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# SIMULATION OF FOREST SNOW PROCESSES AT FRASER WITH A ENERGY BALANCE BASED SNOW MELT MODEL (WEB-DHM-S)

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A newly developed physically based distributed biosphere hydrological model with three layered energy balance snow melt module (WEB-DHM-S) has been implemented at point scale to evaluate the forest snow processes at Fraser Experiment Forest site (USA) for two snow seasons (2003-2005). Results illustrate that the model is capable of representing the sub-canopy snow depth and snow water equivalent well with average correlation coefficient of 0.9. Energy fluxes are analyzed in detail for above canopy and below canopy snow processes. It can be concluded that the radiation energy is dominant in above canopy where sensible heat flux is dominant in addition to the radiation energy in sub-canopy snow processes. Furthermore, the sensitivity runs against the interception capacity shows that the interception capacity plays a major role in canopy snow sublimation.

***Key Words***: *WEB-DHM-S, energy balance, Fraser, forest snow processes, snow depth, snow water equivalent*

## 1. INTRODUCTION

A large fraction of mountainous river basins is usually covered with forest where forest canopy plays a significant role on snow processes. The effect of forest canopy is of great importance in the evolution of seasonal snow cover over the forest floor and in understanding the energy and water balance interactions between the atmosphere and land surface. Forest canopy can dramatically modify the radiation transfer, snowfall interception, and wind regime[1)] and thus for a given canopy structure, the distribution of radiant and turbulent fluxes strongly influences the magnitude of snowmelt runoff and sublimation rate. Despite of the recognition of its importance, an interaction of water and energy fluxes between the atmosphere and canopy, and the sub-canopy snowpack are poorly understood in forested mountainous regions[2)].

Many studies have been conducted for better understanding and representation of forest snow processes in several climate and hydrological models[3-7)]. Some snow model intercomparison studies have been carried out to address the issues related to the current state of snow modeling process[8,9)]. The Snow model intercomparison project 2 (SnowMIP2) provided the first thorough assessment of the shortcomings of 33 forest snow models and indicated that there was no universal ‘‘best’’ model or subset of ‘‘better’’ models, highlighting the need of improvements[9)].

The complexity of existing snowmelt models in atmospheric and hydrologic research community vary greatly that ranges from simple degree day models[3)] to advanced physically based energy balance based models[5,6,7)]. Degree day models cannot replicate the physics of canopy snow processes and thus physically based energy balance snow models are commonly used[9)]. This study attempts to evaluate the performance of newly developed physically based three layered energy balance snow melt model in simulating the forest snow processes at Fraser Experimental site (one of the SnowMIP2 sites) in two continuous snow seasons . The model here used is Water and Energy Budget – based Distributed Hydrological Model with improved snow physics (WEB-DHM-S)[10], developed by coupling three layered snow physics of Simplified Simple Biosphere 3 (SSiB3)[11] and albedo scheme of Biosphere Atmosphere Transfer Scheme (BATS)[12] into Water and Energy Budget – based Distributed Hydrological Model (WEB-DHM)[13]. WEB-DHM-S has shown its capability in capturing the snow processes accurately in both point and basin scales[10,14]. Different from these previous studies, this study aims at investigating the forest snow physics in detail with WEB-DHM-S, to better understand the above-canopy and below-canopy snow processes in seasonal to interannual scale. A series of simulations are carried out to assess the sensitivity of fresh snow albedo and canopy interception to the sub-canopy snow depth and SWE.

## 2. STUDY AREA AND DATA

The study area is Fraser Experimental Forest, one of the forest sites of the SnowMIP2. It is a high-elevation site at 2820 m above mean sea level, located in the U.S. Forest Service at Fraser, Colorado (39.53°N, 105.53°W). The site is cool with long winter having mean temperature of -2°C. The mean annual precipitation is about 750 mm, with nearly two-thirds falling as snow from October through May. Rainfall seldom occurs in winter. A continuous snow cover exists from early November to late April. The site experiences shallow snow depth with the maximum value of about 80 cm. Vegetation includes approximately 27m high pine, spruce and fir. For simulation, vegetation coverage and effective leaf area index (LAI) are set to 100 % and 3.0, respectively[9].

