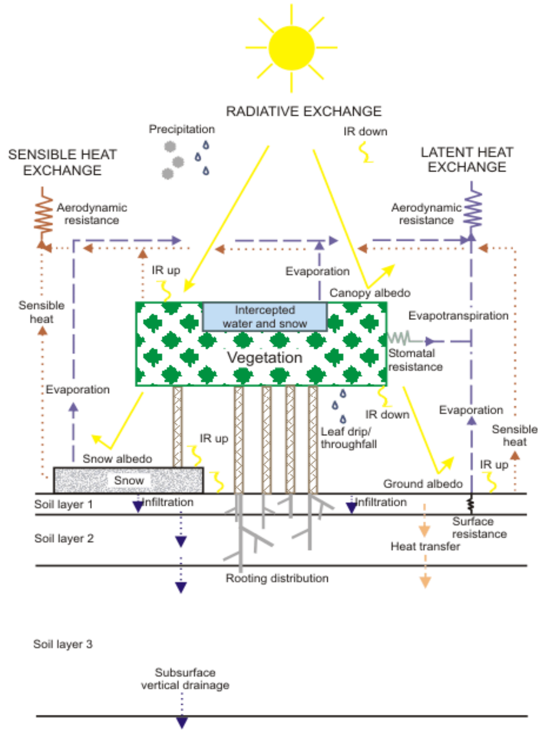
Modelling Snow with CLASS
A Canadian Perspective

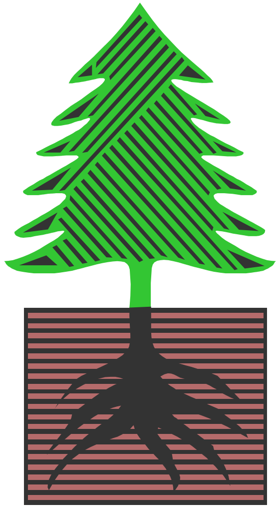


Paul Bartlett
Climate Processes Section

JULES Science Meeting on Forest Processes
University of Edinburgh
June 19-20, 2013

Importance of snow and snow processes in climate models

- large impact on the surface radiation balance
- large positive feedback mechanism in the climate system
- low thermal conductivity → insulates the surface
- freezing and thawing of water (surface and subsurface) introduces a thermal lag with respect to atmospheric forcing



In the Boreal Forest:

- snowpack can hold 1/3 of the annual water budget
- soil thaw and the availability of liquid water in the soil has been found to be a control on the timing of leaf-out / photosynthesis which is a major determinant of the source/sink status of the annual carbon balance (Black *et al*. 2000; Barr *et al*. 2002)

The Canadian Land Surface Scheme

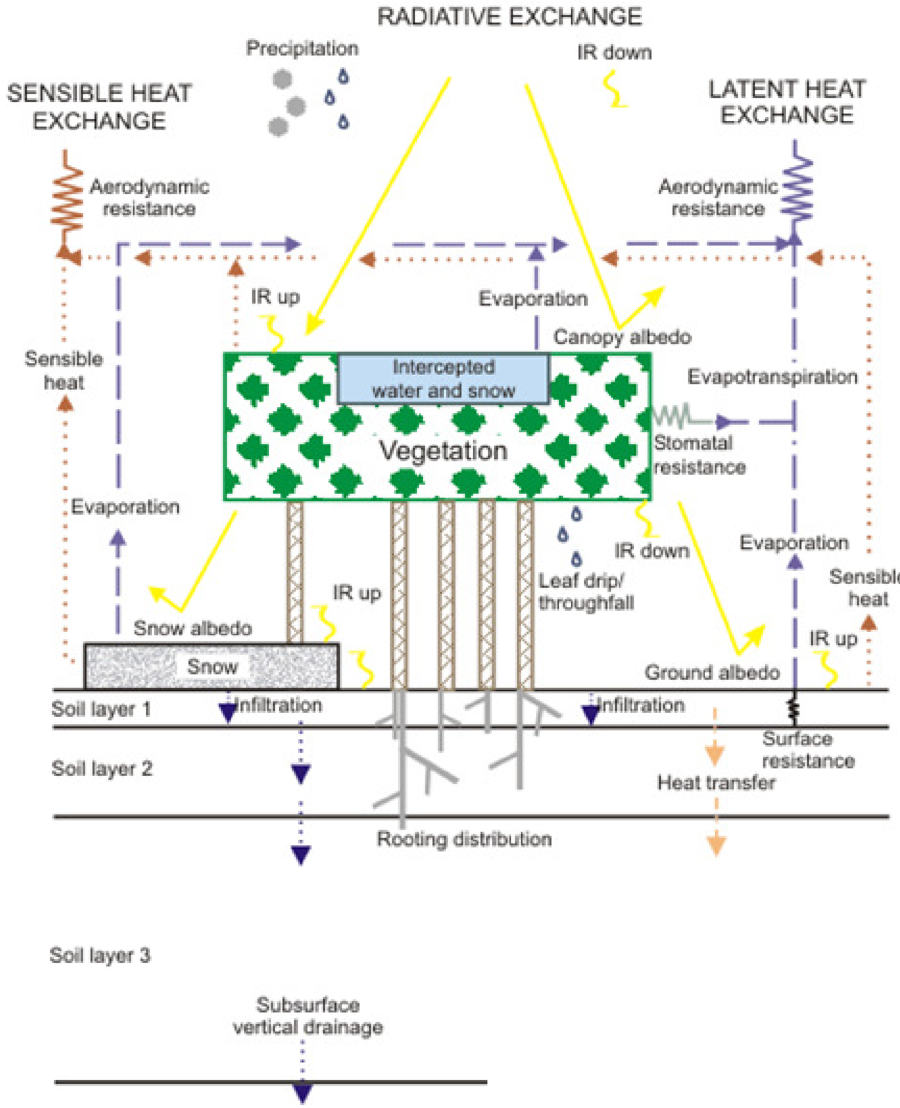
Monin-Obukhov similarity theory

Big-leaf canopy
- Jarvis-Stewart
- Carbon
- Carbon-Nitrogen

Snow interception by canopy
- evaporation, sublimation
- freeze / melt, drip
- unloading

Explicit snow layer
- Liquid water

3 soil layers standard
number of layers now variable



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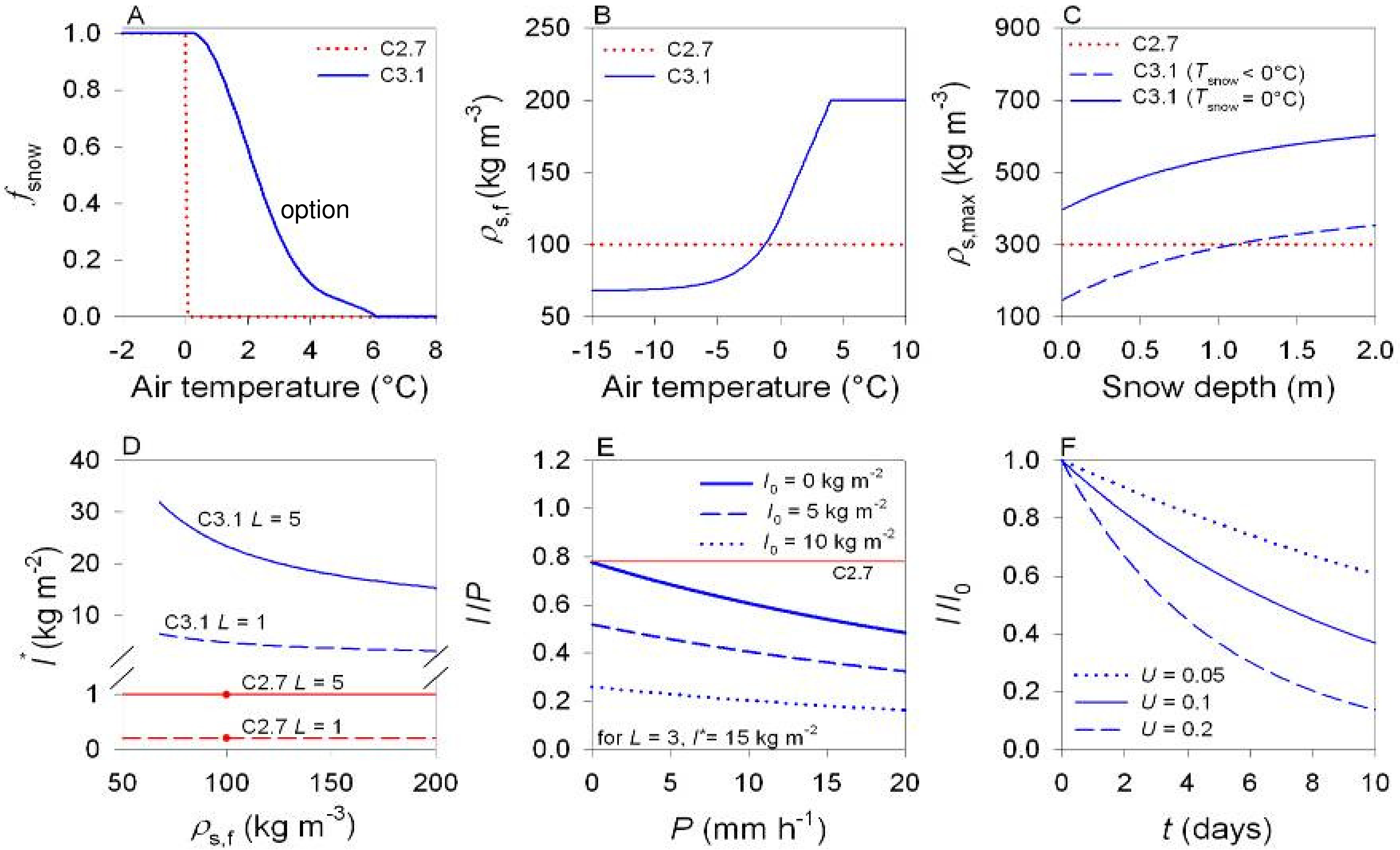
The representation of snow in CLASS

Version	Major features / enhancements
1.0	3 soil layers with 1 snow layer
2.0	Canopy added, interception capacity $I^* = 0.2\ L$ (same as for water), no unloading of snow from canopy, density of fresh snow constant, maximum snowpack density constant, rain/snow partition at 0°C.
3.0	Interception capacity ↑, Implicit unloading (Pomeroy *et al*. 1998), Fresh snow density $f(T_a)$ (Hedstrom and Pomeroy, 1998) Max. snowpack density $f(T_a$,depth) (Tabler *et al*. 1990) Optional mixed precip. (0-2°C or 0-6°C) (Auer, 1974)
3.1	Explicit unloading over time (Hedstrom & Pomeroy, 1998)
3.2	Variable number of soil layers, more layers improves freeze/thaw representation in soil and ameliorates cold bias in winter. Allow liquid water in snowpack.
3.6	Lower snow thermal conductivity (Sturm 1997)
3.6a/3.7	New f_{snow} /canopy albedo algorithm, unloading caused by weather New 4 band snowpack albedo (over bare soil), black carbon

Changes to snow algorithms in CLASS (Version 3.1 – April 2005)



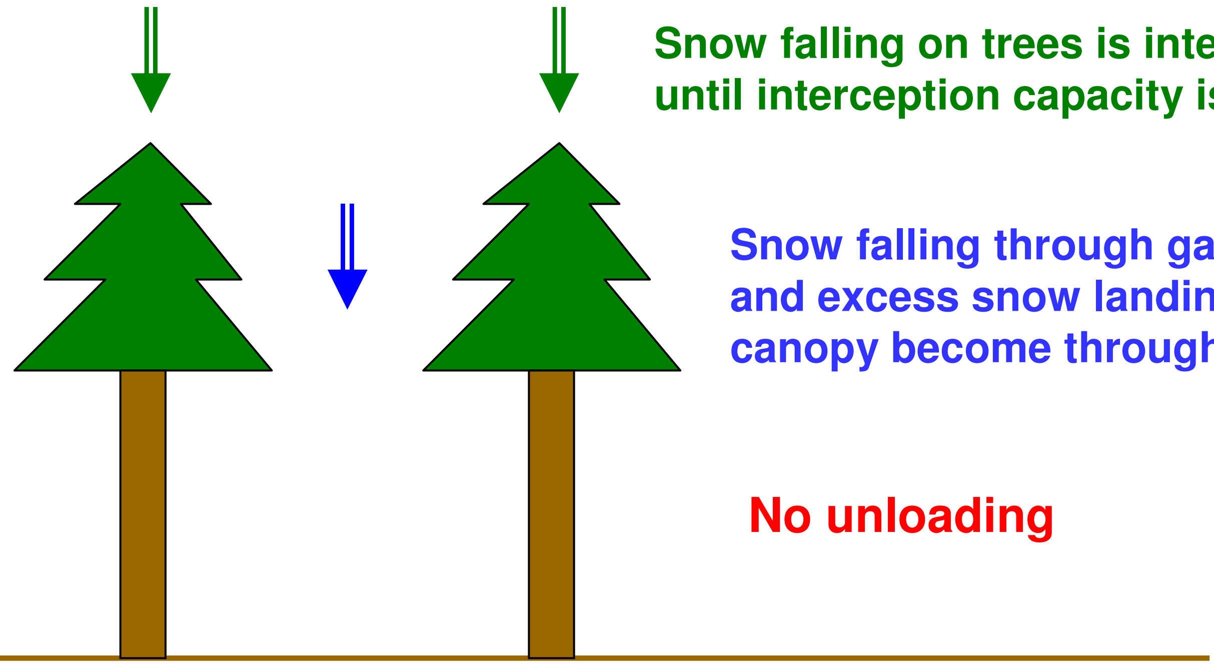
Historical interception and unloading algorithms in CLASS: CLASS 2.X

- **CLASS 2.X:** Simple interception based on gap fraction, no unloading.

  $$I = I_0 + S \cdot Cc \qquad (\text{for } I \leq I^*)$$

  I_0 is intercepted snow at start time step, I is intercepted snow at end of time step, S is snowfall, and Cc is the canopy coverage (1 – gap fraction).

  $I^* = 0.2 \cdot L$ is the snow interception capacity (same as for water).

