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CABLE within ACCESS-CM2: Status update and prospects

Project progress report

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

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Foreword

This report documents the progress of this project and outlines potential areas on ongoing model development and research. 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 Australian community land surface model CABLE and the Earth System model ACCESS is also assumed.

Acknowledgments

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This progress report is based upon an ongoing, collaborative effort involving multiple individuals and institutions. The author wishes to particularly acknowledge the contribution of Jhan Srbinovsky and Martin Dix to that effort and to this report in particular.

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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 2016 a project was initiated to review, and if necessary correct, the current implementation of the coupling. While the scientific requirements of the CABLE, ACCESS and UM communities, in particular, were the primary focus of the review, consideration was given to technical issues.

As the development of the second generation of ACCESS has proceeded, multiple issues regarding the coupling between CABLE and the UM were identified. These can be classified into two areas: issues related to Earth System Science not covered by CABLE but which are required by ACCESS, and issues related to developments within the UM since the first generation of ACCESS. These are briefly documented here.

The long-term robustness of the ACCESS model relies on safeguarding the coupling, even if incorrect, within the UK Met Office's system. As the code base for the second generation of ACCESS is now confirmed, it is appropriate for tasks related to a formal merge between CABLE and the UK land model JULES proceeds. The final section of this report documents tasks identified in a 'scoping phase' for the merge and outlines both an endpoint and sequencing of tasks.

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 CSIRO researchers, the Bureau of Meteorology and the university community (with over 100 users globally) 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). CABLE operates as both a stand alone land surface model and as the land component within meteorological, climate system and Earth System models.

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.

ACCESS with CABLE was successfully used within the CMIP5 program and a detailed comparison of the role of CABLE within ACCESS has been reported on by Kowalczyk et al. (2016). Nevertheless analyses in both the hydrology (Dekker pers. com.) and carbon cycle (Ziehn pers. com.) domains suggested that underlying issues may exist in how CABLE and the remainder of ACCESS, most notably the atmospheric model were coupled together. Further, since that the establishment of ACCESS 1.3, developments within the UK Met Office atmospheric model, specifically ENDGAME dynamics, has necessitated re-development of the coupling between the two models – opening the possibility of further issues. No particular type of error was at that point precluded; potentially both technical (i.e. computer code and implementation related) and scientific (e.g. mutually exclusive assumptions) issues could have occurred.

A project to review and enhance if necessary the coupling between the CABLE and UM code in ACCESS 1.4 was initiated (see Harman 2016). Harman (2016) identified two errors within the technical implementation of the coupling of CABLE within ACCESS, as mediated on a time step by time step basis (i.e. the fast[1] components of land-atmosphere exchange). The implementation of resolutions to the identified problems were documented by Harman (2017), with more detail provided on CABLE community webpages.

[1] In contrast to slower components of land-atmosphere exchange for example pheonology or river routing.

To date this project proceeded in parallel with other efforts concerning the coupling of CABLE within ACCESS. In 2017-18 the two tasks have operated as a single effort and focussed on two areas

1. The development and benchmarking of the next generation of the ACCESS model, for use within the upcoming round of global climate change research (CMIP6).
2. The collaborative effort between CSIRO and the UK Met Office to 'merge' the CABLE and JULES models into one numerical code structure and repository. This TILS project has, as a primary objective, the aim of minimising future effort around coupling while permitting future developments in CABLE, JULES or the UM.

This report documents activities in these two areas with particular emphasis on development activities required for the development of the second generation of ACCESS, ACCESS-CM2. It should be noted that not all issues identified in earlier reports (e.g. Harman 2017) have been successfully incorporated into CABLE for use within ACCESS. This remains a task for the future.

Where given, Ticket numbers and branch names refer to the CABLE community's code management system unless specifically noted otherwise. Further information and documentation can be found on the CABLE webpages at https://trac.nci.org.au/trac/cable/wiki/CableUserGuide.

The current coupled model code base can be retrieved/inspected at https://code.metoffice.gov.uk/svn/jules/main/branches/dev/Share/vn10.6_CABLE/src/

The current code base for development work within the offline model can be retrieved/inspected at https://code.metoffice.gov.uk/svn/jules/main/branches/dev/dannyeisenberg/

Access to the code requires authorisation to be view the UK Met Office code repository.

2 Developments to the coupling of CABLE within ACCESS

The fundamental premise behind the coupling of CABLE to the UM is that CABLE provides the surface fluxes of momentum, energy, water and carbon given time-step mean information concerning the atmospheric forcing as provided by the UM. The UM handles the evolution of the atmospheric boundary-layer and CABLE handles the co-evolution of the land surface, including soil, vegetation, snow and ice processes. CABLE replaces many components of JULES within ACCESS, however the ACCESS co-opts the JULES science and code for the surface-atmosphere exchange over sea and sea-ice and the JULES river runoff scheme, TRIP.

As a reminder (see Harman 2016, 2017) the differences between CABLE-within-ACCESS and stand alone CABLE are that (non-exclusively)

- CABLE is called multiple[2] times for each time step when used within ACCESS.
- On the first (explicit) call the (prognostic) soil states are *not* updated and the (diagnostic) fluxes and surface states from CABLE are utilised primarily to determine the turbulent transfer properties within the UM's boundary-layer module.
- On subsequent (implicit) calls updated meteorology is used to recalculate the energy balance. The soil-snow states[3] are updated and correction terms to the surface energy and water balances are applied to provide surface fluxes at the *end of the time step.*
- The soil-snow states, and other variables with 'memory', are reset to their 'beginning of time step values' between the calls to CABLE within a time step.
- The revised surface turbulent fluxes are then used to evolve the boundary-layer and the revised surface radiative temperature provides a boundary condition for the UM radiation scheme.
- The total (surface and sub-surface) runoff is passed to the JULES river routing scheme, which provides a fresh water flux to the ocean at coastal grid cells.

Harman (2017) outlines a number of challenges and solutions to aspects of the fast components (i.e. time step by time step) of the coupling between CABLE and the UM. This section provides a very brief overview of recent developments to the coupling, as implemented during the development of ACCESS-CM2, operating in both the fast and slow components of ACCESS' biophysics.

[2] Different versions of the UM call the surface code differing numbers of times per time-step. Not all the surface code is called at each call.

[3] If CASA is enabled the carbon pools are also updated only on the second calls.

2.1 Moisture conservation in CABLE and ACCESS

Harman (2017) outlined several sources of energy and water imbalance within CABLE and ACCESS. With the exception of Ticket #152, these have been incorporated within ACCESS-CM2; this includes Ticket #170, identified during the preparation of the report. Two additional developments involving the slow components of the water cycle within ACCESS-CM2 have necessitated changes within CABLE.

2.1.1 Iceberg flux

ACCESS-CM2 invokes a modification of the Met Office/Hadley Centre scheme for ice berg calving. Williams et al. (2017) note that in the latest generation of the Hadley Centre Earth System models

> 'In GC3 snow amounts over land ice are passed through the coupler to (the) prognostic ice berg scheme, maintaining instantaneous water balance for both ice sheets and ocean. This is a simple approach to ensure that in the long term equilibrium the water content of ice sheets and ocean do not drift. This surface mass balance and the geographical distribution of calving will then be used to calibrate a constant iceberg calving for use in transient climate change simulations where it is expected that there will be a substantial build-up of snow which is not immediately discharged as icebergs.'