The atmospheric forcing data such as air temperature, humidity, wind speed, shortwave and longwave radiation were measured at 30 m high tower. Constant surface pressure was prescribed as a function of the site elevation. This study used all the forcing data averaged at 1 hour interval though there were made available at 30 minute interval. Precipitation was observed in a clearing site adjacent to the forested area. Precipitation was classified as snow at air temperatures 2°C and rain above. Snow water equivalent (SWE) and snow depth were used for evaluating the model performance, which were given as the average of 47 stake measurements across the forest. Data from this site have been used in the assessment of many snow models[9,15].

## 3. MODEL

The model used here is the WEB-DHM-S (Water and Energy Budget – based Distributed Hydrological Model with improved snow physics) which inherits the three layered energy balance based snowmelt module of SSiB3 and albedo scheme of BATS. WEB-DHM-S can simulate the variability of snow density, snow depth and snow water equivalent, liquid water and ice content, snow albedo, snow layer temperature and thermal heat due to conduction in 9 biomes as described in SiB2[16].

Snowpack, which is intercepted by the canopy leaves, is treated as single layered irrespective of its total depth where sub-canopy snowpack is divided into three layers when total snowdepth exceeds 5cm. The top layer thickness is kept at a fixed depth of 2 cm regardless of the total snow depth to provide reasonable simulation of the diurnal changes in the snow surface temperature. The maximum thickness of the middle layer is kept at 20 cm, and the bottom layer represents the remaining body of the snowpack. The heat budget of top layer is controlled by surface energy balance where that of the second and third layers is controlled by the heat conduction. The mass budget for each snow layer is calculated accordingly by taking account of the precipitation, direct throughfall, drip fall, evaporation, condensation, compaction, liquid water retention, snowmelt runoff and infiltration into the underlying layers. The schematic view of model processes in WEB-DHM-S is presented in **Fig. 1.**

The energy budget equation for the canopy is

$$C_c \frac{\partial T_c}{\partial t} = R_{nc} - H_c - \lambda E_c \tag{1}$$

where $C_c$ ($\mathrm{Jm^{-2}K^{-1}}$) is the effective heat capacity, $T_c$ is the canopy temperature, $R_{nc}$, $H_c$ and $\lambda E_c$ ($\mathrm{Wm^{-2}}$) are net radiation, sensible heat and latent heat flux for the canopy respectively. WEB-DHM-S uses a two-stream approximation scheme[16] for radiation transfer in the canopy. The equation for enthalpy of each snow layer below the canopy is

$$\frac{\partial H(Z_j)}{\partial t} = -\frac{\partial G_{sn}(Z_j)}{\partial Z} \tag{2}$$

where $H$ ($\mathrm{Jm^{-3}}$) is the volumetric enthalpy of water, $Z_j$ is the snow depth of layer $j$ and $G_{sn}$ ($\mathrm{Wm^{-2}}$) is the heat flux through the snow layer. $H$ *is* defined as

$$H(Z_j) = C_v(Z_j) \times \{T_{sn}(Z_j) - 273.16\} - f_{ice}(Z_j) \times h_v \times \rho_s(Z_j) \tag{3}$$

where $C_v$ ($\mathrm{Jm^{-3}K^{-1}}$) and $T_{sn}$ (K) are mean snow volumetric heat capacity and snow temperature respecitively. $f_{ice}$ is the dry-snow mass fraction in the snow layer, $h_v$ ($\mathrm{Jkg^{-1}}$) is the latent heat of fusion for ice and $\rho_s$ ($\mathrm{kgm^{-3}}$) is the bulk density of snow.