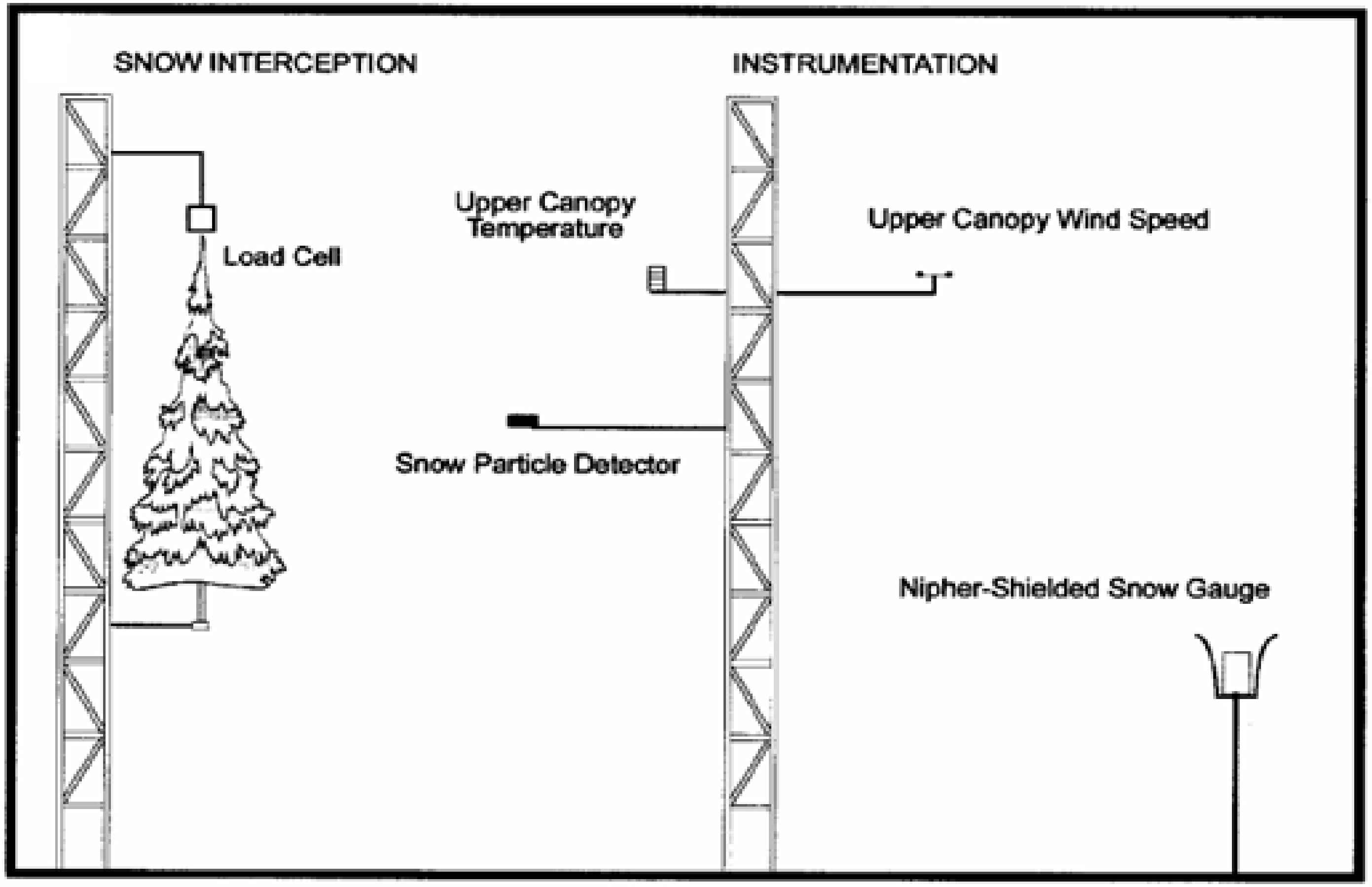


Snow falling on trees is intercepted until interception capacity is reached

Snow falling through gaps and excess snow landing on canopy become throughfall

No unloading

Canopy interception capacity for snow much larger than for water (Pomeroy and colleagues)



(From Hedstrom and Pomeroy, 1998)

Historical interception and unloading algorithms in CLASS: CLASS 3.0 and 3.1

- **CLASS 3.0:** Interception capacity increased (Pomeroy *et al*. 1998).

  $I^* = 6 \cdot (0.27 + 46/\rho_s) L_e$, $\quad I = I_0 + c(I^* - I_0)(1 - \exp(-\chi S/I^*))$

  ρ_s is fresh snow density, L_e is projected leaf area index, c ~ 0.35 is an unloading coefficient, partial unloading occurs instantly, rather than over time.

- **CLASS 3.1:** Unloading over time (Hedstrom & Pomeroy, 1998).

  Interception: $I_1 = I_0 + (I^* - I_0)(1 - \exp(-\chi S/I^*))$

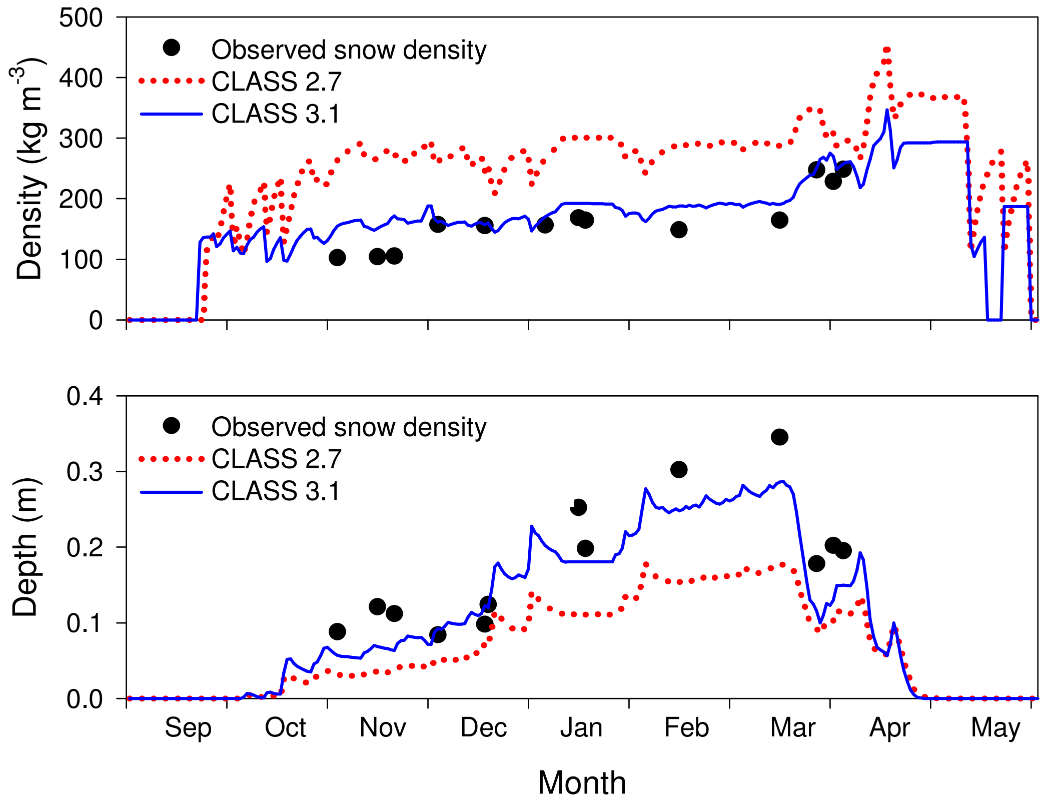
  Unloading: $I = I_1 \exp(-Ut)$

  I_1 is intercepted snow load before unloading, U is the unloading rate coefficient initially set to 0.1 days^{-1}, U^{-1} is the e-folding time of the unloading process (10 days) and t is the model time step (usually 30 min).

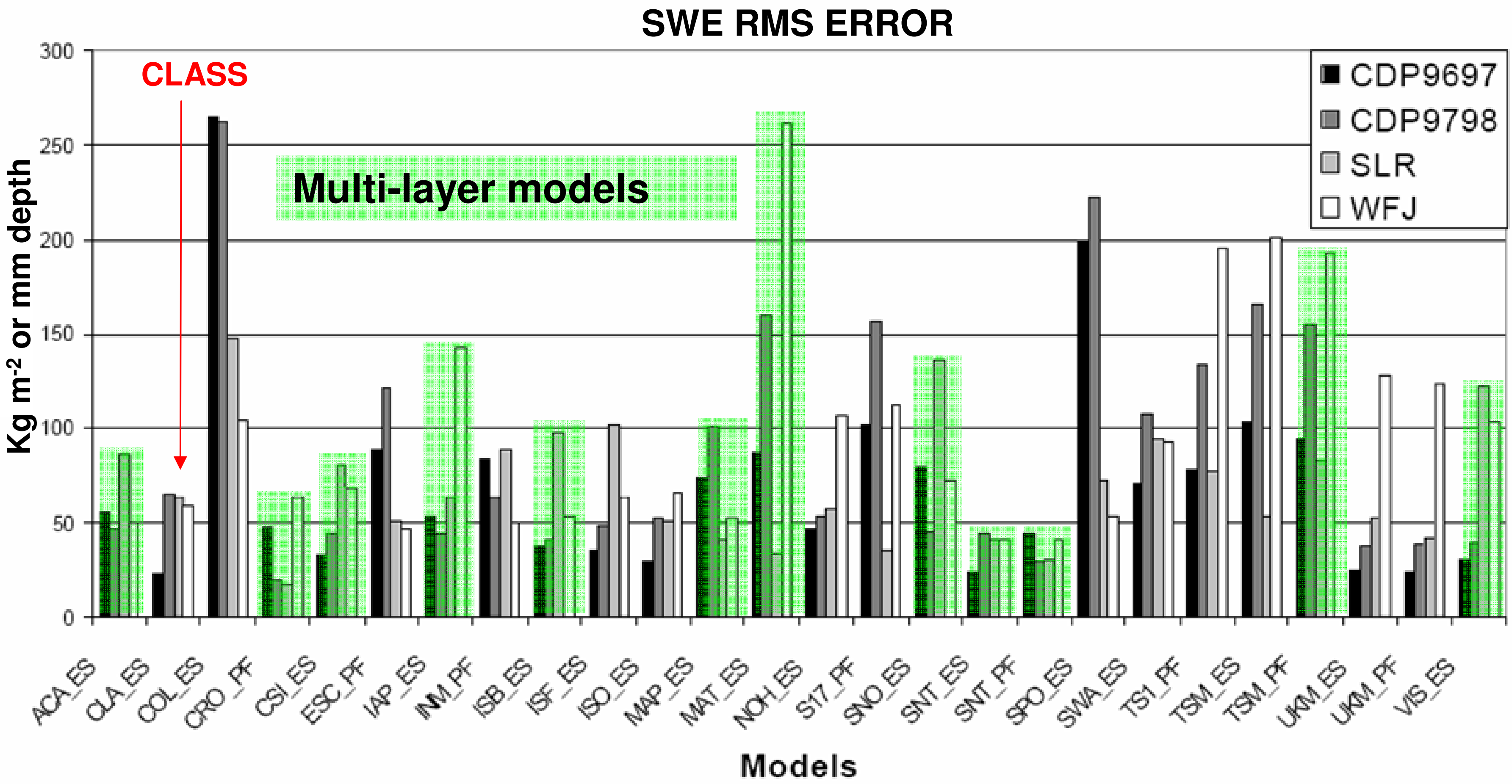
  Unloading occurs over time with an e-folding time of 10 days.

Snow density and depth observed at BERMS – OJP for winter 2002-2003 and modelled using CLASS 2.7 and 3.1

- Snow density is overestimated by CLASS 2.7, whereas CLASS 3.1 incorporates improved algorithms, and performance is better.
- Overestimation of snow density in CLASS 2.7 causes under-estimation of snow depth, while CLASS 3.1 performs better.



SnowMIP: CLASS 2.6+ RMS error in SWE comparable to multi-layer models



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(Courtesy, Ross Brown, Environment Canada)

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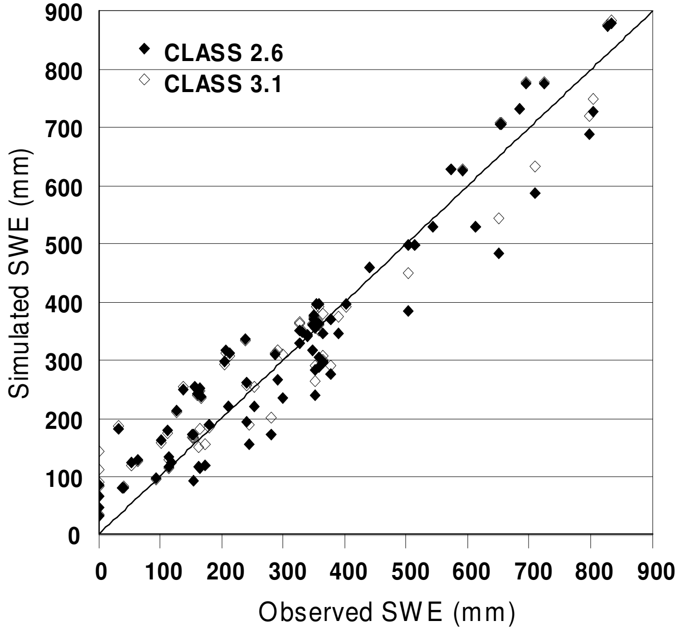
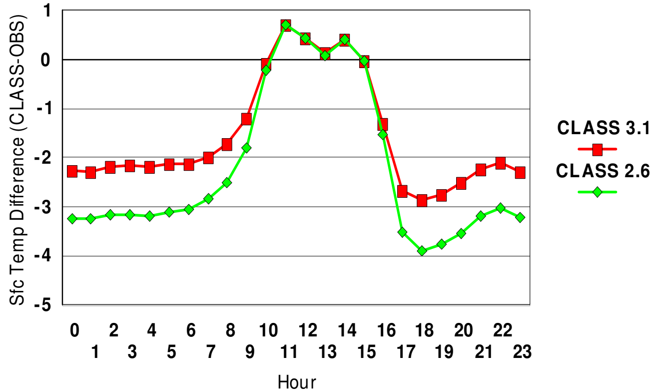
Modified snow aging scheme in CLASS 3.1 improved simulated snow depth and surface temperature bias at Col de Porte, Sleepers River and Weissfluhjoch

SWE Comparison

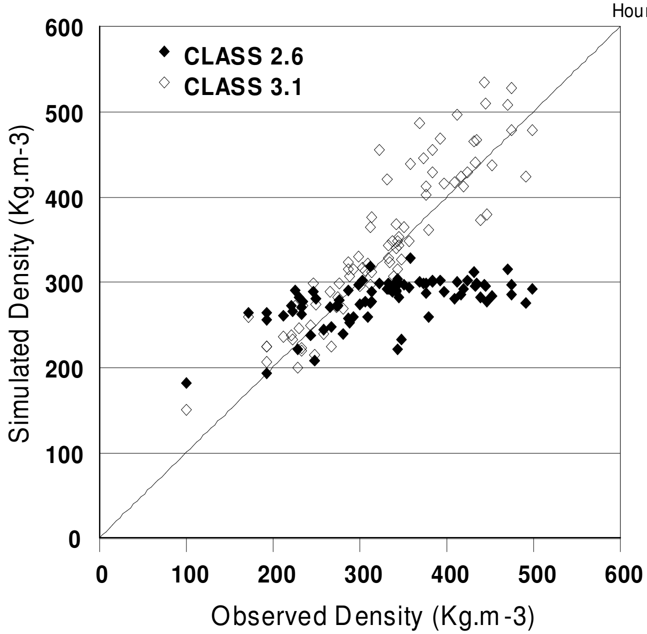


Col de Porte 1996-1997



Snow surface temperature bias

Density Comparison



(Brown et al. 2006)

