Coupling CABLE into the UM: The SSEB package (Ticket 152)

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The CABLE model has several structural differences depending on whether the model is used in surface-only mode or coupled to the UK Met Office's UM atmospheric model in ACCESS. Briefly these are that

1. CABLE is twice per time step when run in coupled mode. The first call only undertakes the diagnostic energy balance calculations; the second call undertakes both diagnostic energy balance and prognostic calculations given (minor) adjustments to the atmospheric forcing.
2. CABLE is required to provide values for the fluxes at the end of the time step to the UM atmosphere; in surface-only mode the default is for the output fluxes to be at the start of the time step.
3. In recognition of 2 an assumed evolution of the surface energy balance of the soil column through the time step is incorporated into the output of CABLE when in coupled mode. These are the 'correction terms'.

These differences imply that CABLE simulations would differ between surface-only and coupled configuration even if the meteorology generated/used was identical. Aspect 1 has been addressed in a separate set of working documents/results. This note outlines concerns about the current (CABLE v3933) implementation of the correction terms, in particular how they are sequenced within the rest of the code. This note will comprise both mathematical manipulations and code discussions (for which some background knowledge of the code will be necessary).

Concerns with the correction terms

There are several interrelated concerns with the correction terms as currently implemented. The following is a brief list of concerns, further details are given in the documentation around the REV_CORR package:

1. They are incomplete in that while the turbulent fluxes of sensible and latent heat are corrected the other fluxes are not corrected. This must have consequences for the (diagnosed) energy balance closure and potentially for ACCESS performance.
2. They appear to be incomplete in that while the impacts of changes (over the time step) in surface soil temperature on the energy balance is incorporated into the correction terms there are no associated corrections due to changes in surface soil moisture content.
3. The functional form of the correction terms appears to be over sensitive, resulting in large values for the correction terms (which potentially violates other assumptions in CABLE and ACCESS, including the formulation of the correction terms themselves).
4. The correction terms have only been written for one particular form of the soil latent heat flux whereas CABLE routinely carries at least two functional forms (Penman-Monteith and humidity deficit).
5. The uncorrected latent heat flux (as per the surface-only model) is restricted by physical limits. However the correction terms and, hence, the corrected latent heat flux is not restricted.
6. The correction terms have an associated implied correction to the soil moisture. In the current code this correction (necessary to conserve water) is applied but on the subsequent time step (i.e. conservation is not assured on a time step by time step basis).

The REV_CORR package introduced earlier addressed concerns 1, 3 and 4. This SSEB package addresses concerns 5 and 6. The primary focus is energy and water conservation when CABLE is run within ACCESS using the default soil_snow scheme. The SSEB package also addresses an error in the current coding of the Penman-Monteith form for soil potential evaporation, which has implications for other parts of the CABLE code.

Origin of the correction terms

As noted above, ACCESS requires CABLE to provide surface fluxes of sensible and latent heat at the end of a time step. As the temperature and moisture within the soil column evolve through the time step, the surface fluxes also evolve. This evolution needs to be incorporated into the fluxes that are passed back to the UM. Within CABLE & ACCESS 1.4 the linearization approach of McGregor et al. (1993) was used – three considerations are particularly relevant for this discussion

1. The increments to the soil fluxes should be small in magnitude so as to be considered minor perturbations and thus conform to the linearization. The increments must also respect any physical limits on their value.
2. Increments to the soil fluxes imply changes to the conservation of energy and moisture within the soil column. The conservation requirements must be satisfied.
3. The McGregor et al. (1993) approach was applied to a model of simpler structure than CABLE.

Despite point 1 ACCESS simulations can be found (Ziehn pers. com.) where the correction terms to the surface fluxes can be substantial (100 Wm^{-2} in magnitude or greater on individual time steps).

Away from conditions involving the melting or freezing of soil moisture, CABLE soil temperature,T_s, evolves according to the heat conduction equation (Kowalczyk et al. 2006)

$$\frac{\partial \rho_s c_s T_s}{\partial t} = -\frac{\partial G}{\partial z} = \frac{\partial}{\partial z}\left(\kappa_s \frac{\partial T_s}{\partial z}\right) \tag{1}$$

where *G* is the flux of energy within the soil (positive downwards). The soil parameters, ρ_s, c_s and κ_s are themselves dependent on soil moisture, however over a time step these are held constant. The boundary conditions for (1) are a zero heat flux at the base of the soil column and the energy balance at the soil surface i.e.

$$-\kappa_s \frac{\partial T_s}{\partial z} = G = (1-\alpha_s)S + L^{\downarrow} - \varepsilon_s \sigma T_s^4 - \lambda E_s - H_s \tag{2}$$

where the symbols take their usual meaning. In (2) three terms directly depend on the surface temperature and hence co-evolve as the soil temperature varies over a time-step. Unfortunately as two of these terms are nonlinear it is problematic to combine (1) and (2) within one solvable system for the temperature (and fluxes) at the end of the time step.

The McGregor (1993) approach linearizes the energy balance (2) around the state at the start of the time step (indicated by subscript 0) to give

$$G = (1-\alpha_s)S + L^{\downarrow} - \varepsilon_s \sigma T_{s0}^4 - \lambda E_{s0} - H_{s0} - \left(4\varepsilon_s \sigma T_{s0}^3 + \lambda \frac{\partial E_{s0}}{\partial T_s} + \frac{\partial H_{s0}}{\partial T_s}\right)\partial T_s \tag{3}$$

Eqns (1) and (3) can be combined in a linear system. CABLE discretises the combined equation, in time and into soil layers, to form a single set of linear equations for the change in T_s over the time step – *this applies in all simulations including surface-only*. The second and third terms in the bracket are the 'correction' terms, specifically

$$H_{cor} = \Delta T_s \frac{\partial H_{s0}}{\partial T_s}, \qquad \lambda E_{cor} = \Delta T_s \lambda \frac{\partial E_{s0}}{\partial T_s} \tag{4}$$

are determined given the change over the time step in soil surface layer temperature, ΔT_s, after the soil temperature is evolved within ACCESS simulations. We term the gradient factors in (4) as 'sensitivities'.

