Improved parameterization of land surface snow processes for Canadian climate models.

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Research Objectives:

The objectives of this CCAF project were focussed on enhancing and extending the snow modelling capability of CLASS (Canadian Land Surface Scheme), the land surface model used in the Canadian global and regional climate models, in order to render it better able to simulate snow processes which can have major effects on surface fluxes of carbon, moisture and energy. The three main objectives were:

1) Validation of CLASS snow algorithms against field data from a variety of Canadian sites.

2) Refinement of treatment of fractional snow cover in CLASS.

3) Incorporation of blowing snow into CLASS. Contribution to Climate Change Action Fund Final Report for project activity:

This report addresses objective 1 of the project.

Ross D. Brown, Meteorological Service of Canada, March 31, 2001

Validation of CLASS snow algorithms against field data from a variety of Canadian sites

The main aim of this sub-project was to determine how well CLASS simulated the main features of the snowpack (start, end, melt, depth, density, and snow water equivalent) for various snow cover climate regimes. A 15-year period of data was identified at Goose Bay (1969-1983) that provided a basis for evaluating the ability of CLASS at simulating interannual variability in snow pack properties (e.g. snow cover onset, disappearance, maximum depth, maximum SWE, density). Detailed validation sets were also obtained from Météo-France for the Col-de-Porte site in the French Alps which included measurements of snow temperature and snowmelt. The Col de Porte site has been used extensively in previous snow model validation studies (Loth and Graf, 1996; Essery *et al*., 1999) and therefore represents something of a performance benchmark. Both Goose Bay and Col de Porte are being used in the international Snow Model Intercomparison Project (SnowMIP).

Dr. Jeana Goldstein was employed as a research assistant with CCAF funds in 1999/2000 to prepare the various datasets for running CLASS, and to implement a sensitivity testing and model validation package in IDL. The package allowed the systematic testing of various modifications such as different snow aging schemes. The following components were tested as part of this process: snow aging, variable snowfall density, mixed precipitation, snow thermal properties, liquid water retention, and sensitivity to initial soil temperature specification. In addition, some initial conclusions on CLASS' performance in the SnowMIP experiment are made, since this was based on much of the work carried out in this project. The main findings are summarized below:

1. Snow Aging:

The original snow aging scheme in CLASS was based on an exponential time decay with a maximum cold snow density of 300 kg.m^{-3}. This was found to age snow too rapidly early in the season and to substantially underestimate snow density later in the snow season. A modified aging scheme was investigated where the maximum snow density was a function of snow depth following Tabler et al. (1990), but this still underestimated snow density later in the snow season. Applying an enhanced settling rate for warm snow (TSNOW $\geq$ 273°K) rectified this problem. The temperature threshold and enhanced settling rate for warm snow were determined empirically. The revised aging scheme is

Cold Snow: ρ_{max} = 450. - (20470 / h_s)*(1.-exp(-h_s / 67.3))

Warm Snow: ρ_{max} = 700. - (20470 / h_s)*(1.-exp(-h_s / 67.3))

where ρ_{max} is the maximum snow density, and h_s is the snow depth in centimeters. A comparison of the old and modified aging schemes for Goose Bay and Col de Porte is shown in **Figure 1**. The old scheme is shown in blue and the new in red. The pink line is a detailed multi-layer snowpack model used by Météo-France for avalanche forecasting (CROCUS, Brun *et al.*, 1989). This modified aging expression has been incorporated in the next version of CLASS (3.0) as well as the ISBA (Interactions Surface-Biosphere-Atmosphere) scheme that was recently implemented as the new surface physics package for the GEM regional model at CMC.

2. Variable Snowfall Density:

Fresh snow is assumed to have a fixed density of 100 $kg.m^{-3}$ in the original version of CLASS. However, field data show that snowfall density can range from 50 to 200 $kg.m^{-3}$ depending on crystal type and temperature (Pomeroy and Gray, 1995). Pomeroy et al. (1998) suggested the following dependence of snowfall density on air temperature below 0ºC

$$\rho_{sfall} = 67.9 + 51.3 \exp(Tair/2.6).$$

For air temperature above freezing, snowfall density was assumed to exhibit a linear increase up to a maximum of 250 $kg.m^{-3}$ based on the data presented in Pomeroy and Gray (1995)

$$\rho_{sfall} = 119.2 + 20\ Tair,\ Tair > 0.$$

The inclusion of variable snowfall density was determined to result in slight improvements in the simulation of daily snow depth (an additional 3-5% explanation of the observed variance) and mean snowpack density at both Col de Porte and Goose Bay. This enhancement was included in CLASS 3.0.