CLASS version 3.2: Completed May 2006

- Option for multiple soil layers at depth
  - lessens winter cold bias
- Modelled liquid water content of snow pack

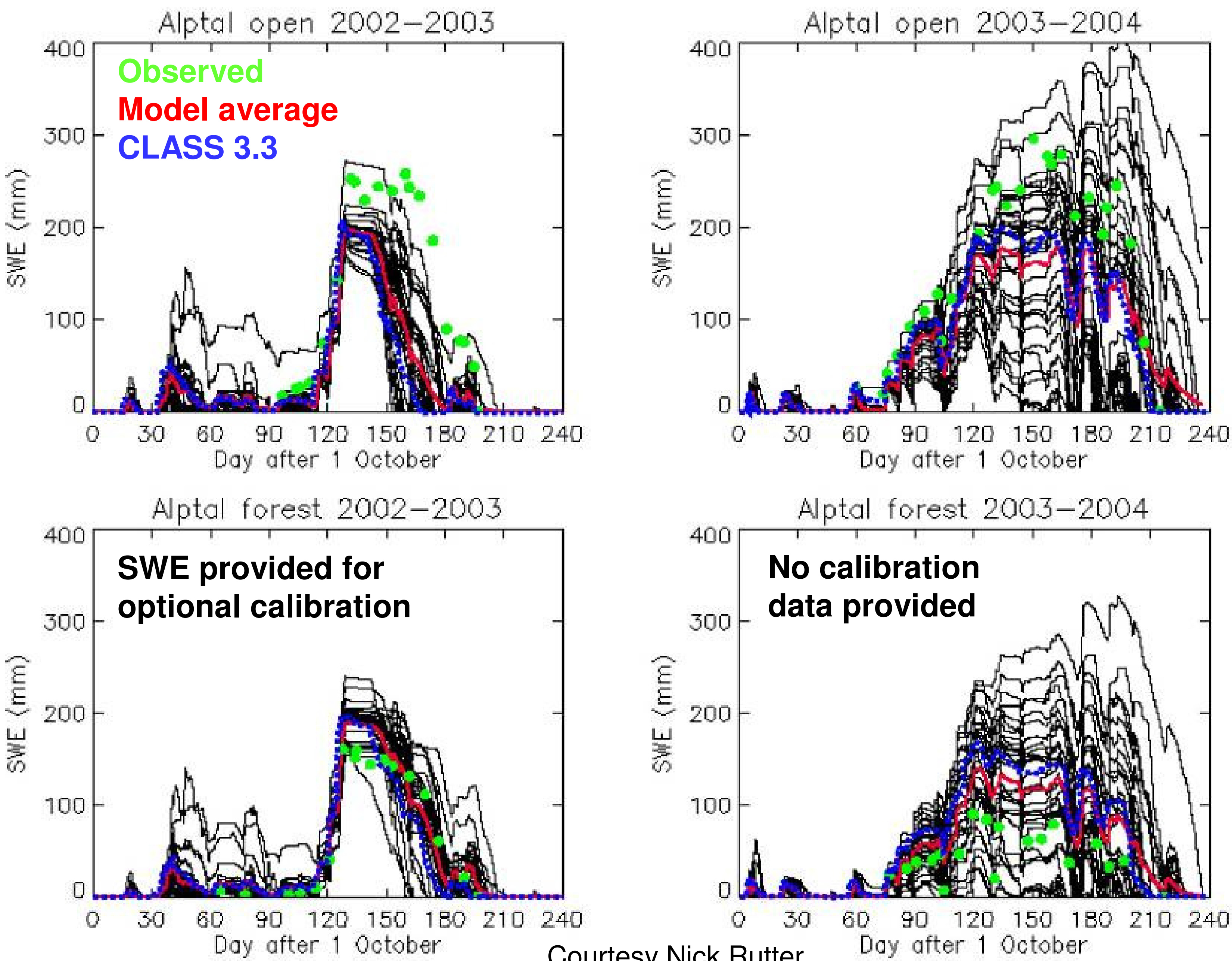
  Snowpack holds up to 4% water by volume before percolation
- Revised radiation transmission in vegetation

  Recognize L_t, L, L_e

  $L = 0.9 * L_t$

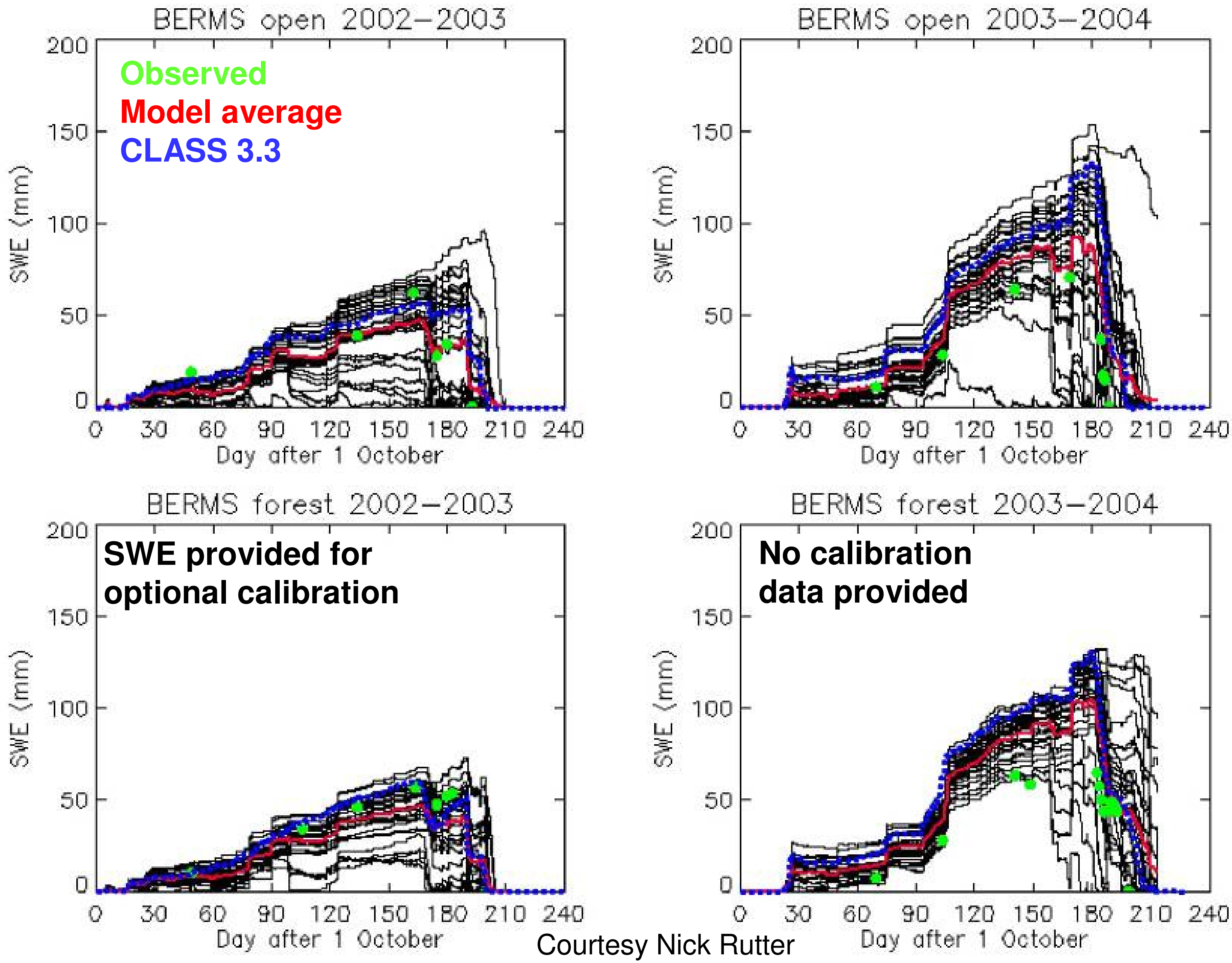
  $L_e = 0.7 * L_t$

Modelled SWE at Alptal for all models participating in SnowMIP2



Courtesy Nick Rutter

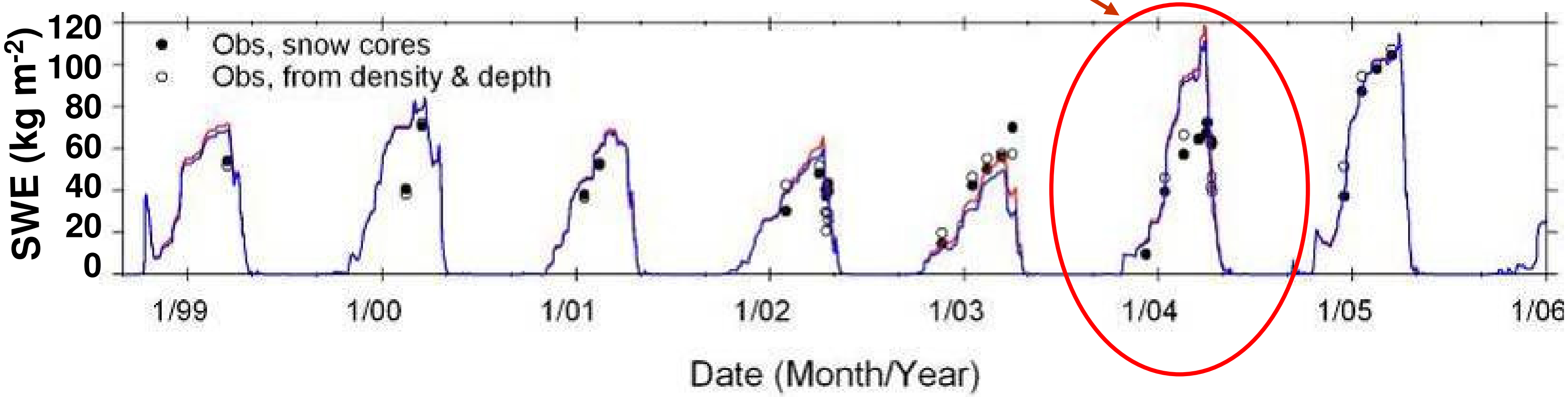
Modelled SWE at BERMS OJP for all models participating in SnowMIP2



Courtesy Nick Rutter

Observed and simulated (CLASS 3.3) SWE at the BERMS Old Jack Pine Site over 7 years

SnowMIP2 non calibration year!



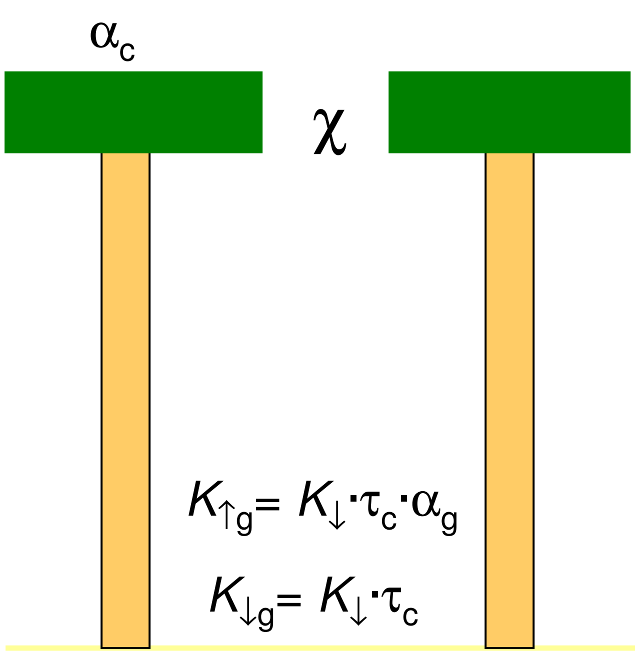
Albedo in CLASS uses a 2 stream Beer's law approach and ignores multiple reflections

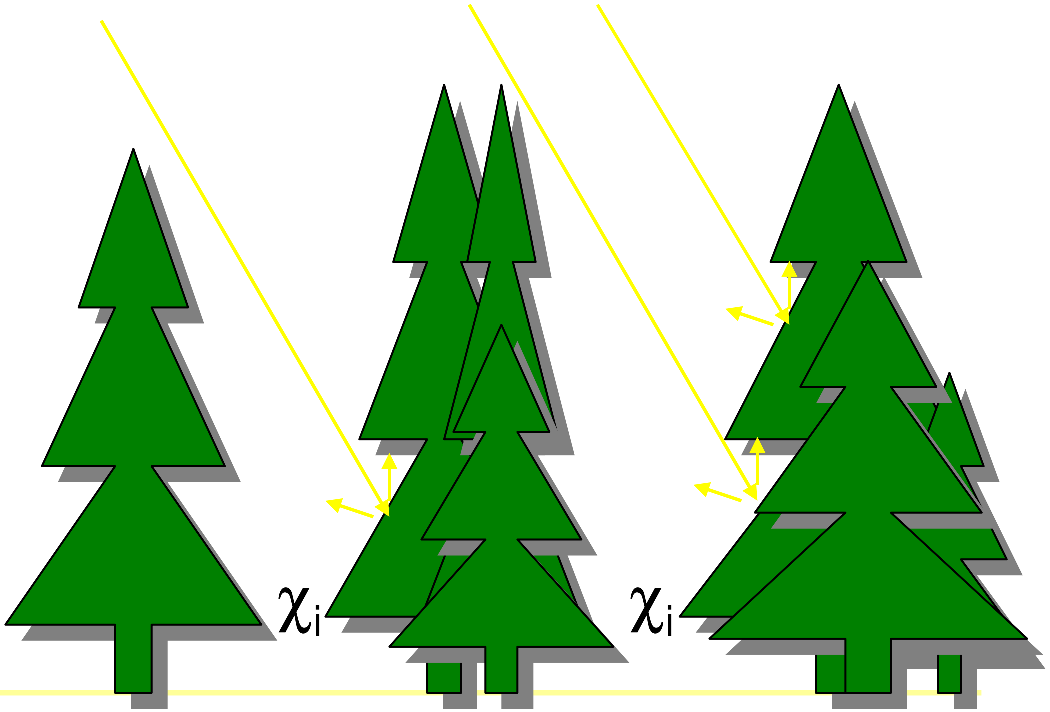
To V3.1: $a = \alpha_c \cdot (1 - \chi) + \alpha_{e,g} \cdot \chi$ $\qquad K^* = K_\downarrow - (K_\downarrow \cdot \alpha_c \cdot (1 - \chi) + K_\downarrow \cdot \alpha_{e,g} \cdot \chi)$