In contrast, within ACCESS 1.4, snow cover over land-ice was capped with additional water (snow) passed immediately to the ocean as runoff. To facilitate and calibrate an equivalent ice berg calving flux within ACCESS-CM2, snow amounts are now permitted to increase without limit over land ice (i.e. Antarctica and Greenland). The averaged mass increment, over time (20 years), is then used to evaluate an equivalent ice berg flux which is passed as a fresh water and energy flux to ACCESS' ocean model, MOM. No compensating removal of water from the snow pack is applied – this remains a task for future work. Only minor changes have been required in order to remove the cap, but exist within both the CABLE core and ACCESS initialisation routines. A specific note will be required in all ACCESS-CM2 publications to emphasise that the global water cycle will not balance, by amount equivalent to the applied (but *a priori* known and fixed) ice berg flux.

2.1.2 River routing, lakes and inland basins

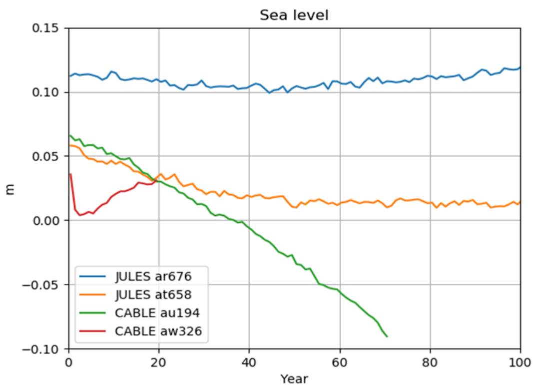
CABLE does not have a dedicated sub-model for the water balance of lakes and other inland water bodies. Within ACCESS-CM2 this includes the Caspian and Black seas as these are not covered by MOM. Lakes are represented within CABLE by permanently saturated bare soil surfaces, meaning evaporation is unrestricted. Saturation is maintained in a two (three) step process. First via a complicated, but conserving, shuffling of water within the soil column. Second, if the ground water module is active, by moving water to/from the aquifer. Third, by adding water to the surface soil layer to ensure saturation at the start of each time step. This last step represents an unconstrained source of water to the global water cycle.

ACCESS co-opts the JULES river routing model, TRIP. CABLE total runoff is passed to the river scheme in an exactly equivalent manner to JULES. However, within JULES any river flow that ends up entering inland water basins, i.e. not into the oceans, is passed back as an infiltration term to the soil moisture at the appropriate grid cell. CABLE does not facilitate this return link between the river routing scheme and land surface. River flow into inland water basins therefore represents an unconstrained sink of water to the simulated global water cycle within ACCESS.

In ACCESS-CM2 a global rescaling of the *river flow into oceans* is applied to ensure conservation of water and the total global ocean water content. The rescaling works as follows: Over each river time step, three terms are evaluated. First, the total water amount added to ensure saturation of all lakes, L_G. Second, the total water flux as river flow into inland water basins, I_G. Third, the total water flux as river flow into the oceans, R_G. Care is taken to ensure grid cell areas are included in the global integrals. The gridded river flow into the oceans, $R(\boldsymbol{x})$, is then rescaled to

$$R(\boldsymbol{x}) \rightarrow R(\boldsymbol{x}) \frac{R_G - L_G + I_G}{R_G} \quad (1)$$

This approach cannot be viewed as being physically based – it solely exists to ensure global conservation. In particular the temporal and spatial characteristics of evapotranspiration, runoff and river flow are different making interpretation complicated. The global rescaling is dominated by evaporation from the large lakes and inland seas (principally the Caspian and Black seas). The global distribution of these water bodies imposes a distinct diurnal cycle on the rescaling, and hence on the river flow into the oceans (at almost 10% of the annual cycle of global river flow). This is unphysically large and unrealistic. A specific note will be required in all ACCESS-CM2 publications concerning the rescaling, to note that the water flux into the oceans does not equal the water flux out of the river systems into the oceans and, consequently, to emphasise that the reported river flow into oceans should not analysed at too high a frequency.



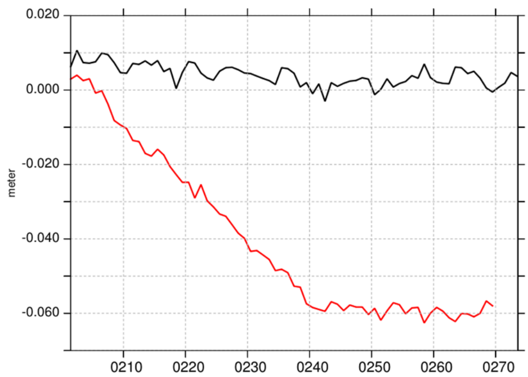


Figure 1: Sea level (a measure of total ocean water content) extracted from ACCESS-CM2 simulations prior (left) and post (right) implementation of the river rescaling. Left: blue and orange are selected ACCESS-JULES simulations; green an ACCESS-CABLE simulation. Red is an ACCESS-CABLE simulation utilising an early, incomplete implementation of the Ground Water module. Right: black is the continuation of the orange ACCESS-JULES simulation; red an ACCESS-CABLE simulation with river rescaling. At year 240 the iceberg flux was recalibrated. Note the change in vertical scale. Figures courtesy of M. Dix.

As the river routing scheme operates on a different time step to the UM and CABLE additional code has been necessary inside CABLE to facilitate the global integration over the river time steps.

2.2 Energy conservation in CABLE and ACCESS

Energy conservation issues in ACCESS arise in two domains. Firs inside CABLE, most often because of mismatched assumptions about how the land surface is forced over the time step. Second within the UM, most often because the requisite variable values have not been passed between land surface and atmosphere correctly. This second cause has two variants – i) cases where there is a genuine science error (impacting the tendencies of the model) and ii) where the diagnostic output is not correctly set (which does not impact the tendencies of the model). During the development of ACCESS-CM2 instances of all three kinds of energy imbalance have been identified and corrected. These included

- addressing a mismatch between the temperatures used in the radiative and turbulent parts of CABLE (Ticket #197 documents the resolution in ACCESS-CM2, Ticket #206 a longer-term full solution – see also Appendix B).
- adding to and revising the variables that need to be reset in between the three calls to CABLE per ACCESS time step.
- revising the evaluation of the surface radiative temperature in ACCESS to account for the correction terms and surface emissivities (Ticket #185 - though note Ticket #203)
- ensuring that the full albedo calculations are available to the UM radiation scheme and therefore the net shortwave seen by the UM corresponds to that by CABLE.
- ensuring that surface evapotranspiration was partitioned correctly into evaporation, sublimation and transpiration for diagnostics purposes.

The first of these issues also applied to, but was not evident within, stand alone CABLE.

