P1.28 SIMULATION OF ENERGY AND WATER BUDGETS IN ASPEN, BLACK SPRUCE AND JACK PINE FORESTS DURING WINTER USING THE CANADIAN LAND SURFACE SCHEME

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1. INTRODUCTION

In the boreal forest, snow covers the ground for more than half of the year and contributes about a third of the annual water budget. Its influence on surface albedo varies with vegetation type and height. Surface albedo strongly affects the surface energy budget, and is a major feedback mechanism in the climate system. Results from BOREAS (Boreal Ecosystem-Atmosphere Study), BERMS (Boreal Ecosystem Research and Monitoring Sites), and other studies have revealed that the timing of spring (Black *et al*. 2000), and the availability of liquid water in the soil (Jarvis and Linder, 2000; Bergh and Linder, 1999), have a strong impact on the annual carbon budget of boreal forest stands. As such, realistic parameterizations of snow processes in surface schemes are important for the representation of boreal forests in climate models.

Version 3.0 of the Canadian Land Surface Scheme (CLASS), contains several improved parameterizations of significance for the boreal forest, including improved treatment of snow processes. In this paper, results are presented for 9-month column runs spanning the winter of 2002-2003, at three boreal forest sites in central Saskatchewan, a mature or old aspen stand (OA), an old jack pine stand (OJP) and an old black spruce stand (OBS). The performance of CLASS 3.0 is compared with CLASS 2.7, the current operational version. Components of the surface energy budget are evaluated using field measurements, with a focus on the snowpack, and its properties.

2. THE CLASS MODEL

CLASS was developed at the Meteorological Service of Canada for use in General Circulation Models (GCMs). Version 1 (Verseghy, 1991) included a three-layer soil model, and a simple treatment of surface-atmosphere interaction. A vegetation canopy was added in version 2 (Verseghy *et al*. 1993), as well as a simple treatment of subgrid-scale heterogeneity; each grid-cell was divided into vegetated and bare soil areas, which were both subdivided into snow-covered and snow-free fractions, as necessary. The representation of heterogeneity is enhanced in version 3.0 with the addition of a mosaic, in which different surface types can be modelled explicitly using separate patches.

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2.1 Canopy resistance

In CLASS 2.7, canopy resistance (r_c), did not vary with vegetation type. A minimum r_c of 50 s m^{-1} was applied to all fully-leafed canopies, and was scaled by a single set of stressor functions (Jarvis, 1976; Stewart, 1988), representing the response to solar radiation, humidity and soil water suction. A linear scaling by leaf area index (*LAI*) was applied to represent canopies with less than the specified fully leafed value of *LAI*. Tests of CLASS showed that this model for r_c was not appropriate in some environments, especially in the boreal forest (Bartlett *et al*. 2000; Bartlett *et al*. 2003) where r_c was underestimated. In CLASS 3.0, each vegetation type has a leaf-level minimum stomatal resistance, which is scaled to the canopy as a function of *LAI* and solar radiation following Kelliher *et al*. (1995). Unlike in CLASS 2.7, the light response and stressor functions can vary between vegetation types.

2.2 Soil properties

The hydraulic properties of mineral soils are calculated from the sand and clay fractions, following Cosby *et al*. (1984). Organic soils are not represented in CLASS 2.7; this hampers the representation of boreal and sub-arctic regions where organic soils are common. CLASS 3.0 contains a parameterization for the hydraulic properties of organic soils, developed by Letts *et al*. (2000), which has been found to improve the modelled hydrology and energy fluxes in a variety of northern wetlands and woodlands (Comer *et al*. 2000; Bellisario *et al*. 2000; Lafleur *et al*. 2000).

2.3 Mixed precipitation

Prior to CLASS 3.0, precipitation was diagnosed as rain or snow based on air temperature using a simple threshold at 0°C. Precipitation was diagnosed as snow when the air temperature was less than or equal to 0°C, and as rain when the air was warmer than 0°C. Observations have shown that snow can fall at temperatures greater than 0°C, and that mixed precipitation, consisting of rain and snow, occurs at temperatures near 0°C. CLASS 3.0 contains a polynomial (Auer, 1974; Fassnacht and Soulis, 2002), to represent the fraction of precipitation that is snow (f_{snow}), allowing for a range of mixed precipitation between 0° and 6°C.

The polynomial for f_{snow} was developed based on U.S. observations. Since precipitation is influenced by topography and atmospheric conditions, we decided to investigate whether this polynomial was appropriate for a range of locations, using data from the Canadian Climate Data Archive. We obtained ten years of hourly values of air temperature and precipitation type, with observations made on the hour, from 39 meteorological stations across Canada representing different climatic zones. Precipitation events were grouped into the categories, *rain*, *snow*, *freezing*, and *mixed snow* (snow + liquid precipitation), and the relative frequency of occurrence for each type was calculated.