V3.2 +: $\alpha = \alpha_c \cdot (1 - \chi) + \tau_c \cdot \alpha_g \cdot \chi$ $\qquad K^* = K_\downarrow - (K_\downarrow \cdot \alpha_c \cdot (1 - \chi) + K_\downarrow \cdot \tau_c \cdot \alpha_g \cdot \chi)$

Above-canopy albedo measurements (canopy, ground, radiation trapping)

Canopy albedo for CLASS includes radiation trapping within the canopy, but not gaps

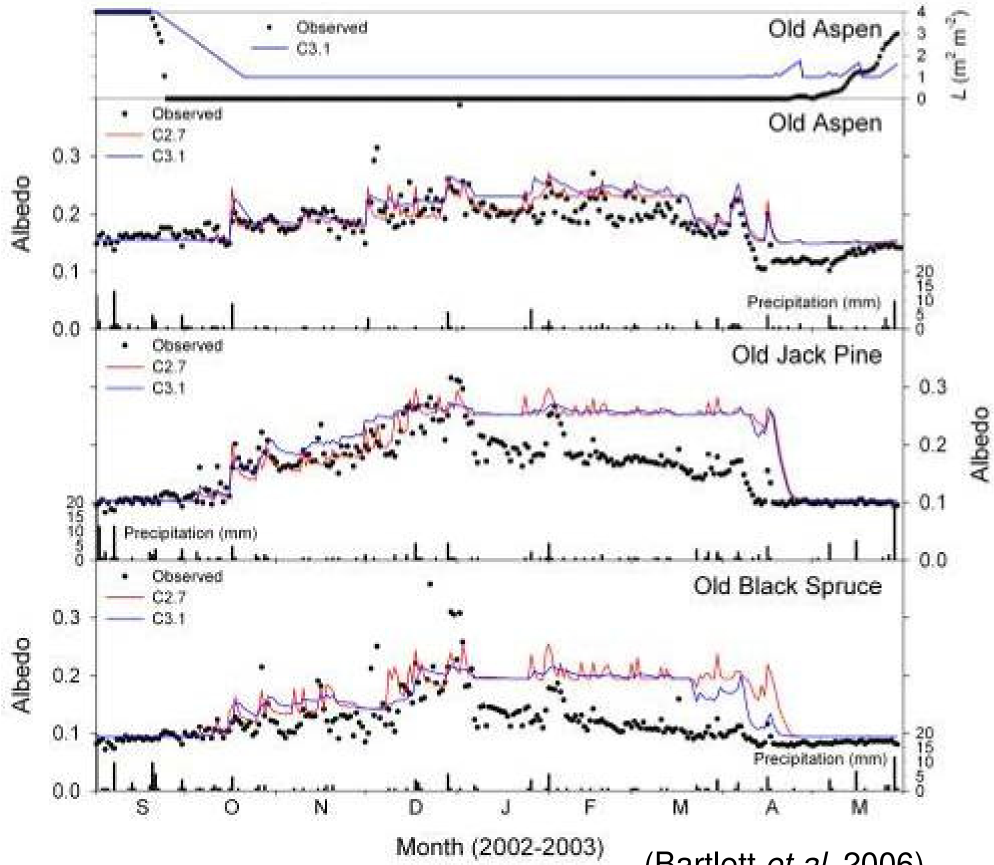




The use of specified 'effective' albedo for the canopy gaps, biased the total (above canopy) albedo.

- In dense vegetation such as forests, where radiation trapping lowers the effective albedo of the surface, the total albedo was overestimated (e.g. BERMS sites) →

- In sparse vegetation, such as shrub tundra (e.g. Trail valley Creek), the effective albedo of the gaps approaches that of the snowpack and CLASS underestimated the total albedo by up to 50%.



(Bartlett *et al.* 2006)

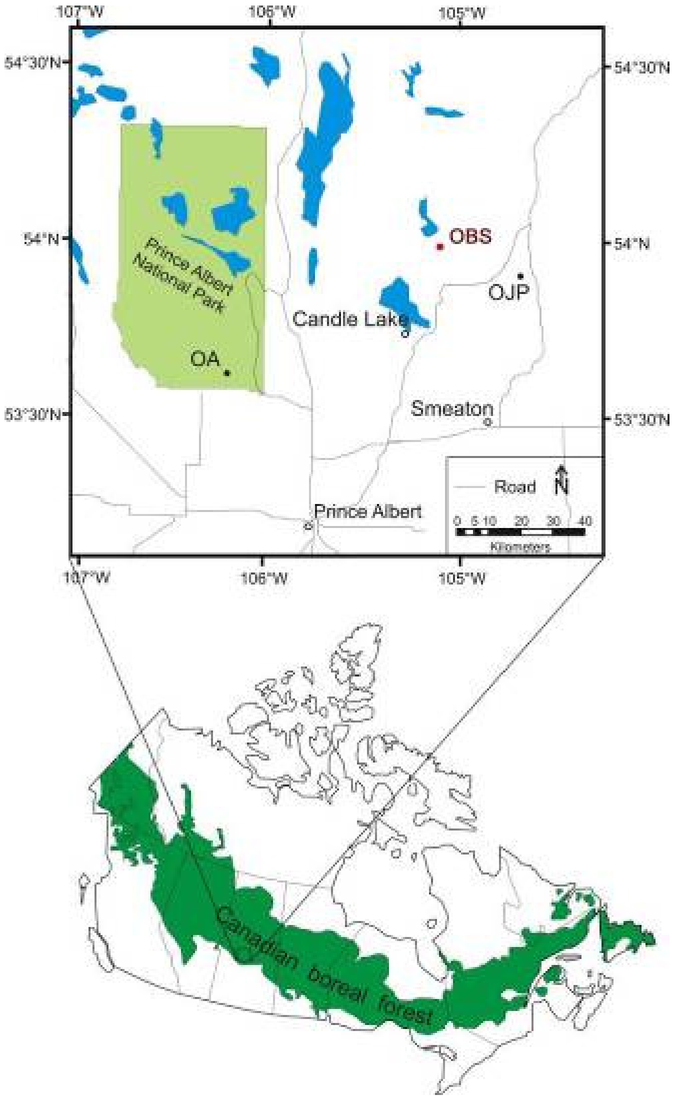
- This work also revealed that the albedo response to snow in forests was too small and often decreased too slowly following a snowfall event.

BERMS Old Black Spruce canopy (from tower)

Conifers have a much larger interception capacity for snow than for water

Following unloading and sublimation, the canopy is snow-free for much of the winter

Interception / Unloading work at the BERMS Old Black Spruce and Old Jack Pine forests in Saskatchewan



- Mature forests
- *L* ~ 4 (OBS), 2.7 (OJP)
- H_{canopy} = 12 m (OBS), 14 m (OJP)
- Soil: peat over sand loam (OBS) and sand (OJP)

Canada

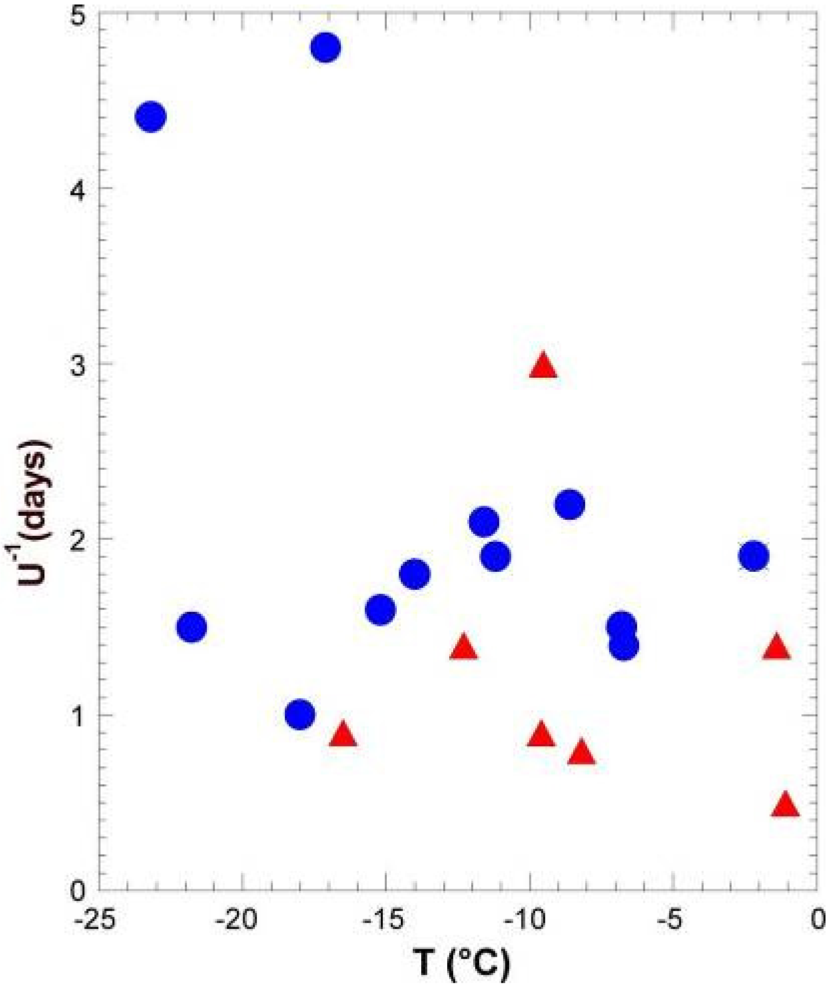
Canopy snow unloading from daily albedo (MacKay and Bartlett, 2006)

- Mature BERMS (Boreal Ecosystem Research and Monitoring Sites) conifer forests in Central Saskatchewan: Old Black Spruce (OBS) and Old Jack Pine (OJP) sites.
- Response of daily albedo to snowfall events analyzed (Laplace convolution theorem).
- Ground was snow-covered to isolate canopy response.
- Assumed that albedo response and intercepted snow fraction are linearly related.