This formulation is specific to the 'soil_snow' default soil scheme – and applies in both offline and coupled simulations. Consequently while identified through consideration of ACCESS, surface-only CABLE simulations are also effected by the concerns raised earlier.

Concern 5: Application of physical limits on soil evaporation with the correction terms

Within the surface-only configuration of CABLE substantial effort is undertaken to ensure that soil moisture stocks are not depleted below physical and physiological limits at, and over, each time step. In contrast no such limits are placed on the magnitudes of the sensitivity terms or correction terms. This has the potential, when interfacing with other parts of the model, to lead to a lack of moisture balance within CABLE (not just in the diagnostic outputs) as some variables are capped and others not. It should be noted that this issue does apply to surface-only simulations as, while the outputted fluxes do not have the correction terms applied, these terms do in effect exist as part of the solution of the soil temperature equation (i.e. via the sensitivity terms in (3)).

A substantive complication to this problem is that the limits apply both on conditions at instants in time (in the case of limits on the flux) and over the time step (in the case of limits on the water budget). As ΔT_s is not known until the soil temperature is evolved, it is impossible to evaluate the correction terms ahead of time to ensure that any limits are not crossed. To apply limits on the corrections terms therefore implies changing the solution methodology of the soil temperature equation.

Concern 6: Time stepping of the water balance with correction terms

There is a fundamental difference in how CABLE time steps its soil temperature and soil moisture variables. Both are governed by diffusion-like partial differential equations – the difference lies in the upper boundary conditions. Soil temperature, as discussed above, is evolved in partnership with the soil surface energy balance, i.e. the surface fluxes are assumed to vary during the time step in a linear (in T_s and time) manner. Soil moisture, in contrast, is evolved using specified, and assumed constant, values for the evaporation/infiltration (as the upper boundary condition).

In ACCESS 1.3 it was recognised that if the latent heat flux passed to the atmosphere reflects the flux at the end of the time step and is assumed to be constant over the time step, then there is an impact on the water balance of the soil, i.e. $\Delta t\ \Delta T_s\ \partial E_s/\partial T_s$, that is not accounted for within CABLE's surface-only soil moisture calculations. The approach taken to address this conservation issue was to i) diagnose the water increment once ΔT_s (including the snow freeze/melt terms) is known and ii) apply this as an increment to the infiltration/evaporation *on the next time step*. Water conservation is violated on the time step but conserved over longer runs.

However, sequentially the evaluation of plant transpiration, the soil wetness factor, β, and many other components of CABLE occur prior to the application of the infiltration/evaporation within the soil moisture dynamics. Consequently evaporation, transpiration etc. on the next time step are set by an incorrect value for the soil moisture – with unknowable consequences. Furthermore - with the crossed time stepping - it is possible that a correction flux is quantified as a water flux but implemented as an increment to the snow pack (or vice-versa), which leads to a further loss of conservation. Ideally we require the evaporation and infiltration applied at each time step to reflect conditions on that time step (within any appropriate limits), i.e. the increment to the water balance should be applied on the same time step as the correction term.

Again, as the correction terms are not known before the soil temperature is evolved, as many of the snow/soil moisture equation coefficients are calculated *prior in sequence* to the evolution of the soil temperature, and as there are interactions between soil temperature and snow cover/soil moisture, placing the increment to the snow/soil moisture on the correct time step is non-trivial.

Other Concerns: Formulation of the Penman-Monteith form for soil potential evaporation

The Penman-Monteith form for λE_s comprises 2 terms – one linked to the available energy and the other to aerodynamic mixing. Theoretically the aerodynamic term depends on whether the evaporation is of snow/ice or liquid water, however CABLE makes no such distinction and so is incorrect (see later).

The SSEB package

The SSEB package is a set of code modifications that incorporate fixes to address the above concerns within CABLE. The code changes are distributed through the biophysics parts of the code and activated via a cable_user logical switch (L_REV_SSEB) in the CABLE namelist file (default is set to false). It is anticipated that the code changes will, in the future, be part of default CABLE removing the need for the logical switch. The SSEB package has been written to work alongside the REV_CORR package – scientifically the preferred option is that both options are set to true however the code should operate with either flag set to true on its own. To facilitate the code changes new variables (both typed and temporary variables) have been introduced. The typed variables imply changes in other cable code. The cable subroutines altered are

- biophysics: cable_canopy, cable_cbm, cable_soilsnow
- ancillary: cable_common, cable_define_types
- MPI: cable_mpimaster, cable_mpiworker, cable_mpicommon

The code set sits in CABLE repository /branches/inh599/CABLE-2.0_SSEB/ .

Some specific notes on the implementation:

A) The SSEB package can be envisioned as three co-developed advances to CABLE – these however cannot easily be disentangled. SSEB(1) addresses the time-stepping issue and places the increment to the water balance on the same time step as the energy balance. SSEB(2) co-locates the soil energy balance components of CABLE into one set of subroutines (instead of being dispersed through the canopy module) and addresses the Penman-Monteith formulation issue. SSEB(3) rewrites the soil temperature evolution algorithm so as to ensure that physical limits are not violated when CABLE is run within ACCESS.

B) To address the time stepping issue SSEB(1) undertakes three code changes:

1. relocates the calculation of the correction terms (including the extensions introduced by the REV_CORR package) from their current locations (split between cable_cbm and the end of cable_soilsnow) and moves them to between the soil temperature and soil moisture calculations in cable_soilsnow (after the call to soilfreeze and before the call to surfbv).
2. When a site is snow covered the snow mass, density and depth are adjusted consistent with the water balance increment.
3. The correction term λE_{cor} is initiated to zero at the start of the energy balance calculations. In the original algorithm λE_{cor} needed to be carried across time steps.