Figure 1 shows the results from all 39 stations as well as Auer's polynomial. Our frequency of occurrence for snow is slightly lower than Auer's curve, although both suggest the termination of snowfall at 6°C. However, if the freezing precipitation and much of the mixed snow were included in the snow category, which is reasonable since precipitation types other than rain or snow are not yet recognized by surface schemes, the two curves would be more similar, validating Auer's polynomial. While the results varied somewhat from station to station, we did not find systematic differences between locations. Given that Auer's polynomial appears to be widely applicable and indeed more suitable than the previous boundary at 0°C, we decided to run a test to investigate the effects of the change, and to subsequently adopt the polynomial as the standard for future model runs.

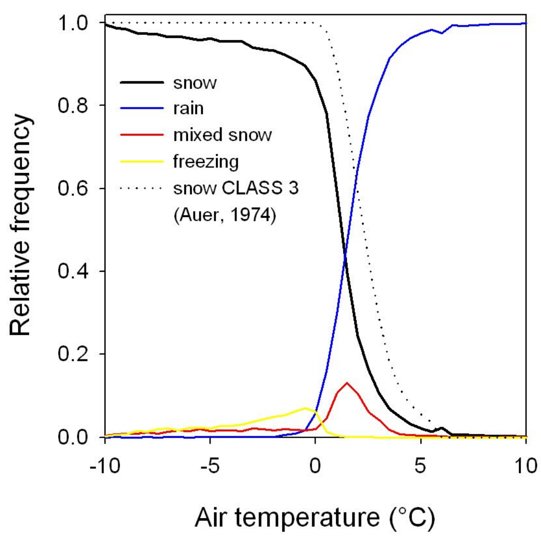

Figure 1: Relative frequency of precipitation types from 10 years of hourly observations at 39 meteorological stations across Canada, compared with the function of Auer (1974) for f_{snow}, the fraction of precipitation that is snow.

Allowing mixed precipitation results in a small increase in modelled surface albedo, *SWE* and snow depth, with differences being manifest primarily during the transition seasons when temperatures are likely to be in the range affected by the polynomial (Fig. 2). At temperatures in the range of 0° – 6°C, precipitation that would be diagnosed as rain by the previous algorithm, is now diagnosed as partially snow. Initial differences in *SWE* and snow depth can be maintained for long periods in the absence of significant melt, whereas increases in albedo are short-lived because of snow unloading from the canopy, snowpack aging and subsequent precipitation events. Snowpack density can be increased or decreased, depending on the conditions. Wet snow falling at temperatures above 0°C is denser than snow that falls at colder temperatures, and so the additional snow diagnosed early in the season results in a larger initial snowpack density. However, late in the season, rain falling on a cold snowpack will freeze at the density of ice, and so mixed precipitation rather than pure rain results in a less dense snowpack.

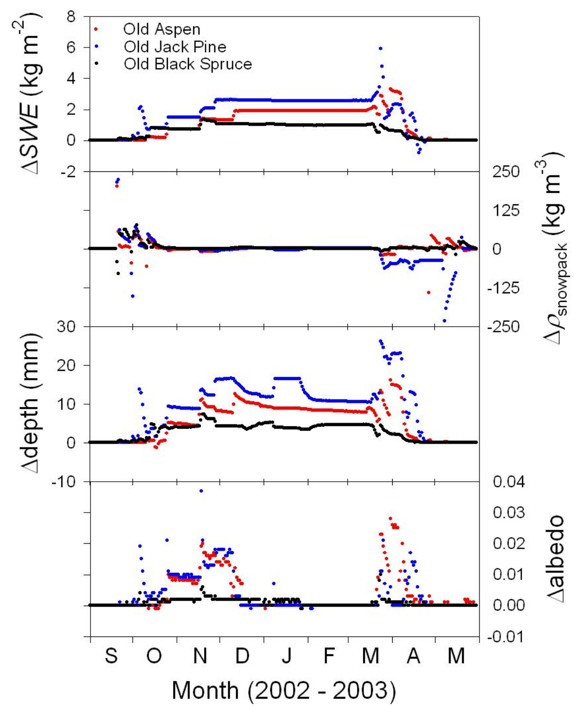

Figure 2: Differences in modelled *SWE*, $\rho_{snowpack}$, snowpack depth and stand albedo that result from allowing mixed precipitation between 0° and 6°C in CLASS 3.0 (See Fig. 1 and Fig 3A).