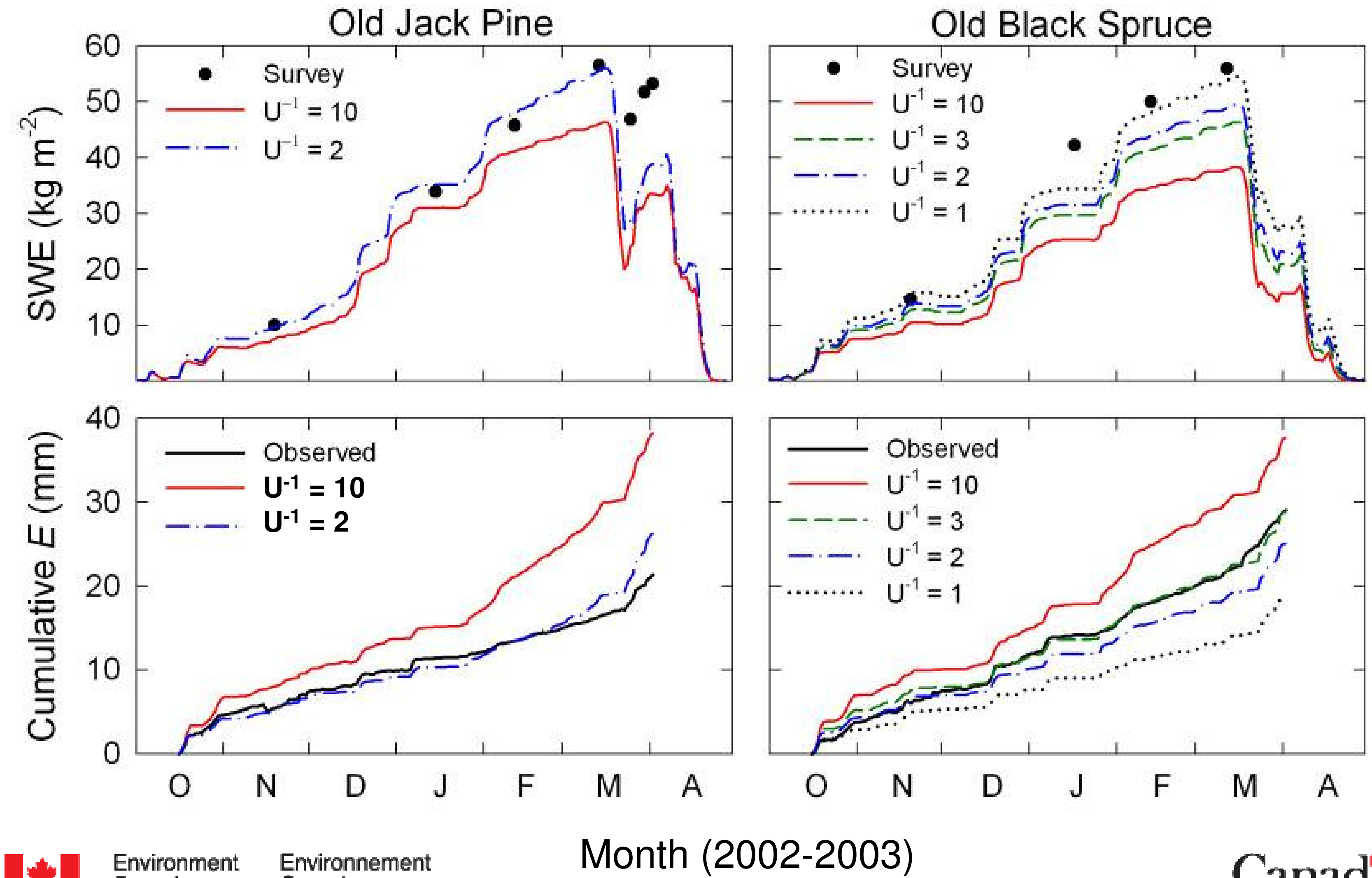
U^{-1} ~ 1 day at OBS ▲

~ 2 days at OJP ●

- Default in CLASS is U^{-1} = 10 days

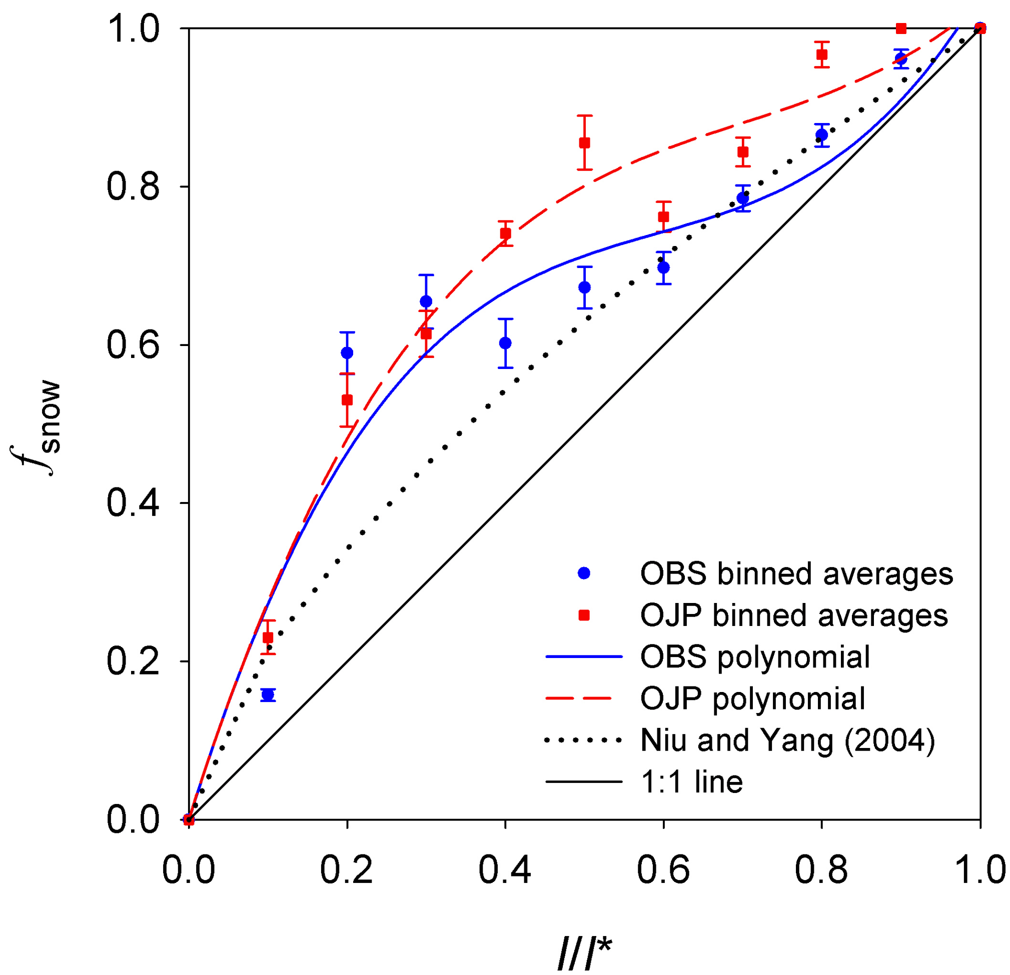


Modelled SWE and cumulative E are improved with the use of smaller (faster) unloading coefficients



Relationship between fraction of canopy covered with snow (f_{snow}) and relative mass load (I/I^*) at OBS and OJP

- CLASS models f_{snow} as I/I^*.
- Evidence from photographs shows that fresh snow can cov the canopy (f_{snow} ~ 1.0) while I/ is relatively small.
- When I^* was underestimated (CLASS 2.X) f_{snow} could still approach 1.0 following most snowfall events, but beginning with CLASS 3.0, the response f_{snow} and albedo were muted.

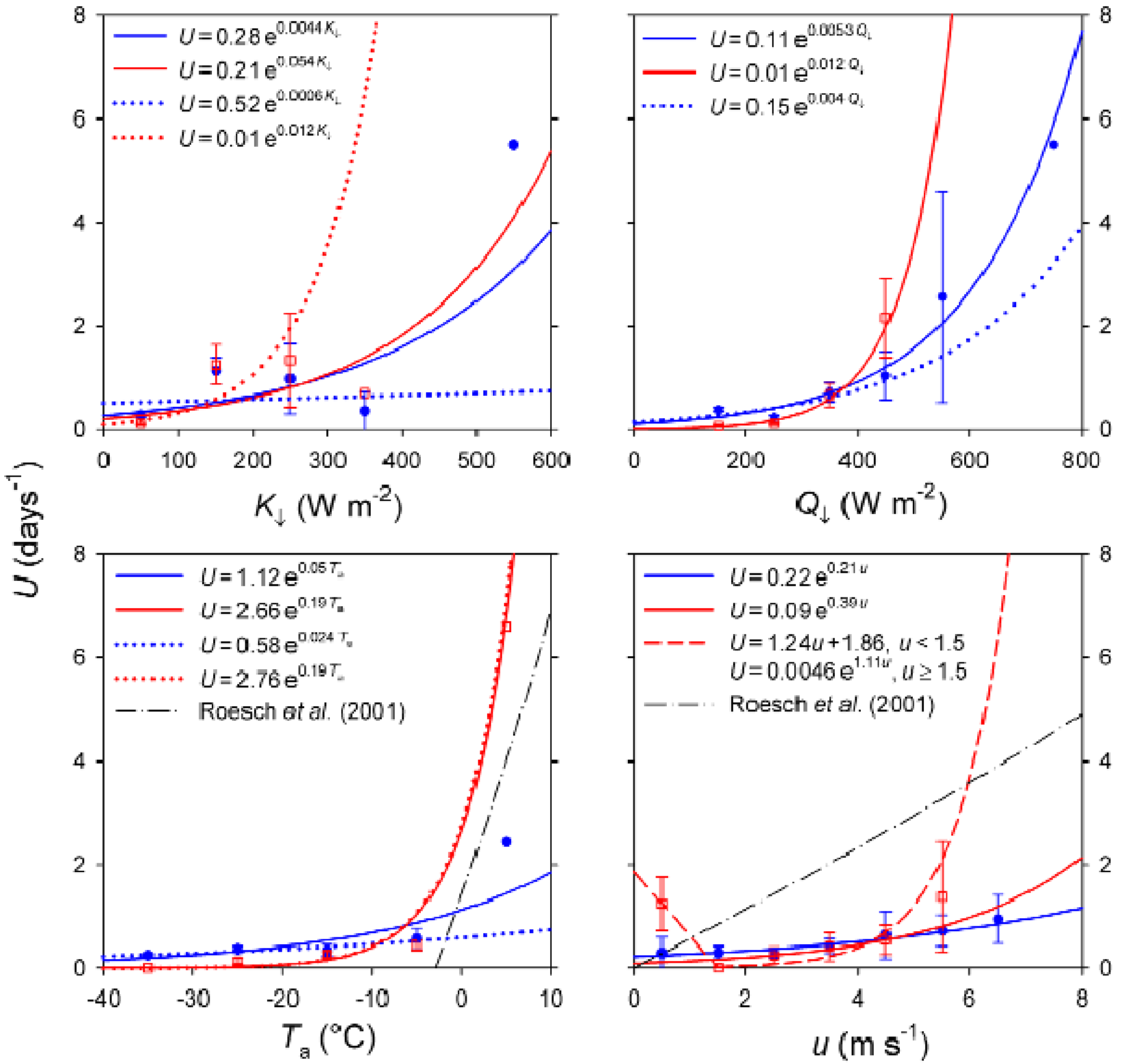


Methodology: Estimate canopy snow load and coverage using ~1500 photos from 2002-2005 and calculate unloading rates between subsequent photos

- Photos viewed in random order.
- Estimated relative intercepted load (I/I^*), and fraction of canopy with snow cover (f_{snow}) (10 pt. scale).
- Unloading rates calculated for mass and coverage as:
- $$U_{mass} = -\ln\left[\frac{I/I^*_{photo\ 2}}{I/I^*_{photo\ 1}}\right] Dt^{-1}$$
- $$U_{coverage} = -\ln\left[\frac{f_{snow}\ photo\ 2}{f_{snow}\ photo\ 1}\right] Dt^{-1}$$
- In MacKay and Bartlett (2006) we set the threshold for full canopy coverage in CLASS to I = 2 kg (somewhat arbitrary).

Modelled U_{mass} at OBS and OJP based on meteorological variables

- Unloading more sensitive to conditions that promote unloading at OJP, with a slower unloading rate for calm, low energy periods.
  - Possibly related to droopy branches at OBS allowing a more continuous unloading response.
- Modelling of coverage based on meteorology abandoned.

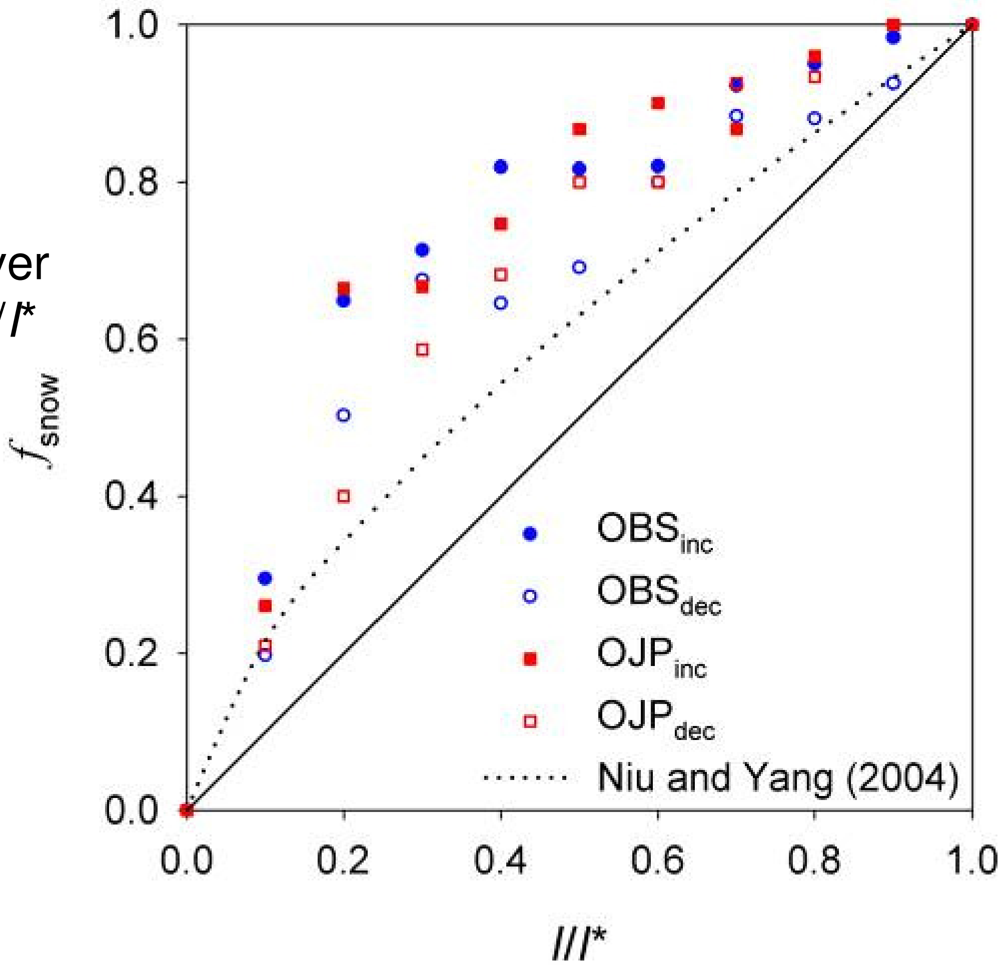


Relationship between fraction of canopy covered with snow (f_{snow}) and relative mass load (I/I) at OBS and OJP*

- CLASS models f_{snow} as I/I^*.

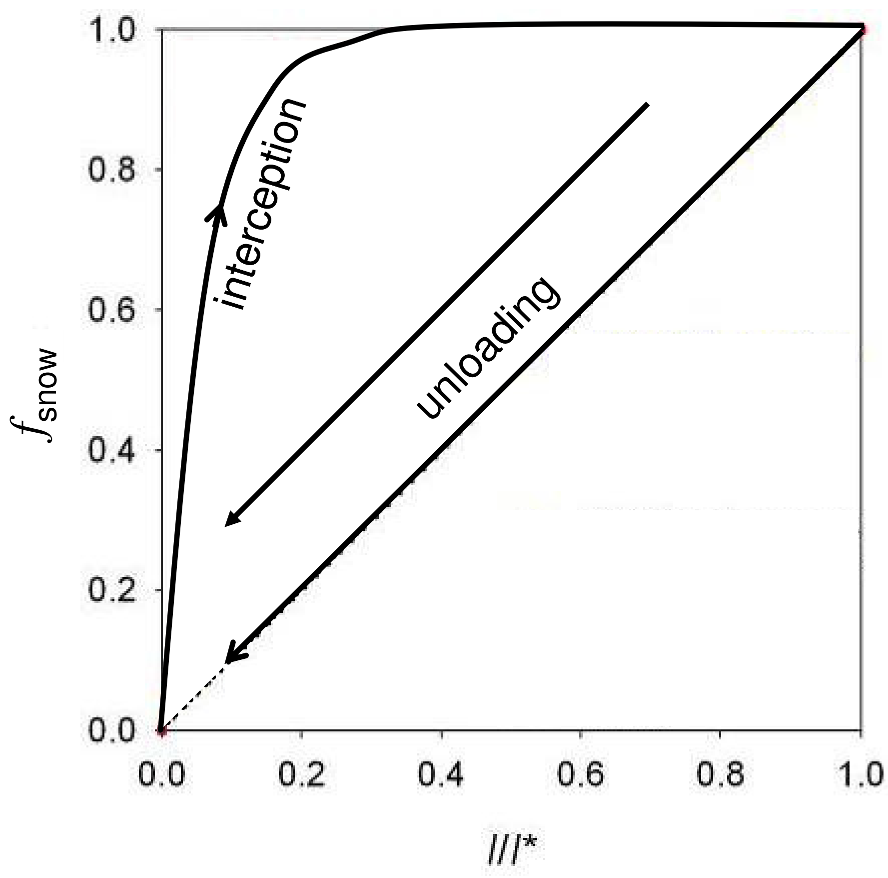
- Evidence from photographs shows that fresh snow can cover the canopy (f_{snow} ~ 1.0) while I/I^* is relatively small.