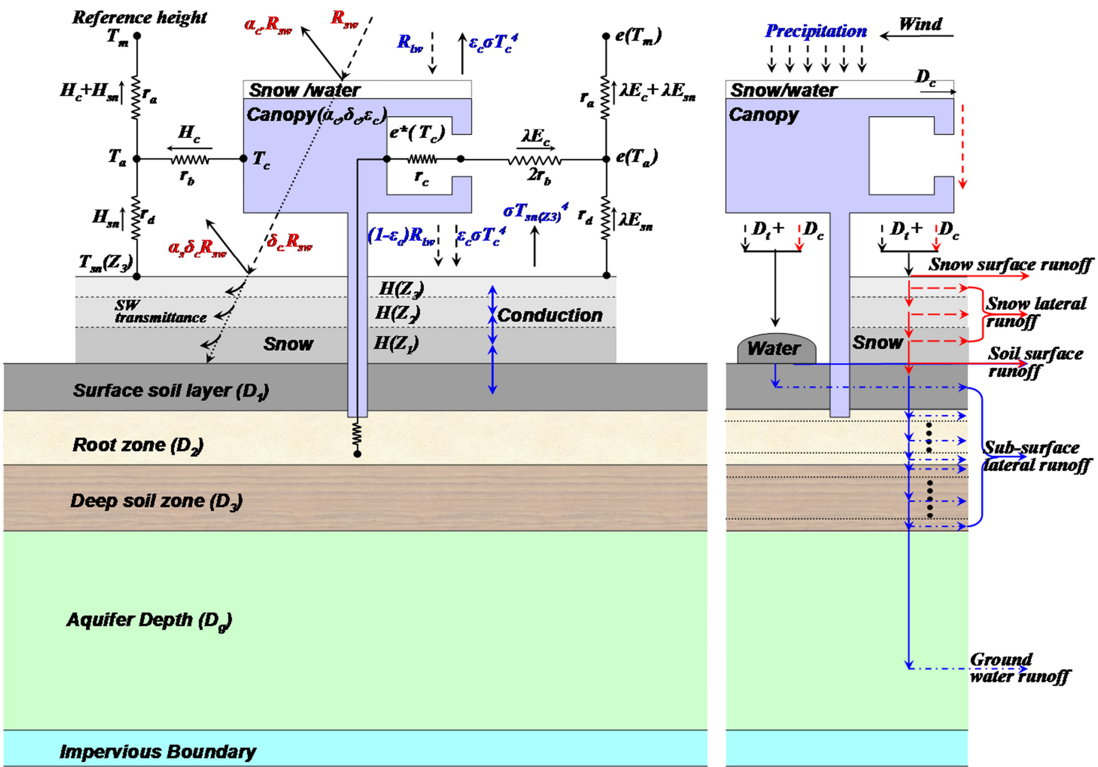


**Fig. 1** Energy and water balance processes in WEB-DHM-S ($R_{sw}$,$R_{lw}$ are downward shortwave and longwave radiation, $\alpha_c$,$\alpha_s$ are canopy and snow albedo, $r_a$,$r_b$,$r_c$,$r_d$ are aerodynamic resistances, $\varepsilon_c$ is emissivity, $\delta_c$ is transmissivity, $T_m$ and $T_a$ are air temperature, e($T_m$) and $e(T_a)$ are vapor pressures at reference height and canopy air space respectively. Details can be found in Sellers et al.[16]

$$G_{sn}(Z_j)=\begin{cases} R_{nsn}-H_{sn}-\lambda E_{sn}+G_{pr}\ , \ j=3 \\ K(Z_j)\dfrac{\partial T_{sn}(Z_j)}{\partial Z}+SW_{sn}(Z_j),\ j=2,1 \end{cases} \quad (4)$$

$G_{sn}$ is defined in **equation 4** where $R_{nsn}$ (Wm$^{-2}$), $H_{sn}$ (Wm$^{-2}$), $\lambda E_{sn}$ (Wm$^{-2}$), $G_{pr}$ (Wm$^{-2}$), $K$ (Wm$^{-1}$K$^{-1}$) and $SW_{sn}$ (Wm$^{-2}$) are net radiation, sensible heat, latent heat flux, thermal energy from rain at the snow surface, thermal conductivity of snow and shortwave radiation flux absorbed by the snow layer respectively.