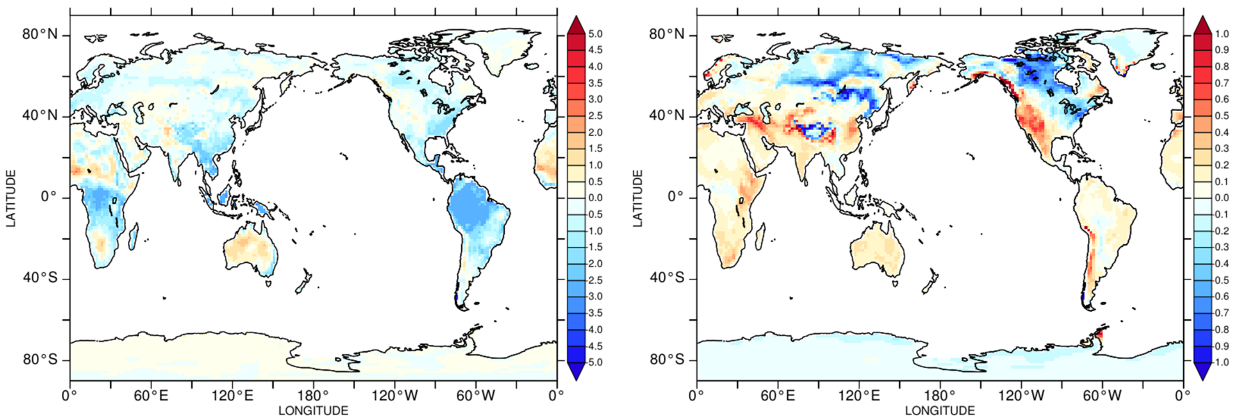


Figure 2: Surface energy imbalance in different generations of ACCESS-CM2 as reported by the UM diagnostics. Left: prior to implementation of energy conservation fixes (40 year average). Right: including the energy conservation fixes (25 year average). Note the change in colour scale. Figures courtesy of M. Dix.

Prior to these advances the land energy balance in ACCESS-CM2 was locally unbalanced by up to 5Wm^{-2} (Fig 2 left panel). This reflected both errors inside CABLE (i.e. CABLE was not closing the energy balance correctly) and at the interface. The efforts to date listed above have significantly improved the model performance with energy balance (both internal to CABLE and in ACCESS-CM2) locally at less than 0.2Wm^{-2} (Fig 2 right panel). Effort is ongoing to identify and address the causes of the remaining imbalances though it is likely that ACCESS-CM2 will retain some sources of energy imbalance. The major sources of error appear to be linked to snow covered regions and originate in the net radiation and snow melt components of the energy balance (Fig 3 – see also Harman 2017).

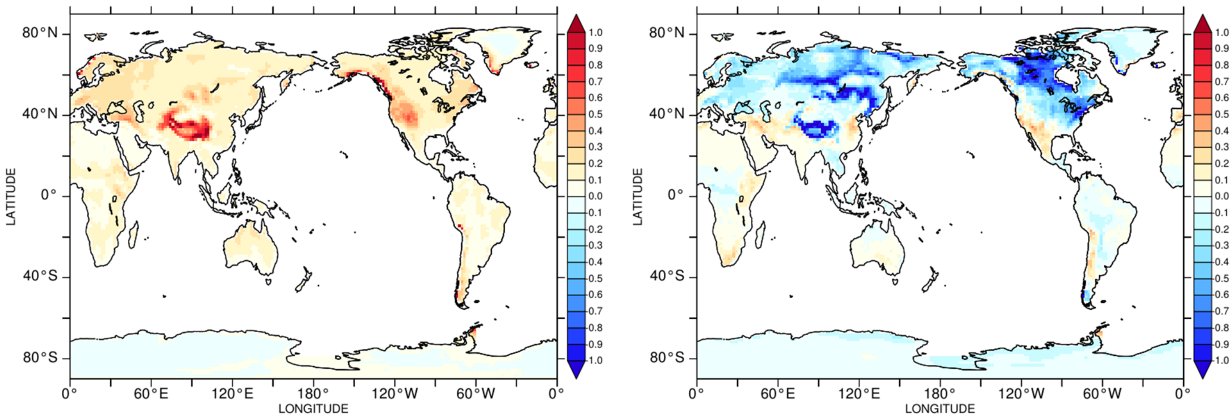


Figure 3: Components of the residual energy imbalance (with reference to the right panel of Figure 2). Left: net radiation as reported by the UM – net radiation as reported by CABLE. Right: Ground heat flux – snow melt flux. Both panels should be uniformly zero in the long-term mean. Figures courtesy of M. Dix.

2.3 Other developments

Three other developments in ACCESS-CM2 merit noting at this time. First, ACCESS-CM2 now utilises the PFT dependent root distributions in line with the stand alone model. This capability was not active in ACCESS 1.3.

Second, the UM utilises soil moisture within its routines for determining dust emissions. In the analysis of ACCESS1.3 it was noted (Vohralik pers. comm.) that the atmospheric loading of dust was substantially too small. This issue was traced to a conversion factor in the dust model linking soil moisture (as provided by CABLE) to soil moisture fraction (as used in the modelled dust source strength). This conversion factor is assumed equal to one, as appropriate for JULES, and discarded from the code. However, as CABLE has different soil layer depths, this assumption does not hold in ACCESS leading to a fourfold (approximately) too small a dust source strength for the same soil moisture content. The necessary solution has been (re)implemented in ACCESS-CM2 leading to satisfactory dust burdens and spatial distributions.

ACCESS-CM2 utilises the UKCA model for its atmospheric chemistry, both for the obligatory chemistry required by CMIP but also for research purposes involving more complete chemistry (e.g. ozone recovery). UKCA requires surface sources and/or surface exchange coefficients for a number of chemical species, with many of these enumerated within the code and being PFT dependent. UKCA is set up assuming a specific PFT ordering that is inappropriate for use with CABLE. Consequently, a small amount of code has been developed, but not extensively tested, to ensure that the appropriate sources and coefficients are used by UKCA within ACCESS, given the land map that CABLE uses. Some elements of this work – in particular emissions from tundra and hydrogen emissions – will need to be revisited by researchers with more domain expertise.