2.4 Snow density

Like most surface schemes, CLASS 2.7 assumes a value of 100 kg m^{-3} for the density of fresh snow ($\rho_{fresh\ snow}$). CLASS 3.0 employs a variation with air temperature (Fig. 3B) developed by Hedstrom and Pomeroy (1998). Over time, snowpack density increases, due to the effects of crystal settlement and metamorphism in the snowpack, sublimation, wind packing, melt and refreezing (Fassnacht and Soulis, 2002; Pomeroy *et al*. 1998). In the absence of melting, CLASS 2.7 employed a constant maximum snowpack density ($\rho_{max,\ snowpack}$) of 300 kg m^{-3}, while in CLASS 3.0 (Fig. 3C) an exponential relationship with depth is used (Tabler *et al*. 1990; Pomeroy *et al*. 1998), with an additional 250 kg m^{-3} allowed for an isothermal snowpack at 0°C.

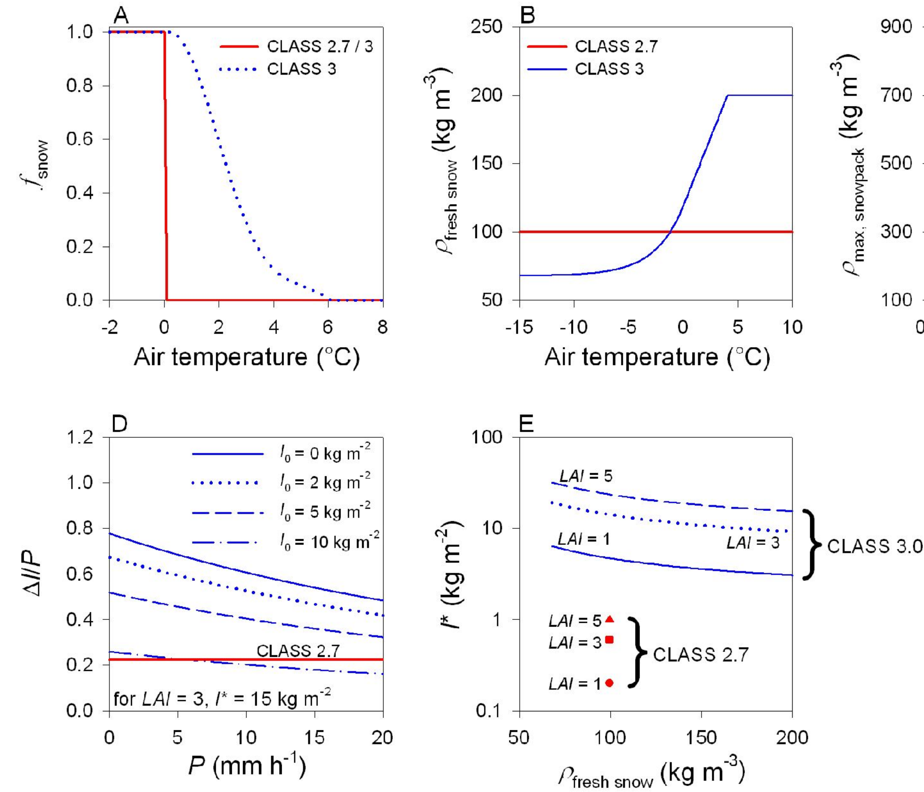

Figure 3: Functions used to model snow parameters in CLASS 2.7 (red) and 3.0 (blue). A. Fraction of precipitation falling as snow, B. Variation in fresh snow density with temperature, C. Variation in the maximum density of a snowpack (in the absence of melting) with depth and temperature, D. Fraction of snowfall intercepted for different values of initial snow load, I_0, and a range of snowfall rates, E. Variation in canopy storage capacity, I^*, with the density of fresh snow, $\rho_{\text{fresh snow}}$, and leaf area index, *LAI*.

2.5 Snow interception

Interception of snow by the canopy was treated in the same way as rainfall in CLASS 2.7. All snow falling on the canopy, rather than through the gaps, was intercepted until the storage capacity (I^*), was reached. I^* was set to 0.2 kg m^{-2} of water equivalent per unit of *LAI*. Hedstrom and Pomeroy (1998) showed that for snow, this underestimates I^* by more than an order of magnitude. They measured intercepted snow load (I) weekly, using above- and below-canopy snow gauges and by weighing jack pine and black spruce trees suspended in their respective canopies, and derived an expression for I^* as

$$I^* = S_p\, LAI\, (0.27 + 46/\rho_{\text{fresh snow}}), \qquad (1)$$

and for the amount of additional snow intercepted during a snowfall or time interval (ΔI), as

$$\Delta I = (I^* - I_0)\,(1 - e^{-C_C P / I^*}). \qquad (2)$$

S_p is a species coefficient with a value of about 6 kg m^{-2} for conifers, I_0 is the initial snow load on the canopy from the end of the previous time step, C_C is the canopy coverage and P is the amount of snowfall during the time interval. With equations 1 and 2 (Fig. 3D and E), interception efficiency decreases with P and I, and increases with *LAI*.