The logic behind these changes is that (except for glacier sites) the soil-snow temperature profile is fully updated after the soilfreeze subroutine. At this point the correction terms to the energy and water balances are also knowable. By evaluating the correction terms at that point in the code, the appropriate, fully incremented, forcing to the water balance of the soil can be applied via the infiltration/evaporation term on the same time step (i.e. within surfbv).

In contrast, the evolution of a snow pack is dealt with prior to the soil temperature calculations – and so the increment needs to be applied to the snow pack variables as a separate adjustment. This adjustment is an approximation to the full snow pack calculations.

The current implementation is somewhat complicated by the different way the soil latent heat flux variable (canopy%fess) is handled with/without the REV_CORR package. For good code management purposes the snow pack adjustment may merit being moved to a separate subroutine.

For glacier sites, there is a further update to the soil-snow surface temperature within the surfbv subroutine. With SSEB, the evaluated correction terms and increment to the snow pack may not therefore be consistent with the evolved soil-snow surface temperature. Energy and moisture are conserved.

C) To facilitate good code management, to facilitate the application of physical limits on the correction terms, and to rectify the Penman-Monteith formulation for soil evaporation SSEB(2), undertakes one code change.

- Three new algorithms for the soil energy balance are created, predominantly consisting of a rearrangement of existing formulations. There is a single entry point between the main cable_canopy routine and the new code. This grouping of algorithms includes the evaluation of soil evaporation and puddle fluxes, the evaluation of the sensitivity terms and the identification of physical limits on the primary estimates and correction terms. This co-location should facilitate future code developments that are internally consistent – in contrast to the current algorithms which are distributed through the cable_canopy module.

D) The new code management has permitted a simple implementation of a correct form of the Penman-Monteith formulation for soil (potential) evaporation. The current code has that

$$\lambda E_{pot} = c_1\left((1-\alpha_s)S + L^{\downarrow} - \varepsilon_s\sigma T_s^4 - G_0\right) + c_2\lambda\rho\,(q_s(T_s) - q_{vair})/r_{tsoil}$$

where the first term is the available energy term and the second the aerodynamic term. c_1 and c_2 are known, air temperature dependent, coefficients. This equation is appropriate for evaporation of liquid water, however over snow the latent heat flux used should be that for sublimation. As the two terms involved differ with respect to the inclusion of the latent heat it is incorrect to then post-multiply λE_{pot} by the ratio of the latent heats for snow sites as is currently implemented. In practice the correct is

$$\lambda E_{pot} = c_1\left((1-\alpha_s)S + L^{\downarrow} - \varepsilon_s\sigma T_s^4 - G_0\right) + c_2\lambda f_{cls}\rho\,(q_s(T_s) - q_{vair})/r_{tsoil}$$

However this implementation requires several other adjustments to the code

1. The %potev variable evaluated by the Penman-Monteith and Humidity Deficit methods algorithms must now be interpreted as the latent heat flux associated with potential evaporation. The earlier form was inconsistent in this usage.
2. Consequently care over the inclusion (or not) of factors of %cls must be taken when using the %potev variable. For example the calculation of the diagnostic variable %epot is adjusted.
3. An initial estimate of %cls is required prior the call to the revised Penman Monteith algorithm – though can be updated within the main soil energy balance algorithm if needed.

E) As discussed previously there is a need to ensure that the correction terms are limited in a consistent manner to their uncorrected counterparts. The limit arises through biophysical limits on transpiration – but this could be extended to include other processes. The soil moisture level in the uppermost soil layer, η_1, is required to stay above $\alpha\,\eta_{wilt}$ throughout the time step, (where α is 0.5 or 1 depending on the value of CABLE switch l_new_reduce_soilevap). This in practice requires that (over non-snow surfaces) the soil evaporation is restricted

$$E_s \le (\eta_1 - \alpha\,\eta_{wilt})\frac{\Delta z_1}{\Delta t} - T_1$$

where T_1 is the transpiration flux from the uppermost soil layer[1]. Corresponding upper limits apply on the sublimation of snow cover with the sublimation flux being required to be less than that required to remove all snow mass (the transpiration term is disregarded).

[1] From a physics perspective this prioritisation between transpiration and evaporation is incorrect. If soil moisture levels drop below wilting then transpiration shuts off. However soil evaporation can continue provided the molecular/aerodynamic transport processes are sufficient to extract water vapour from the soil matrix. However algorithmically there is no means to go back and re-evaluate the transpiration and photosynthesis over the time step if the physical limit is violated – hence CABLE chooses to restrict soil evaporation in these circumstances.

To apply the same limits on the correction terms we need to enforce two conditions. First, if E_{s0} is at its limit then the sensitivity term $\partial\lambda E_s/\partial T_s$ should be zero, and hence the correction term be zero regardless of any change ΔT_s. This condition is evaluated within the new soil energy balance algorithm as part of SSEB(2). This restriction applies to both surface-only and coupled CABLE simulations!

Second, an upper bound to the correction term is required to be enforced as part of the calculations in *coupled simulations only*. This upper bound is given by

$$E_{cor} \le (\eta_1 - \alpha\, \eta_{wilt})\frac{\Delta z_1}{\Delta t} - T_1 - E_s$$

For snow surfaces the corresponding limit is

$$E_{cor} \le \frac{\rho_{snow} z_{snow}}{\Delta t} - E_s$$

where $\rho_{snow} z_{snow}$ is the mass of snow (per square metre) at the start of the time step. The limit is evaluated within the new soil energy balance algorithm as variable %fescor_upp (SSEB(2)) and is initialised to an unphysically large, positive value. The enforcement of the limit is undertaken by SSEB(3) and discussed in further detail in F). Both the zero sensitivity term and upper limit are needed as cases can exist where E_{s0} is not at the limit but ΔT_s is sufficiently large that E_{cor} would exceed it.