The mass balance equation for the canopy is

$$\frac{\partial M_{cs}}{\partial t}=P-D_t-D_c-\frac{E_{ci}}{\rho_w} \quad (5)$$

where $M_{cs}$ is snow water equivalent stored on the canopy surface (m); $P$ is precipitation rate (ms$^{-1}$); $D_t$ is canopy throughfall rate (ms$^{-1}$); $D_c$ is canopy drainage rate (ms$^{-1}$); $E_{ci}$ is evaporation rate from canopy interception stores (kgm$^{-2}$s$^{-1}$); $\rho_w$ is density of liquid water (kgm$^{-3}$). The mass balance equation for sub-canopy snow is

$$\frac{\partial M_{snow,j}}{\partial t}=\begin{cases} D_t+D_c+IF_0-IF_j-R_j-\dfrac{E_{sn}}{\rho_w},\ j=3 \\ IF_{j+1}-IF_j-R_j,\ j=2,1 \end{cases} \quad (6)$$

where $M_{snow,j}$ (m) corresponds to the SWE at snow layer $j$, $IF_j$ (ms$^{-1}$) is the actual liquid water infiltration flux at the interfaces, $R_j$ (ms$^{-1}$) is runoff from the lower interface and $E_{sn}$ (ms$^{-1}$) is the combined evaporation and sublimation rate. Three snow compaction processes, namely destructive metamorphism, densification due to snow overburden and compaction due to snow melting, are parameterized following Jordan[5]. The bulk density of ice for new snowfall is calculated following the formulation used in the CROCUS snow model[17]. The snow albedo for canopy is computed using two stream approximation model and details can be found in Sellers et al.[16]. The snow albedo over ground surface is parameterized using a physically based prognostic snow albedo scheme of the BATS[12]. The snow albedo is computed for visible (VIS) and near infra red (NIR) spectral bands with adjustments for illumination angle and snow age.

The model is run for two snow seasons from November to May in 2003-2004 and October to May in 2004-2005 with initial conditions of observed soil temperature and volumetric soil moisture content.

## 4. RESULTS AND DISCUSSIONS

### (1) SWE, snow depth and snow density

Simulation results and observations of the SWE, snow depth and snow density on the forest floor at Fraser in two snow seasons (2003-2005) are shown in **Fig. 2**. In 2003–2004,snow gradually accumulates from November with abrupt increase in January following subsequent variations and remains till the beginning of May. The SWE is found simulated fairly well with correct timing of the end of the snowmelt. However the model overestimates the SWE from mid of February to late March. Snow depth is underestimated from the beginning of March to mid of April. The correlation coefficient between the observed and simulated SWE is 0.98 and that for snow depth is 0.95. Error statistics as shown in **Table 2** demonstrates that the snow depth is underestimated by 0.137 m whereas the SWE is overestimated by 0.018 m. The RMSE for the SWE and snow depth are simulated to the values of 0.02 m and 0.14 m respectively. Model parameters specific to Fraser site are given in **Table 1**.

**Table 1** The parameters used in WEB-DHM-S at Fraser.

| | |
|---|---|
| VIS & NIR albedo of fresh snow | 0.95;0.65 |
| VIS & NIR albedo of soil | 0.05;0.10 |
| Vegetation coverage (%) | 100 |
| Canopy top height, $z_2$ (m) | 27.0 |
| Canopy base height, $z_1$ (m) | 5.0 |
| Roughness length of snow surface (m) | 0.001 |
| Roughness length of ground surface (m) | 0.001 |
| Roughness length of canopy surface (m) | 5.1 |
| Sat. hydraulic conductivity for soil ($ms^{-1}$) | 0.00002 |
| Sat. hydraulic conductivity for snow ($ms^{-1}$) | 0.01 |
| Zero plane displacement height (m) | 17.10 |
| Effective Leaf Area Index (LAI) | 3.0 |

