Water conservation over snow/frozen soils using the default CABLE soil_snow module

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The following is a brief document outlining some concerns that have emerged while considering the coupling of CABLE to the atmospheric model (UM) within ACCESS. While one of these issues is specific to CABLE when coupled, the other 3 issues apply to all CABLE simulations which involve snow and/or frozen soil conditions. All four involve inconsistencies around whether the latent heat for evaporation or sublimation is used in different parts of the code i.e between those used in the energy balance code (cable_canopy and cable_cbm) to set the latent heat flux and those used in the soil moisture code that distributes the corresponding fluxes of water through the soil/snow column (cable_soilsnow).

The underlying source of the inconsistencies lies in how the latent heats are coded in the two code sections and the conditions (and sequencing) when the heats are interchanged. Within the energy balance code, the current CABLE trunk uses the variable (constant) %rlam to denote the latent heat of evaporation and a factor %cls to denote whether the latent heat should be altered to that of sublimation (i.e. %cls =1.1335 if the latent heat for sublimation is to be used). In contrast the soil moisture-snow component of the code uses two constant %HL and %HLF. These quantities are critical as they relate the fluxes of energy associated with water phase changes with the fluxes of water themselves. Inconsistencies in use therefore lead to either energy or water mass conservation issues (or both).

1: Repeated application of %cls to the correction terms

The coupling of CABLE within ACCESS requires the use of so-called correction terms to the latent (and sensible) heat fluxes[1] from the soil. These are calculated after all other energy balance/soil moisture calculations and, away from conditions of snow melt, formulated as

$$\lambda E_{\mathrm{scor}} = \phi_{\lambda E} \Delta T_s$$

i.e. a multiple of the change in surface-layer soil temperature over the time step. The multiplying factor $\phi_{\lambda E}$ depends on the surface state and meteorology at the start of the time step. Importantly $\phi_{\lambda E}$ (line 720 of cable_canopy) includes the factor %cls and so recognises which of the latent heats should be used. Unfortunately at the point of quantification of λE_{scor} (line 158 of cable_cbm) a second factor of %cls has been included.

Furthermore, and somewhat surprisingly, the latent heat flux passed to the atmospheric model (%fes) includes λE_{scor} without the double factor of %cls, yet the λE_{scor} (%fes_cor) that is used on the subsequent soil moisture calculations does[2]. Consequently, energy balance closure is maintained yet the increment to the water (snow or ice) balance is too large in magnitude.

[1] More to come on this issue later.

[2] The contribution of the correction terms' to the energy balance applies on the current time step. However the associated contribution to the moisture balance is applied on the subsequent time step. Conservation is obtained in the long-run but not on a time-step by time-step basis.

Fix: Trivial

The factor %cls at line 158 of cable_cbm should be removed.

Impact of fix

While the correction terms can be large locally in time and space the majority of the effect cancels in time; they only result in a small net loss of water. This bug is therefore likely reducing the snow pack from the value that would be consistent with the energy balance, but by a near-trivial amount. There is the potential for feedback onto the climate through surface albedo effects. Perhaps more importantly is if there has been any calibration of CABLE or ACCESS parameters that depend on the agreement of the snow pack with observations (e.g. snow aging and/or river runoff parameters) as the optimal parameters will be (slightly) different with this bug present.

2: Latent heat of sublimation during frost

On each time step the factor %cls is reset and quantified within the subroutine latent_heat_flux(). The conditions for when %cls=1.1335 (i.e. the latent heat of sublimation is to be used in the energy balance) are

$$d_{\text{snow}} > 0.1 \quad \& \quad \lambda E_{\text{pot}} > 0$$

i.e. there needs to be some snow cover and a positive value for the potential evaporation. In contrast the latent heat flux is set as sublimation of snow (in subroutine snow_accum) by the simpler condition

$$d_{\text{snow}} > 0.1$$

at which point the water mass flux, E_s, is related to the (known) energy flux, λE_s, as

$$E_s = \lambda E_s / (\lambda + \lambda_{\text{sub}})$$

Consequently, if $\lambda E_{\text{pot}} < 0$ and $d_{\text{snow}} > 0.1$ (i.e. frost onto snow) then the latent heat flux is set with %cls =1 but the mass adjustment assumes %cls =1.1335. Consequently the amount of water deposited onto the surface is 1/1.1335 of that expected by the energy balance.