However, the counter case also exists. If conditions are such that the soil evaporation limit is only just reached by E_{s0}, so the sensitivity term has been set to zero, and $\Delta T_s < 0$ over the time step, we would ideally allow for $E_{cor} < 0$. The algorithm does not permit this and hence CABLE would overestimate evaporation. To address this case would require a diagnosis of not only whether E_s is limited but also the temperature at which it would no longer be limited and the duration through the time step when that temperature would eventuate. While theoretically necessary for completeness and accuracy, this set of conditions has been not been addressed.

A corresponding variable for a lower limit on E_{cor} (%fescor_low) has been included as part of SSEB but is not currently utilised. An example of when such a limit could be useful would be to consider cases when T_s crosses the freezing point during a time step. It may be appropriate to remove that variable for efficiency reasons (associated adjustments to the mpi code would be required).

F) To enforce the upper limit on evaporation/sublimation requires that the soil temperature and sensitivity terms are assessed so as to not violate the physical limit on E_{cor}. SSEB(3) achieves this via an updated soil temperature algorithm (inv_trimb). The premise of the existing scheme (trimb) is to discretise the soil temperature profile into a number of layers, discretise the soil temperature diffusion equation in time and across those layers and solve using a centred-in-space, implicit-in-time numerical solver (Gaussian elimination type). The existing trimb algorithm starts the elimination by progressing down the soil column before back-solving up the soil column. This methodology implies that the surface energy balance, equations (1) and (3), is applied at two points (at the start and end of the algorithm). Consequently ΔT_s is not known until the very end of the calculation. If a physical limit were violated then the entirety of the algorithm would need to be re-evaluated.

In contrast the inv_trimb algorithm solves the same system by eliminating up the soil column then down. The energy balance is applied at one point in the algorithm and ΔT_s can be checked earlier. Any revisions necessary, due to E_{cor}, are also much easier to implement as fewer stages of the soil temperature calculation need to be unpicked.

In more detail the inv_trimb algorithm is structured as follows:

1. Initial estimates for the sensitivity terms $\partial\lambda E_s/\partial T_s$, $\partial G_s/\partial T_s$ etc. and limits on E_{cor} are provided.
2. The discretised matrix equation for the soil column temperature is as before, i.e.
$$\begin{pmatrix} b_1 & c_1 & \\ a_k & b_k & c_k \\ & a_N & b_N \end{pmatrix}\begin{pmatrix} T_1 \\ T_k \\ T_N \end{pmatrix} = \begin{pmatrix} r_1 \\ r_k \\ r_N \end{pmatrix} \qquad \begin{matrix} k=1 \\ k=2, N-2 \\ k=N \end{matrix}$$
Noting that the sensitivity coefficient $\partial G_s/\partial T_s$ is a component of both b_1 and r_1.
3. Perform the upwards elimination to remove entries above the leading diagonal up to row 1, i.e.
$$\begin{pmatrix} b_1 & c_1 & \\ \tilde{a}_k & 1 & \\ & \tilde{a}_N & 1 \end{pmatrix}\begin{pmatrix} T_1 \\ T_k \\ T_N \end{pmatrix} = \begin{pmatrix} r_1 \\ \tilde{r}_k \\ \tilde{r}_N \end{pmatrix} \qquad \begin{matrix} k=1 \\ k=2, N-2 \\ k=N \end{matrix}$$
where the tilde's indicate that the coefficient is modified. A copy of the coefficients of the partial solution for row 1 is taken.
4. Perform the final upwards elimination step of the upwards sweep, followed by the first step of the downwards sweep, i.e.
$$\begin{pmatrix} 1 & & \\ \tilde{a}_k & 1 & \\ & \tilde{a}_N & 1 \end{pmatrix}\begin{pmatrix} T_1 \\ T_k \\ T_N \end{pmatrix} = \begin{pmatrix} \widehat{r_1} \\ \tilde{r}_k \\ \tilde{r}_N \end{pmatrix} \qquad \begin{matrix} k=1 \\ k=2, N-2 \\ k=N \end{matrix}$$
where the hat indicates that the coefficient is 'fully' modified.
5. Check that the solution $T_1 = \widehat{r_1}$ does not imply that ΔT_s is too large and that the correction term E_{cor} would violate the prescribed limit. If, and only if, this does occur reset the sensitivity term as
$$\frac{\partial\lambda E_s}{\partial T_s}_{new} = \frac{\text{limit}}{\Delta T_s}$$
Recalculate $\partial G_s/\partial T_s$ and then b_1 and r_1.
6. Repeat steps 4-5, using the coefficients copied in stage 3, until a solution is found[2] where the combination of T_1 and $\partial\lambda E_s/\partial T_s$ does not violate the limit.
7. Complete the downward elimination sweep to obtain
$$\begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}\begin{pmatrix} T_1 \\ T_k \\ T_N \end{pmatrix} = \begin{pmatrix} \widehat{r_1} \\ \widehat{r_k} \\ \widehat{r_N} \end{pmatrix} \qquad \begin{matrix} k=1 \\ k=2, N-2 \\ k=N \end{matrix}$$
as the final solution for the temperature profile.

The physical limit on E_{cor} is accommodated via changes to both the temperature increment and to the sensitivity terms. Importantly the sensitivity term of both the latent heat and ground heat need to be changed consistently.

By design, ΔT_s evaluated by the new soil temperature algorithm satisfies the necessary physical limits and consequently the associated water increment can be applied as an additive term to the evaporation/infiltration forcing of the soil moisture evolution calculations without further consideration. The corresponding increment to the snow pack, when necessary, does require a more careful implementation (to both the energy and water balances) to ensure that a negative snow mass is not predicted, e.g. due to numerical precision reasons. This is undertaken as part of SSEB(1).

