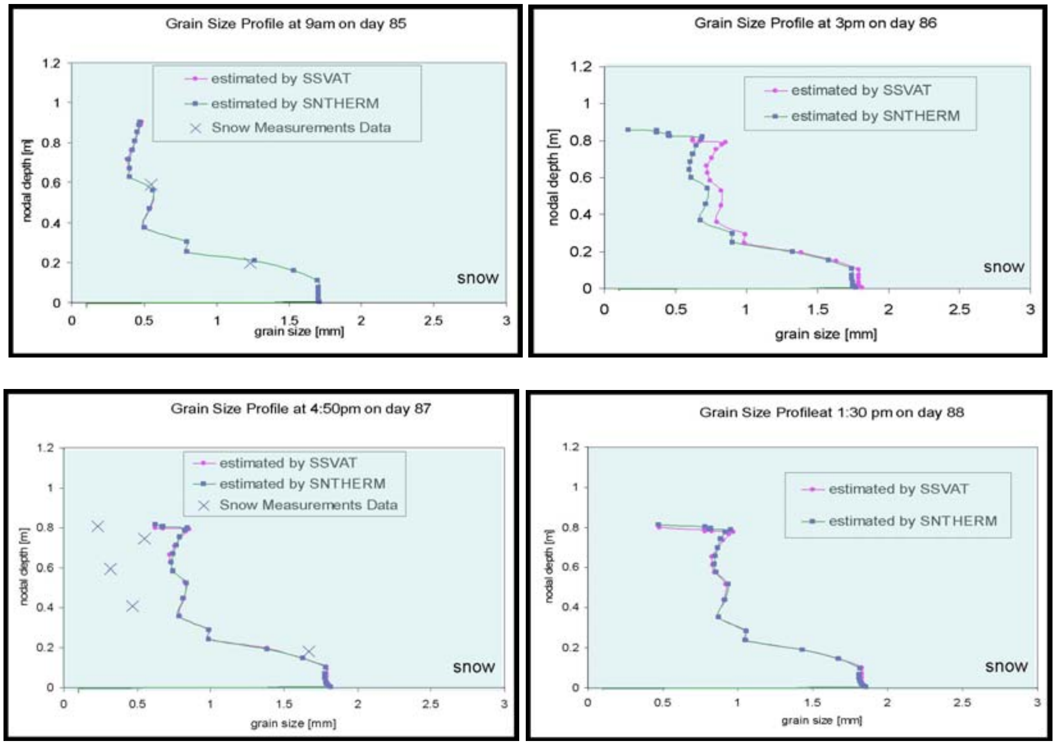

Figure 11(b). Simulated snow grain size profiles in early spring.

CONCLUSIONS

The SSVAT model was validated with data from the CLPX field experiment conducted in late winter and early spring near Fraser, Colorado, in 2003. We show an example where soil/snow fluxes increase the energy stored within the snowpack by as much as 17%. Thermal conduction was the predominant soil/snow energy flux. Other energy fluxes, those associated with air convection and vapor diffusion, were 10^{-7} smaller but do contribute to the formation of depth hoar and to grain size growth. Grain sizes in the upper snowpack are increased by soil/snow fluxes. Because radiobrightness scatter darkening at frequencies above 19 GHz increases with grain size, static Snow Water Equivalent (SWE) algorithms that use scatter darkening to estimate SWE become less reliable when the soil/snow vapor fluxes are large as they would be when the soil is wet and unfrozen.

The maximum difference between soil temperatures of SSVAT and observations was 0.3 K in late winter. The maximum difference between soil temperatures for SNTHERM in that period was 1.7 K. The maximum difference between snow temperatures of SSVAT and observations was 2.8 K in early spring. The maximum difference between snow temperatures of SNTHERM and observations in that period was 6 K. That is, comparisons of SNTHERM and SSVAT with the CLPX data show that SSVAT provided better estimates of soil temperature by 1.4K in late winter and of snow temperature by 3.2 K in early spring. SSVAT also provides better moisture profiles in both snow and soil.

The combination of SSVAT and a new radiobrightness module will enable monitoring of water stored in snow over frozen or unfrozen soil during periods when the snowpack is experiencing thawing and refreezing. It will also contribute to the design of the NASA Cold Lands Processes Pathfinder (CLPP) field experiment planned for the Arctic and help prepare the cold lands community to interpret the 1.4 GHz brightness observations from SMOS.