2.4 Configuration tests

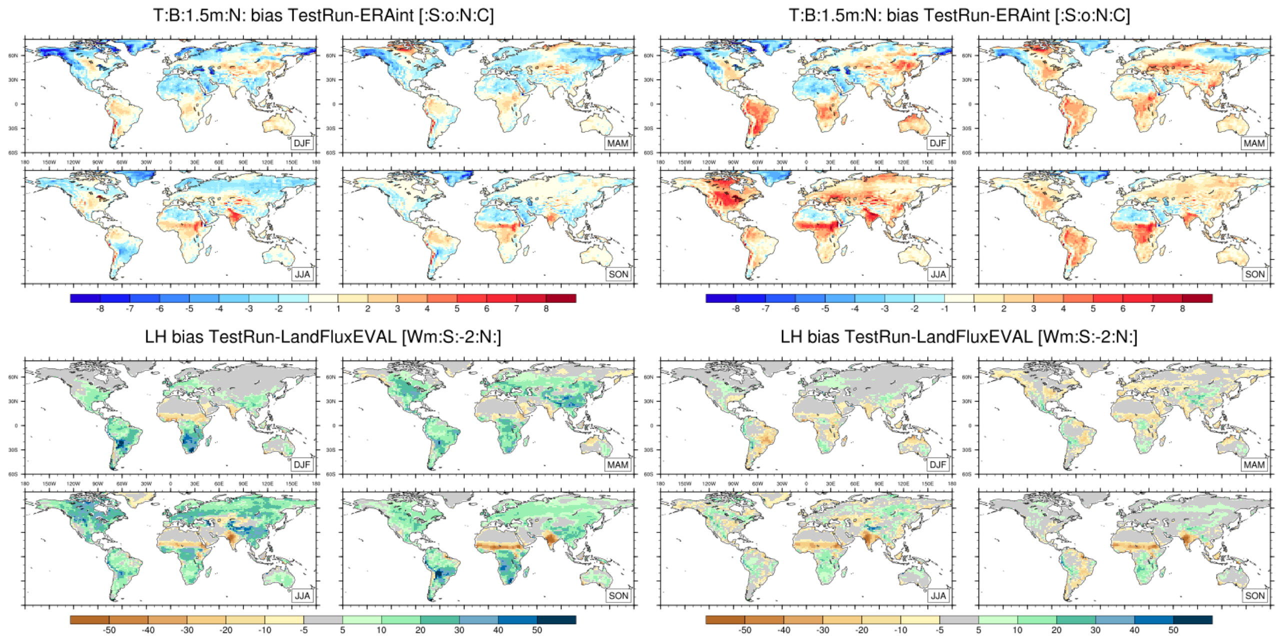


Figure 4: Comparison of performance for two candidate ACCESS-CM2 configurations. Left panels using a conservative configuration of CABLE (see Appendix C but with the gs_switch set to 'leuning' and root distributions as per ACCESS1.3); right panels as left but with the addition of the Or parameterisation for soil evaporation activated. Top panels surface air temperature biases from a 20 year AMIP simulation as compared to the ECMWF ERA-interim reanalysis. Bottom panels: latent heat flux biases from the same 20 year AMIP simulation as compared to the (independent) LandFlux product, as derived from FLUXNET observations and satellite retrievals. The AMIP simulations did not utilise the full atmospheric forcing, e.g. greenhouse gas concentrations, appropriate to the time period of the observational products. Figures courtesy of J. Srbinovsky and S. Wales.

CABLE has multiple science options available, most but not all of which can be utilised within ACCESS (see Appendix C). There is then a requirement to determine a preferred configuration of CABLE-within-ACCESS. It should be noted that a configuration does not equate to a particular point in the code development – as the same configuration should be possible from multiple points/branches over time. The determination of a preferred configuration involves a quantitative, multi-metric assessment against predetermined benchmarks alongside a more qualitative, quality of science evaluation. The qualitative component is needed; for example a well-calibrated but internally inconsistent and non-conserving configuration of CABLE could perform better than other configurations yet should be ignored. The quantitative assessment process would ideally be formalised and automatic – but is yet to be so.

Configuration assessment of CABLE-within-ACCESS has proceeded alongside the ongoing developments (Sections 2.1-2.3) and formed the basis for much of the analysis and identification of issues discussed. The assessment would ideally be re-evaluated using a finalised code base prior to a decision on configuration for ACCESS-CM2 being taken and CMIP6 runs commenced. However, time and resources are likely to prevent this. However, using the simulations undertaken to date, it is possible to identify some typical model behaviours that are common to all assessed configurations.

Figure 4 shows the long term performance of two CABLE configurations against two benchmarks, observation products for the climatological near-surface air temperature and surface latent heat flux. The left panels show the results using a conservative configuration which involves minimal changes form that used in ACCESS 1.3 (CMIP5) and ACCESS 1.4. Note that with this configuration the simulated latent heat flux is too high and the surface air temperature too low, compared to observations, particularly in the summer hemisphere. The annual cycle in temperature is suppressed, compared to observations in most regions.

In contrast the right panels show the performance where only one additional process has been included – the Or model for soil evaporation. The latent heat flux is far better simulated with only localised regions of remaining bias. However, this is compensated for by a significant warm biases over most land masses particularly during the summer months. The underlying cause of this behaviour appears to be an overestimate of the incoming radiation that reaches the surface within ACCESS (as seen by comparing net shortwave and net radiation against satellite reconstructions – Decker pers. comm.). Both terms involve both atmospheric and surface processes; CABLE cannot compensate for the bias in incoming radiation without evaporating too much (left panels) or heating up too much (right panel).

There are features common to both configurations which point to underlying model weaknesses: desert regions remain colder than in the reanalysis and there are distinct issues in both latent heat and temperature in the monsoon regions of India and Africa. While only preliminary, this analysis illustrates that decisions around model configuration and calibration will involve a trade-off between compensating biases and will be an ongoing cause for effort. It is also highly suggestive that configuration decisions and CABLE calibration will necessarily involve working within ACCESS. It cannot be assumed that model improvements in stand alone CABLE will improve ACCESS performance given the coupling between the land and atmosphere.