The current implementation performs steps 3 and 7 in parallel across sites. The limit checking process and iteration of steps 4-6 is done on a site-by-site basis. The number of iterations around steps 4-6 is limited to a finite number. Offline testing indicates that four iterations is sufficient to converge the eventual solution to within numerical precision. Adjusting step 5 for a faster, if less accurate, convergence may be possible.

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[2] A priori it is only an assertion that this solution exists. Testing has indicated that this is a stable algorithm.

G) As noted above, the enforcement of the upper limit on E_{cor} through the changed soil temperature algorithm only applies for coupled simulations. The current implementation triggers[3] the use of inv_trimb through the joint use of the cable flags cable_user%L_REV_CORR and cable_user%cable_runtime_coupled, otherwise the existing trimb algorithm is used. There may be more appropriate cable flags to use; this requires review and further advice.

H) Testing of the SSEB package has primarily occurred in single site and global, GSWP2-driven, offline simulations. No further code modifications are anticipated in order to utilise the package within ACCESS (not even within the CABLE-UM interface and initialisation routines). However this will need to be reviewed and tested before full acceptance.

Additional components to the SSEB package

This code package includes a fix to a recently identified error in the canopy radiation code (Ticket #147). The code set is also built upon earlier bug fixes to the %cls variable (#122, 135, 136 and 137) and to the friction velocity calculations (#138).

Intersection with the other CABLE developments

CABLE v3933 carries both the default soil scheme (soil_snow) as used in ACCESS and the Haverd Soil-Litter-Isotope enabled scheme (SLI). SLI is premised on different and separate soil energy balance and soil temperature/moisture algorithms. In particular SLI evolves the soil column through the use of multiple (smaller) time steps per CABLE time step – with the diagnosed energy balance being the average over the time step. This contrasts to CABLE soil_snow in both offline and coupled (i.e. ACCESS) configurations. **The need for, the mathematical form of and the numerical stability motivation for the correction terms will need to be revisited if/prior to SLI being used within ACCESS.** In practice the most likely modification required will be to switch off the correction terms if SLI is active and CABLE is coupled to the UM – this condition has not been implemented.

Both the REV_CORR and SSEB packages have been developed to permit the co-use of the Haverd litter scheme (with soil_snow). Further co-management/tidying would be worth considering.

The Dekker set of developments around soil evaporation clearly intersect with both the REV_CORR and SSEB packages. **It is expected that further effort will be required to successfully merge the three developments.**

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[3] Testing of the SSEB package when run within CABLE operating in the surface-only-as-coupled configuration occurred without this logic condition applied.

Indicative results

By construct, SSEB is aimed at minimising differences in CABLE performance, at least for the majority of cases. The primary advance is around energy and water conservation, code structure (for future developments of the coupled model) and in placing the water flux associated with the correction terms on the appropriate time step.

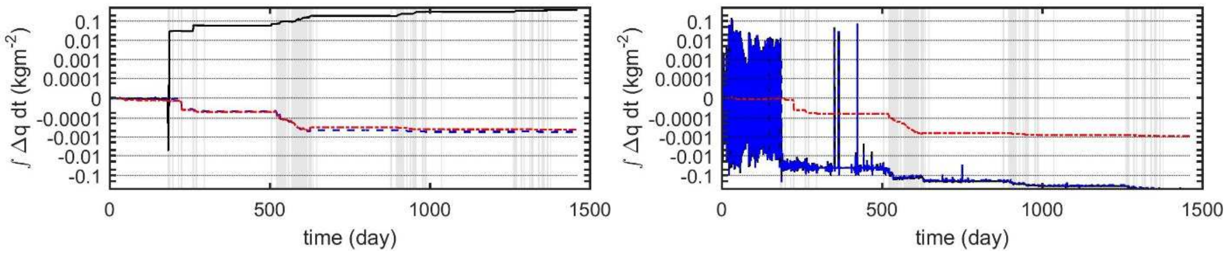

Figure 1. Illustrative time series of the accumulated water balance metric %wbal for the Tumbarumba FLUXNET site under different CABLE configuration. More detail in main text. On the right panel the black and blue lines are mostly coincident.

Figure 1 shows time series of the diagnostic accumulated water balance variable (%wbal) from a four year simulation of the Tumbarumba FLUXNET site. A perfectly conserving model would have a 0 value for this metric (and the corresponding energy balance metric). Note that the vertical axis has been scaled logarithmically! Vertical grey bars indicate times when a snow pack was simulated. The left panel shows the results from typical, surface-only, configurations of CABLE; the right panel shows the corresponding results from the same (parameter settings etc.) versions of CABLE but where these have been configured to incorporate the correction terms as if CABLE were being run in coupled mode. In practice this CABLE surface-only-as-coupled configuration evaluates the correction terms are evaluated, includes these in the diagnostic outputs and applies the associated water balance increment soil moisture/snow dynamics. This configuration is as close to fully coupled CABLE as is possible without running a full ACCESS simulation.

In each panel the black line gives the performance of the current CABLE trunk (v3933). The blue, dashed line the performance of the REV_CORR package. The red, dash-dotted line the performance of the SSEB+REV_CORR packages. Output is given every 30 minute time step.

