UNIVERSITY OF SASKATCHEWAN

IP3 Improved Processes & Parameterisation for Prediction in Cold Regions

Simulation of Snow Accumulation and Melt Using the Cold Regions Hydrological Model

Chad Ellis, John Pomeroy and Tom Brown

Centre for Hydrology, University of Saskatchewan, Canada

Marmot Creek Research Basin

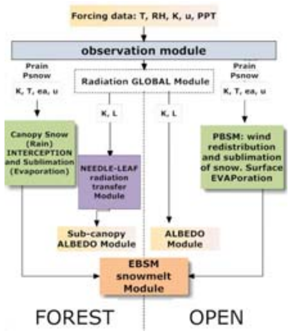
Centre for Hydrology

www.usask.ca/hydrology

Objective: Evaluation of the physically-based Cold Regions Hydrological Model (CRHM) in simulating energy exchanges to snow as well as snow accumulation and melt in open and forest environments.

The Cold Regions Hydrological Model: Overview

• CRHM is based on a modular, object-orientated structure in which component modules represent site descriptions, observations, or physically-based algorithms representing meteorological/hydrological processes.



• Meteorological forcing data (observations) requirements include (i) air temperature (T), (ii) relative humidity (RH), (iii) incoming shortwave irradiance (K), (iv) wind speed (u), and (v) precipitation (PPT).

• In the observation module, single-point observations are distributed to each specified hydrological response unit (HRU) according to the parameterization of each (e.g. temperature lapse rate with elevation, geometric correction of shortwave irradiance for slope and aspect).

• The hydrological processes represented in CRHM are user-defined according to the selection of the desired process modules (module names shown capitalized).

Process Modules:

• As evaluation of CRHM was performed for forest and forest-clearing areas, the specifics of the prairie blowing snow module (PBSM) are not discussed here. A detailed overview of PBSM as well as the warm season hydrological processes within CRHM is provided by Pomeroy et al. (2007).

Needle-leaf (radiation) Module: The transmissivity (τ) of the canopy layer to above-canopy shortwave irradiance (K↓) is estimated as a function of the effective-leaf-area index (*LAI*`) and solar elevation angle (θ) by:

$$\tau = \exp[-1.081\theta\cos(\theta)\frac{LAI`}{\sin(\theta)}]$$

• Sub-canopy longwave irradiance (*Lsc*↓) is determined as the sum of above-canopy longwave irradiance (*L*↓) and forest emissions weighted by the relative proportions of canopy-cover ($1-\upsilon$) and open sky (υ) of the overhead forest scene:

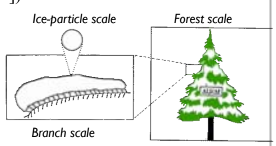
$$Lsc\downarrow = L\downarrow(\upsilon) + (1-\upsilon)\varepsilon\sigma T^4$$

where ε is the emissivity of the forest (0.98), σ is the Stephan-Boltzmann constant (W m^{-2} K^{-4}) and *T* is the radiating temperature of the forest (K).

Interception Module: Intercepted snow and rain by the canopy is subject to sublimation and evaporation back to the atmosphere, respectively. The amount of snowfall, *P* (kg m^{-2}) that may be intercepted by the canopy prior to unloading is related to the (i) antecedent intercepted load, *Lo* (ii) the maximum intercepted load, *I** (which is related to LAI` and the density of falling snow) and the 'canopy-leaf' contact area, *Cp* via (Hedstrom and Pomeroy, 1998):

$$I = (I^* - Lo)(1-\exp[-Cp\,P/I^*])$$

• Sublimation of intercepted snow is calculated by the Pomeroy et al. (1998) multi-scale model in which the sublimation flux from a single small ice-sphere is scaled up to the branch and forest scales by determining the exposure of intercepted snow to the atmosphere