Fix: Minor

The use of the latent heat of evaporation (%cls=1) in conditions where atmospheric water vapour if frosting onto the surface is clearly unphysical. Consequently the 'if-condition' (line 879 in cable_canopy) needs to be altered so that any negative latent heat flux over snow surfaces ($d_{\text{snow}} > 0.1$) implies sublimation of/frosting onto the snow. For code change transparency, this change has been implemented as an additional if condition at (around) line 879 of cable_canopy.

Unfortunately implementation of this fix is not quite this trivial. CABLE carries two methods to determine λE_{pot} - the Humidity-Deficit-Method and Penman-Monteith approaches. The HDM method permits a trivial rewrite of the 'if-condition' in its current positioning within the code. However the Penman-Monteith approach[3] requires that %cls is known in order to determine λE_{pot} and consequently a more flexible approach is to move the calculation of %cls out of latent_heat_flux

[3] The current implementation of the P-M approach is wrong over snow/frozen soil surfaces!

and forward in the code. This latter point is not addressed in the current package of code modifications but will be returned to in future code updates.

Impact of Fix

The resultant modified CABLE has a better moisture conservation for sites/grid cells with snow cover. A small increase in snow depth in time is to be expected and hence minor changes to snow cover and albedo.

3: Latent heat of sublimation during snowfall over thin snow layers.

As noted above the conditions for when the soil latent heat flux is deemed to be as sublimation from snow or as evaporation from the soil critically depends on the value of d_{snow} at use in subroutines latent_heat_flux and snow_accum. Unfortunately d_{snow} is repeatedly altered by the soil-snow routines, in particular by the addition of snow from precipitation, prior to when the latent heat flux is converted to an adjustment of the snow layer depth (or adjustment to the soil moisture). Consequently different conditions can be satisfied at the different points in the code (e.g. $d_{\mathrm{snow}} \gtrless 0.1$) and so different latent heat values get used in the energy balance and soil moisture-snow calculations. There are then impacts on conservation of moisture.

Fix: Trivial/Minor

The simple fix is to ensure that the value of d_{snow} used in the two locations is the same, i.e. the value of d_{snow} at the start of the time step (variable %osnowd) should be used at line 900 (in cable_soilsnow) in place of %snowd.

However, there are two complicating factors: First, the water mass flux associated with the correction terms could still be associated with the other value for the latent heat due to (legitimate) changes in d_{snow} from the previous time step. Second, e.g. in case of heavy snow onto uncovered soil, it may be physically more appropriate to accept the change in latent heat. However the energy balance (latent heat flux and ground heat flux) would need to be adjusted at the same time.

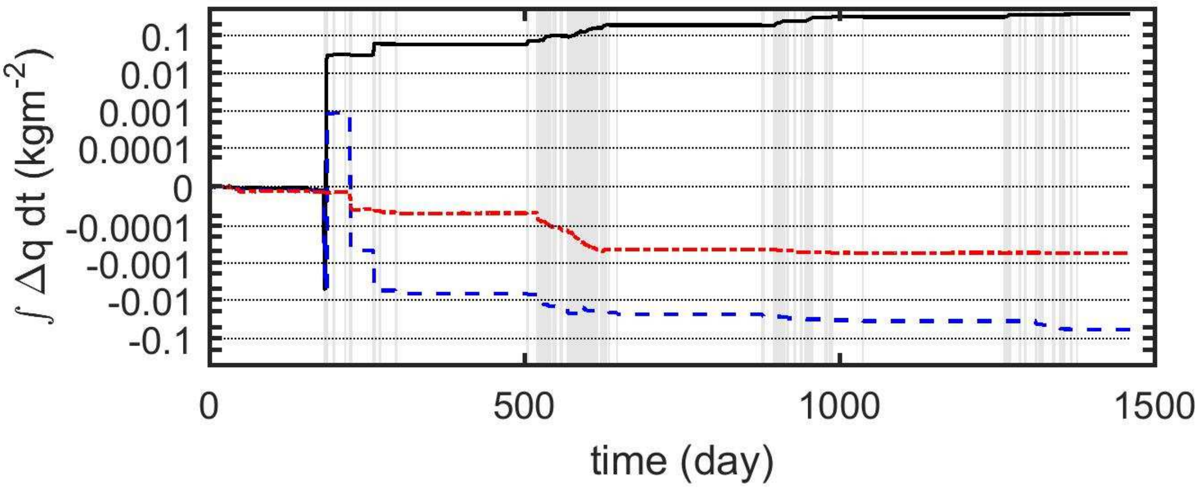
The former concern requires placing the correction terms on the correct (earlier) time step[1]. The latter concern is possible to accommodate but would require a subjective criteria as to those conditions when switching and recalculating is required and has not been investigated further.