3. Snow Thermal Properties:

According to Anderson (1976), the correct estimation of the density of the snow surface layers is especially critical, as this is where the largest temperature gradients occur. In CLASS, snow thermal properties are computed from the <u>average</u> snow density. A snow layer accounting subroutine (SNO_LAYERS) was therefore added to CLASS which keeps track of snow accumulation and aging in individual layers following Anderson (1976). Mass is removed from the top layers from melt and sublimation, and refrozen water is added to the bottom layer. Layers that differ by less than 10 $kg.m^{-3}$ are merged. The surface (top 10 cm) layer snow density was then used to compute the thermal properties of the snow for temperature calculations in CLASS, and to test alternate parameterizations of snow albedo (see below). **Figure 2** shows the difference between the simulated average and surface densities. Differences on the order of 200 $kg.m^{-3}$ can occur when fresh snowfall falls on the established snowpack. This corresponds to about a two-thirds decrease in the computed values of heat capacity and thermal conductivity.

The effect of the modification was a slight decrease in the computed snow surface temperature due to the greater insulating effect of the usually lower density surface layer. This exacerbated an observed cold bias in snow surface temperature in CLASS at the Col de Porte site (**Figure 3**), but this bias may be due to unrepresentative wind speeds at Col de Porte which cause CLASS to underestimate heat fluxes to the snow pack. The French increased the turbulent heat transfer coefficient in CROCUS to improve results at Col de Porte.

4. Mixed Precipitation:

The original version of CLASS assumed a 0ºC threshold for rain/snow separation; however, mixed phase precipitation is not uncommon in winter, particularly over eastern Canada. Previous assessments of snow model performance (e.g. Loth *et al*., 1993) concluded that correct separation of solid and liquid precipitation was one of the more important factors for realistic simulation of snow cover and runoff from a snowpack. A number of empirical expressions have been proposed for diagnosing precipitation phase from air temperature. Analysis of precipitation phase at Goose Bay computed from synoptic weather reports suggested that the solid fraction exhibited an approximately linear dependence on air temperature from a value of 1.0 at 0ºC, to 0.0 at 2ºC.

CLASS was modified to handle mixed precipitation events and a number of tests were performed using observed phase, estimated phase, and a 0ºC threshold. The addition of the mixed precipitation phase resulted in improved simulation of SWE and runoff in nearly all of the test cases (**Figure 4**), and the diagnosed phase results were similar to those obtained with observed phase. The ability to handle mixed precipitation phase, and the estimation of phase from air temperature (if not otherwise specified) have been included in CLASS 3.0.

5. Liquid Water Retention:

During the melt period, a snowpack retains a fraction of liquid water (~3-10% of volume). A number of studies (Loth and Graf, 1996; Jin *et al*., 1999) have demonstrated that this liquid water storage has an important impact on snow surface temperature, snow water equivalent, and runoff. In the original version of CLASS, there is no liquid water storage in the snow layer, and any liquid water is assumed to pass directly through to the soil layer. To investigate the effect of liquid water storage, a water storage term was added to subroutine SNINFL following Loth *et al*. (1993, eqn. 15) where the liquid water retention capacity is defined as a function of snow density from a minimum value of 3% of dry snow mass, to a maximum of 10%.

This change resulted in increased SWE at the end of the snow season (**Figure 5**) and slightly warmer snow temperatures, in agreement with results obtained when liquid water storage was incorporated in ISBA (Stéphane Belair, pers. comm). The impact of liquid water retention varied between the various test cases depending on the particular meteorological conditions. In general, the modification resulted in an overestimation of SWE, but this could be compensated for by a decrease in the minimum snow albedo from 0.50 to 0.40 (**Figure 6**). The lower value is still well within the range of published values for the albedo of melting snow. Runoff was much more sensitive to changes in minimum albedo than the inclusion of liquid water storage.