• Rain Interception: the maximum storage depth of rain on the canopy (*Smax*) is set *a priori* by the user (typical values for needle-leaf forests range from ~1-2 kg m^{-2}, Ward and Robinson, 2000). Evaporation from the canopy with an intercepted rain storage of *C* is determined by:

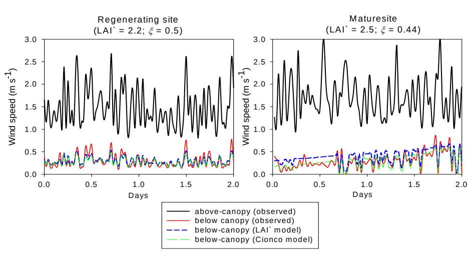
$$E = Ep\frac{C}{S\max}Cc$$

where *Ep* is the evaporative flux calculated for a fully saturated canopy using via the Penman-Monteith formulation with stomatal resistance set to zero and C_C is the horizontal canopy-coverage fraction. Rainfall exceeding a depth of *Smax–C* is delivered to the sub-canopy. To determine the diffusivity of sublimation and evaporative fluxes from the canopy, the sub-canopy wind speed ($u(\xi)$) is determined as a function of wind speed at the canopy top (u_0)

$$u(\xi) = u_0\exp[-\gamma\,LAI`\xi]$$

where γ is the forest wind extinction coefficient and ξ is the ratio distance from the canopy top to the total distance between the canopy top and snow surface (Eagleson, 2002).

Observed sub-canopy wind speed as compared to simulations using the above-formulation and an empirically-derived Cionco model at two forest sites in Saskatchewan.



Albedo Module: Snow albedo is calculated separately for forest and open environments. Both however, calculate albedo decay as a function of time since fresh snow fall, *t*

forest

$$albedo(t) = 0.85 - \left(\frac{0.05}{n}\right)t^{0.6}$$

open

$$albedo(t) = A_i - Yt$$

where n is the number of modelling time steps per day, A_i is the antecedent snow albedo, and Y is the snow albedo decay coefficient for snow in open environments, equal to 6.8E-3 day^{-1} prior to active snow melt and 7.1E-2 day^{-1} during active snowmelt when *t* is in days (Gray & Landine, 1987).

Energy-Balance Snowmelt Module: The energy budget requires that the amount of energy used for melt (*M*) and internal energy change (dU/dt) is equal to the sum of the fluxes transferred to the snowpack by net shortwave (*K**) and longwave radiation (*L**), turbulent transfers of sensible (*H*) and latent heat (*QE*), advection from precipitation (*QP*), and conductive ground heat (*G*). The change in the internal energy of a volume of snow is expressed:

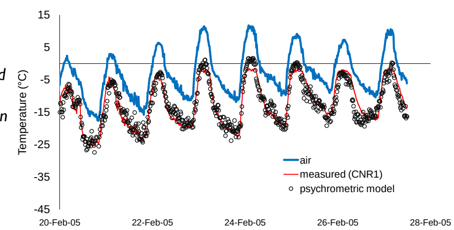
$$M + \frac{dU}{dt} = K^* + L^* + H + QE + QP + G$$

A critical energy component is that of longwave exitance (*L*↑) from the snow surface, which is directly related to the snow surface temperature, *Ts*. In open environments, ventilation of the snow surface depresses its temperature to a balance between the net longwave radiation and the ice-bulb temperature, which is calculated in CRHM using the following longwave-psychrometric expression by Pomeroy *et al.* (in preparation):

$$Ts = T + \frac{\varepsilon\left(L\downarrow - \sigma T_a^4\right) + L[Q_a - Q_{sat}(T_a, P_s)]\rho / r_a}{\varepsilon\sigma T^3 + (c_p + L\Delta)\rho / r_a}$$

where Q_a and Q_{sat} are the observed and saturation vapour pressures of air, r_a is the aerodynamic resistance, ρ is the density of air, c_p is the heat capacity of air and Δ is the slope of the Clausius-Clapeyron equation relating Q_{sat} to *T*.