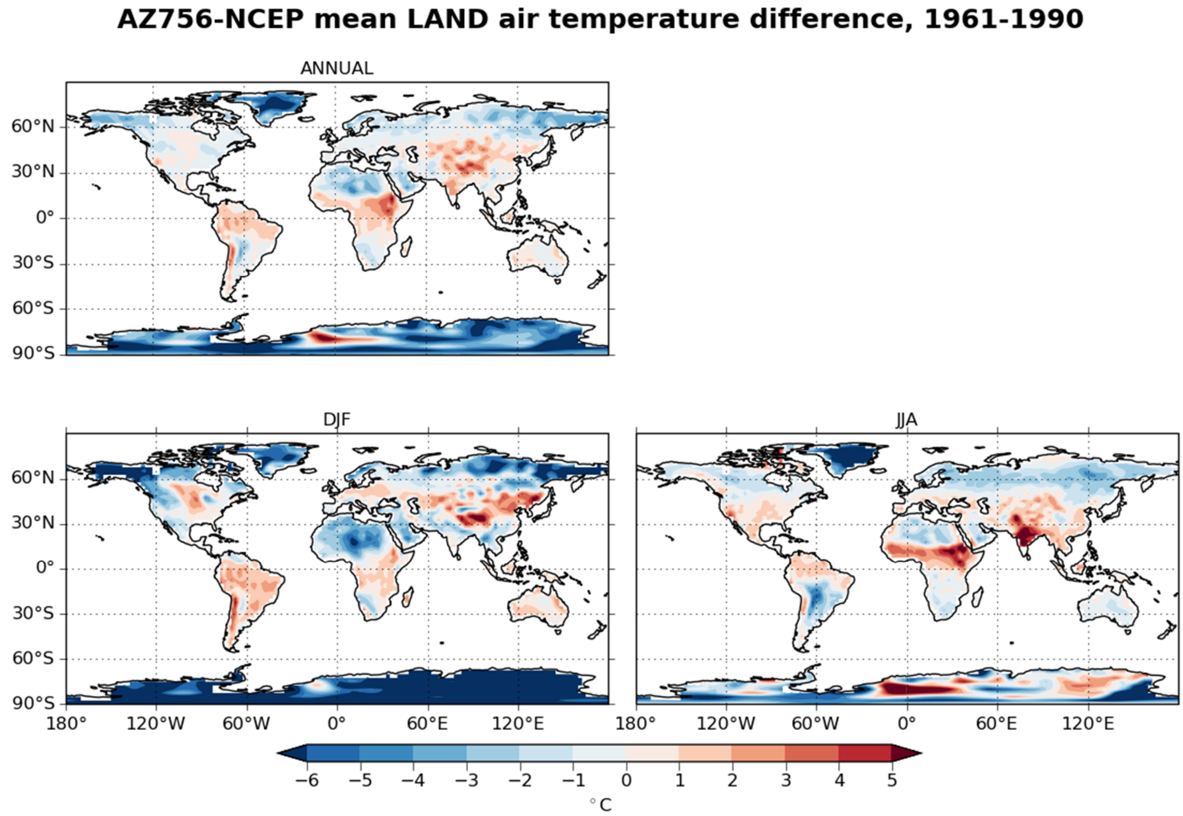


Figure 5: Annual and seasonal biases in surface air temperature, as compared to the NCEP re-analysis, established from a centennial AMIP simulation utilising the full set of CMIP6 atmospheric forcing. Figure courtesy of R. Bodman.

One particular feature common to all ACCESS-CM2 CABLE configurations assessed is a significant cold bias (compared to multiple reanalysis products and ACCESS-JULES simulations) over the permanent ice regions, particularly in the summer months. This cold bias is associated with low level wind bias (too high winds) over Antarctica (O'Farrell pers. comm.) and is also responsible for 70% of the difference in global mean air temperature between JULES and CABLE simulations. Given the Australian community's interest and expertise in Southern Ocean and Antarctic climate this model feature merits further exploration. There are two obvious candidates for this model feature – surface roughness and snow albedo over ice regions, both of which are treated as special cases by CABLE. Surface roughness over permanent ice is fixed at a very small value (1×10^{-7}m). The albedo for snow on permanent ice is fixed at 0.82 in both the visible and near-infrared region and does not depend on snow aging. Both attributes appear unphysical, in particular satellite observations (the GlobAlbedo product, Muller et al. 2011) indicate that the visible albedo over Antarctica is approximately 0.9 whereas as the near-infrared albedo is closer to 0.6. Unfortunately attempts to assess the role of these properties in setting the Antarctic climate have not resolved the issue and, instead, served to highlight further coding issues within CABLE's core (Ticket #205). It is hoped that a satisfactory calibration of the surface roughness and albedo parameters for Antarctica can be determined prior to use within CMIP6.

3 CABLE within JULES: JAC

JULES and CABLE both operate successfully as land surface exchange models when operating in stand alone (surface only) mode. To safeguard ACCESS to developments in the UM it is proposed to merge (a version of CABLE) into the JULES repository. This will enable automatic testing of ACCESS (at least in AMIP configuration) by both the UK and Australian communities. Co-locating CABLE within the JULES repository would also permit the testing (at least) of CABLE within the Bureau of Meteorology's operational weather forecasting systems. However, in order to couple properly to the UM and be merged within the JULES repository, some special considerations apply that CABLE does not automatically satisfy. These are that CABLE is complete – it provides at least all the information required by the UM – and that it satisfies the numerical stability requirements of the UM. CABLE does not consider all components of surface exchange; consequently within ACCESS, JULES representations of those processes are co-opted. The primary examples of this co-opting are for the surface exchange over sea and sea-ice, for dust and aerosol exchange with the surface, for chemistry at the surface and for river routing – and these need to managed within a shared code base.

Ensuring that CABLE satisfies the numerical stability requirements of the UM is more complicated. CABLE and JULES have inherently different structures, numerical architectures and time stepping methods. The UM and JULES have co-evolved over time and to function within ACCESS, CABLE-within-ACCESS has had to be configured largely in line with the JULES structure. This involves i) developing interface routines to enable the evaluation of subsections of CABLE science at appropriate points and ii) the adoption of the iterative, if inefficient, solution for the fast processes on the land (CABLE's energy balance is called three times per time step – see Section 2.1). JULES in contrast operates with a linearization (or linear tangent approximation) method that vastly simplifies the calculations and automatically satisfies the numerical stability requirements of the UM's boundary layer scheme (Diamantakis et al. 2006, Wood et al. 2007). The need for CABLE to co-opt JULES representations and the different numerical bases of the algorithms in the associated 'shared layer' of science represents one of the key challenges in establishing and maintaining CABLE-within-ACCESS. Numerical stability considerations within ACCESS remain largely a 'try-and-see' issue.

There are six key locations of intersection between CABLE and JULES within ACCESS.

1. Control level architecture - including memory allocations and input data reading (ancillaries, namelists boundary conditions and restart files).
2. From the radiation code (surf_couple_radiation)
3. From the boundary-layer scaling code (surf_couple_explicit)
4. From the boundary-layer solver code (surf_couple_implicit)
5. From the surface processes code (surf_couple_extra)
6. Diagnostic output structures.

In addition a surface process representation is also invoked within the dust and chemistry science. Since the control level and diagnostics are largely technical in nature these are left for consideration elsewhere.

Within JULES, the four science interfaces handle:

2. Evaluating surface albedo(s) as needed by the UM radiation scheme.
3. Providing an estimate of the surface energy balance and evaluating other surface exchange related exchange variables and fluxes for use within the UM boundary-layer.
4. Evaluating the surface energy balance at the end of time step, via a linearization method, as needed for the **co-evolution** of the surface energy balance and boundary-layer states (the fast processes in surface exchange)
5. Evaluating the evolution of the soil temperature and moisture, river flow and other ‘slow’ parts of the surface physics.

An equivalent posing of CABLE is difficult (if not impossible):

i. CABLE is a multi-tile, dual source model – at this time JULES (remembering that CABLE needs to retain the JULES sea and sea-ice representations) cannot handle dual sources in its linearization.
ii. The linearization/sensitivity terms for CABLE are not currently available. CABLE is inherently more nonlinear with respect to surface temperature, air temperature and vapour pressure deficit than JULES. These terms may not ever be possible to frame analytically.
iii. The energy balance within CABLE is fundamentally, and iteratively, interlinked with the evaluation of GPP (not just the stomatal response). For consistency any linearization should also involve and apply to the fast components of the carbon cycle. (JULES does not evaluate these associated terms).
iv. Unlike JULES (which applies an implicit correction to the energy balance with respect to air temperature and humidity), CABLE applies an implicit correction to the energy balance with respect to soil temperature, i.e. CABLE cannot evaluate the full energy balance unless the soil temperature is evolved.

The iterative approach adapted by CABLE-within-ACCESS attempts to provide the same information at the corresponding points in the evaluation but using different numerical approaches:

- in 2. CABLE determines the surface albedo.
- in 3. CABLE determines the energy balance and fast components of the carbon cycle on each land tile and for the grid box.
- in 3. CABLE co-opts the JULES representations for dust and aerosol exchange, and surface exchange over sea and sea-ice.
- in 4. CABLE determines the air temperature and humidity that would have been determined if the grid box energy balance had been maintained over the time step.
- in 4. CABLE re-evaluates the entire land surface energy balance and fast carbon cycle given the updated air temperature and humidity.