Following interception, snow falls or unloads from the canopy at a rate that is affected by a number of factors which are difficult to parameterize. Hedstrom and Pomeroy (1998) used an empirical relationship to estimate the effect of unloading of snow over time on I, as

$$I = I_1\, e^{-Ut}. \qquad (3)$$

$I_1 = I_0 + \Delta I$ is the amount of snow on the canopy before unloading, t is the time step, and U is the unloading rate coefficient with dimensions of time^{-1}. Using weekly measurements, they were unable to determine U and t separately because they did not know the time since snowfall, but they found $e^{-Ut} \approx 0.7$. If t averages 3.5 days for their weekly observations, as a first approximation, U has a value of about 0.1 days^{-1}. Snow Interception is modelled in CLASS 3.0 using equations 1 - 3.

3. STUDY SITES AND METHODOLOGY

The field sites are located in central Saskatchewan; the Old Aspen stand (53.6°N, 106.2°W) is in Prince Albert National Park, while the Old Jack Pine (53.9°N, 104.7°W) and Old Black Spruce (54°N, 105.1°W) stands are located 80-100 km to the east-northeast. The sites were first instrumented for the BOREAS project, but are now operated for the BERMS study. Each site contains a full suite of surface meteorological and eddy covariance flux measurements (Griffis *et al*. 2003), as well as soil and snow temperatures and soil moisture. Snow surveys were conducted periodically to obtain spatial averages of snowpack depth, density ($\rho_{snowpack}$) and snow water equivalent (*SWE*), while point values of snow depth were obtained using automated ultrasonic snow depth sensors.

For each forest stand, versions 2.7 and 3.0 of CLASS were forced with observed meteorological data with a half-hourly time step, from September 1, 2002 through May 30, 2003. The site properties employed in CLASS are shown in Table 1. The version of CLASS 3.0 that is employed contains a modified algorithm for representing boundary-layer resistance (r_b). The previous algorithm underestimated r_b and failed to adequately limit canopy evaporation and sublimation.

Table 1: Site properties used in CLASS 2.7 and 3.0.

Parameter	OA	OJP	OBS
canopy height (m)	21	14	12
maximum *LAI* (m^2 m^{-2})	5.6	2.5	4.5
PAR albedo	0.03	0.04	0.03
NIR albedo	0.28	0.13	0.13
$r_{s,min}$ (sm^{-1}) (CLASS 3.0)	90	350	350
soil layer 1 (CLASS 2.7)	L	S	SL
soil layer 1 (CLASS 3.0)	Pf	S	Pf
soil layer 2 (2.7 and 3.0)	L	S	SL
soil layer 3 (2.7 and 3.0)	SCL	S	S

Note: L = loam, S = sand, SL = sandy loam, SCL = sandy clay loam, Pf = fibric peat.

4. RESULTS

4.1 Model runs

Model runs were performed at each site using CLASS 2.7 and 3.0. At the Old Aspen stand (Fig. 4), the modelled albedo was significantly overestimated during the winter. CLASS does not include a separate plant area index for the woody component of trees, but uses the minimum *LAI* to represent the leafless plant area. While the default value is 0.5, Barr *et al*. (submitted) reported a plant area index of 0.72 for the aspen trees and 0.33 for the hazel understorey. Since mutual shading would not be great under leafless conditions, we treated the values as largely additive and increased the minimum *LAI* in CLASS to 1.0, which served to improve the modelled albedo. We present the results from both model runs for CLASS 2.7 and 3.0.

At the Old Black Spruce stand (Fig. 6), *SWE* was underestimated. Upon examining the literature, it was discovered that the interception algorithm of Hedstrom and Pomeroy employed in CLASS 3.0 was developed using effective *LAI*, or *LAI* not corrected for clumping, while we provide CLASS with the single-sided *LAI* for deciduous species, and the hemi-surface area for coniferous species. Comparisons of effective and actual *LAI* at the coniferous sites suggested a ratio of about 0.7 for jack pine, and 0.5 - 0.55 for black spruce. We modified equation 1 to multiply *LAI* by 0.7 at OJP and by 0.5 at OBS in CLASS 3.0. The results show that this change had almost no effect on model performance.