**Table 2** Error statistics for SWE, Snowdepth & Snow density

| Year | SWE (m) | | Snowdepth (m) | | Snow density($kgm^{-3}$) | |
|---|---|---|---|---|---|---|
| | MBE | RMSE | MBE | RMSE | MBE | RMSE |
| 2003-2004 | 0.018 | 0.021 | -0.137 | 0.143 | 129 | 139 |
| 2004-2005 | -0.010 | 0.017 | -0.104 | 0.137 | 40 | 48 |

In the following winter (2004-2005), SWE is well simulated throughout the snow season. The model remarkably underestimates the snow depth in January and February with MBE = 0.104 m and RMSE being 0.137 m. However, the model is able to replicate the mid season ablation during mid April and after that the snow depth is well simulated in the late melting season. The correlation coefficient between observed and simulated SWE and snow depth were 0.94 and 0.81. MBE for snow depth is found less in 2005 as compared to that in 2004, primarily due to increased number of observations in 2005. But the time slice evaluation shows that the snow depth is underestimated by about 0.19 m in mid January. The nature of underestimation of snow depth is totally different in these two seasons. In the former year, snow depth is simulated less in melting season while in the later season; it is underestimated in accumulation season. The possible reason for this bias may be due to the

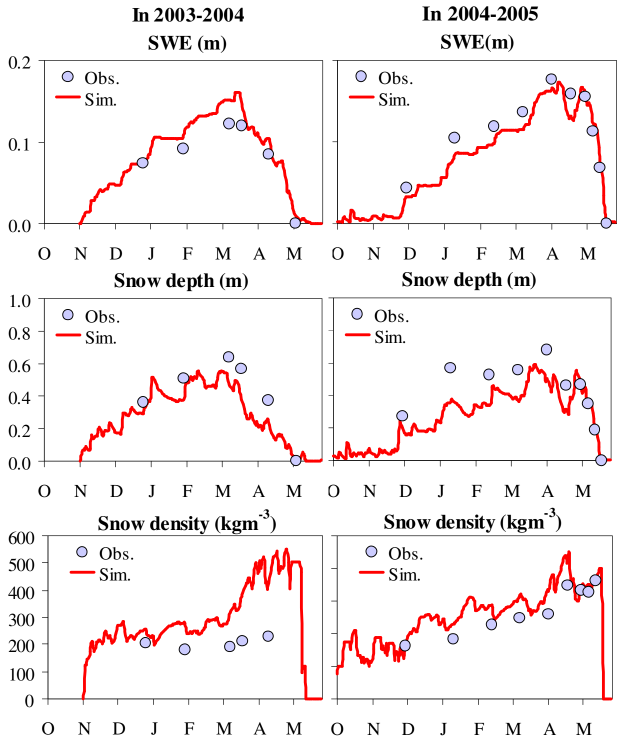


**Fig. 2** Observed and simulated snow water equivalent (SWE), snow depth and snow density in 2003 -2004 and 2004-2005

uncertainty in the density of freshly fallen snow, since density of new snow has been parameterized based on air temperature and wind speed[17)] derived from relations at specific site. However, it can not be ignored that the observed values are the average of 47 stake measurements across the study region, which may also attribute this bias, since the model considers the entire grid as one biomass with same LAI and same meteorological forcing.

The results for the snow density as shown in **Fig. 2** reveal that the model is able to capture the trend of the seasonal variation in the snow density (with correlation coefficient of 0.92 and MBE of 40 $kgm^{-3}$). While in 2003-2004, the density is overestimated from the beginning of March with MBE = 129 $kgm^{-3}$, mainly due to the bias in the snow depth simulation. In general, WEB-DHM-S is found to simulate the variability in the snow depth, SWE and snow density under the forest canopy satisfactorily.