- in 4. CABLE retains the (implicit) sea and sea-ice calculations – and hence works over coastal grid cells.
- Section 4 gets called twice per time step due to the ENDGAME reset of the fast physics (double call to atmos_phys2) within the UM– this includes the estimation of the updated air temperature and humidity.
- in 4. CABLE also evolves the soil temperature and moisture. All soil and other prognostic variables are reset between the two calls to CABLE within Section 4.
- in 5. CABLE extracts soil temperature and moisture information and passes the requisite runoff information to JULES rivers' scheme.

As no alternate approach is currently available, the intent is to retain this 'iterative' approach into the future. However the co-opting of JULES science and algorithms has led to a complex mix of CABLE and JULES science in a shared layer sitting between the surf_couple interfaces and CABLE's core code. Addressing this shared layer, with the aims of providing numerical and scientific clarity and resilience to future changes in CABLE, JULES and the UM, is the primary challenge for the establishment of JAC – JULES-and-CABLE.

The proposed structure of JAC largely retains that of the current implementation in ACCESS-CM2. The four primary interfaces with the UM will remain as is. The principal difference with JAC is the removal (at least in name) of the shared layer. Immediately within each of the surf_couple routines will be a branch point between JULES and CABLE. No code that is not used by the respective model is to reside below the branch points. Everything below the branch points will be owned and maintained by CABLE or JULES (and not shared) – however

- complete subroutines can be called from either branch, provided
- no or minimal instances of 'if CABLE/JULES then' structures exist within each co-called subroutine, and
- any instances of 'if CABLE/JULES then' are self-contained within each co-called subroutine.

To facilitate the development of JAC it is proposed that JULES undergoes an internal technical restructure into sections dedicated to land, sea and sea-ice exchange, alongside sections for grid box averaging etc. This will facilitate the co-use of the dedicated sea and sea-ice subroutines within the CABLE branch of JAC. Further modularisation, e.g. of the dust and aerosol exchange, will be considered at a later date.

The general structure of JAC is already in place within the current implementation of CABLE within ACCESS. The overall partitioning exists within the surf_couple interface routines. The challenges reside in the layers below that and are substantially complicated by the current interweaving of JULES' land, sea, sea-ice etc. science. The primary tasks involved to develop JAC are

- develop the partitioned JULES
- ensure that CABLE-in-JAC satisfies JULES coding standards and can function in stand alone mode. This requires resolving data input requirements and CABLE's variable structures to the satisfaction of the UM, JULES and CABLE communities.
- clarify the content of the layer of code that sits in between the surf_couple* layer and CABLE core science and (re)develop the appropriate intermediate layers.
- modify the surf_couple interface routines, and possibly some UM routines, so that both CABLE and JULES can be called from the UM using identical calling points (and also from stand alone JULES). This requires resolving some data passing challenges to the satisfaction of the UM, JULES and CABLE communities and handling some forcing information is provided in stand alone mode.
- address any remaining technical challenges pertaining to the diagnostics.

An important consequence for the CABLE community is that this structure involves CABLE taking ownership of a set of code, and the associated science, that is currently not CABLE. It is possible that the volume of science that falls into this category (currently dust, aerosols, chemistry and rivers) could grow through time as ACCESS choses to co-opt further JULES modules. There is an immediate issue around ownership, management and maintenance of these components of CABLE-within-ACCESS that needs to be addressed. Importantly this is a science challenge, as well as a technical issue, as ensuring consistency of science in the face of changes to the UM and/or JULES will be a critical task.

A JULES Ticket #834[4] has been opened to collate discussions on the proposed structure. Further detail on the proposed structure is given in Appendix A.

[4] Permission to access the UK Met Office systems is needed.

4 Prerequisites, sequencing and potential challenges for JAC

While the development of JAC is in its formative stages, several more detailed, prerequisite tasks can already be identified. This will assist in formulating a more detailed work plan and the necessary sequencing of development.

4.1 Coding Standards

JULES and the UM operate with strictly enforced coding standards and code management practices, this includes documentation requirements. Some key challenges to satisfying these requirements are evident at this time and must be resolved as part of JAC:

- CABLE's general coding standards are insufficient. In the majority of cases this requires a simple revision of the existing science base, however, some specific instances (e.g. removing all hard wired indices) will need more substantive changes.
- CABLE employs dedicated data modules to pass information a) between its own sub-components and b) between disconnected parts of the UM and CABLE. It is not known whether these data modules will be acceptable. Alternate solutions are likely possible for b) but not for a).
- CABLE does not satisfy restart reproducibility (at least within ACCESS). Given the same initial conditions, ancillary information and processor decomposition it should not matter if CABLE is run for two time steps successively or separately with an intermediary 'restart'. Four (five) sources of lack of restart reproducibility that need to be tackled are
    - the use of JULES' albedos on the first time step. This is a consequence of when CABLE's ancillary information is read within ACCESS and should be resolvable as a consequence of efforts to get CABLE embedded within JULES in stand alone mode.
    - CABLE's albedo code requires the 4 band shortwave radiation to fully function, yet this is not available at the first call to the albedo code.
    - the correction term for latent heat requires to be passed from time step to time step but is not passed into the restart file (see Ticket #152)
    - initialisation of soil moisture in (at least) permanent ice regions is hard-wired not read in through a restart.
    - more general instances of variable initialisation, particularly for newer science modules and/or where corresponding UM-JULES variables do not exist.
- CABLE's documentation is insufficient. At least two areas of major work will be needed – i) documenting core CABLE to a sufficient level and ii) documenting the interface, and particularly any changes to the UM and JULES, to the full UM standards.

4.2 Revisiting existing science

The technical implementation within ACCESS of at least seven areas of existing science need to be reviewed. These form self-contained elements of effort:

- implementing a surface soil layer depth dependence for dust emissions into the UM code. This is in effect a hard-wired assumption within the UM that needs to be formally addressed as part of the merge.
- the implementation of CABLE-specific edits to the rivers scheme.
- the canopy water content (canopy%cansto) is the only state variable in CABLE that is time-stepped within the energy balance section of code. Correspondingly a different methodology is required to handle its evolution within ACCESS compared to all other surface state variables. This is unsatisfactory and can be addressed.
- ACCESS utilises both the JULES fully implicit-linearization method over sea and sea-ice grid cells and the CABLE iterative method for land grid cells. Harman (2017, Section 2.1.1) noted that the order of operations (JULES sea/sea-ice then CABLE land) was likely incorrect for coastal grid cells if the full intent of JULES sea and sea-ice is to be maintained. This remains the case in ACCESS-CM2.
- CABLE has co-opted JULES-UM code for the screen level temperature and humidity diagnostics and low level winds calculation. This involves retaining physics parameterizations that are likely inappropriate for CABLE and should be removed. However managing this science over land (inappropriate), sea and sea-ice (appropriate?) will result in further technical challenges.
- CABLE has co-opted JULES-UM code to evaluate the surface sources of dust and aerosols. This is despite the underlying assumptions around turbulence in the two land models being dissimilar. It appears to be possible to directly determine corresponding surface exchange coefficients from CABLE variables (in contrast to invoking the JULES equations).
- Within ACCESS, CABLE applies edits to the UKCA (chemistry) code specifically around surface sources/sinks of emissions. This is necessary because UKCA assumes a tile/PFT order that does not map directly onto CABLE.