- f_{snow} based on photographs found to be greater for a given relative interception (I/I^*) when new show is on the canopy (i.e. when I/I^* has recently increased)



Conceptual relationship between fraction of canopy with snow (f_{snow}) and relative mass load (I/I*)

- The relationship must lie on or above the 1:1 line.
  (may depend on grid-cell size)
- Estimate depth of new intercepted snow in time step.
- Set a critical depth for refreshing f_{snow} to unity.
- Allow partial refreshment based on proportion of critical depth added.
- During unloading f_{snow} is based on ratio of intecepted load to the last peak.
  (unloads from sides)



Albedo of a coniferous canopy with snow

CLASS 3.X tends to mute the response of albedo to intercepted snow

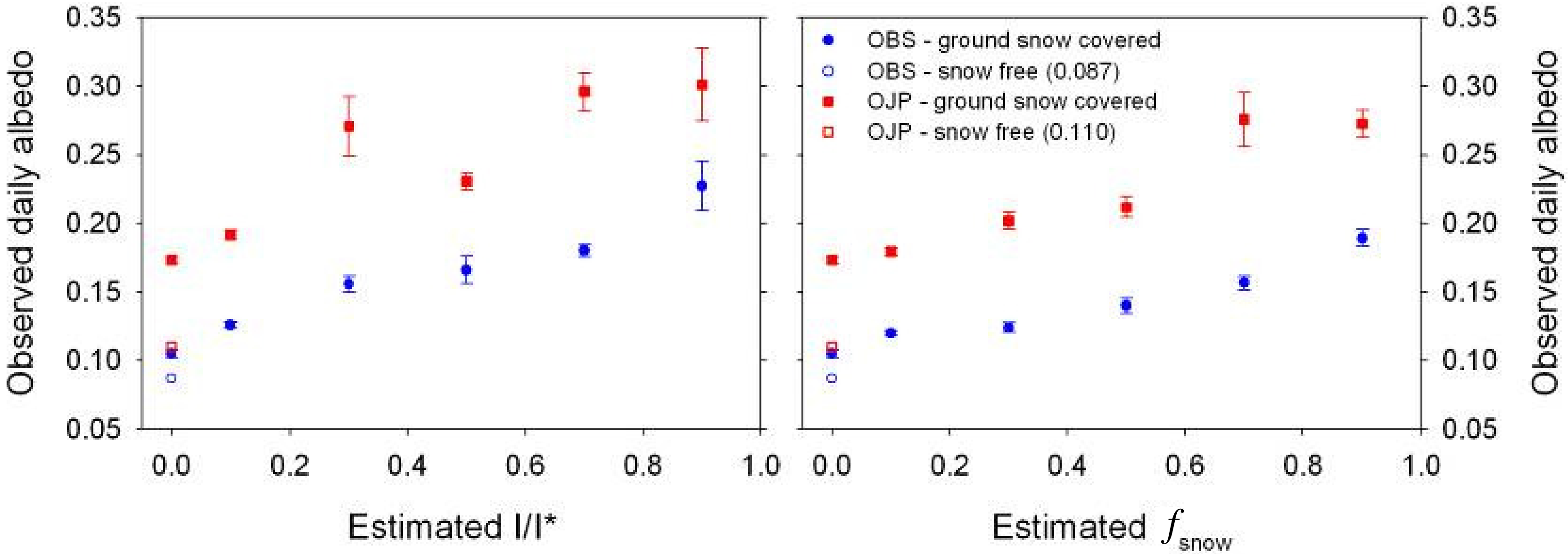
- partly caused by calculating f_{snow} as I/I^*
- also by small effect of intercepted snow assumed in CLASS
- for a canopy with snow α_{VIS} = 0.17, α_{NIR} = 0.23

Disagreement in literature over effect of snow interception on forest albedo:

- Pomeroy and Dion (1996) reported very little effect
- Suzuki and Nakai (2008) suggest a large effect (→0.4 dense forest)
- BERMS data show a substantial effect between these two
- Moody *et al*. (2007) provided a range of spectral albedo values for various snow-covered surfaces (affected by clearings/gaps).

Observed daily albedo at the BERMS OBS and OJP forests for binned averages of relative intercepted snow load (I/I) and f_{snow} estimated from photographs.*

- The snow-free albedo is 0.087 at OBS and 0.110 at OJP.
- Snow-cover on the ground increases the albedo by ~2% at OBS and by ~6% at the sparser OJP forest. Boreal forests are effective at trapping solar radiation.
- Canopy snow increases the albedo by 12-13% at both sites (average ±SE). Both sites show $\alpha > 0.30$ (all data viewed) that do not appear erroneous.



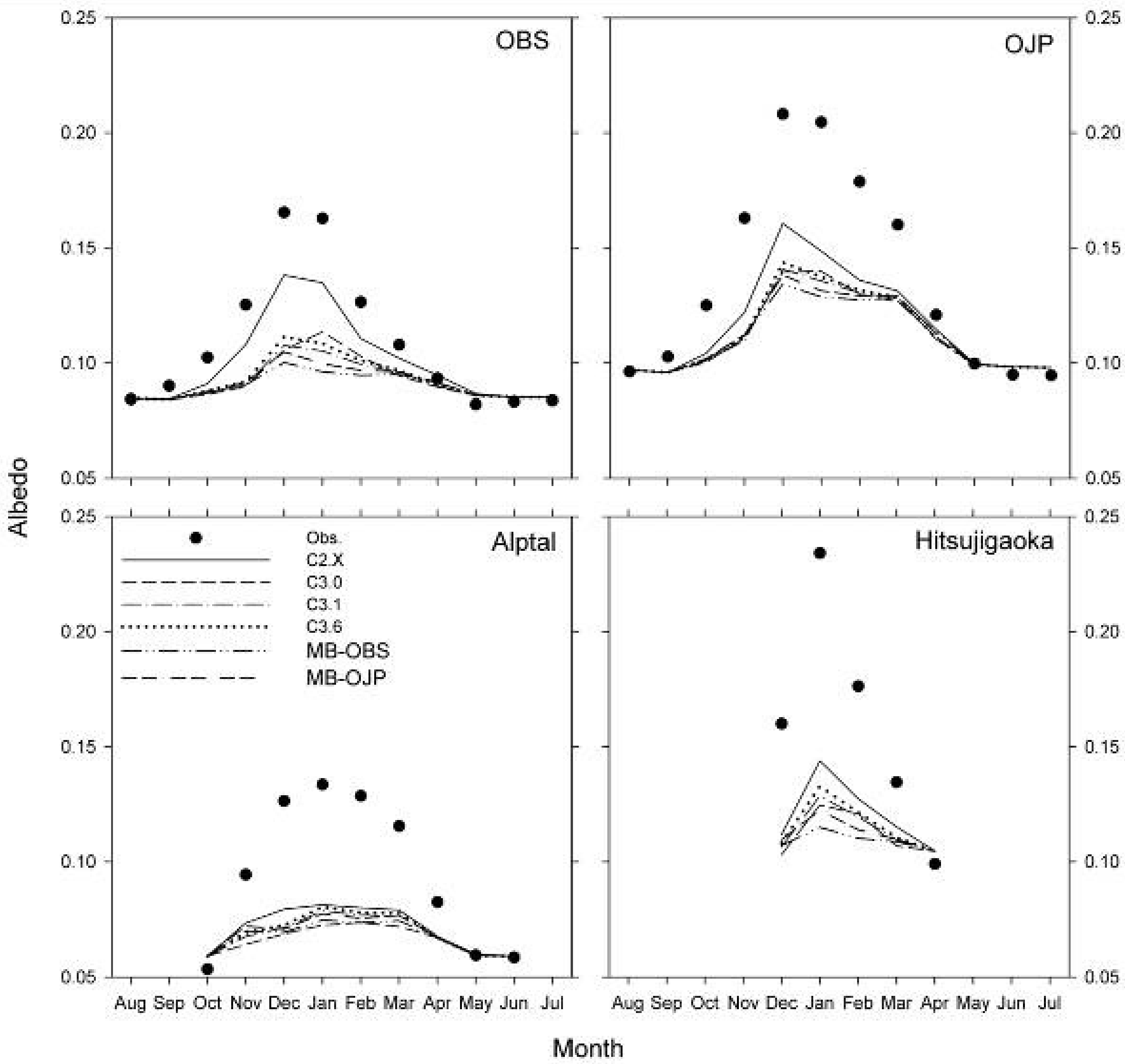
Added 2 SnowMIP2 forest sites Alptal, Switzerland and Hitsujigaoka, Japan

- Conducted 200+ simulations at each site
- Testing various combinations of unloading based on weather and historical algorithms
- Sensitivity test of critical depth of new intercepted snow for full refreshment of f_{snow}
- Sensitivity test of albedo of snow-covered canopy

Monthly albedo at four forests for historical interception/unloading algorithms in CLASS 3.6.

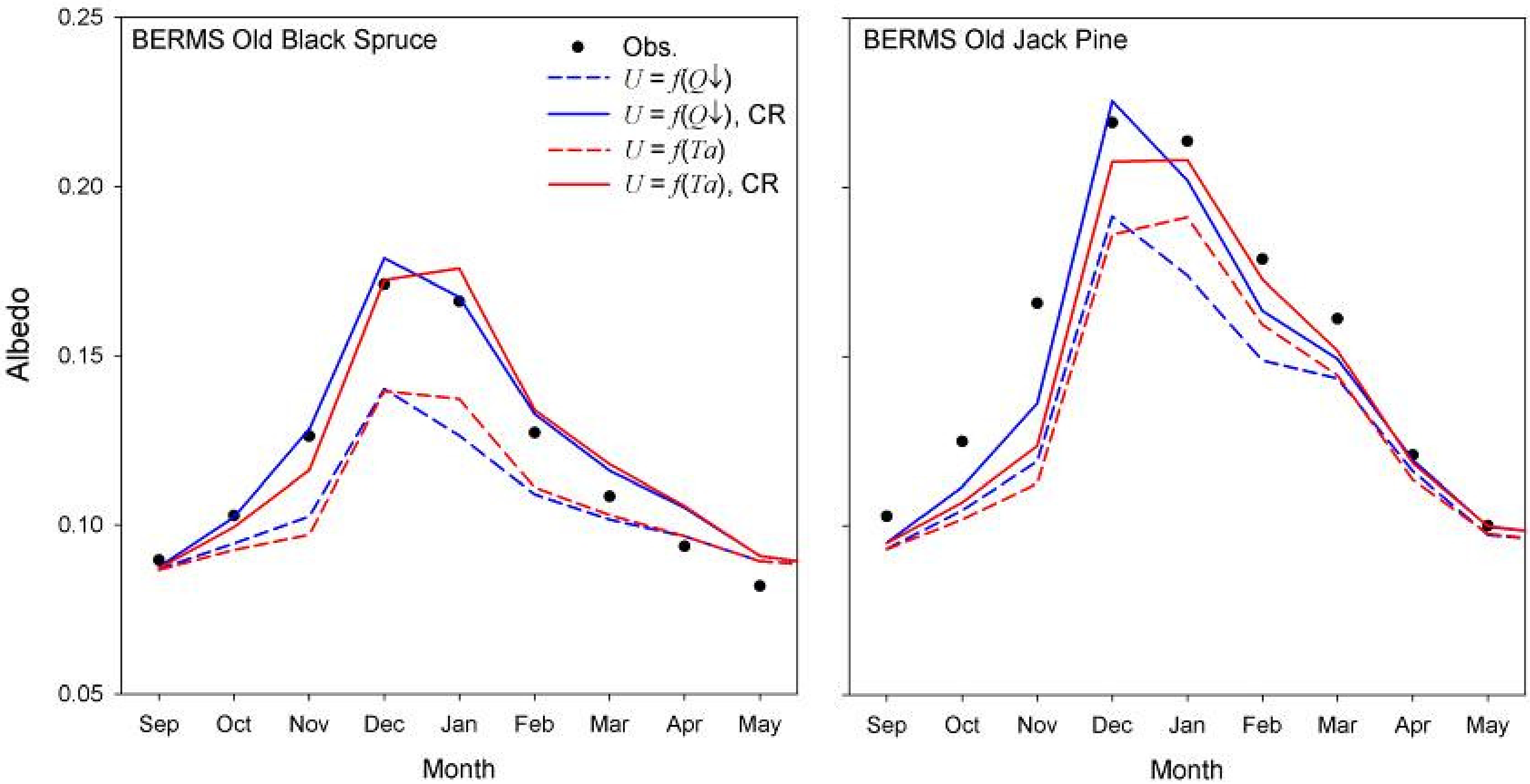
- CLASS 2.X algorithm performs best, for wrong reasons:
- No unloading
- Low interception capacity

- Unloading speed or mechanism (weather) not important yet
- f_{snow} = I/I*
  full coverage rare
- Albedo of canopy with snow is too small.
- $\alpha_{VIS,cs}$ = 0.17
- $\alpha_{NIR,cs}$ = 0.24



Observed and simulated monthly albedo at BERMS OBS and OJP sites: Unloading based on weather, and recent f_{snow} algorithm.

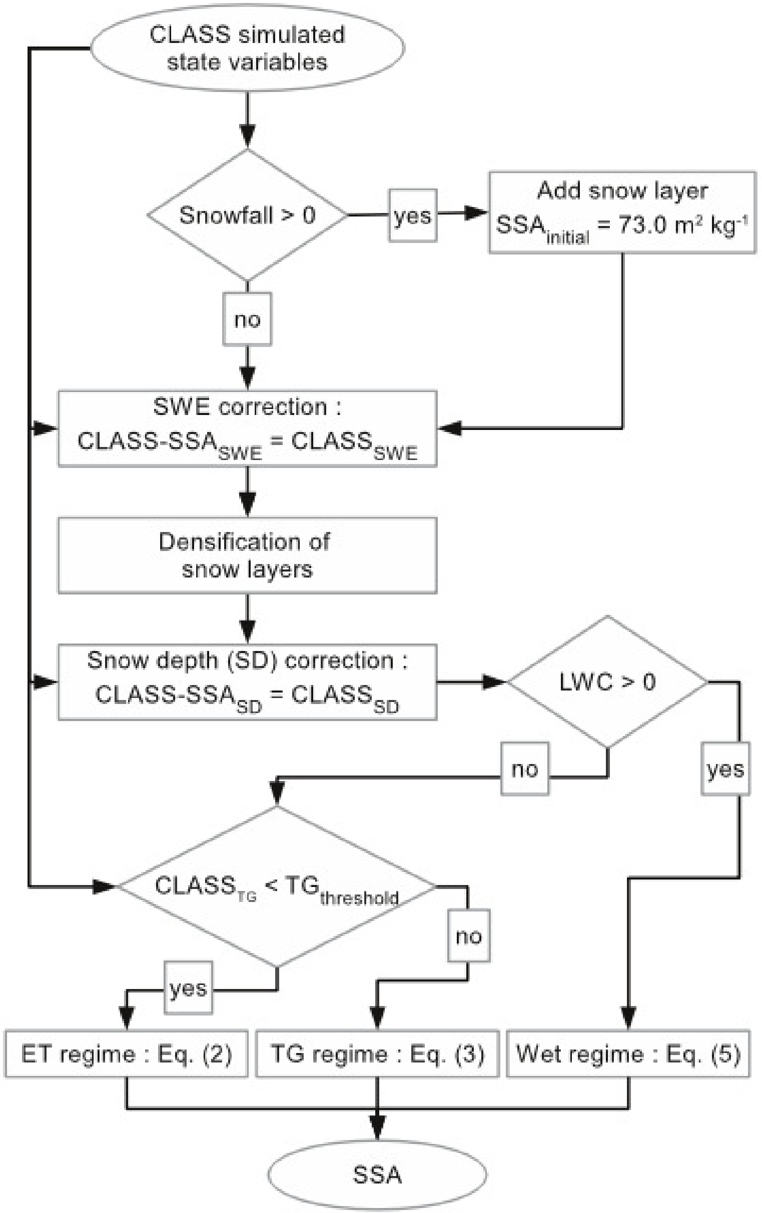
- Unloading based on weather, including increased albedo values for a canopy with snow underestimate the monthly albedo.
- Performance is much better with canopy snow coverage (f_{snow}) refreshed with smaller snowfall events.



