OCEANS AND ATMOSPHERE
www.csiro.au

The robust coupling of the land surface model CABLE into the Earth system model ACCESS

Project progress report

Ian N Harman

18 October 2016

for, and in partnership with, the ARC Centre of Excellence for Climate System Science

Citation

Harman IN (2016) The robust coupling of the land surface model CABLE into CSIRO's Earth system model ACCESS. CSIRO, Australia.

Important disclaimer

Foreword

This report documents the aims and initial progress of this project. The report is written in a descriptive, not overly technical manner, however a background knowledge of land surface modelling, Earth System modelling and numerical modelling, more generally, is assumed. Some detailed knowledge of the CSIRO land surface model CABLE and the Earth System model ACCESS is also assumed, however where critical this material is included for completeness.

Acknowledgments

This progress report has been written following discussions with collaborators within CSIRO Oceans and Atmosphere, the United Kingdom Meteorological Office and the Climate Change Research Centre of the University of New South Wales. The project is supported by the ARC Centre of Excellence for Climate System Science and the CSIRO Climate Science Centre.

Contents

Executive summary

The scientific and technical integrity of the coupling of the land surface model, CABLE, to the atmospheric model, UM, is critical for the current and longer-term use of the Australian Earth system model ACCESS. In light of some perceived performance issues, this project seeks to review the current implementation of the coupling. The aims of the project are to identify any issues within the current implementation, devise and implement solutions for those issues and to foreshadow the potential for issues in the future. This review considers, and will consider, the requirements of both CABLE and the UM primarily from scientific and research community perspectives, however consideration is and will be given to technical issues.

The project is in its formative stage, nevertheless, two substantive issues (concerning meteorological forcing and time-stepping of the energy balance) have been identified within the current implementation and are described. A solution has been proposed to address the meteorological forcing issue; this is currently being tested. The time-stepping issue, while less pressing, is more problematic to resolve as it involves multiple components of CABLE and has implications beyond ACCESS. Skeleton work plans to address these two issues within both the current, ACCESS 1.4, and imminent, ACCESS-CM2, versions of ACCESS are provided but require further development and consultation within the wider community prior to enactment. A series of potential issues for the future, given the understanding of the demands on, and likely development paths for CABLE and ACCESS, is presented however no prioritisation is given.

Through the initial stages of the project other issues within CABLE have also been identified, these are also noted for completeness in the Appendix.

1 Introduction

The CABLE land surface model (Kowalczyk et al. 2006, Wang et al. 2011) provides a focus point for Australian scientific research around land surface processes within environmental and climate sciences. Research activity using CABLE is conducted by both CSIRO researchers, the Bureau of Meteorology and the university community and includes efforts in the hydrology, meteorology, carbon cycle and climate domains (e.g. Best et al. 2015, De Kauwe et al. 2015, Haverd et al. 2016, Lu et al. 2013).

The Australian Earth System model ACCESS (Bi et al. 2015, Kowalcyzk et al. 2015) represents an Australian contribution to the global research effort in climate science (e.g. the CMIP5). ACCESS has been developed, in partnership with the Australian university community, the Australian Bureau of Meteorology and the UK Met Office, from existing models for the different components of the Earth system (Bi et al. 2015). Within ACCESS, CABLE is the preferred representation of the land surface (Kowalcyzk et al. 2015), though for some applications the UK Met Office land surface models, MOSES (Essery et al. 2001) or JULES (Best et al. 2011), are used in its place.

Despite the successful use of ACCESS within the CMIP5 program and detailed comparison of the role of CABLE within ACCESS (Kowalczyk et al. 2016) recent analyses in the climate extremes (Lorenz et al. 2014), hydrology (Dekker pers. com.) and carbon cycle (Ziehn pers. com.) domains suggest that underlying issues may exist in how CABLE and the remainder of ACCESS, most notably the UK Met Office's atmospheric Unified Model (UM), have been coupled together. It is not known whether any issues are technical (i.e. computer code and implementation related), scientific (e.g. mutually exclusive assumptions) or both.

Consequently a review of the CABLE and UM code components for ACCESS 1.4 has been initiated with a particular emphasis on the implementation of the coupling strategy. This effort relies on and builds upon the extensive work that was undertaken to couple CABLE within ACCESS in the first instance (Kowalczyk, Srbinovsky and Stevens). While ACCESS 1.4 is to be imminently superseded, ACCESS 1.4 represents the most recent benchmarked version of ACCESS, and the most recent version for which the community is confident that the majority of technical issues have been identified and rectified. Any issues remaining within ACCESS 1.4 are therefore most likely to be replicated within the newer versions of ACCESS. Furthermore, aside from some minor adjustments, solutions to scientific issues that function within ACCESS 1.4 should be readily transferable to later versions of ACCESS.

This report documents the results of this investigation so far, identifies some possible candidate issues and outlines method(s) to address these issues. As part of the wider code inspection other (non-coupling) issues have also been identified and are documented within the Appendix. This project and report concentrates on the scientific basis of the coupling. The technical aspects are a prerequisite for a functioning coupled model. In contrast invalid models can readily be constructed even if they are technically functional.

It should be noted that this project is proceeding in parallel with two other efforts concerning the coupling of CABLE within ACCESS.

1. The development and benchmarking of the next generation of the ACCESS model for use within the next round of global climate change research (CMIP6).
2. A collaborative effort between CSIRO and the UK Met Office to 'merge' the CABLE and JULES models into one numerical code structure with the aim of minimising future effort around coupling and to accommodate developments in either CABLE or the UM (the TILS project).

It is important that the results from this exercise are fed into both of these efforts as a matter of course. Code management, as practiced by both the CABLE and UM communities, will facilitate the transfer – assuming that issues can be identified and solutions to those issues can be determined.