6. Sensitivity to Initial Soil Specification:

The specification of the initial soil layer temperatures in CLASS affects the ground heat flux into the snowpack. To investigate the importance of this effect, a number of sensitivity runs were carried out with cold, normal and warm soil initial temperature profiles at Col de Porte and Goose Bay. The results revealed that errors in initializing soil temperature had the greatest impact where the snowpack temperature was close to freezing such as Col de Porte (**Figure 7**) – there was no observed impact at Goose Bay where the soil freezes early in the snow season.

8. SnowMIP Project:

The work carried out in this project contributed to the participation of CLASS in the international Snow Model Intercomparison Project (SnowMIP). Preliminary results of the mode intercomparison were released to the project participants in early-September, 2001. The results indicate that CLASS was one of the better-performing models, although it demonstrated a tendency to overestimate SWE, and did not replicate observed snow cover conditions for the test case from the Sleeper River site in northern Vermont (neither did many of the other models). Unfortunately the results cannot be shown here, as they are restricted to the internal use of the project participants. One contributing factor to CLASS overestimating SWE was a noticeable underestimation of sublimation loss compared to other models. This problem was addressed in work carried out by Déry and Taylor as part of this CCAF project, and a blowing snow sublimation scheme is being incorporated into CLASS 3.0.

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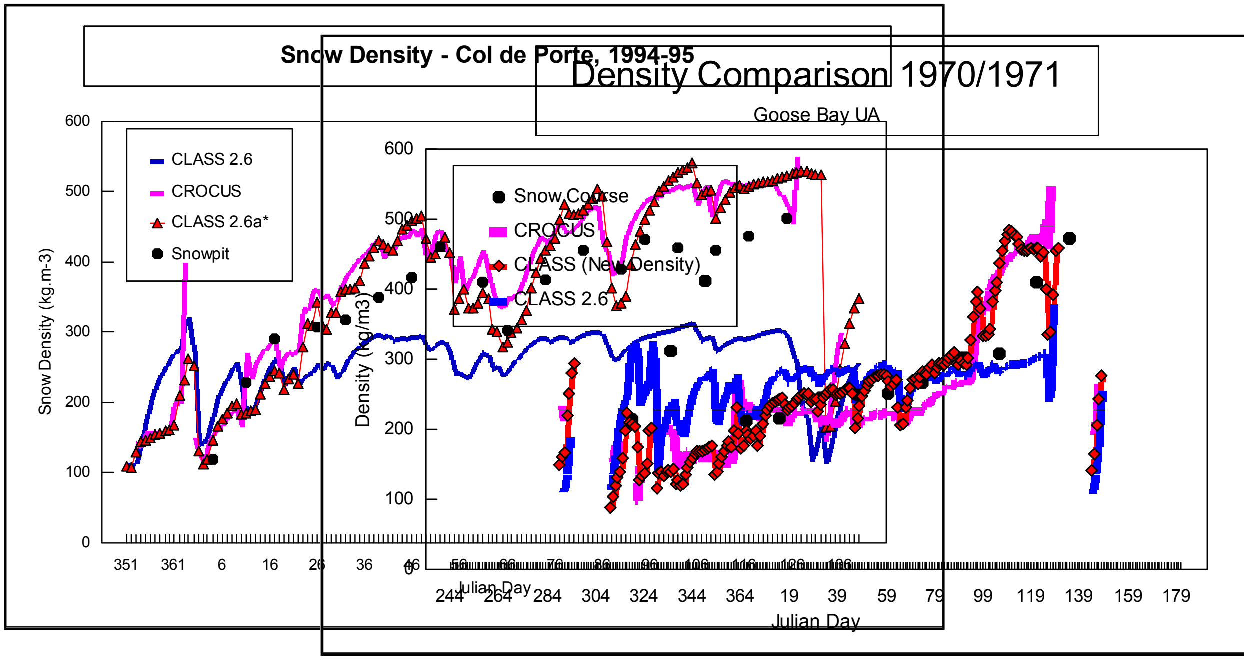

Figure 1: Comparison of old and new snow aging schemes for CLASS at Col de Porte and Goose Bay.