The difference between the performance in surface-only and surface-only-as-coupled configurations (black lines in each panel) is not-systematic and depends on the site considered – it originates from non-linearities in the functional form of the correction terms, asymmetries in meteorological forcing through the diurnal cycle and how these interact with the soil moisture calculations. The majority of the improvement in moisture conservation with the new packages originates from the REV_CORR package (specifically the corrected use of the different latent heats in different parts of the code). This improvement is consistent across sites. However it is the placement of the correction terms onto the appropriate time step (SSEB) that eliminates the numerical noise in the surface-only-as-coupled configuration (red line, right panel). The noise (a non-systematic lack of closure on a time step by time step basis) in the water balance is accompanied by lack of closure in the energy balance (not shown) of order 25-50 Wm^{-2} and is accompanied by differences in the soil surface temperature of order 0.2-0.5K (again variable not systematic). These differences are non-trivial but not substantial. It is also clear from these results that while the two packages have improved water conservation in both the surface-only and surface-only-as-coupled configuration (from an already reasonable base) there are still issues with conservation when snow cover is simulated.

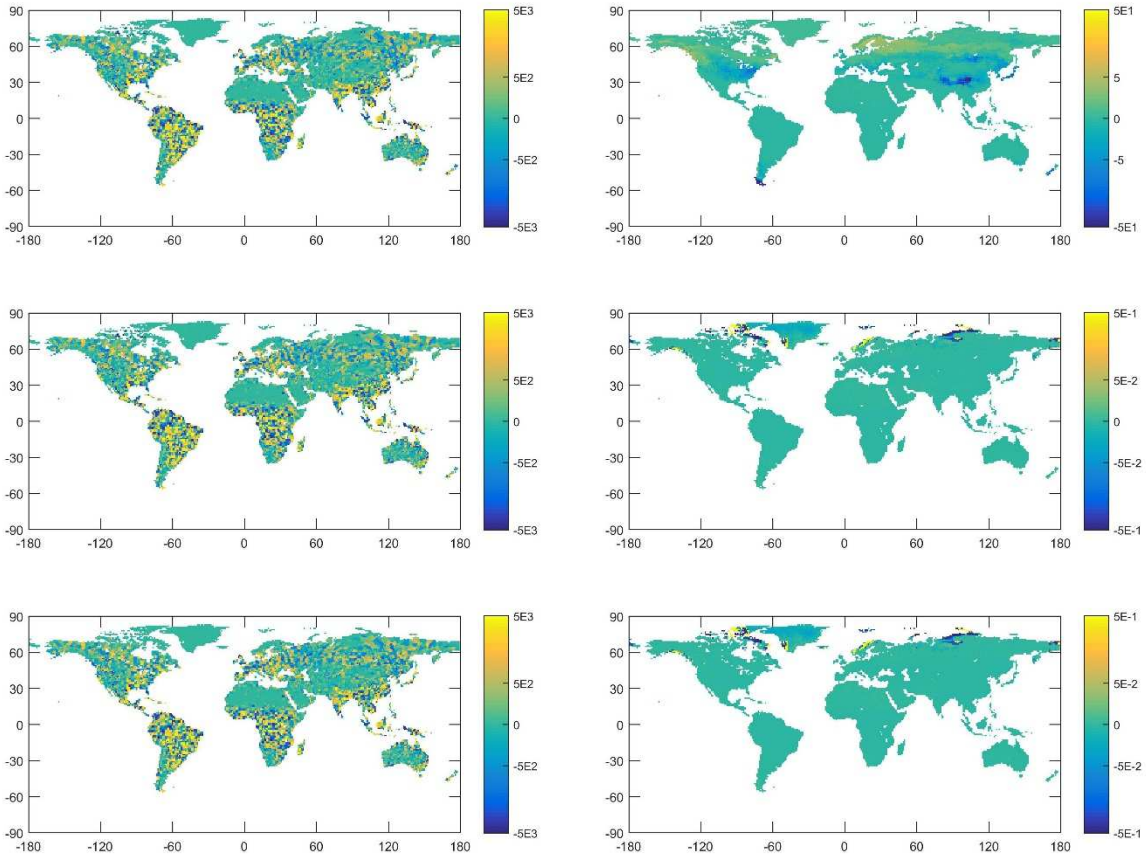

Figure 2. Annual accumulations of the energy balance (left) and water balance (right) metrics for CABLE using 5-years from a simulation using the surface-only configuration of CABLE as forced with GSWP2 meteorology. Note that the colour bars vary with the panel and have been scaled nonlinearly. The upper row shows the performance of the current CABLE trunk, middle row that of the REV_CORR package and the lower row that of the SSEB+REV_CORR package.

Figure 2 shows the energy and water conservation performance of CABLE in surface-only configuration when forced by GSWP2 meteorology for the current trunk, REV_CORR and SSEB+REV_CORR packaged. In this surface-only configuration the energy is conserved to within numerical precision (a value of 5×10^{-3} for this metric equates to energy closure to within 10^{-6} Wm^{-2} on a time step basis - on average). Clearly the REV_CORR and SSEB packages have not degraded CABLE's energy closure. In contrast the REV_CORR package clearly improves CABLE moisture conservation on an annual time scale (by approximately a factor of 100 – Fig 1 indicates that the same improvement in closure applies at the sub-diurnal time scale.) The remaining regions of concern are those with snow cover.

Figure 3 shows the same metrics of energy and water conservation with CABLE surface-only-run-as-coupled configuration. One component of the REV_CORR package was that it extended the set of correction terms to include corrections to the ground heat and net radiation. Consequently there is a significant improvement in energy balance with the REV_CORR package (back to numerical precision levels). In contrast, the REV_CORR package does not fully address issues with water conservation and there are still arid regions of the world with a non-trivial water imbalance. The SSEB package, likely the application of the physical limits to the soil evaporation, makes significant improvements (factor 100) in the remaining imbalance. The resulting performance is similar in magnitude/regional pattern to that of the surface-only simulations but there are a few 'rogue' grid cells away from snow cover.