2 CABLE within ACCESS

There are several background concerns regarding how models for the land surface and atmosphere should be coupled within an Earth System Model (ESM) that must be considered alongside the specifics of any particular methodology or algorithm. Many of these, such as conservation of key quantities (momentum, energy, water, carbon), are equally important when a land surface model (LSM) is run separately from the atmosphere (i.e. uncoupled or offline). Many others are important to any numerical modelling exercise; briefly these concerns are

- numerical stability of the model
- accuracy of the model
- performance of the model
- computational efficiency of the model.

Note that the performance of the model, as measured against independent data, is a separate, secondary issue to accuracy i.e. conservation.

The key difference when considering a coupled model is that algorithms that satisfy these methodological concerns when each component operates in isolation, or even in a particular combination of components, may not work for the fully coupled model. This difference may necessitate that different algorithms be adopted for different settings and the components' code adjusted to accommodate this.

When considering the specifics of coupling CABLE within ACCESS there are two additional, and somewhat contradictory, concerns. These are

- flexibility of development path
- consistency of science.

The first of these issues recognises that, as a community LSM with multiple applications, CABLE needs to be able to accommodate many different development paths. The numerical requirements of one application (in this case ACCESS) cannot be used to dictate the algorithms used or the model structure for CABLE. Instead the challenge is transformed into developing a coupling methodology that can accommodate all (foreseeable) development paths.

The second issue recognises that the same physical processes may need to be represented in more than one component of the coupled model. In such cases, identical representation of those processes is needed in both of the components involved, otherwise conservation issues are likely to arise. In reality this concern limits the sought after flexibility.

2.1 Contrasting JULES and CABLE

As LSM's MOSES/JULES and CABLE have many similarities. They both parameterise the processes that couple the land surface to the atmosphere and so quantify the fluxes of matter, momentum and energy (in all forms) at the land surface. Both models use similar representations for radiative transfer, bulk transfer representations of turbulent transfer, and diffusion/drainage of moisture and conduction of heat in the soil column. Both models can be coupled to carbon cycle models and phenology models. Both models represent land cover complexity through a tiling scheme.

However as MOSES/JULES was designed with the specific aim of operating in partnership with the UM atmospheric model (AM) there are certain differences in model structure and algorithm choice. The pertinent differences (there are many) are that when operated coupled to the UM

- JULES inherently linearizes its dependencies on air temperature and humidity; CABLE requires nonlinearity to be allowed.
- JULES has only one temperature for the surface for each tile and consequently has a simple structure for the fluxes of energy between the surface and atmosphere; CABLE has multiple temperatures for the surface for each tile and a complex network structure for the fluxes.
- The JULES energy balance is partitioned into two stages (an initial calculation of the energy balance and transfer coefficients, followed by an incremental update via the linearization); CABLE's energy balance requires full solution each time it is called.
- The JULES energy balance increment is formulated for consistency with, and solved as part of, the UM boundary-layer scheme; CABLE's energy balance is largely independent of any atmospheric model consideration.
- Soil moisture availability is ensured within JULES by applying a final adjustment in cases where limits are reached through the time step; CABLE applies limits to the moisture fluxes to ensure that soil moisture availability is maintained over the time step.

There is an implied assumption that the increment to the JULES energy balance is sufficiently small that the linearization is valid.

2.2 Adjustments to CABLE for use within ACCESS

It is potentially possible to rewrite CABLE to facilitate full similarity with JULES and hence direct interoperability between JULES and CABLE within the UM. Indeed many of the algorithmic challenges to doing so have been solved (Best pers. com., Ryder et al. 2016). However this is a substantial effort and would impose a rigid structure on CABLE and hence fail the aim of ensuring flexibility of development path.

Instead a number of technical and algorithmic changes have been made to both the UM-within-ACCESS and CABLE to permit their coupling (Kowalczyk et al. 2015). An aim of minimal changes was taken to facilitate continued flexibility of development but this posed a risk of fragility in the coupling. On the UM side the changes mainly involved the passing of information around the code, manipulating i/o and removing code whose purpose is directly duplicated by CABLE. Larger changes were made to CABLE to facilitate the coupling. Specifically

- Interface routines have been devised to initialize CABLE and to permit the use of CABLE from within the UM. This includes specific routines to transition necessary variables between the gridded UM data constructs to CABLE vector constructs.
- The input/output and parameter setting routines operate through the UM systems.
- Additional variables, primarily exchange coefficients, are now calculated by CABLE. These are for use within the UM and permits those parts of the UM that rely on surface information to function even though CABLE does not need those variables.
- CABLE is called multiple times per atmospheric timestep in different configurations:
    - First, the radiation and energy balance parts of CABLE are called (the explicit step).
    - Second, the energy balance is repeated and the soil parts are called (implicit step).

  This two stage approach replicates the split approach of JULES. The two steps are called from the equivalent locations in the UM as the two parts of JULES. Different atmospheric forcing is used on the second part call. Additional calls are also made to the radiation-albedo component of CABLE as required by the UM's radiation scheme.
- 'Correction' terms to the turbulent fluxes of sensible and latent heat are applied.

The correction terms are determined through a linearization of the soil energy balance evaluated after the soil column is updated on the second call. There is an implied assumption that the correction terms are sufficiently small that the linearization holds, though this condition is not formally quantified. The coupling of CABLE to the Mk3 and CCAM models also includes these correction terms – see Section 4.

2.3 Initial findings

On review (so far) there are two, possibly interconnected, major and two minor scientific issues in the coupling that need further investigation. Inspection of the code and documentation suggests

1. The atmospheric forcing used on the second call to CABLE is inappropriate and consequently the CABLE energy balance does not align with the meteorological forcing.