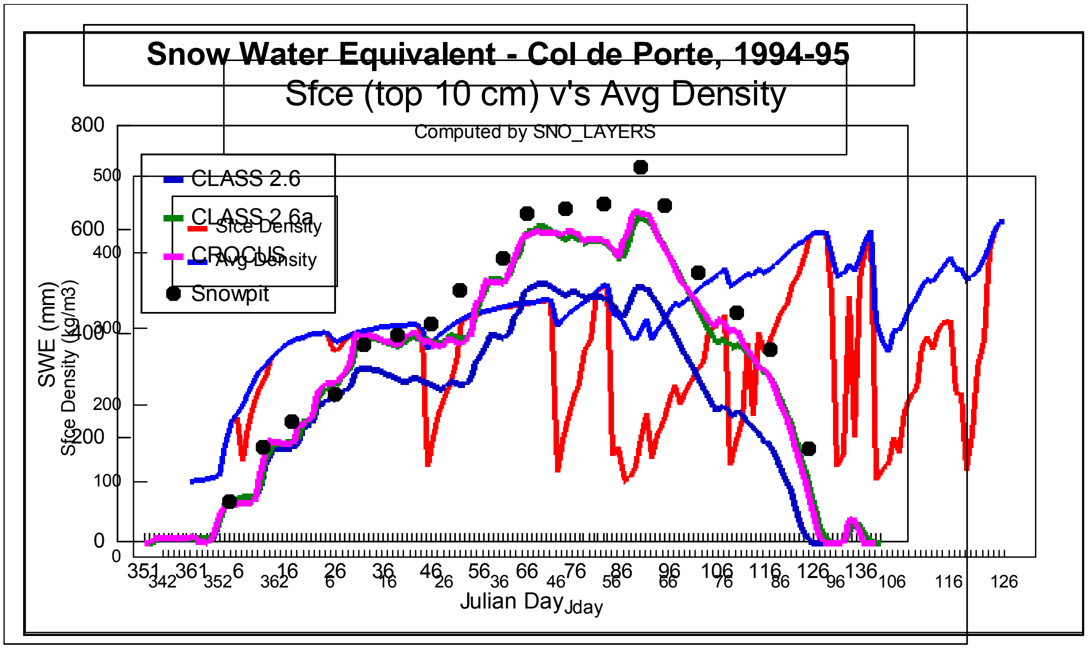

Figure 2: Difference between estimated average and surface snow density for Col de Porte, 1988-1989.

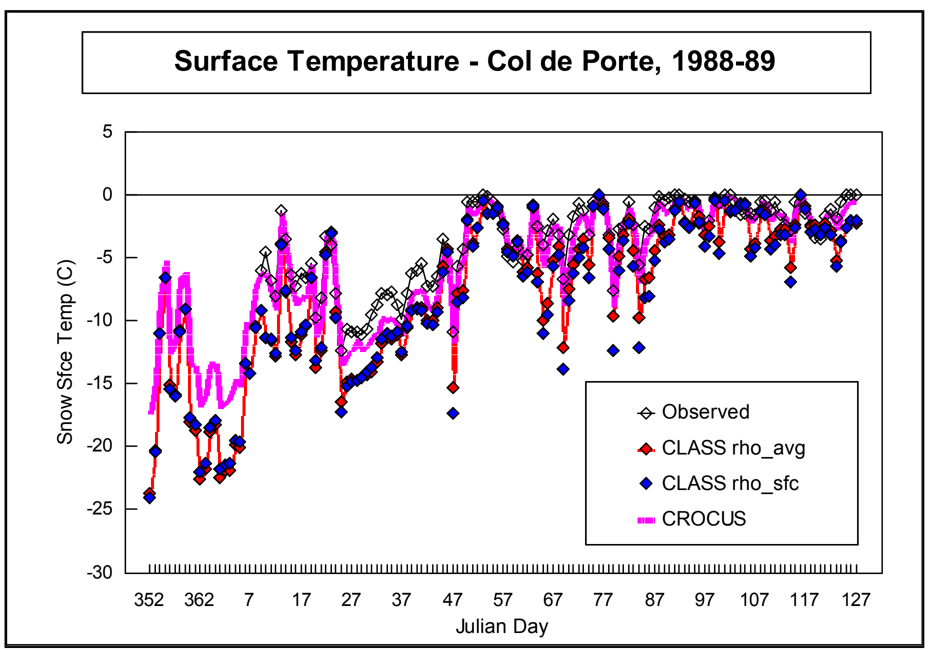

Figure 3: Effect of using snow surface density (rho_sfc) on computed snow surface temperature for Col de Porte, 1988-1989.