**2) Energy Fluxes**

**Fig. 3** presents the simulated energy fluxes (net radiation, sensible and latent heat flux) above and below canopy in two snow seasons. The direct observations of these fluxes are not made available through SnowMIP2. In 2003-2004, the canopy energy balance is dominated by sensible and latent heat flux till early February and after that, net radiation flux gradually increases and attains high value at the end of the simulation. The net radiation

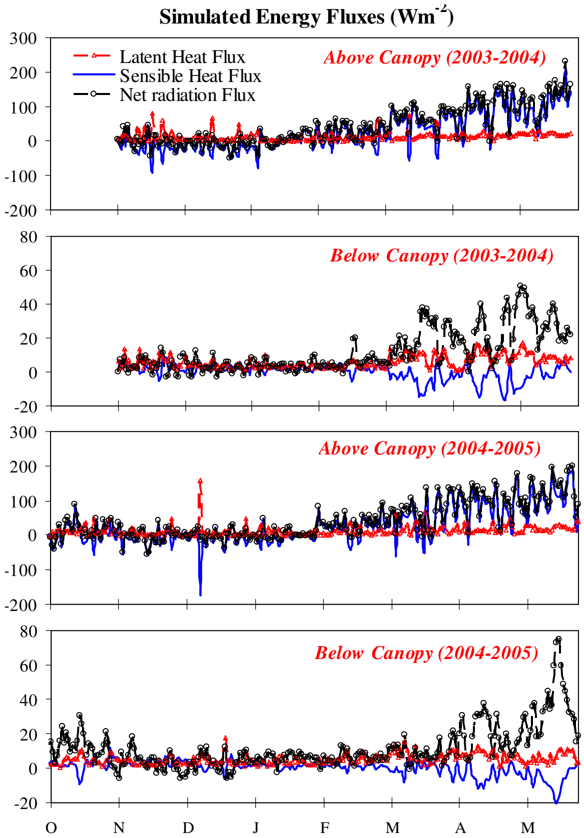


**Fig. 3** Simulated energy fluxes above and below canopy in 2003 -2004 and 2004-2005.

flux energy is largely consumed for the sensible heat and a very small amount of the flux is used in latent heat. In forest floor, the effect of net radiation flux and sensible heat are noticed after early March, and both of them are fully used in heating the snowpack. Latent heat is used for the sublimation of intercepted snow and evaporation of intercepted water in canopy surface. Canopy interception loss is simulated to a value of 50 mm which is about 15% of the total precipitation (320 mm). Snow sublimation from forest floor is about 33 mm. In this site, canopy evapotranspiration plays a significant role in water balance which is about 40 mm.

In 2004-2005, the energy fluxes for canopy and forest floor snowpack follow the similar trend as simulated in 2003-2004. However, the net radiation and sensible heat flux below the canopy become dominant in early April (one month later than that in the former season). Mid season ablation is well captured due to remarkable increase in net radiation and sensible heat flux from 10 to 20 April (see Fig. 3). As compared to former season, the canopy interception loss is smaller (13%) even though the simulation period is one month longer and total precipitation is higher (426 mm). The probable reason for less loss is because of the relatively cold winter and spring.

We attempted to validate these energy fluxes indirectly through analyzing the cold content of the

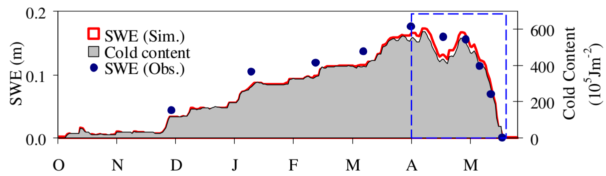


**Fig. 4 (a)** Simulated SWE and cold content in 2004-2005

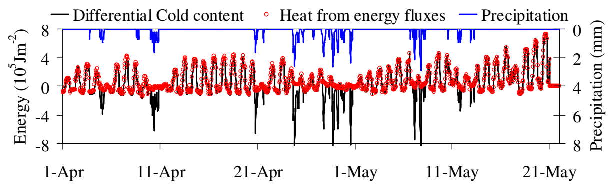


**Fig. 4 (b)** Simulated differential cold content vs heat available from radiant, sensible and latent energy fluxes in 2004-2005 (April-May).