The implemented fix utilises a different method to ensure consistency between latent_heat_flux and snow_accum. Since %cls is uniquely set within latent_heat_flux this provides the natural variable upon which to control whether the snow pack or soil moisture is impacted within snow_accum. Correspondingly the relevant WHERE condition (line 900 of cable_soilsnow) utilises %cls not %snowd.

Impact of Fix

The resultant modified CABLE has a better moisture conservation for sites/grid cells with snow cover. Changes in the snow depth through time are to be expected but these should be small. Minor changes to snow cover and albedo would follow.

As an illustration of issues 2 and 3 consider the following figure which shows CABLE's cumulative water (im)balance (%wbal) through four years of a surface-only simulation for the Tumbarumba FLUXNET site. Positive values indicate that precipitation has exceeded the other terms in the water balance, ie. the increases in the water stored in the soil/snow column have been too small given the prescribed precipitation and calculated evaporation flux. It is important to note that evaporation term in the above originates from the energy balance component of the code as $\lambda E_s/\lambda c_{ls}$. The grey banding shows those times where there is precipitation as snow or snow cover, and the *y*-axis is on a log-like scale.



The black line shows the default CABLE trunk performance. Typically, at this site, default CABLE's imbalance is a trivial/modest 0.4kgm^{-2} per year – however this will scale up to be significant at the regional and catchment scale. The blue line shows the same case but where issue 2 has been addressed. A factor 10 smaller imbalance of opposite sign is obtained. Finally the red line shows the same case but where both issues 2 and 3 have been addressed and further improvements (factor 50) are seen. All remaining periods of 'notable' imbalance occur during snow conditions.

To date a similar improvement in water conservation has been detected at all sites/grid cells, if snow is present during the simulation.

4: Latent heat over frozen but uncovered soils.

Four further, likely even more trivial in magnitude, issue merits mention at this point.

First, the conditions for when %cls=1.1335 (i.e. the latent heat of sublimation is to be used) are $d_{\text{snow}} > 0.1$ & $\lambda E_{\text{pot}} > 0$. However several subroutines (snow_melting, snow_freezing) also utilise a condition on whether the soil temperature is below or above freezing to set the relevant latent heat. This third intersecting condition, especially as it relies on soil temperature which (like d_{snow}) is incrementally evolved through the soil-snow algorithms, opens up multiple opportunities for different latent heats to be used for the conversions between energy and mass at different points in the code. Addressing this potential issue has not been attempted at this time. as it would require an extensive revisiting of the snow scheme in CABLE

Second, in default CABLE $\lambda E_s > 0$ from a surface with no or little snow cover ($d_{\text{snow}} \leq 0.1$) is assumed to occur as evaporation from the liquid fraction of soil moisture. Sublimation from the ice within the soil column is not accommodated and the soil ice is assumed to form part of the soil matrix. However, there is an upper limit to the fraction of water that is ice (85% - line 540 of cable_soilsnow) and hence there is always a positive liquid water fraction in the column which permits evaporation, even when even in the case of $T_s < T_{FRZ}$. If $E_s > 0$, $d_{\text{snow}} \leq 0.1$ and the soil ice fraction is close to the limit then the existing limit on E_s (line 871 of cable_canopy) ensures that soil moisture is not completely depleted. However the ice-fraction can then (temporarily) exceed the 85% limit and is capped. This leads to an unexplained loss of water (as ice) from the soil column.

In practice the existing condition (line 871) requires altering to

$$0 \leq \lambda E_s < \frac{\lambda \Delta z_1}{\Delta t}\left(w_{b1} - \frac{w_{bice1}}{0.85}\right)$$

to ensure that the 85% limit is not exceeded.

Third, physically if $T_s < T_{FRZ}$ then any deposition of water associated with a latent heat flux occurs as frost. It is therefore more appropriate that this flux of water is associated with the latent heat of sublimation and represented as a deposition (as solid water) onto the snow pack (not as dew onto the liquid fraction of soil moisture as currently). This represents an additional condition that needs to be incorporated into latent_heat_flux.

Finally, throughout the soil-snow algorithms care is taken to ensure that snow depth and soil surface layer solid/liquid fractions cannot become negative. It is not apparent that the corresponding changes to the energy balance are implemented. This concern is particularly relevant to the correction term to the latent heat flux as applied within the coupled model.