4.2 Snowpack properties

Modelled snowpack density in CLASS 3.0 is much closer to the observed values; snow density is overestimated in CLASS 2.7. At the cold temperatures experienced at these sites, modelled $\rho_{fresh\ snow}$ in CLASS 3.0 is smaller than the constant 100 kg m^{-3} employed in CLASS 2.7. Also, at the snowpack depths achieved in these model runs, $\rho_{max,\ snowpack}$ of a non-isothermal snowpack in CLASS 3.0 remains lower than the constant value of 300 kg m^{-3} in CLASS 2.7. These two factors combine to produce a deeper snowpack in the CLASS 3.0 runs that is closer to observed values than in the CLASS 2.7 model runs.

Based on the snow surveys, *SWE* is underestimated during the ablation period at OJP, for the latter part of the winter at OA, and for most of the winter at OBS. While increasing the minimum *LAI* in CLASS improved the modelled albedo at OA, it also resulted in a further underestimation of *SWE*. This may be caused by CLASS not representing canopy structure adequately at the sites. While the canopy is leafless at OA, CLASS treats the minimum *LAI* as foliage rather than stems and branches. Chen *et al*. (1997) found that the shoots were highly clumped at the OBS stand, and clumping results in a larger number of gaps for an equivalent *LAI*. In CLASS, canopy gaps are represented by the sky view factor (χ). We believe that CLASS is underestimating χ at OBS and at OA in winter. More research is required to address this issue.

4.3 Snowpack and soil temperatures

Wintertime snowpack and soil temperatures are underestimated by CLASS 3.0, but more so by CLASS 2.7. This difference is caused by two factors. First, CLASS 2.7 does not represent organic soils, whereas the top soil layer at OA and OBS are modelled as organic in CLASS 3.0. Organic soils have a lower thermal conductivity than mineral soils, and act to insulate the lower soil layers. Second, CLASS 2.7 overestimates $\rho_{snowpack}$, which causes the modelled snowpack to be too thin and its thermal conductivity to be too high, thus underestimating the insulating effect of the snow. At OJP, where mineral soils are employed in CLASS 2.7 and 3.0, modelled soil temperatures begin to diverge as the snowpack is formed (Fig. 5).

This pattern in the snow and soil temperatures is part of a systemic problem with CLASS; the thermal regime of the soil is exaggerated on both diurnal and seasonal time scales. While the soil temperatures were initialized to observed values on September 1, 2002, they are underestimated in winter, and overestimated by the end of the model runs in May, 2003. This exaggeration in the thermal regime may be the cause of the rapid ablation of the snowpack, because the soil is warming too quickly during the ablation period. The thick soil layers employed in CLASS may be the source of this problem, which is under investigation.

4.4 Albedo

Winter albedo is modelled better at the conifer stands than in the default model runs at the Old Aspen stand, where albedo is overestimated throughout the snow season. Modelled albedo is larger in the CLASS 3.0 runs in the early part of the season. This is a result of a lower snowpack density in CLASS 3.0, which results in increased snow depth. CLASS models the fraction of a grid-cell that is snow-covered based on snow depth, with full coverage when the depth reaches 0.1 m. Thus, a deeper snowpack will result in a larger snow covered fraction, and a higher surface albedo.

If the sky view factor, χ, were increased at OA and OBS as suggested in section 4.2, the modelled albedo would be overestimated because the fraction of exposed snow, which has a higher albedo than the canopy, would increase. CLASS calculates the total albedo by weighting estimated albedo values for the canopy and for snow under the canopy that is 'seen' through gaps, by (1 - χ) and χ, respectively. In CLASS, the total albedo does not respond to changes in the modelled albedo of the under-canopy snowpack. Thus, in Figures 4-6, while the observed albedo at these sites decreases somewhat over time between snowfalls, especially later in the winter, CLASS shows a constant minimum, with short term increases in response to snowfall events which deposit snow on the canopy. It is not known whether the decreases in observed albedo are primarily caused by melting and unloading of snow from the canopy, or by changes in the snowpack under the canopy.

4.5 Sensible and latent heat fluxes

The fluxes of sensible (Q_H) and latent (Q_E) heat show largest deviations from observations in the autumn and spring transition seasons. At the conifer stands, CLASS 2.7 shows larger Q_E values during these periods because a minimum canopy resistance of 50 s m^{-1} is employed for all vegetation types, which is too small for these boreal forest stands. CLASS 3.0 uses a more appropriate model for canopy resistance, and produces values for Q_H and Q_E that are closer to observed values. Overestimation of Q_E in the spring may be related to the overestimation of surface layer soil temperatures in CLASS, which has a strong effect on the initiation of spring photosynthesis and transpiration, and which will also increase evaporation from the soil surface. At Old Aspen, in the autumn modelled *LAI* decreased more slowly than suggested by a radiation and degree-day based model developed for the site (Barr *et al*., submitted), while in the spring modelled *LAI* began increasing before observed leaf-out. This resulted in an overestimation of Q_E and an underestimation of Q_H during these transition periods.