Snow specific surface area simulation using the one-layer snow model in the Canadian LAnd Surface Scheme (CLASS)

Roy et al. (In Press) Universite de Sherbrooke

- Offline multilayer model driven by CLASS single layer snow model
- Snowpack stretched or compressed to match CLASS SWE, depth, density.
- Simulates decrease in SSA based on
  - snow age
  - temperature
  - temperature gradient
  - wet snow metamorphism
- Single snow layer in CLASS limits wet snow metamorphism
  - liquid water content underestimated
- SSA simulations of interest for satellite passive microwave brightness temperature assimilations, snow mass balance retrievals and surface albedo/energy balance studies.



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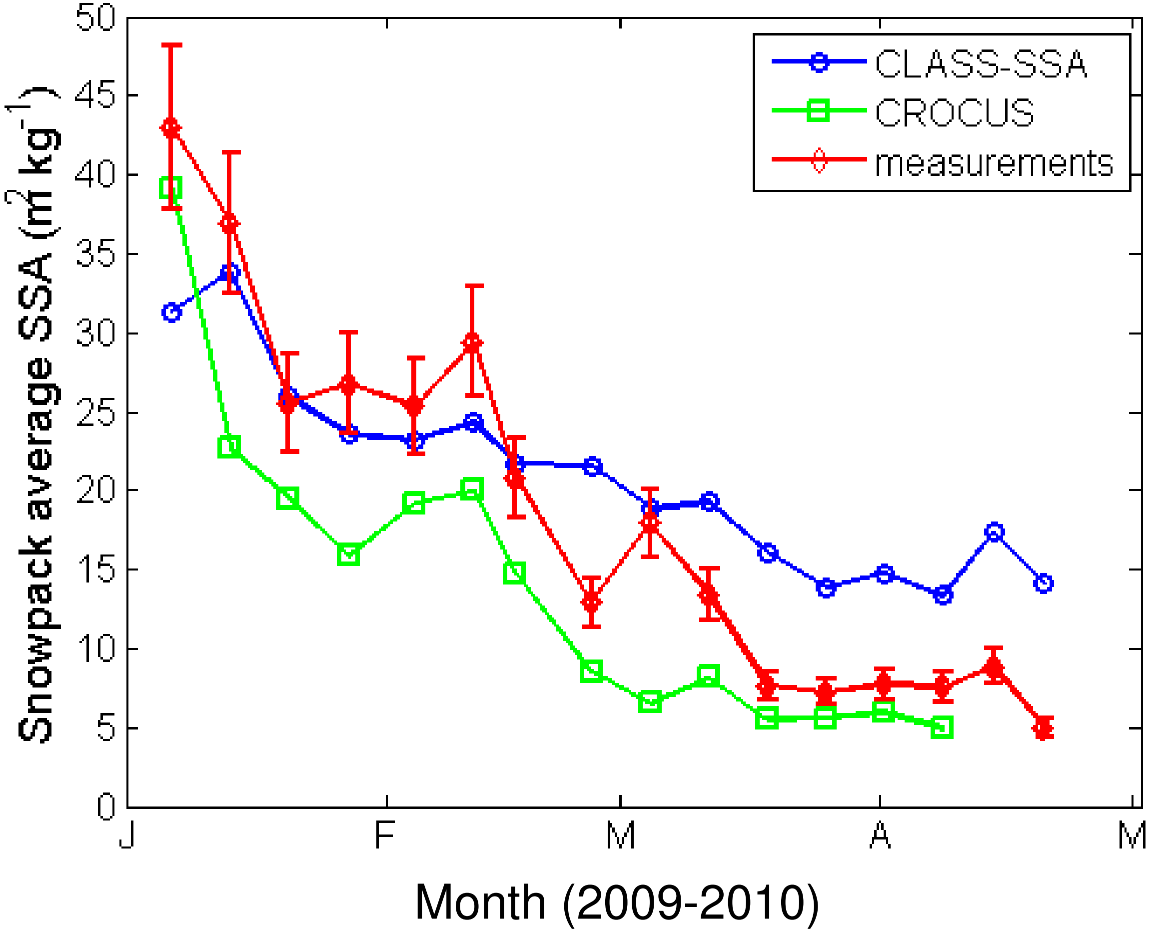
Snowpack-averaged SSA evolution with time at Col de Porte for CLASS-SSA, Crocus and measurements.

- Crocus and CLASS-SSA underestimate SSA under dry conditions with CLASS-SSA performing better.
- When wet conditions occur following Feb. 25th, CLASS underestimates the snowpack liquid water content and over-estimates SSA.
- Crocus continues to underestimate SSA under wet conditions.

(Roy et al, In Press)



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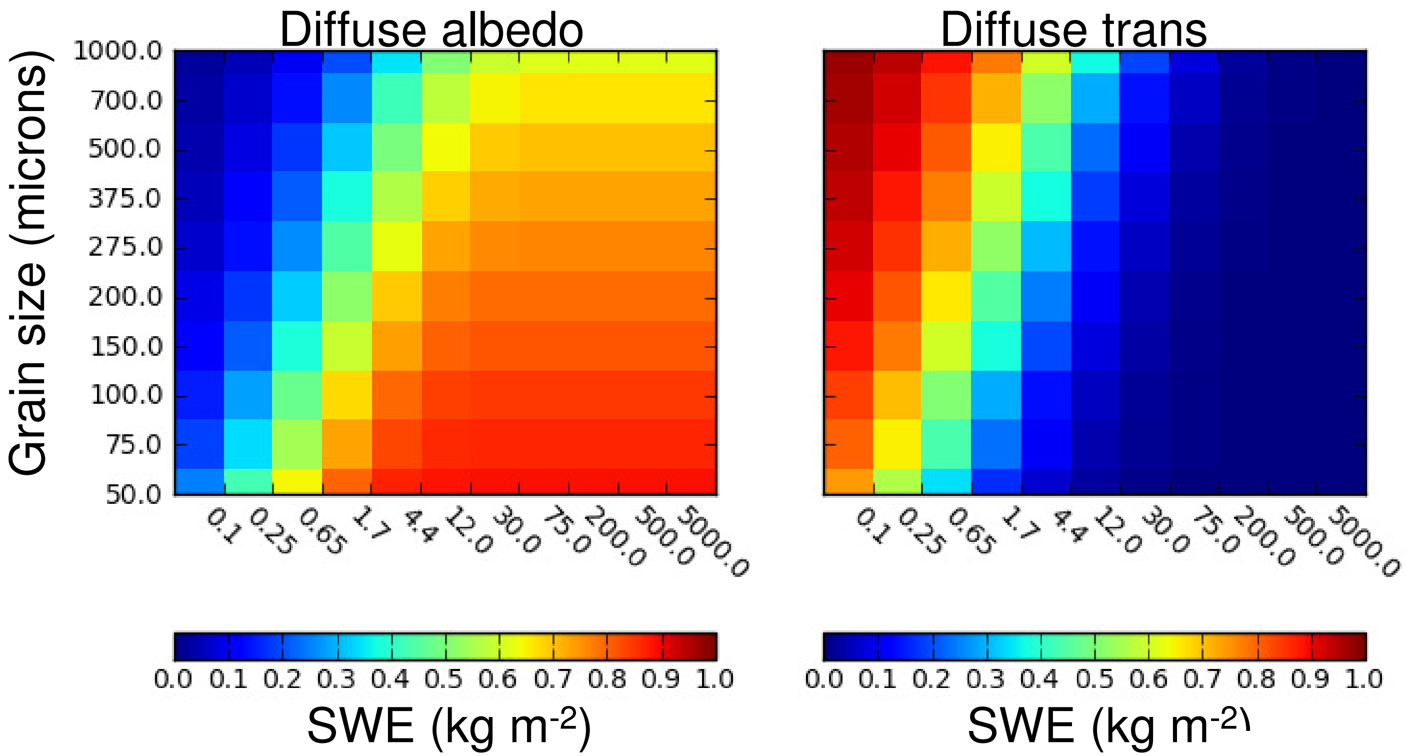
New snow albedo for unvegetated areas

- Lookup table function of: SWE, black carbon concentration, underlying albedo, cosine solar zenith angle, snow grain size, wavelength interval
- One table for diffuse albedo, direct albedo, diffuse transmission, direct transmission
- Assume single layer of snow (consistent with CLASS), use offline DISORT calculations at 280 wavelengths and average over CCCma solar radiation bands
-Total albedo for each band is weighted average (based on incident radiation) of direct and diffuse albedo

Mean 0.2-0.69 microns, black surface, θ=0º



Slide courtesy of Jason Cole, CCCma, Environment Canada)

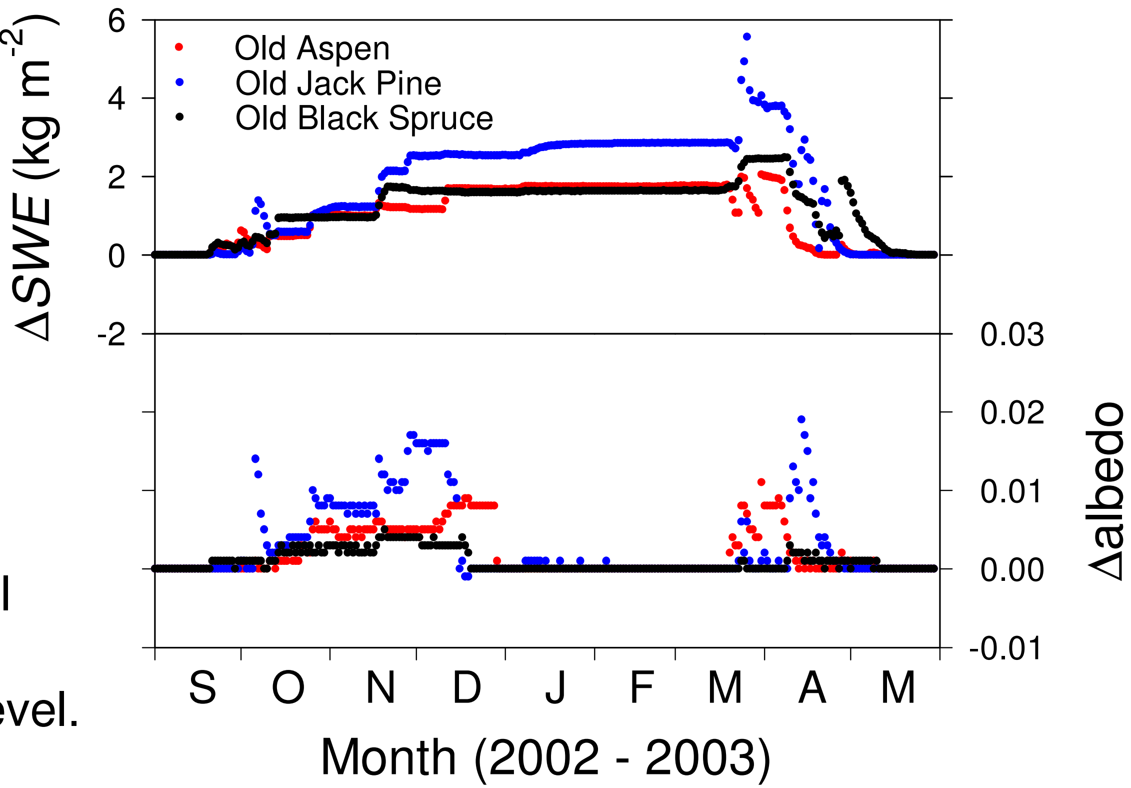

Thank you!

Effects of mixed precipitation in CLASS

- When 0° < T_a < 6°C, more precipitation is diagnosed as snow. This increases the *SWE* in the snowpack and the surface albedo.

- Differences in *SWE* persist until a melt, while differences in albedo are subsumed by snowpack aging and subsequent snowfall events.

- Recent RCM simulations over Quebec suggest polynomial diagnoses too much snow. Lowest model layer air temperature is at 50 m rather than screen level.