snowpack. A summary of analysis in 2004-2005 is presented in **Fig. 4(a,b)**. Cold content mimics the pattern of SWE as shown in **Fig. 4a**. As SWE is simulated well relative to the observed one, the change in cold content can reflect the effect of energy fluxes in melting season. The differential cold content or heat energy of the snowpack per unit time step is calculated first and compared with the heat available form the energy fluxes. **Fig. 4b** shows the validation of energy fluxes with good agreement to the differential cold content from April to May (melting season). Moreover, differential cold content of the snowpack is simulated remarkably high when snowfall occurs.

### 3) Uncertainties

Despite of "so called" good models, a large amount of uncertainties exist in the forcing dataset, model parameters, initial conditions and validating datasets. Regarding the forcing data, precipitation has the largest uncertainty. At Fraser, the precipitation measured at 4m high instrument in the open site is used as the forcing to the canopy, which may impose some biases. Model parameters such as snow albedo, threshold temperature for snow/rain and morphological parameters of the canopy also affect the simulation. A number of sensitivity runs are carried out by assigning the VIS albedo of fresh snow to the values of 0.7 to 0.95. It is found that the sensitivity of fresh snow albedo is insignificant in simulation of the snow depth, SWE and energy fluxes, as expected, since the energy fluxes to the forest floor are comparatively very low as compared to the energy available to the canopy surface.

Maximum canopy interception capacity (*MCIC*) significantly controls the interception of snowfall by the canopy and the snow loading to the forest floor. Currently, WEB-DHM-S uses *MCIC* as the function of LAI, as formulated in SiB2. This capacity is calculated as 0.3mm for LAI = 3. The sensitivity

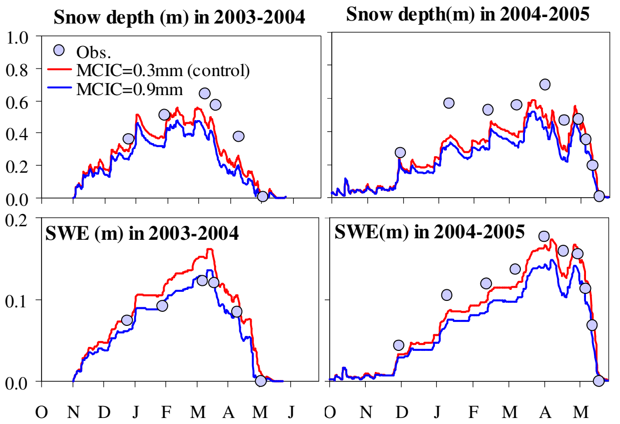


**Fig. 5** Observed and simulated snow depth and SWE for control run and run with *MCIC* = 0.9mm

runs are carried out to envision the impact of canopy interception to the snow depth, SWE and interception loss. It is found that with the increase of the interception capacity by 3 times, the canopy interception loss is increased up to 28% in 2004 and 22% in 2002. MBE for SWE is enhanced by 0.01 m and that for snow depth is degraded by 0.02 m in 2003-2004 whereas MBE for SWE and snow depth are degraded by 0.02 m and 0.06 m respectively in 2004-2005 (see **Fig. 5**). It shows that the canopy storage function is very critical in simulating snow processes beneath canopy.

## 5. CONCLUSIONS

The energy balance based snow melt model (WEB-DHM-S) was evaluated at Fraser site for forest snow process simulation from 2003 to 2005. The model is able to capture the seasonal and interannual variability of observed SWE, snow depth and snow density on forest floor. Simulated energy fluxes above and below canopy demonstrates that the net radiation is dominant in above canopy where sensible heat flux is equally important to the net radiation in sub-canopy snow processes. In general, it can be argued that the WEB-DHM-S can simulate sub-canopy snow processes well, since it provides physical basis of energy and water fluxes above and below canopy in detail. An addition of blowing snow module and advanced canopy interception model to the current version will be further research for better representation of forest snow processes in future.

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