5. CONCLUSIONS

CLASS 3.0 shows improvements over CLASS 2.7 in winter surface simulations in a number of areas. New snow density algorithms produce a modelled snowpack density and depth that are in better agreement with observations, which also improves the thermal regime. The ability to model organic soils in CLASS 3.0 also improves the thermal regime of surfaces with organic soils. The recently validated polynomial function for representing mixed precipitation produces a small increase in modelled *SWE* during the transition periods. It can have significant effects on the surface albedo and the energy balance over short time scales, which would be important for weather prediction models.

The canopy resistance model in CLASS 3.0 improves the sensible and latent heat fluxes in the pre- and post-snow periods at the conifer stands. At the Old Aspen stand, performance is hampered by errors in modelled leaf area index. Modelled albedo and interception are strongly tied to the sky view factor, which may be underestimated at the Old Aspen and Old Black Spruce stands. Modelled albedo is too large at the Old Aspen stand with the default minimum *LAI*, and is somewhat large late in the winter at all three sites. This may be caused by a modelled total albedo that is not affected by changes in the albedo of a ripening snowpack under the canopy. Further work on the representation canopy architecture and albedo is proceeding.

6. ACKNOWLEDGEMENTS

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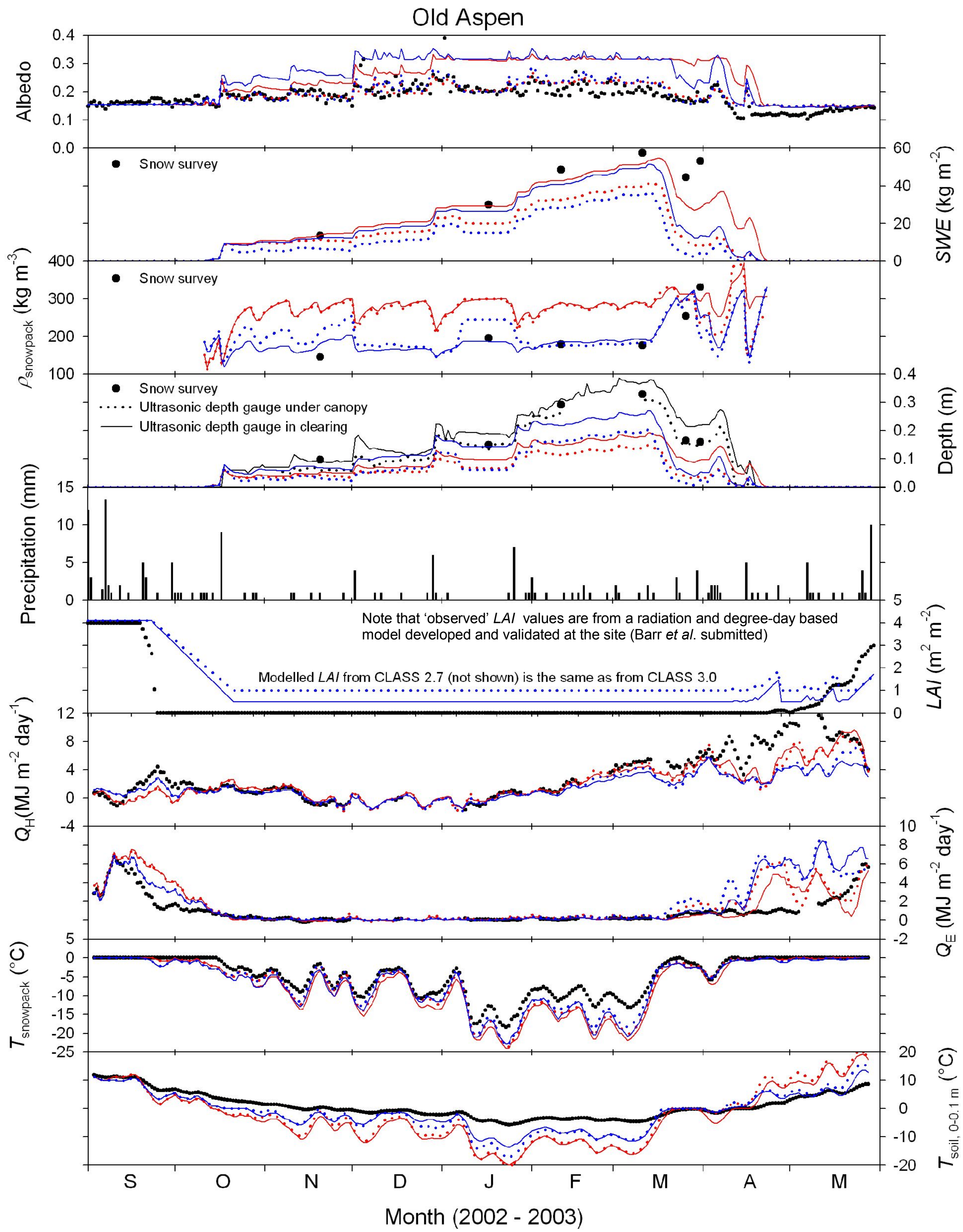