A detailed analysis of ACCESS simulations in tropical, dry conditions (Ziehn pers. com.) indicates

2. The 'correction' terms can be sufficiently large to negate the assumption that they are 'small', indeed they can dominate the energy balance.

The remainder of this report outlines these two issues in more detail. Finally,

3. CABLE adjusts the air temperature passed to it from the UM by an amount related to the vertical grid, surface roughness and dry adiabatic lapse rate (g/c_p). This adjustment is small (~0.2K) and approximately constant through a simulation (Ziehn pers. com.).

Clarification is required on the purpose and form of the adjustment and an explanatory comment is required within the code.

4. The precise location of the second call to CABLE may need to be moved forward to facilitate consistency with the intent of JULES for mixed land-sea or land-sea ice grid cells.

3 The atmospheric forcing of CABLE

The basic premise of coupling a LSM to an AM (e.g. CABLE to the UM within ACCESS) is that the AM provides meteorological forcing (radiation, air temperature, humidity and wind at/near to the surface) to the LSM, which then performs two related tasks. First the LSM returns surface state variables (e.g. temperature) and fluxes back to the AM. Second, the LSM evolves the land surface state consistently with those fluxes. The process representation within both LSM's and AM's typically take the form of partial differential equations for the conservation of key quantities (mass, momentum, energy). The solution of pde's have known restrictions around numerical stability, particularly when discretised in space and/or time, so care is required when designing algorithms for their solution.

3.1 Solving the boundary-layer and surface energy balance

3.1.1 The origin of the double call to CABLE

Within most AM's, including the UM, the representation of the action of turbulence within the boundary layer is as a diffusive process. In mathematical form the UM boundary layer seeks to solve

$$\frac{\partial T_L}{\partial t} = -\frac{\partial F_{TL}}{\partial z} + \left.\frac{\partial T_L}{\partial t}\right|_{NT} \tag{1}$$

where T_L is a moisture and density adjusted air temperature, subscripts *NT* denote known non-turbulent tendencies and F_{TL} is the upwards flux of T_L from below[1]. F_{TL} at the surface corresponds to H/c_p. F_{TL} is further partitioned into local and non-local contributions and the local contribution parameterized via a first-order gradient closure i.e.

$$F_{TL} = -K_h \frac{\partial T_L}{\partial z} + F_{TL}^{NL} \tag{2}$$

where K_h is an atmospheric state diffusivity. Combining (1) and (2) results in the diffusive equation for the evolution of T_L; corresponding equations linking water vapour, q_w, to evaporation, E, and the wind vector to the stress vector are also addressed.

The conventional methodology used to ensure numerical stability of such systems is to solve for the state variables *and* fluxes together at the end of the time step (e.g. Essery et al. 2001, Wood et al. 2007). Letting ΔT_L denote the change from the (initial) reference state, T_{L0} indicated by subscript 0, gives

$$\frac{\partial \Delta T_L}{\partial t} = \frac{\partial}{\partial z}\left[K_h\left(\frac{\partial T_{L0}}{\partial z} + \frac{\partial \Delta T_L}{\partial z}\right)\right] + \left.\frac{\partial T_L}{\partial t}\right|_{NT} \tag{3}$$

[1] Formally the UM uses a hybrid pressure-distance co-ordinate for the radial component of a spherical coordinate system which requires additional coefficients in these equations to ensure conservation. For simplicity the discussion is written using a simple vertical distance form.

Discretising in time and assuming that K_h is constant over the time step, Δt, then gives

$$\frac{\Delta T_L}{\Delta t} = \frac{\partial}{\partial z}\left[K_h\left(\frac{\partial T_{L0}}{\partial z} + \frac{\partial \Delta T_L}{\partial z}\right)\right] + \frac{\Delta T_{LNT}}{\Delta t} \tag{4}$$

The first term on the right of (4) represents the flux divergence of T_L at the start of the time step. The sum of the first two terms on the right of (4) represents the flux divergence of T_L at the end of the time step. The LSM coupled to the UM is required to provide the surface fluxes of sensible heat, latent heat and kinematic stress at the start of the time step (as these are needed to calculate K_h) and at the end of the time step to provide the lower boundary condition on (4). The split nature of JULES, and the double call to CABLE, is thus a direct consequence of the numerical algorithm for the UM's boundary layer scheme.

3.1.2 Incrementing CABLE atmospheric forcing

The meteorological forcing used to force CABLE at the two calls within a UM time step is aimed at establishing the surface fluxes at the beginning and end of the time step. The forcing differs between the two calls in two substantive ways

1. Precipitation information is included on the second call (i.e. at the end of the time step).
2. The air temperature and humidity are incremented by UM variables ΔT_L^1 and Δq_w^1 on the second call, i.e. $T_{L0} \rightarrow T_{L0} + \Delta T_L^1$, $q_{w0} \rightarrow q_{w0} + \Delta q_w^1$.

In principal this method is correct. Precipitation over the time step does not influence the fluxes at the start of the time step nor (to the same order of approximation) K_h (nor is it known at the time of the first call). Radiation within the UM is assumed constant over a time step. JULES does not incorporate changes to wind speed in its incremental step of the surface energy balance, so this is consistent (though possibly incorrect) with the UM expectation. This leaves only the influence of increments to the air temperature and humidity over the time step to be captured.