Figure 4: Effect of inclusion of observed precipitation phase in CLASS (2.6a) for Col de Porte, 1994-1995. The blue line is the CLASS simulation using a 0ºC rain/snow threshold.

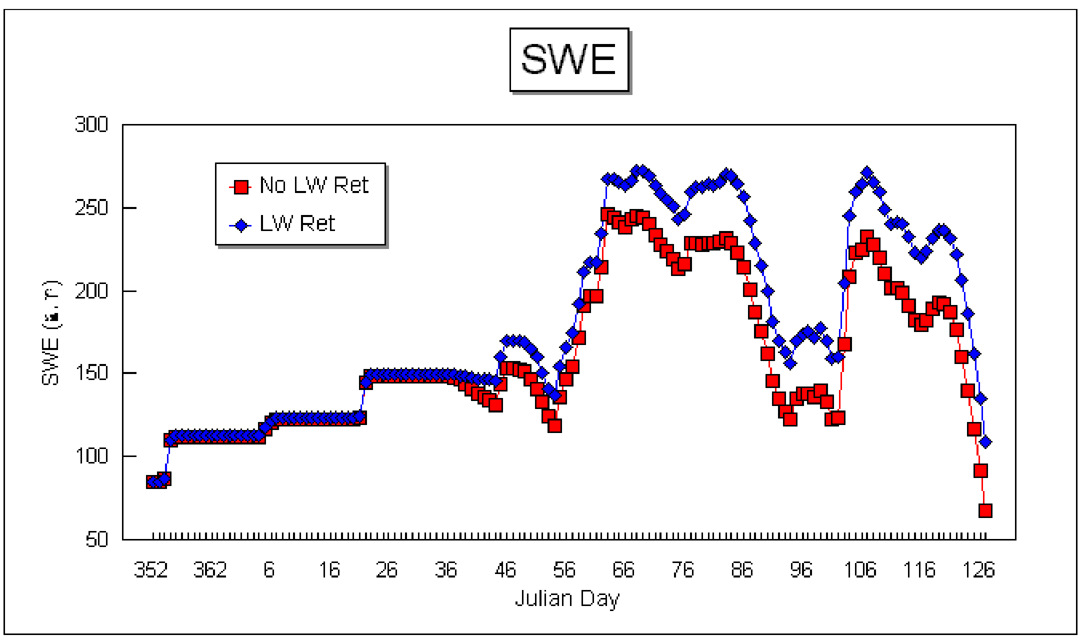

Figure 5: Effect of including liquid water retention in CLASS for Col de Porte 1988-1989.