Figure 4: Observed and modelled surface properties for winter runs of CLASS 2.7 and 3.0 at the Old Aspen site. Observed values are in black. CLASS runs using the default minimum LAI of 0.5 are shown with solid lines and runs using a minimum LAI of 1.0 are shown with dotted lines, red for CLASS 2.7 and blue for CLASS 3.0.

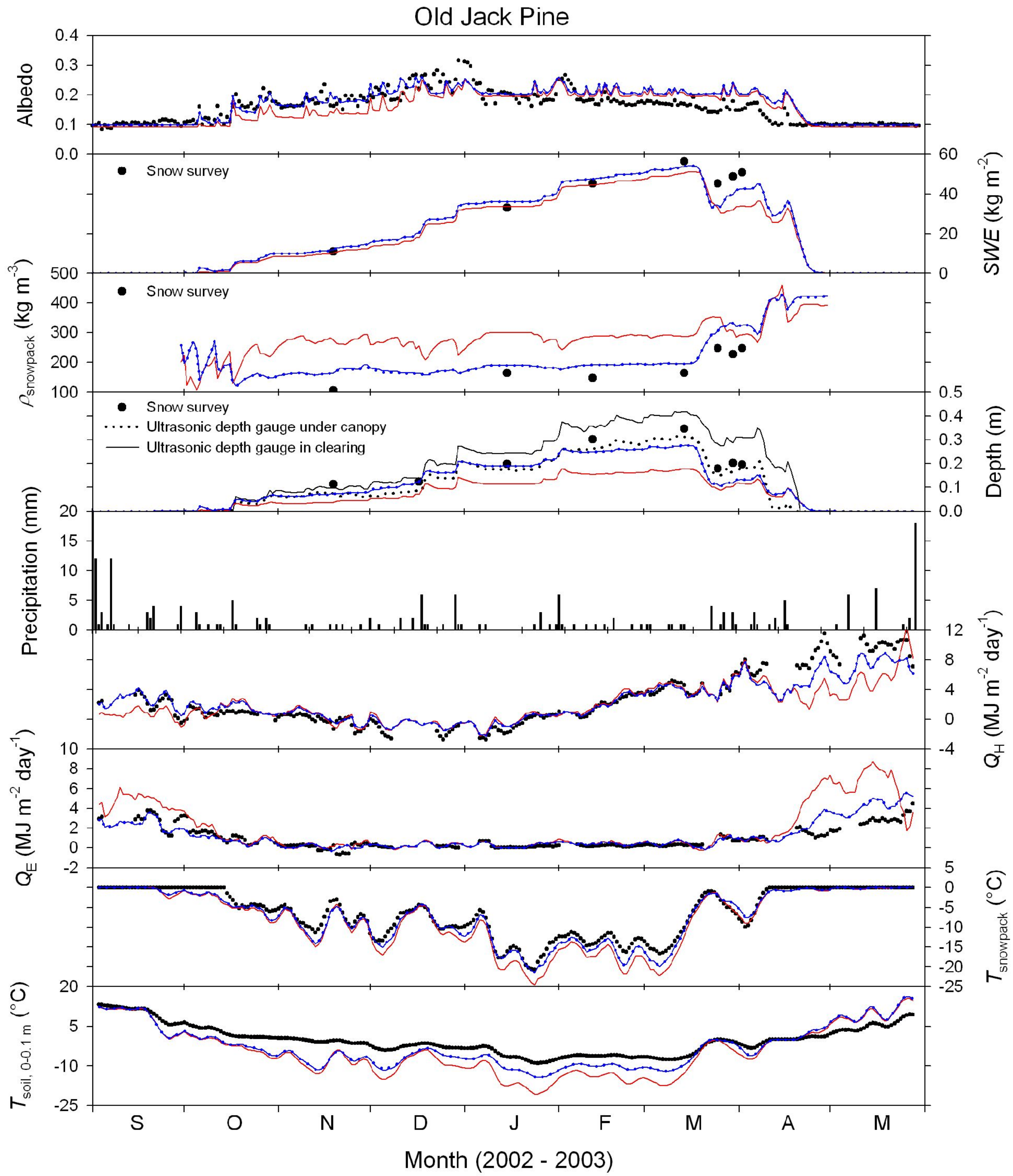

Figure 5: Observed and modelled surface properties for winter runs of CLASS 2.7 and 3.0 at the Old Jack Pine site. Observed values are in black. CLASS runs using the default settings are shown with solid lines, red for CLASS 2.7 and blue for CLASS 3.0. A run of CLASS 3.0 in which *LAI* is multiplied by 0.7 in the calculation of the interception storage capacity of the canopy (to account for clumping) is shown with a dotted blue line.