The first two issues are prerequisites for JAC, the remaining four can be postponed as future development tasks.

4.3 Activating full CABLE

The CABLE biophysics core code includes components which have been successfully tested within ACCESS and others which have been tested but require further work (e.g. the Ground Water module) and those which have not yet been tested (e.g. SLI, hydraulic redistribution). Similarly the CABLE biogeochemistry core code involves code which have been successfully tested within ACCESS-ESM1.5 and other science which has not yet been tested in any ACCESS environment. Management of the partially and untested code during the merge to JAC requires careful consideration given that coding standards and UM-style testing applies to the full code base.

Ideally the variant of CABLE that works within JAC would permit the use of both the ground water module and SLI – i.e. all major biophysical modules available in stand alone CABLE. Some remaining challenges (initialisation and interface with the rivers scheme) exist for the ground water module. SLI has yet to be tested within ACCESS and its architecture (in particular the use of sub-time stepping) may present significant technical challenges. However, given time pressures on JAC (see LFRic below) it may be more appropriate to develop JAC against the existing CABLE version and then incorporate the other biophysics and Earth System components at a later date. Inactive code can be commented out as an interim, but not long-term, measure. The preference is that code that is inactive within ACCESS be included at compilation and managed via namelist controls.

Finally, it should be noted that representing the soil energy balance via a Penman-Monteith representation will require further effort to ensure that this functions correctly over snow surfaces and operates correctly with the within_canopy subroutine.

4.4 Prospective challenges

Through discussions with UK Met Office and JULES community researchers several prospective challenges to and opportunities for the ongoing success of JAC have been identified. These include

- LFRic – the new dynamic core for the UM – is likely to involve non-trivial technical challenges for all partnering components. This includes CABLE and the expectation is that partnering components will be revised accordingly. LFRic aims to be complete and operational within three years.
- It is proposed to extend/apply the UM's existing predictor-corrector algorithm for the boundary-layer onto the surface energy balance. CABLE's iterative time-stepping approach would need to be revisited if this were to eventuate and may require CABLE to written in a linear tangent form.
- JULES is undergoing development to permit dual sources and multi-layer canopies (as part of the Hydro-JULES project). This will likely lead to opportunities and challenges to ensure the JULES-CABLE interface remains consistent and functional.
- the UK Met Office is (re)developing an alternate atmospheric radiation scheme. One key advance will be the facilitation of spectrally resolved surface emissivities and more spectral resolution in the albedos, placing demands on JULES and CABLE.
- JULES permits tiled soils – but only in stand alone configuration. The UK Met Office intends to extend this capability to coupled simulations. This will facilitate an easier interface between CABLE and JULES soils schemes, for restarts and for the soil diagnostics.
- the JULES community wishes to separate out the restart for the land variables from that for the atmospheric variables. This technical development is still in the discussion phase but, if adopted, would represent a technical challenge for the CABLE community to address.

- as JAC develops and the number of active CABLE components included increases through time, it is likely that further dissimilarity between desired diagnostic outputs from JULES and CABLE will emerge. A potential solution would be the creation of a dedicated CABLE STASH section.
- JULES carries multiple science modules for processes that CABLE currently does not represent. With due caution around model structure, variable meaning etc. and the need to develop appropriate interfaces, JAC could facilitate the adoption of that science within CABLE. Potential topics available include lakes, urban, general phenology, crops, fire and irrigation.

4.5 Resourcing

There are both short- to mid-term and long-term resourcing implications for JAC. In the short- to mid-term there is a need to accelerate the development of JAC so that (a variant) CABLE resides on the UK Met Office systems and is protected during routine and non-routine (i.e. LFRic) development. There is a risk that if JAC is not developed quickly then other developments would necessitate a complete review and redesign of JAC. This task is largely technical in nature, although there are some science aspects involved, but shouldn't be underestimated especially given the status of Earth System science within ACCESS.

In the longer term there are a number of aspects to JAC that imply that additional, dedicated and ongoing resourcing will be required. First, JAC expands the code base and associated science that is nominally CABLE. This will require both science and technical expertise (i.e. individual staff) to continually manage the CABLE branch of JAC and the computational resourcing for ongoing testing. The CABLE community will not be able to 'set and forget' the coupling with the UM, especially since both the UM and JULES are themselves continually being developed – though with the establishment of JAC the degree of resourcing should be reduced. Second, resources will also be needed to support communication between the CABLE and JULES-UM communities. For example, when UM or JULES developments break the CABLE branch of JAC then it is likely that CABLE scientists and technicians will be needed to provide advice and possibly revise CABLE.

Finally, the current (initial) version on JAC retains the use of JULES science within the CABLE branch for those land surface processes that CABLE lacks. As noted earlier, while sensible as an interim measure, this approach risks internally inconsistent representations of the same, or related, processes being used, and is not robust to change. There is a need for ongoing research and development in the science of the coupling, including extensions of CABLE into those other land processes where JULES science is being used, not just the maintenance of the technical coupling. The need to develop 'in-house' representations of processes CABLE lacks, and to extend the general suite of processes considered within the CABLE branch of JAC, provides a natural rationale for additional resources (staff and computation). The specific science focus involved would need to reflect the community and stakeholder views of the priorities at the time.

5 Conclusions and future plans

Substantial progress has been accomplished in developing the CABLE land surface representation for use within ACCESS-CM2 and within the CMIP6 exercise. This has built upon the CABLE community's activities over multiple years alongside a more recent, dedicated effort to ensure the rigour of the coupling and resulting conservation of energy and water within ACCESS. New coupling points between CABLE and JULES and between CABLE and the UM have been developed for use within ACCESS-CM2 – concerning river flow, and the surface sources of chemistry. Existing coupling points have been re-implemented (dust) and/or revised – concerning ice berg calving and the many instances resulting from the advance to ENDGAME dynamics by the UM. Furthermore some errors within CABLE, which only manifest in a coupled modelling environment, have been identified and resolved. The developments have resulted in a climate system model with substantively better energy and water conservation than previously – though many model performance issues remain to be addressed in the future. Selective model results have been included as an illustration only; the choice of a specific CABLE configuration for use within CMIP6 is a matter for the CABLE and ACCESS communities to determine.

CABLE is a community model, and effort has been taken to ensure that as many science options as possible are available for use within ACCESS. However, there have been occasions where this has not been possible within the time frame available. This includes cases where multiple development lines have occurred simultaneously which operate on the same, or connected, parts of the CABLE code. Care is required when merging these development lines to ensure technical and scientific consistency. There are also cases, e.g. the SLI soil model and the Ground Water model, where the functionality exists in a stand-alone configuration, but the necessary development and testing within ACCESS has yet to be finished.

The immediate future focus for this project will be strongly contingent on the community's needs and plans for ACCESS-CM2, participation in CMIP6 and the aim to safeguard the effort to date by formally merging the CABLE (including coupling) and JULES code bases. An initial structure and sequencing of the tasks involved to develop JAC is presented. This will require continued collaboration with and across the broader CABLE community.