The UM provides increments ΔT_L^1 and Δq_w^1 to JULES for this purpose and these variables have been utilised by CABLE. However

the currently implemented increments ΔT_L^1 and Δq_w^1 are inappropriate for CABLE

The algorithmic origin of the increments currently applied follows the discretization of (4) over a number of layers within the atmospheric boundary layer, followed by a partial solution of the system of equations. For the lowest model layer of the atmosphere this gives (Eqn 66 of Essery et al. 2001)

$$\begin{aligned} \Delta T_L &= \Delta T_L^1 + \gamma_T \, \Delta t H / c_p \Delta z_1 \\ \Delta q_w &= \Delta q_w^1 + \gamma_q \, \Delta t E / \Delta z_1 \end{aligned} \tag{5}$$

where Δz_1 is the depth of the lowest atmospheric layer and γ_T and γ_q are order 1 parameters determined by the boundary layer state and matrix equation solution. In (5) the surface turbulent fluxes *H* and *E* take their value at the end of the time step, i.e. they are not yet known. ΔT_L^1 and Δq_w^1 are (known) transitional variables in the UM's boundary layer scheme. They incorporate the influence of the non-turbulent tendencies but only part of the influence of turbulence.

The corresponding equations in JULES, are

$$
\begin{aligned}
H &= H_0 + \Delta T_L^1\, \partial H/\partial T_L + \Delta q_w^1\, \partial H/\partial q_w \\
E &= E_0 + \Delta T_L^1\, \partial E/\partial T_L + \Delta q_w^1\, \partial E/\partial q_w
\end{aligned}
\tag{6}
$$

where the sensitivity terms are known and established at the start of the time step. (5) and (6) represent four equations in four unknowns; the solution is conducted in the second part of JULES. This framework also avoids numerical issues when applied to tiled surfaces (Best et al. 2004). Since ΔT_L^1 and Δq_w^1 do not include the influence of the surface fluxes they are incomplete, have no realisable physical interpretation and *should not be used* outside of the UM-JULES framework.

3.1.3 Magnitude of error

While the use of ΔT_L^1 and Δq_w^1 is in principal incorrect, it is problematic to quantify a likely magnitude of the associated error. This requires a statement of what is the correct approach to contrast (which is unknown). However we can estimate a likely error by considering the magnitude of the increment that is applied to the meteorological forcing after the energy balance calculations under typical conditions From (5) these are $\Delta t H/c_p \Delta z_1$ for temperature and $\Delta t E/\Delta z_1$ for humidity and hence depend not only on the meteorology at the time but also the model set up. However, these errors could easily amount to ~3K in temperature and ~1×10^{-3} kgkg^{-1} in forcing for a typical ACCESS set up (if $H = 170$Wm^{-2}, $\lambda E = 140$Wm^{-2}, $\Delta t = 1800$s, $\Delta z_1 = 100$m). Incorrect forcing, of course, results in incorrect fluxes. The errors are therefore significant but unlikely to result in obviously unphysical results.

Qualitatively, the error in forcing will trigger a series of feedback processes within the atmosphere and subsurface. Initially the error will result in larger turbulent fluxes than would be expected and, in particular excess evapotranspiration and a dry down of the soil column.

3.2 Work plan

As CABLE is not structured in a linearizable manner, equations equivalent to (6) are not readily established and direct substitution of CABLE for JULES is not possible. This implies that the double call of the entirety of CABLE model and the meteorological increments are required. To rectify the issue identified above alternate, more appropriate, meteorological forcing is needed to be passed from the UM to CABLE on the second (implicit) call within a time step.

3.2.1 Alternative forcing

Two alternate forms for the meteorological increments can be easily constructed. First are those that would be established if the rates of change for T_L and q_w were established from conditions at the start of the time step and then assumed to hold constant over the time step. This gives

$$
\begin{aligned}
\Delta T_L &= \frac{\Delta t}{\Delta z_1}\left(\frac{H_0}{c_p} - K_h^{(1.5)} \frac{T_{L0}^{(2)} - T_{L0}^{(1)}}{\Delta z_{1.5}}\right) + \Delta T_{LNT} \\
\Delta q_w &= \frac{\Delta t}{\Delta z_1}\left(E_0 - K_h^{(1.5)} \frac{q_{w0}^{(2)} - q_{w0}^{(1)}}{\Delta z_{1.5}}\right) + \Delta q_{wNT}
\end{aligned}
\tag{7}
$$

where the numbers in superscripts indicate the atmospheric level considered. These increments are readily established within the boundary-layer routines of the UM, though new code is required, and can be passed within the UM and the existing current coupling routines to CABLE with few technical issues.

Second are those increments that would be established if the surface fluxes established at the start of the time step are assumed to hold constant. Mathematically the meteorological increments are then given by (5) with $H = H_0$ and $E = E_0$, i.e. the values calculated by the first call to CABLE are used to directly generate ΔT_L and Δq_w. These increments are also readily established within the boundary-layer routines of the UM, some new code is also required.

Of the two alternative forms considered the second form is more closely aligned in intent with JULES and is likely more robust to future developments in the boundary-layer scheme of the UM. Other forms for the revised increments may be also possible.

3.2.2 Implementation and testing within ACCESS 1.4

An implementation methodology for the two alternative meteorological increments, i.e. (7) and (5) with the known first call surface fluxes, has been developed and applied to the boundary layer scheme of the UM. This implementation affects four UM subroutines and two CABLE subroutines within ACCESS 1.4. A logical flag has been introduced to permit switching between methods without the need to recompile the code.

Initial testing and comparisons is underway using short run AMIP simulations to check for realism and expected impacts. Preliminary results indicate that the second set of alternative meteorology increments is more robust. Once the short run simulations are successful the code will be shared with CSIRO, UNSW and other colleagues to facilitate longer simulations in both AMIP and coupled configurations. Standard testing around conservation will be undertaken at that point, alongside considerations as to whether the modifications to the coupling have fully, partially or negligibly addressed the hydrology and carbon cycle issues motivating this project.