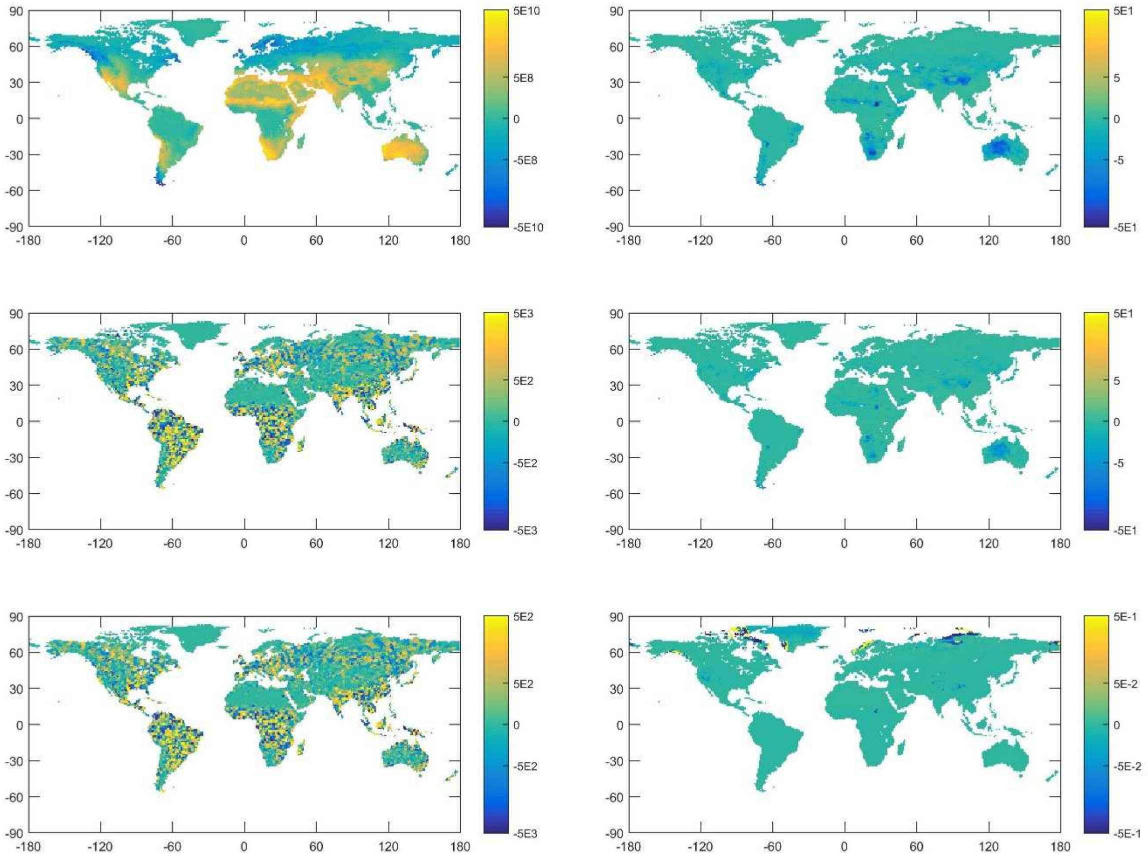

Figure 3 Annual accumulations of the energy balance (left) and water balance (right) metrics for CABLE using 5-years of a simulation using the surface-only-as-coupled configuration of CABLE. The forcing is the same GSWP2 meteorology as Figure 2. Note that the colour bars vary with the panel and have been scaled nonlinearly. The upper row shows the performance of the current CABLE trunk, middle row that of the REV_CORR package and the lower row that of the SSEB+REV_CORR package.

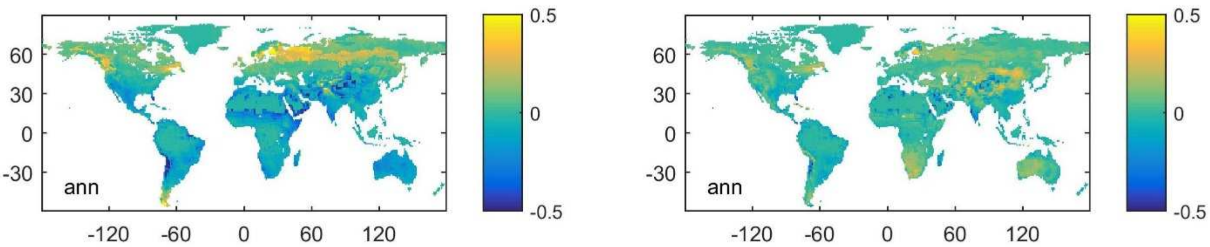

Figure 4 Difference in annually averaged screen level temperature between CABLE+REV_CORR+SSEB – CABLE trunk. Left panel – surface-only configuration; right panel surface-only-as-coupled configuration.

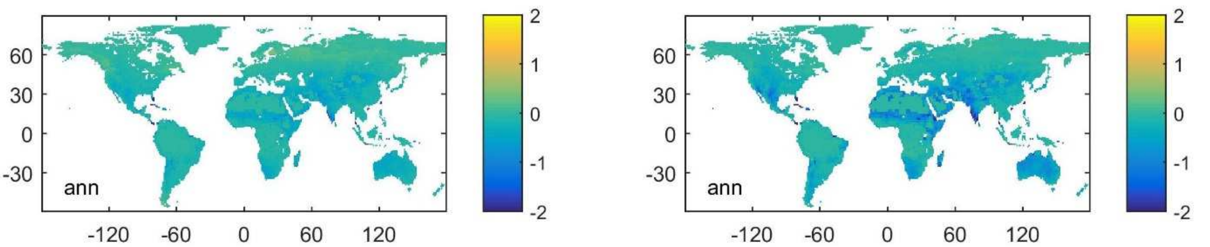

Figure 5 Difference in annually averaged daily minimum screen level temperature between CABLE+REV_CORR+SSEB – CABLE trunk. Left panel – surface-only configuration; right panel surface-only-as-coupled configuration.