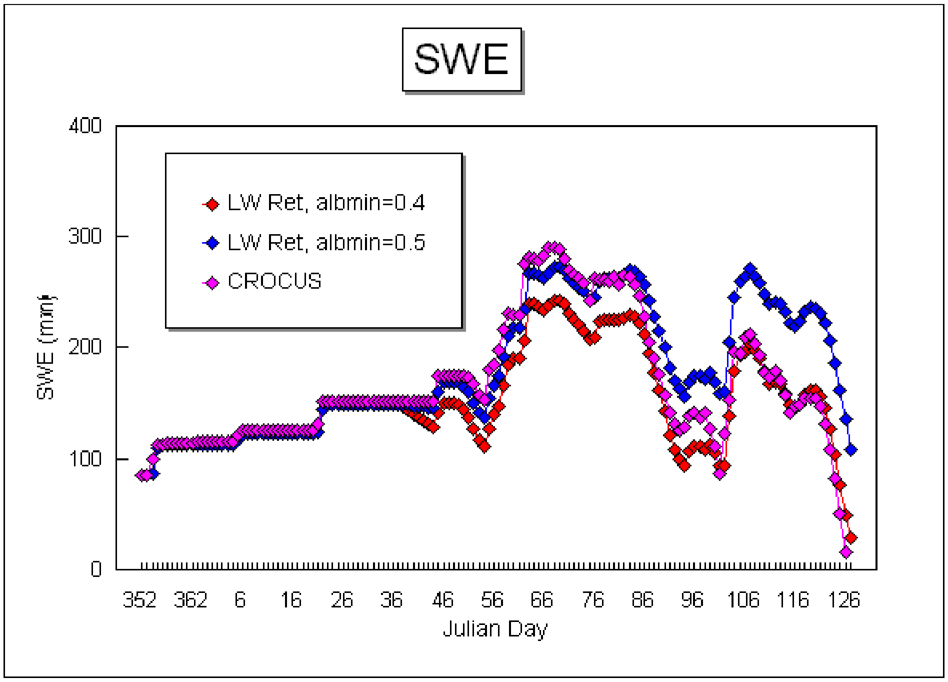

Figure 6: Effect of change in minimum snow albedo on SWE simulation at Col de Porte, 1988-1989.

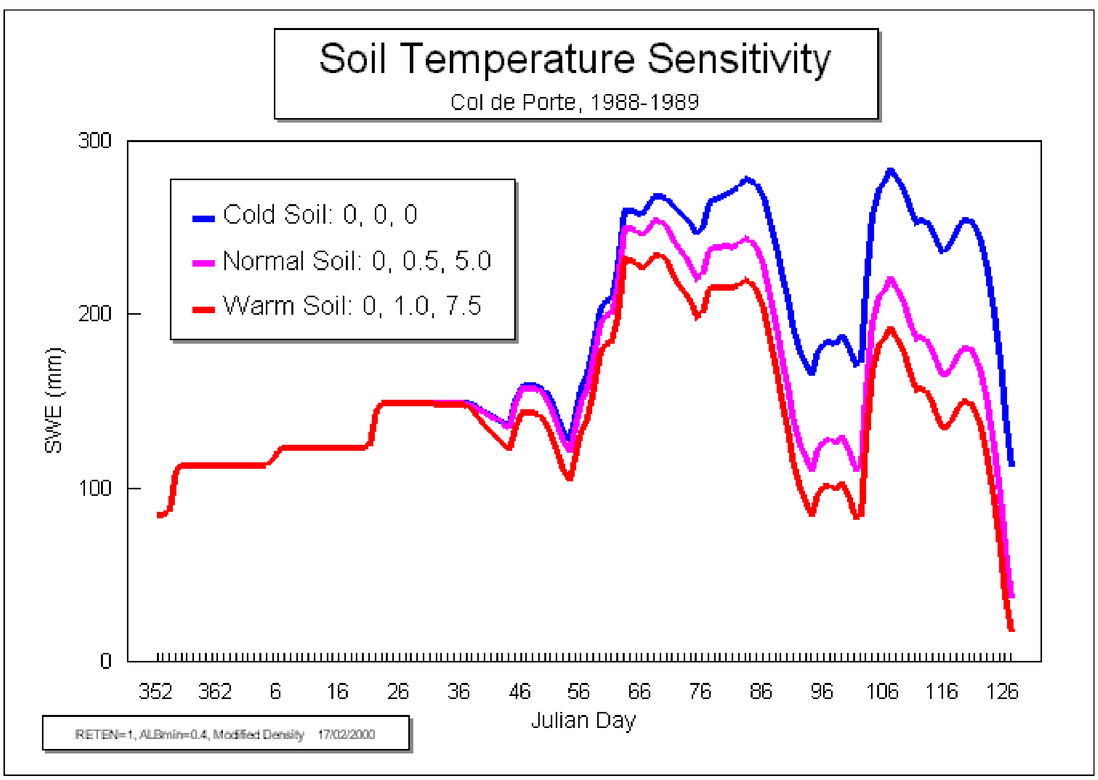

Figure 7: Sensitivity of SWE to soil temperature initialization, Col de Porte 1988-1989. The values in the legend correspond to the initial temperature (ºC) of the three soil layers in CLASS.