Fix: Minor/Major

A two part fix has been implemented to cover the second and third issues. The second issue involves altering the existing upper limit on λE_s to ensure the ice fraction will not exceed the limit. The third issue requires an additional case to be incorporated into latent_heat_flux in which %cls is set to 1.1335 if $T_s < T_{FRZ}$ and λE_s<0 (at around line 879 of cable_canopy).

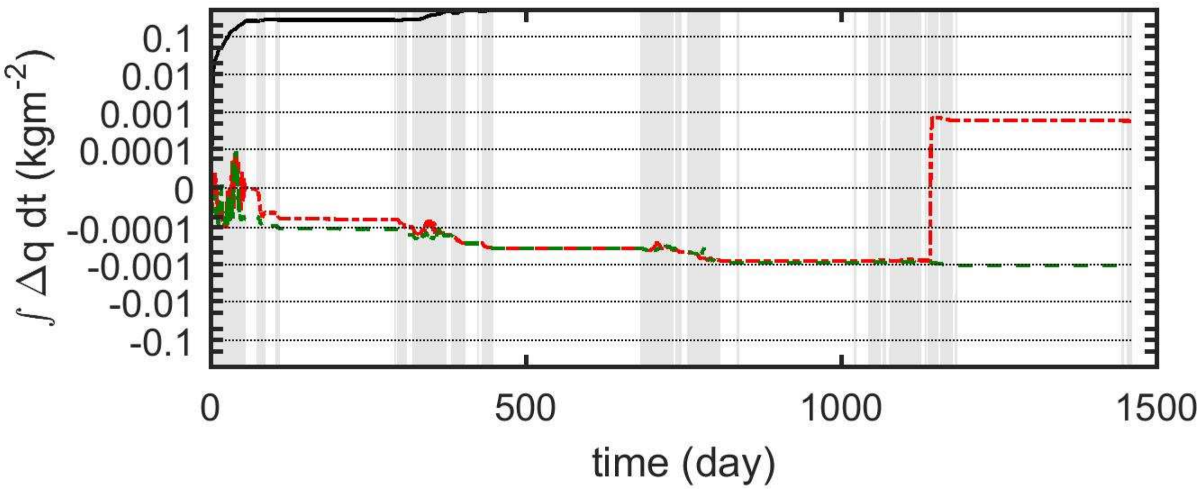
Impact of Fix

The resultant modified CABLE has a similar degree of moisture conservation for sites/grid cells with snow cover to that described earlier. However there are improvements in the removal of spikes in the imbalance from the water balance. Changes in the snow depth, snow cover and albedo do follow but to date have been seen as trivial.

With all changes imposed the code now represents evaporation from/deposition onto the soil in one of four categories

i) evaporation from/dew onto surfaces with no snow and T>freezing
ii) sublimation from/frost onto surfaces with snow cover.
iii) evaporation of liquid water in the soil if no snow and frozen soil
iv) deposition of frost onto frozen surfaces with no/little snow

The following figure shows an example of how the last two modifications to CABLE manifest on the corresponding water imbalance plot for the Tharandt FLUXNET site. For this simulation, default CABLE (black) attains an imbalance of over 1.4kgm^{-2} over the four year simulation and the red line (both %cls fixes as above) shows a similar improvement to the Tumbarumba simulation. Of interest is the spike in the red line, this occurs in conditions of deposition onto frozen soil with a very shallow snow layer.



The green line shows a CABLE run with the final two parts to issue 4 resolved. This particular spike in moisture imbalance is clearly resolved. However this is at the expense of slightly worse conservation at other times through the simulation.

Concluding comments

Code changes to implement these suggested modifications to CABLE have been packaged as the 'CLS' package under Ticket 137. This new Ticket incorporates and extends on existing Tickets 135 and 136. The changes are made entirely within 3 science modules – cable_cbm, cable_canopy and cable_soilsnow; there are no implications to CABLE i/o or the technical coupling within ACCESS (performance changes are to be expected).

Global scale offline simulations and/or coupled simulations have not been undertaken but no difficulties are foreseen as these are small scale changes to the existing code structure.

Finally, it should also be remembered that there are limits to the ability, e.g. through numerical precision, of any surface scheme to conserve absolutely. The corresponding energy balance closure is not exact either, typically amounting to 1E-6Wm^{-2} on each time step. Any conservation issues need to be placed in the context of the wider model performance, CPU usage and model usage. Consequently it may not be appropriate for further effort (and code complications) to be undertaken to address any remaining issues. The relatively simple, but nevertheless advantageous, changes suggested here for issues 1-4 can easily be implemented without any (much) additional overhead.