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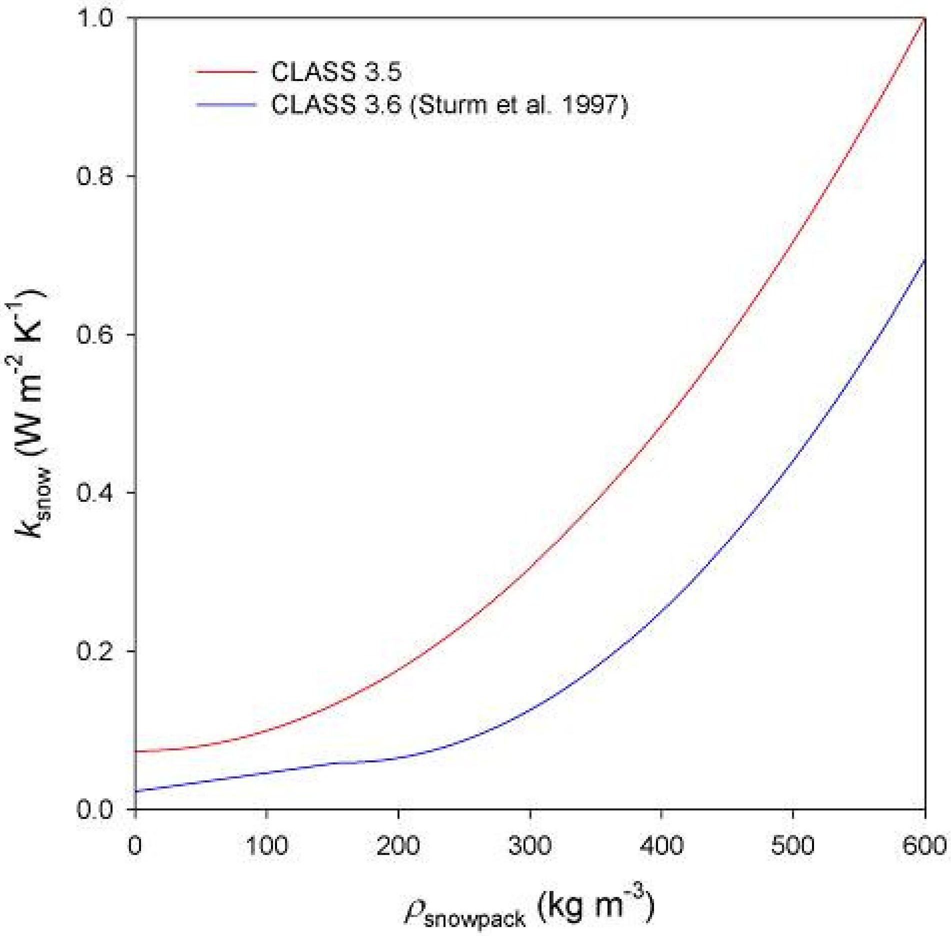
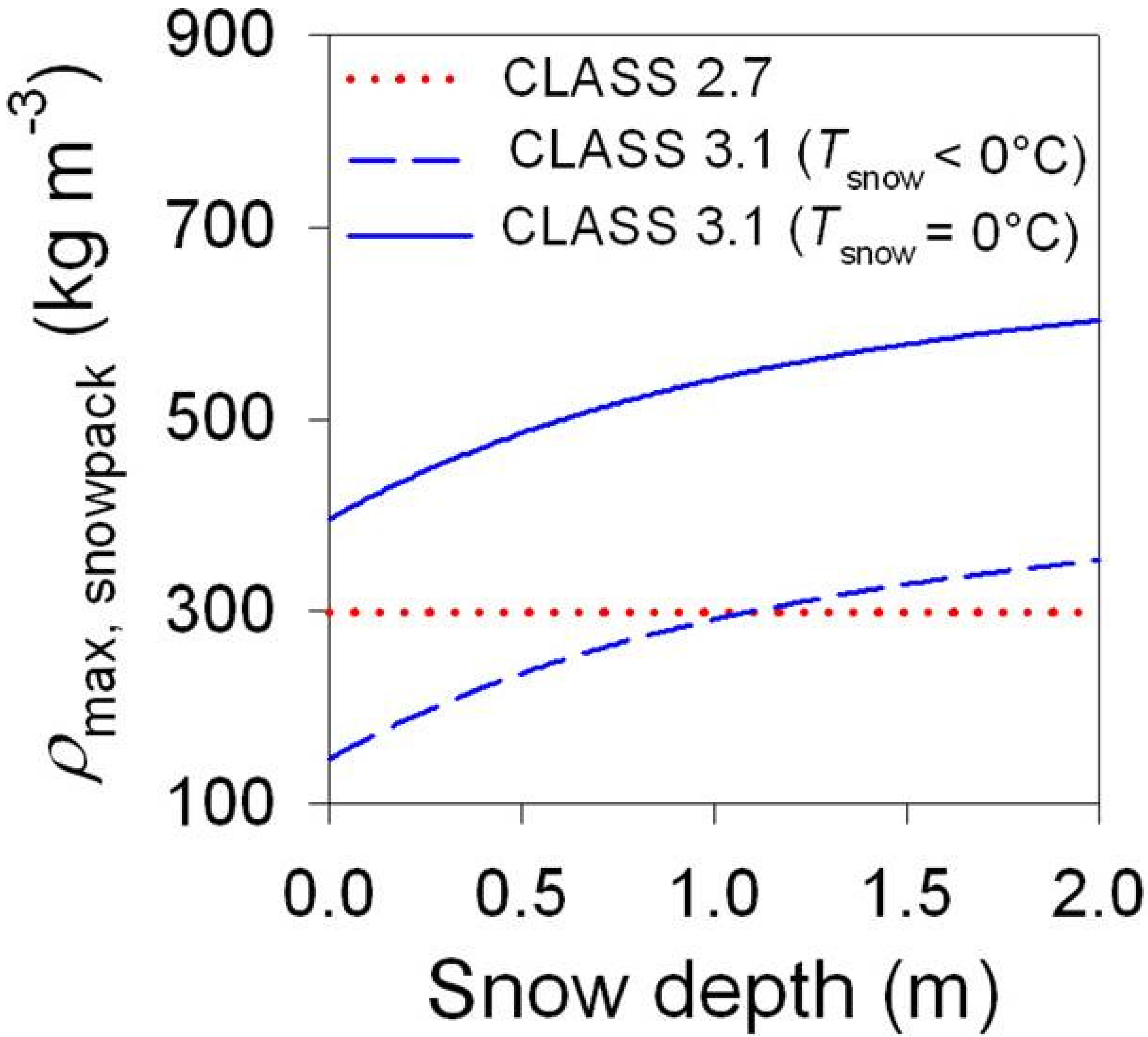
CLASS version 3.6: Completed January 2012

- New snow thermal conductivity relationship (Sturm 1997).
- Decreased thermal conductivity lessens winter cold bias slightly.



Maximum snowpack density



CLASS 2.7:
Maximum snowpack density, $\rho_{max,snowpack}$, is constant at 300 kg m^{-2}.

CLASS 3.1:
$\rho_{max,snowpack}$ varies with snowpack depth,

$$\rho_{\max,snowpack} = 450 - \frac{20470}{z_{snow}}\left[1 - e^{z_{snow}/67.3}\right]$$

and is larger for an isothermal snowpack

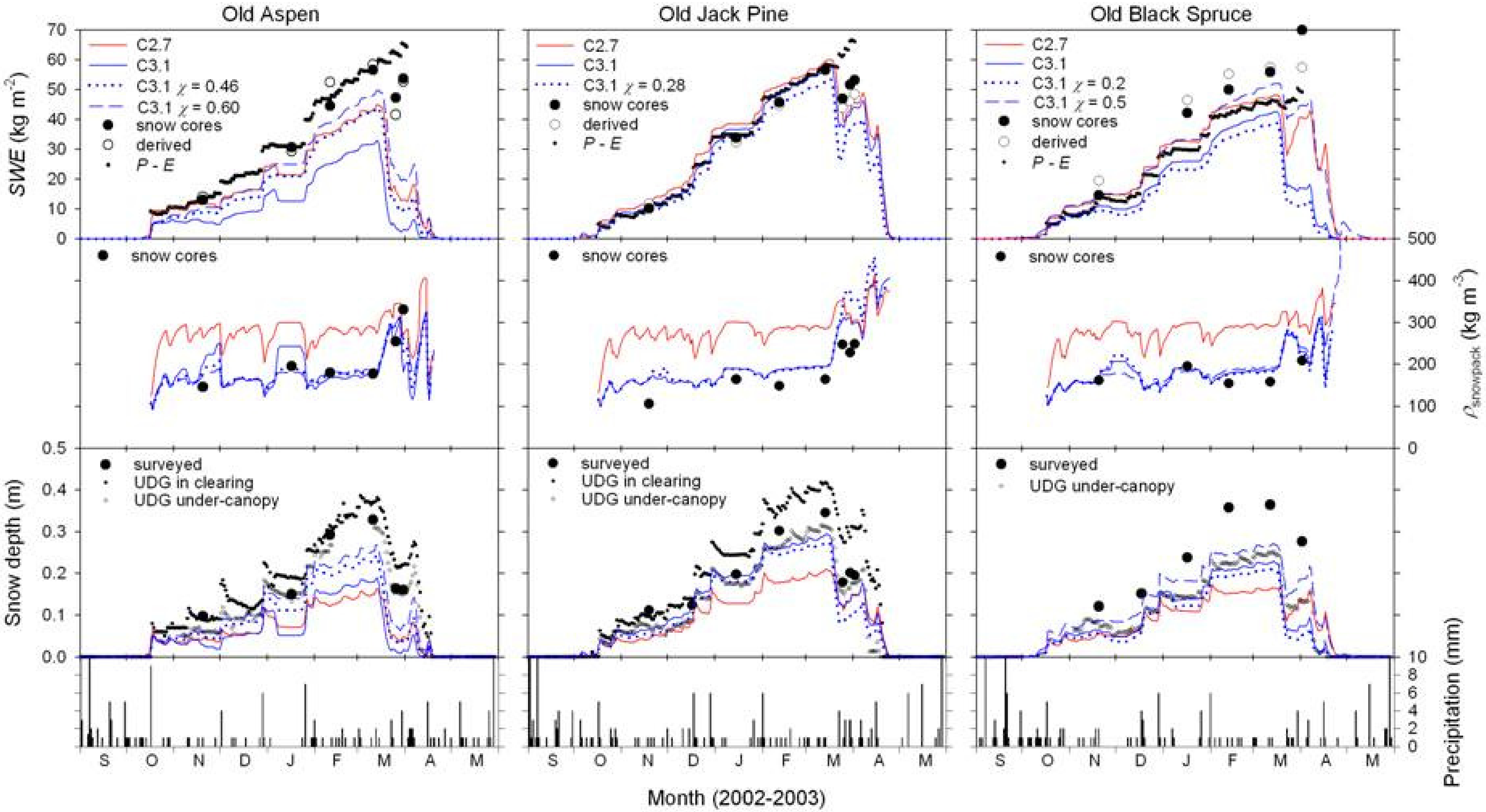
$$\rho_{\max,snowpack} = 700 - \frac{20470}{z_{snow}}\left[1 - e^{z_{snow}/67.3}\right]$$

(Pomeroy *et al*. 1998; Tabler *et al*. 1990)

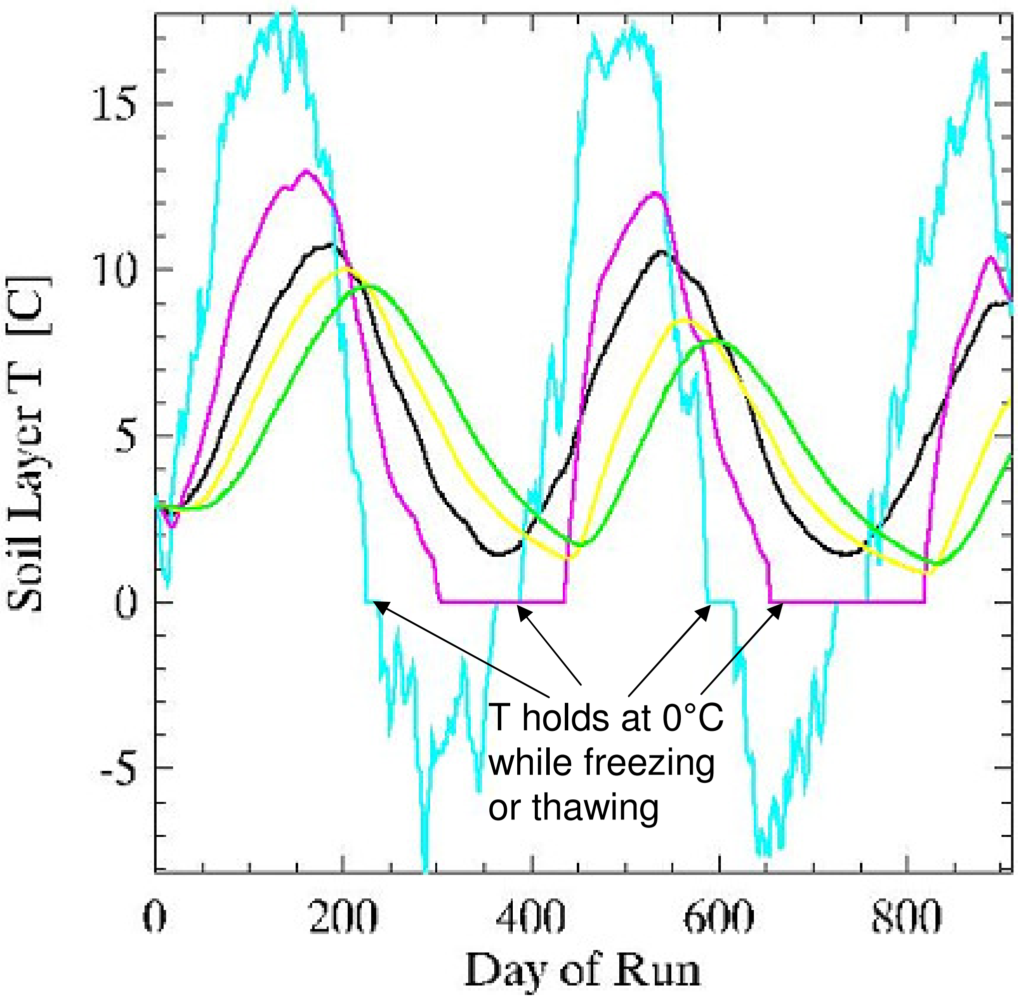
Canada

SWE, density and snowpack depth

- Underestimated *SWE* and overestimated density result in an underestimation of snowpack depth.
- Improved snow density in CLASS 3.1 lessens the underestimation of depth, as does the use of observed gap fraction at Old Aspen.



Effect of additional soil layers on freeze-thaw in soil



Black: T of soil layer 3 in three-layer run.

Blue, **purple**, **yellow**, **green**: T of soil layers 3, 6, 8 and 9 in nine-layer run.

Average T of layer 3 in three-layer run does not fall below 0°C. The depth of the 0° isotherm could in principle be obtained from the quadratic temperature profile, but this neglects the heat sink of the phase change of water in the upper part of the layer.

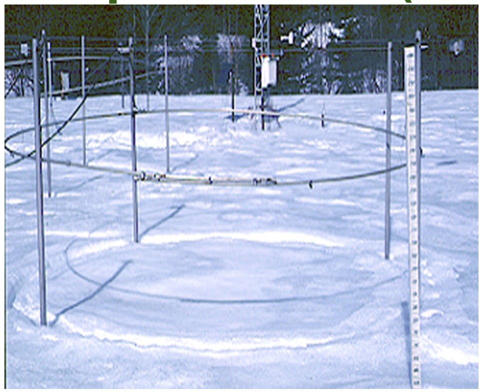
In the nine-layer run, freezing occurs to layer 6 which partially freezes.

Thus, for an accurate determination of the freezing depth or active layer depth in soil, multiple subdivisions of the third soil layer are necessary.
Also reduces winter cold bias in near-surface soil layers.

CLASS 2.6 participated in SnowMIP: Snow model intercomparison project

Goose Bay Airport (GSB)

Sleeper's River (SLR)



Weissfluhjoch (WFJ)

Col de Porte (CDP)

(Courtesy, Ross Brown)

CLASS 3.3 participated in SnowMIP2

- Current Land Surface Schemes (LSS) in models either neglect or use highly simplified representations of physical processes controlling the accumulation and melt of snow in forests
- **Snow M**odel **I**nter-comparison **P**roject **2** (**SnowMIP2**)
  - to quantify uncertainty in simulations of forest snow processes
  - a range of models of varying complexity (not just LSS)
- Primarily evaluate the ability of models to estimate SWE
  - 32 models
  - 5 locations: 2 sites per location: forest and clearing (open)

Effect of splitting soil layer 3 into 2 layers on modelled winter soil temperatures in CLASS

- With 3 soil layers, the third layer does not fall below 0°C because the entire layer would have to freeze.

- Additional layers near the top of the old third layer will freeze, and the heat of fusion released lessens the cold temperature bias in layers 1 and 2.