Results of the investigation/simulations will be shared with the community and the code moved into the CABLE code repository through the existing protocols. A comparison of the two alternative increments against other possible revisions may be undertaken if deemed necessary. Publication of the results of the change will be necessary, however the appropriate means (journal article, technical note, internal memo) can only be determined once the magnitude of the changes are known.

3.2.3 Implementation and testing within ACCESS-CM2

The longer term development path for ACCESS is to transition to a) an updated version of the UM and b) have CABLE residing within the JULES framework. Both aspects of this plan will require minor modifications to the implementation of the revised meteorological increments.

In particular the newer versions of the UM utilise a boundary layer scheme (the predictor-corrector scheme of Wood et al. 2007) that now has three calls to JULES (but only two calls to the energy balance components of JULES). Accompanying the new algorithm is a revised vertical grid, a revised code structure and changes in variable naming. Together these changes imply that code for ACCESS1.4 is not directly transferable to ACCESS-CM2.

An outline of the necessary adjustments to the UM (for v10.x) for both alternative forms for the revised increments to the meteorology has been written and the development of specific code will proceed once the initial short run simulations for ACCESS1.4 above have been checked. As it is hoped that the coupling methodology used for ACCESS-CM2 will remain largely unchanged for some time and code is required within the UM, discussions will be required with the Met Office to ensure that a) coding standards are met as part of this implementation and b) the science of the coupling has been correctly adjusted to match the updated boundary layer scheme.

Any additional changes to the implementation methodology as needed to position CABLE within JULES (the TILS project) are expected to be minor and mostly technical (not scientific) in nature.

4 Correction terms

As noted in Section 3 the UM's boundary-layer scheme expects the LSM to provide surface fluxes of sensible and latent heat at the end of a time step, as boundary conditions on (4). The canopy component of CABLE is diagnostic so provides fluxes appropriate to the meteorological forcing provided – consequently, given the incremented meteorological forcing on the second call, CABLE provides canopy fluxes appropriate to the end of the time step. In contrast, the soil component of CABLE is prognostic. Consequently, 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.

The method used to address this issue within ACCESS 1.4 was to adopt the linearization approach of McGregor et al. (1993) – further details given next – and ensure that the fluxes communicated to the UM reflects change through the time step. A similar approach has been utilised within the coupling of CABLE to the CCAM model (Thatcher pers. com.). 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 to the overall fluxes and to 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 surface exchange scheme of simpler structure than CABLE.

Recent carbon cycle simulations (Ziehn pers. com.) demonstrate that the correction terms to the surface fluxes can be substantial (100 Wm^{-2} in magnitude or greater) and appear to grow in magnitude through a simulation. Increments of this size certainly violate the small magnitude criterion. Large values for the increments also suggest that the evolution of the soil temperature is inaccurate and lead to poor predictions of the soil state.

4.1 Evolving the soil column and surface energy balance

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)

$$\frac{\partial \rho_s c_s T_s}{\partial t} = -\frac{\partial G}{\partial z} = \frac{\partial}{\partial z}\left(\kappa_s \frac{\partial T_s}{\partial z}\right) \tag{8}$$

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 (8) are a zero heat flux at the base of the soil column and the energy balance at the soil surface i.e.

$$-\kappa_s \frac{\partial T_s}{\partial z} = G = (1 - \alpha_s)S + L^{\downarrow} - \varepsilon_s \sigma T_s^4 - \lambda E_s - H_s \qquad (9)$$

where the symbols take their usual meaning. In (9) 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 (8) and (9) within one solvable system for the temperature at the end of the time step.

The McGregor (1993) approach to address this issue is to linearize the energy balance (9) around the conditions at the start of the time step (indicated by subscript 0) to give

$$G = (1 - \alpha_s)S + L^{\downarrow} - \varepsilon_s \sigma T_{s0}^4 - \lambda E_{s0} - H_{s0} - \left(4\varepsilon_s \sigma T_{s0}^3 + \lambda \frac{\partial E_{s0}}{\partial T_s} + \frac{\partial H_{s0}}{\partial T_s}\right)\frac{\partial T_s}{\partial t} \qquad (10)$$

(8) and (10) can be combined in a linear system. CABLE discretises the combined equation, in time and into 6 soil layers, to form a single set of linear equations for the change in T_s over the time step.

The second and third terms in the bracket are the 'correction' terms that have been identified as potentially problematic since the linearization of (9) can only be valid if these terms are small.

The linearization (10) of the boundary condition for CABLE's soil temperature is applied for *both* offline and coupled simulations. However it is only when coupled to the UM that the turbulent fluxes from the soil are corrected prior to being passed to the diagnostic output, and passed back to the boundary layer as part of the boundary conditions on (4). The 'correction' terms are therefore a manifestation of the different *time stepping* approach imposed on CABLE's output by the UM's boundary layer scheme (i.e. the requirement to provide turbulent fluxes at the end of the time step). Nevertheless, any issues with formulation of (10) and the correction terms apply to all CABLE simulations but may not necessarily be apparent from the routine diagnostic output for offline simulations.

4.2 Issues with the current implementation

There are multiple, potential, issues in how the linearization and associated correction terms to the soil column boundary condition have been implemented within CABLE. Many of these apply to both offline and coupled simulations. These are

- The functional forms for the sensitivity terms ($\partial E_s/\partial T_s$ and $\partial H_s/\partial T_s$) are taken directly from McGregor et al. (1993) and do not reflect the increased complex structure of CABLE. Initial assessments indicate that the current forms are both incorrect and incomplete, resulting in an overly sensitive system.
- The soil flux E_{s0} is subject to physical limits, in particular from soil moisture limitations. The corrected flux $E_{s0} + \Delta T_s\, \partial E_s/\partial T_s$ is not. This inconsistency impacts both the corrected fluxes, and hence the evolution of the atmosphere in ACCESS simulations, but also the evolution of the soil temperature (through (10)).