Comparison of measured snow surface temperature to that modelled the longwave – psychrometric formulation (air temperature is shown in blue) for open snow cover in a clearing in Kananaskis, Alberta.



Simulations:

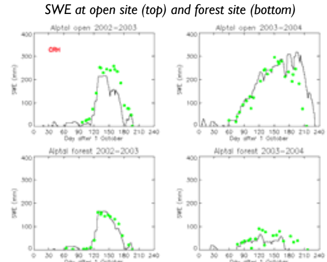
Simulations were performed for three open and forest sites as part of the SnowMIP2 inter-comparison project (Essery and Rutter: http://users.aber.ac.uk.rie/snowmip2.html).

Site:	latitude	elevation	slope/aspect	height/species	LAI`	Cc
Alptal, Switzerland (forest)	47°3' N	1185 m	3°/west	25 m spruce and fir	2.5	0.96
Alptal, Switzerland (open)	47°3' N	1220 m	11°/west	-	-	-
BERMS, Canada (forest)	53°55' N	579 m	level	12-15 m jack pine	1.66	0.72
BERMS, Canada (open)	53°57' N	579 m	level	-	-	-
Fraser, U.S.A. (forest)	39°53' N	2820 m	17°/305°	~27 m pine, spruce and fir	3	not given
Fraser, U.S.A. (open)	39°53' N	2820 m	17°/305°	2-4 m sparse trees	0.4	not given

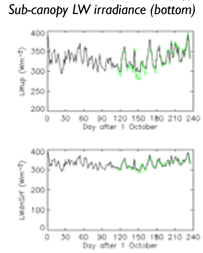
The following are the preliminary results received from SnowMIP2 for the Alptal (Switzerland), BERMS (Canada) and Fraser Experimental Forest (U.S.A.) sites. CRHM simulations shown in black and measurements are in green.

Alptal, Switzerland

SWE at open site (top) and forest site (bottom)

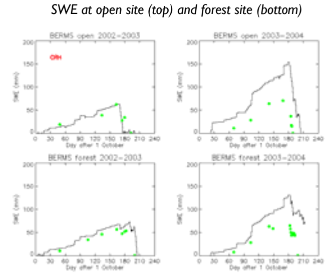


Forest site: snow LW exitance (top)
Sub-canopy LW irradiance (bottom)

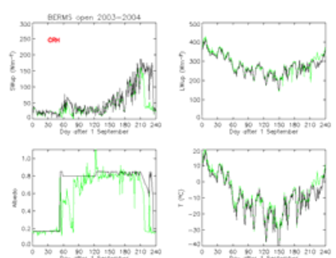


BERMS, Canada

SWE at open site (top) and forest site (bottom)

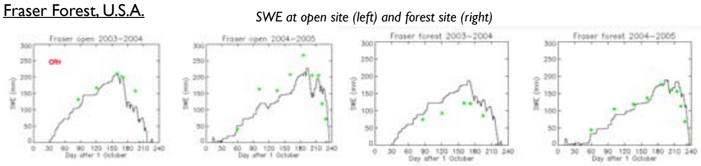


Open site: reflected SW irradiance (top-left); LW exitance from snow (top-right); snow albedo (bottom-left); snow surface temperature (bottom-right).



Fraser Forest, U.S.A.

SWE at open site (left) and forest site (right)



Discussion and Conclusions: Simulation results show CRHM generally provides satisfactory estimation of snow accumulation and melt and some diagnostic variables from the radiation balance in both open and forest environments without calibration. The good results from regions far away from the zone of its derivation suggest that it is sufficiently physically based and robust for general application. However, at the BERMS site in Saskatchewan, snow accumulation was substantially over-estimated at both open and forest sites in 2003-2004. This is perplexing as the modules that control snow interception, blowing snow and snow accumulation were based on field studies near to the BERMS site. Further diagnosis of the difficulties in this year will require inspection of the forcing meteorology.