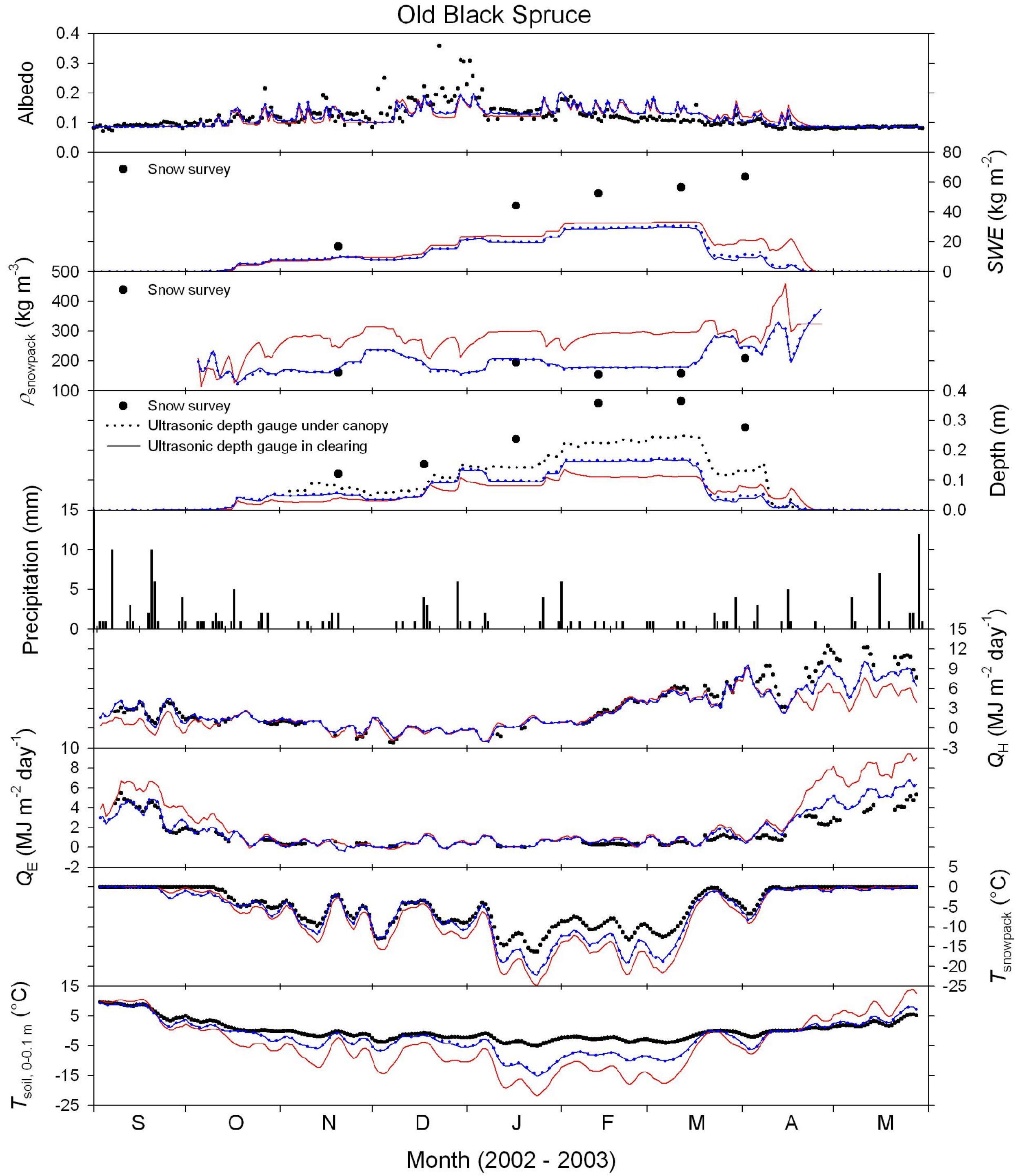

Figure 6: Observed and modelled surface properties for winter runs of CLASS 2.7 and 3.0 at the Old Black Spruce site. Observed values are in black. CLASS runs using the default settings are shown with solid lines, red for CLASS 2.7 and blue for CLASS 3.0. A run of CLASS 3.0 in which *LAI* is multiplied by 0.5 in the calculation of the interception storage capacity of the canopy (to account for clumping) is shown with a dotted blue line.

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