- The functional form for E_s permits variation through a time step to both T_s and soil moisture (via CABLE variable [wetfac]). Variation with soil moisture couples this evolution to the transpiration from the uppermost soil layer. The two effects could be comparable in magnitude yet only one effect is captured within CABLE.
- A correction to E_s (as given by (10) and incorporated into CABLE's soil temperature equations) implies an increment to the water balance of the soil. In standard offline CABLE[2] this increment is not applied, either as a correction or through the boundary condition on soil moisture. This violates water conservation.
- CABLE permits two functional forms for E_s (the humidity deficit method and Penman-Monteith form) yet $\partial E_s/\partial T_s$ is only provided for one (the humidity deficit method). Hence the evolution of the soil temperature is incorrect if the PM option is used.
- The diagnostic output of offline CABLE[2] does not incorporate these corrected fluxes. In practice the energy balance is internally consistent but the soil temperature evolves in a manner inconsistent with the diagnostic output.

When coupled to the UM some additional issues arise,

- In contrast to the above: A direct increment is applied to the soil moisture of the uppermost soil level at the next time step to account for the correction to the soil evaporation. However CABLE's transpiration and soil evaporation calculations (on both calls to CABLE) occur prior to the increment being applied and so do not take the corrective increment into account.
- The diagnostic outputs for latent and sensible heat are incremented but the associated ground heat and longwave radiation fluxes are not incremented. This has consequences for energy conservation.
- Conservation in general is problematic. CABLE is mixing fluxes at a single point in time (E_s, H_s and the diagnostic canopy fluxes) with fluxes over a time step (which control the evolution of the soil moisture and temperature). It may be that the fluxes passed to the diagnostic outputs should be different to those passed back to the UM.
- The current implementation of CABLE within the UM utilises the incremented meteorological forcing to determine E_{s0} and H_{s0} and the two sensitivity terms. This is counter to the JULES implementation where the non-incremented meteorology is used to determine these quantities. This potential inconsistency in intent requires further investigation.

Finally, it should be noted that this issue around the form and implementation of the correction terms is substantively complicated by the method of implementation chosen or, perhaps, necessary within CABLE. The relevant code for the correction terms is distributed through no less than 6 substantive subroutines. This raises the risk of errors both at present and into the future.

[2] The recent Haverd-Dekker update to CABLE may address this issue.

4.3 Work plan

To address these issues requires careful consideration of the entirety of the energy balance and both soil temperature and soil moisture components of CABLE. Solutions are likely to require substantive code changes to these three components of CABLE and also to the diagnostic outputs. Few, if any, changes are expected at the interface between CABLE and the UM – so efforts can proceed within ACCESS 1.4 and be readily transferred to ACCESS-CM2 at a later date. The multiple options for the soil column algorithms and the potential for interaction between the correction terms, the snow scheme and melting/freezing within the soil column substantially complicate the task involved.

The two immediate priorities are: First, at a minimum, the functional form of the sensitivity terms should be corrected (a relatively trivial task). Second, the physical limits on E_s also need to be applied to the corrected flux – this may require fundamental changes in the soil temperature algorithm.

However, it may not be possible to address all the identified issues fully in an internally consistent manner, especially within both the offline and coupled versions of the CABLE. Consequently defensible approximations may need to found. Indeed, for simplicity, and to maintain closer comparability with the offline code, it may be appropriate to drop the correction terms from the coupling code entirely – though the consequences of this in terms of model performance, energy and water conservation and numerical stability would need to be carefully assessed. The potential need for widespread modifications to CABLE, some of which may not be backwards compatible, will necessitate that this work proceeds with consultation and through collaboration with the wider community.

To develop appropriate corrections to CABLE will require that both offline and coupled simulations be undertaken. Given the likelihood that this process will be an incremental approach the use of an appropriate testing environment is paramount. Single site simulations for the offline case, paired with FLUXNET site observations, are the obvious testing environment for the offline simulations – and are readily available. However it is not obvious that a corresponding, inexpensive, testing environment for coupled simulations exists. A single column version or limited domain version of ACCESS, including CABLE, with appropriate forcing, initial conditions and benchmarked output would represent such a testing environment – but may need to be developed/established prior to substantive effort to address the correction terms. Such a testing environment would represent a valuable asset to the CABLE community as a whole, and if such an environment exists should be widely promoted.

An important note: The carbon-cycle simulations that were used to demonstrate that the correction terms can be substantive also indicate that these correction terms are most problematic in meteorological conditions where the surface turbulent fluxes are large. These are also the conditions where the use of incorrect meteorological forcing, identified in Section 3, is expected to be most problematic. The two issues may be interacting and the issue with the correction terms, while present, may not be substantive. While some adjustments to CABLE are almost certainly needed, the detail and urgency of such adjustments will not be evident until after the work identified in Section 3 is completed.