REFERENCES

Akitaya, E, 1974. Studies on depth hoar. Contributions from the Institute of Low *Temperature Science, Series A*, **26**:1–67.

Boone A, Etchevers P, 2001. An intercomparison of three snow schemes of varying complexity coupled to the same land surface model: Local scale evaluation at an alpine site. J. *Hydrometeor.*, **2**: 374–394.

Chung YC, England, AW, 2005. A coupled soil–snow–atmosphere transfer model. *Proc. of the IEEE International Geoscience and Remote Sensing Symposium*, IGARSS'05, Seoul. `

Chung YC, England AW, De Roo RD, Weininger E, 2006(submitted). Effects of vegetation and of heat and vapor fluxes from soil on snowpack evolution and radiobrightness. *Proc. of the IEEE International Geoscience and Remote Sensing Symposium*, IGARSS'06, Denver, CO.

Cline D (Chair, Cold Land Processes Working Group), Armstrong R, Davis R, Elder K, Liston G., 2001. NASA Cold Land Processes Field Experiment Plan Home Page<http://www.nohrsc.nws.gov/~cline/clpx.html>.

Cline D, Armstrong R, Davis R, Elder K, and Liston G., 2002, Updated July 2004. CLPX-Ground: ISA Snow Pit Measurements. Edited by M. Parsons and M.J. Brodzik., Boulder, CO: National Snow and Ice Data Center. Digital Media,

England AW, 2003. CLPX-Ground: Micrometeorological Data at the Local Scale Observation Site (LSOS). Boulder, CO: National Snow and Ice Data Center. Digital Media.

Graf T, Koike T, Fujii H, Brodzik M, Armstrong R, 2003. CLPX-Ground: Ground Based Passive Microwave Radiometer (GBMR-7) Data. Boulder, CO: National Snow and Ice Data Center. Digital Media.

Flerchinger GN, Hanson CL, 1989. Modeling soil freezing and thawing on a rangeland watershed. *Trans. Amer. Soc. of Agric. Engr.*, **32**(5): 1551–1554.

Hardy J, Melloh R, Koenig G, Pomeroy J, Rowlands A, Cline D, Elder K, Davis R, 2002, updated 2004. Sub-canopy energetics at the CLPX Local Scale Observation Site (LSOS). Boulder, CO: National Snow and Ice Data Center. Digital Media.

Jordan R, 1991. A one-dimensional temperature model for a snow cover. Technical documentation for SNTHERM.89, Special Technical Report 91-16, US Army CRREL.

Jordan R, Andreas E, 1999. Heat budget of snow-covered sea ice at North Pole 4. J. *Geophys. Res.*, **104**(C4): 7785–7806.

Judge J, 1999. Land surface process and radiobrightness modeling of the Great Plains, Ph.D. thesis, University of Michigan.

Lehning et al., 1998. A network of automatic weather and snow stations and supplementary model calculations providing SNOWPACK information for avalanche warning, *ISSW 98 International Snow Science Workshop*, Sunriver, Oregon.

Liou, YA, 1996. Land surface process/ radiobrightness models for northern prairie, Ph.D. thesis, University of Michigan.

Su, GW, Geller, JT, Pruess, K, Wen, F, 1999. Experimental studies of water seepage and intermittent flow in unsaturated, rough-walled fractures," *Water Resources Research*, **35**: 1019–1037.

Tao, Y.-X. and Gray, D.M.. 1994. Prediction of Snow-Melt Infiltration into Frozen Soils. Numer. *Heat Transfer Part A*, **26**: 643–645.

Waldner, PA, Schneebeli, M, Zimmermann, US, Fluhler, H, 2004. Effect of snow structure on water flow and solute transport. *Hydrological Processes*, **18**: 1271–1290.

Yang, ZL, 2004(in press). Description of recent snow models. Book Chapter, in Snow and Climate, E. Martin and R. Armstrong (editors), International Committee on Snow and Ice.

Zhang, T, Osterkamp, TE, Stamnes K, 1997. Effects of Climate on the Active Layer and Permafrost on the North Slope of Alaska, U.S.A. *Permafrost and Periglacial Processes*, **8**: 45–67.