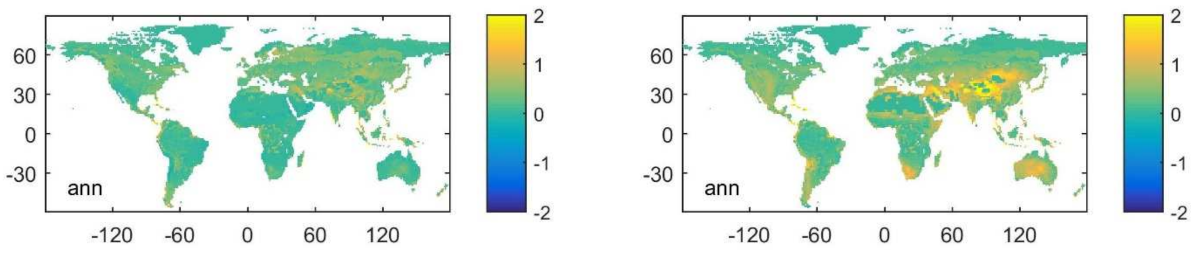

Figure 6 Difference in annually averaged daily maximum screen level temperature between CABLE+REV_CORR+SSEB and CABLE trunk. Left panel – surface-only configuration; right panel surface-only-as-coupled configuration.

Figures 4-6 show the impact of the REV_CORR+SSEB packages on the averaged, averaged daily minimum and averaged daily maximum screen-level temperatures, respectively, over the five years of the simulations assessed in Figs 2 and 3. The left panels show results from surface-only configuration and the right panels those from the surface-only-as-coupled configurations. These modest changes are primarily the result of the changes to the sensitivity terms introduced by the REV_CORR package (for the minimum temperatures) and the imposition of physical limits on the sensitivity and corrections in the SSEB package (for the maximum temperatures). The overall tendency is to increase the diurnal range (a diagnosed weakness of ACCESS1.4 – Lorenz et al. 2014) however these results also suggest that these changes would make the performance of ACCESS against observed northern America maximum temperatures worse.

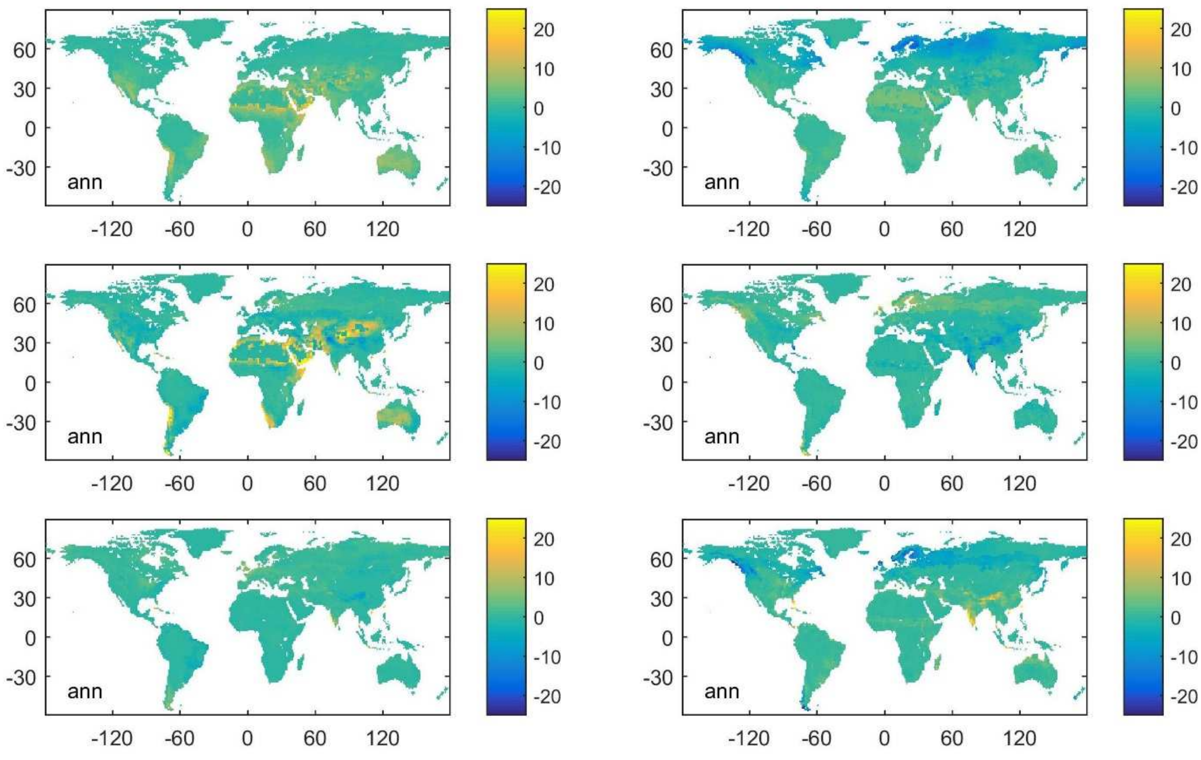

Figure 7 Difference in annually averaged components of the surface energy balance between CABLE+REV_CORR+SSEB and CABLE trunk. Left panel – surface-only simulations; right panel surface-only configured as if coupled. Upper panels – net radiation, middle panels – sensible heat, lower panels – latent heat.

Figure 7 shows the corresponding changes to the surface energy balance in the surface-only (left) and surface-only-as-coupled (right) configurations when both the REV_CORR and SSEB packages are applied. In surface-only configuration only minor changes are evident – with spatial patterns consistent with changes in the temperature. An important feature with the surface-only-as-coupled configuration are the decreases net radiation and latent heat (with corresponding change to ground heat) in some boreal regions. The latent heat in these regions has been diagnosed as being too high within ACCESS 1.4.