5 Future considerations

Looking further ahead neither the UM nor CABLE are fixed, both continue to undergo technical and scientific advancement. The following provides a brief overview of prospective and known developments in both CABLE and the UM that may necessitate a review of the coupling strategy:

- Incorporation of increments to the wind vector, alongside those to air temperature and humidity, as part of the second call to CABLE energy balance algorithms when coupled to the UM.
- Facilitating data assimilation, including for land surface variables such as soil moisture, is critical for the uptake of CABLE by the Bureau of Meteorology [underway].
- A new dynamic core of the UM may have substantive implications for the technical aspects of the coupling (Lfric) [underway].
- The potential role for LiS to serve as a means of coupling CABLE to the UM.
- Prognostic phenology and population dynamics, including fire (POP) [underway].
- High resolution simulations (4km and higher) and the interface between the convection, boundary-layer and surface exchange schemes, including advances in the understanding of near-surface turbulence over high roughness surfaces [underway].
- Interface between CABLE and other parts of the surface exchange scheme within the UM (soil column tiling, sea ice, coastal, river routing, fire, dust and other Earth system components). Initial considerations indicate that the second call to CABLE is incorrectly positioned within ACCESS.
- The representation of complex landscapes, including urban.
- Extensions in the UM and CABLE to facilitate multi-layer surfaces.
- The representation of sub-grid scale topography within surface exchange schemes.
- Extensions to facilitate other chemical species, including fully coupled CO_2.

and, for completeness, issues 3 and 4 identified in Section 2.3 should be resolved.

6 Conclusions

An initial review of the current implementation of the coupling between the land surface and atmospheric components of ACCESS, CABLE and the UM respectively, has identified two issues that require further attention. In brief these two issues concern i) the meteorological information passed to CABLE from the UM and ii) the time stepping of CABLE when coupled to the UM which results in the need for 'corrections' to the soil sensible and latent heat fluxes. Priority should be/is being given to correcting the meteorological information passed to CABLE as this, relatively trivial to correct, issue acts as a preconditioner for all and any other issues. The time stepping of the soil energy balance is a more complex problem and has wider implications for the algorithmic formulation and structure of CABLE, separate from and in addition to how CABLE is coupled within ACCESS.

Given the preliminary nature of the work it is not known how these two issues have manifested in results using ACCESS to this point, nor whether these issues are important in resolving some perceived weaknesses of ACCESS within the hydrology and carbon cycle research domains.

It is evident, even from this early stage of the project, that two further issues will require dedicated attention to facilitate the aims of developing a robust, long-term coupling of CABLE and the UM. Firstly, the coupling of CABLE to the UM is slave to developments within the UM and consequently it is imperative that CABLE be positioned within the UK Met Office native LSM JULES. This will require collaboration with the UK Met Office to facilitate the joint running of both JULES and CABLE-within-JULES as the latter requires both removal and addition of code within the atmospheric component of the UM not just the interface. This code will therefore be subject to the coding and documentation standards of the UM. Second, efforts to investigate and develop solutions for technical and scientific issues concerning the coupling will be greatly facilitated by an inexpensive testing environment. The creation of such an environment is likely a key development step for the success of this project.

Finally, much of the necessary investigative work needed to identify and resolve issues in the technical coupling is severely hampered by a lack of documentation of both the science and technical details of the current methodology. Aside from general good practice, such documentation is needed to facilitate the understanding of the code and to help identify areas where the implementation has deviated from the intent (and hence pick up errors). The creation of such a document should be matter of priority.

Appendix A Other identified issues within CABLE

For completeness the following items have been identified as possible issues requiring rectification within CABLE. Many of these items relate to both coupled and offline modes of CABLE. Some of these items may have been addressed in the recent Haverd/Dekker update to CABLE. Some of these items may represent justifiable approximations, consistent with other aspects of CABLE. Some of these items may be incorrectly identified through a misunderstanding of the intent of the code on the part of the code reviewer. Code variable names under discussion are given in [ ].

- The calculation of the stomatal resistance and transpiration ([fwsoil] and [gs_coeff]), which act over the time step, is determined by conditions at the start of the time step, i.e. independently of the known (knowable) soil evaporation and precipitation.
- The 'medlyn' form of the stomatal conductance ([gs_coeff]) cannot be run with any other option for soil moisture control other than the standard form ([fwsoil]).
- Within the dry leaf section transpiration is limited to the integral over soil layers of soil moisture above 1.1 times wilting point. Yet the soil moisture factor [fwsoil] is set as simply the integral over soil layers of soil moisture above wilting point. No indication is given for the inconsistency.
- Within the dry leaf section transpiration can be limited by soil moisture, yet there is no feedback onto the associated photosynthesis and carbon fluxes.
- Within the remove_trans subroutine of the soil hydrology scheme, in the case of insufficient water for transpiration (i.e. dry soil layers and a high value of soil latent heat) unmet demand for transpiration is satisfied by passing the demand to the layer below. However this may not resolve the issue if the root fraction in the layer below is insufficient to extract available water or the entire soil column is dry. In this case there remains an unresolved demand for transpiration – and in effect an unquantified source of water.
- The soil latent heat flux has limits set by soil moisture and transpiration demand. From a physics perspective this is an odd prioritisation.
- The canopy wetness factor ([fwet]) takes different forms (different limits) when evaluated within subroutines wetLeaf and surf_wetness_factor.
- The location and triggering of the initialisation of the soil/snow column permits inadvertent re-initialisation part way through a simulation.
- The hydraulic redistribution code appears to allow moisture to move into a soil layer even if the soil is below wilting point ([accommodate]). This would appear to violate the biology of the soil-plant-moisture continuum.
- The screen temperature section of the code would fit better within a separate subroutine.
- A CABLE ticket (#121) has been initiated regarding moisture limitation affecting the CASA carbon allocation scheme ([btrans]).

Abbreviations and acronyms

ACCESS	Australian Community Climate and Earth System Simulator
AM	Atmospheric model
AMIP	Atmospheric Model Intercomparison Project (atmosphere-land only simulations)
CABLE	Community Atmosphere Biosphere Land Exchange model
ESM	Earth System model
JULES	The Joint UK Land Environment Simulator (successor to MOSES)
LSM	Land Surface Model
MOSES	The UK Met Office’s Surface Exchange Scheme model
UM	The UK Met Office’s Unified Model
UNSW	Climate Change Science Centre, University of New South Wales

References

Best MJ, Beljaars A, Polcher J and Viterbo P (2004) A proposed structure for coupling tiled surfaces with the planetary boundary layer. J Hydromet, 5:1271-1278

Best MJ, Pryor M, Clark DB, Rooney GG, Essery RLH, Menard CB, Edwards JM, Hendry MA, Porson A, Gedney N, Mercado LM, Sitch S, Blyth E, Boucher O, Cox PM, Grimmond CSB and Harding RJ (2011). The Joint UK Land Environment Simulator (JULES), model description Part 1: energy and water fluxes. Geosci Model Dev, 4:677-699. doi: 10.5194/gmd-4-677-2011

Best MJ, Abramowitz G, Johnson HR, Pitman AJ, Balsamo G, Boone A, Cuntz M, Decharme B, Dirmeyer PA, Dong J, Ek M, Guo Z, Haverd V, Van den Hurk BJJ, Nearing GS, Pak B, Peters-Lidard C, Santanello JA, Stevens L and Vuichard N (2015) The Plumbing of Land Surface Models: Benchmarking Model Performance. J Hydromet, 16:1425-1442. doi: 10.1175/JHM-D-14-0158.1

Bi DH, Dix M, Marsland SJ, O'Farrell S, Rashid HA, Uotila P, Hirst AC, Kowalczyk E, Golebiewski M, Sullivan A, Yan HL, Hannah N, Franklin C, Sun ZA, Vohralik P, Watterson I, Zhou XB, Fiedler R, Collier M, Ma YM, Noonan J, Stevens L, Uhe P, Zhu HY, Griffies SM, Hill R, Harris C and Puri K (2013) The ACCESS coupled model: description, control climate and evaluation. Austr Meteorol Oceano J, 63:41-64

Diamantakis M, Wood N and Davies T (2006) An improved implicit predictor-corrector scheme for boundary-layer vertical diffusion. Q J Royal Meteorol Soc, 132:959-978. doi: 10.1256/qj.05.37

De Kauwe MG, Kala J, Lin YS, Pitman AJ, Medlyn BE, Duursma RA, Abramowitz G, Wang YP and Miralles DG (2015) A test of an optimal stomatal conductance scheme within the CABLE land surface model. Geosci Model Dev, 8:431-452. doi: 10.5194/gmd-8-431-2015

Essery R, Best M and Cox P (2001) MOSES 2.2 Technical Documentation. Hadley Centre Technical Note 30. Hadley Centre, UK Met Office, August 2001.

Haverd V, Cuntz M, Nieradzik LP and Harman IN (2016) Improved representations of coupled soil–canopy processes in the CABLE land surface model (Subversion revision 3432). Geosci Model Dev, 9:3111–3122. doi: 10.5194/gmd-9-3111-2016

Kowalczyk EA, Wang YP, Law RM, Davies HL, McGregor JL and Abramowitz G (2006) The CSIRO Atmospheric Biosphere Land Exchange (CABLE) model for use in climate models and as an offline model. CSIRO Marine and Atmospheric Research paper 013, CSIRO, November 2006.

Kowalczyk EA, Stevens L, Law RM, Dix M, Wang YP, Harman IN, Haynes K, Srbinovsky J, Pak B and Ziehn T (2013) The land surface model component of ACCESS: description and impact on the simulated surface climatology. Austr Meteor Oceano J, 63:65-82

Kowalczyk EA, Stevens LE, Law RM, Harman IN, Dix M, Franklin CN and Wang YP (2016) The impact of changing the land surface scheme in ACCESS(v1.0/1.1) on the surface climatology. Geosci Model Dev, 9:2771–2791. doi: 10.5194/gmd-9-2771-2016

Lorenz R, Pitman AJ, Donat MG, Hirsch AL, Kala J, Kowalczyk EA and Srbinvosky J (2014) Representation of climate extreme indices in the ACESS1.3b coupled atmosphere-land surface model. Geosci Model Dev, 7:545-567. doi:10.5194/gmd-7-545-2014

Lu XJ, Wang YP, Ziehn T and Dai YJ (2013) An efficient method for global parameter sensitivity analysis and its applications to the Australian community land surface model (CABLE). Ag For Meteorol, 182:292-303. doi: 10.1016/j.agrformet.2013.04.003

McGregor JL, Gordon HB, Watterson IG, Dix MR and Rotstayn LD (1993) The CSIRO 9-level atmospheric general circulation model. CSIRO Atmospheric Research Technical Paper no 26.

Ryder J, Polcher J, Peylin P, Ottle C, Chen Y, van Gorsel E, Haverd V, McGrath MJ, Naudts K, Otto J, Valade A and Luyssaert S (2016) A multi-layer land surface energy budget model for implicit coupling with global atmospheric simulations. Geosci Model Dev, 9:223-245. doi: 10.5194/gmd-9-223-2016

Wang YP, Kowalczyk E, Leuning R, Abramowitz G, Raupach MR, Pak B, van Gorsel E and Luhar A (2011) Diagnosing errors in a land surface model (CABLE) in the time and frequency domains. J Geophys Res, 116:G01034. doi: 10.1029/2010JG001385

Wood N, Diamantakis M and Staniforth A (2007) A monotonically-damping second-order-accurate unconditionally-stable numerical scheme for diffusion. Q J Royal Meteorol Soc 133:1559-1573. doi: 10.1002/qj.116

CONTACT US

t 1300 363 400
+61 3 9545 2176
e csiroenquiries@csiro.au
w www.csiro.au

FOR FURTHER INFORMATION

Oceans and Atmosphere
Ian Harman
t +61 0 0000 0000
e ian.harman@csiro.au
w www.csiro.au/en/Research/OandA