Abbreviations and acronyms

ACCESS	Australian Community Climate and Earth System Simulator
ACCESS 1.3	ACCESS as used within the CMIP5 Project
ACCESS-ESM	ACCESS variant with carbon cycle enabled
ACCESS-CM2	ACCESS variant to be used within CMIP6 – physical climate science only
AM	Atmospheric model
AMIP	Atmospheric Model Intercomparison Project (atmosphere-land only simulations)
CABLE	Community Atmosphere Biosphere Land Exchange model
CMIP5	the fifth iteration of the Coupled Model Intercomparison Project
CMIP6	the sixth iteration of the Coupled Model Intercomparison Project
ESM	Earth System model
JAC	JULES and CABLE – a proposed combination of the two land surface models
JULES	The Joint UK Land Environment Simulator (successor to MOSES)
LFRic	The in-development updated dynamic core of the UM.
LSM	Land Surface Model
MOSES	The UK Met Office's Surface Exchange Scheme model
PFT	Plant functional type
TRIFFID	The UK terrestrial carbon cycle and dynamic vegetation model.
UM	The UK Met Office's atmospheric model, the Unified Model
UNSW	Climate Change Science Centre, University of New South Wales

Appendix A

The following outlines in more detail a proposed structure for JAC, providing the breakdown between JULES and CABLE interface code and highlighting which elements will be co-opted. A more extensive knowledge of both JULES and CABLE is assumed.

surf_couple_radiation

CABLE and JULES are required to provide the 4-band albedo over sea, sea-ice and for each land tiles. After some development a simple CASE statement will facilitate the branch point.

```
Additional CABLE related USE statements pertaining to existing UM_JULES modules

first_call = .TRUE.
select CASE(lsm_id)
        CASE('jules')
                ftsa
                ...                 [soot and zenith angle code]
                tile_albedo
        CASE('cable')
                ftsa
                if (first_call) then
                        ...
                        tile_albedo
                        first_call = .FALSE.
                else
                        dummy initialise surf_sw_down_cable
                        initialise albobs_sc_ij
                        cable_rad_main
                end if
        CASE DEFAULT
```

The longer-term aim is to completely remove the (first_call) section in the CABLE branch as this will facilitate restart reproducibility. Minor developments are needed within CABLE's core code and the ancillary reading section before that can happen.

surf_couple_explicit

JULES and CABLE are tasked to provide an estimate of the surface fluxes at the start of the time step and evaluate other boundary-layer and surface exchange parameters for use later. The science layers below the control layer however are complicated and require further consideration. It is not possible to be entirely definitive prior to that exercise and the associated technical restructure of JULES, the structure will be close to

Additional CABLE related USE statements pertaining to existing UM_JULES modules

```
select CASE(lsm_id)
        CASE('jules')
                explicit_jules_land
                explicit_jules_seaseaice
                explicit_jules_finalise
                sf_aero
        CASE('cable')
                explicit_cable_land
                explicit_jules_seaseaice
                explicit_jules_finalise          [or possibly explicit_cable_finalise]
                sf_aero
        CASE DEFAULT
```

The routine explicit_cable_land covers the land based science in JULES routines sf_expl and sf_exch and includes science related to dust and aerosol exchange. The broad structure of that routine is likely to be

```
tile_pts                        [shared]
windshear                       [shared: new, maybe land specific or in surf_couple_explicit]
cable initialisations
cable_explicit_main
sf_rib + other existing boundary-layer scaling code [shared]
aerosol exchange                [possibly shared]
```

surf_couple_implicit

JULES and CABLE are tasked to provide the surface fluxes at the end of the time step. This routine has to function with the predictor-corrector algorithm for the UM boundary-layer. The structure will be close to

Additional CABLE related USE statements pertaining to existing UM_JULES modules

```
select CASE(lsm_id)
        CASE('jules')
                ice_fraction code
                im_sf_pt2
                implicit_jules_land
                imlicit_jules_seaseaice
                implicit_jules_finalise   (may not be needed)
                screen_tq*
                winds (corrector step)
        CASE('cable')
                ice_fraction code         [copied]
                im_sf_pt2_cable
                implicit_cable_land
                        cable_implicit_main
                        land diagnostics
                implicit_jules_seaseaice                [shared]
                implicit_jules_finalise          (or possibly implicit_cable_finalise)
                screen_tq_cable*
                winds (corrector step)           [shared]
        CASE DEFAULT
```

surf_couple_extra

This is possibly the most complicated interface routine – but not the most problematic from a science perspective. The complication arises because the interface handles many different science modules and diagnostics routines, only some of which CABLE wishes to co-opt. The JAC guideline is to include those routines that each model could wish to use, in contrast to managing all routines via the namelists. The structure is likely to be

```
Additional CABLE related USE statements pertaining to existing UM_JULES modules
Additional working variable – gridded water imbalance = 0.

select CASE(lsm_id)
        CASE('jules')
                ...
                revised rivers (takes in gridded water imbalance)
                ...
        CASE('cable')
                hydrol_cable            [layer may not be needed]
                        hydrology initialisations
                        cable_hyd_main          [includes setting gridded water imbalance]
                        soilmc                  [shared]
                revised rivers
                diagnostics_hyd                         [shared?]
                diagnostics_riv                         [shared]
                diagnostics_veg                         [shared?]
                diagnostics_cablecasa
        CASE DEFAULT
```

CABLE wishes to co-opt the JULES rivers scheme when operating within ACCESS (not necessarily in stand alone configuration). However, as per Section 2, a small modification is required to ensure global conservation of water. At this time the proposal is to implement this modification in a manner to be common to both JULES and CABLE (without changing JULES results) thereby facilitating the same, but revised, rivers code. However it may turn out more appropriate to create a dedicated CABLE_rivers routine given that the TRIP rivers model used may cease to be supported by the UK Met Office and JULES.

The diagnostics_cablecasa routine does not exist currently but may be necessary to handle CABLE specific diagnostic outputs within the shared code.

Detangling TRIFFID code from JULES is a potential obstacle to JAC as TRIFFID code appears in multiple locations, is often unmarked as such and variables are occasionally uninitialised.

Appendix B

Both the Raupach et al. (1997) and Wang and Leuning (1998) components of CABLE utilise bulk aerodynamic representations for the sensible heat flux (see Kowalcyzk et al. 2006) i.e.

$$H \propto \rho c_p \, \delta T \qquad (B1)$$

where the symbols take their usual meanings. The proportionality constant depends on canopy architecture, reference heights for the two temperatures involved in establishing the temperature increment, turbulence properties and diabatic stability. A chain of such relationships is established between the soil, canopy and air temperatures within CABLE. In some parts of CABLE's algorithms (e.g. soil energy balance) equation (B1) is used to evaluate *H* given other information; in others (e.g. the within canopy routine) it is used to evaluate the temperature given *H*.

In contrast JULES represents the sensible heat flux as

$$H \propto \rho c_p \left(T_s - T_a(z_r) - \frac{g}{c_p}[z_r + z_{0m} - z_{0h}] \right) \qquad (B2)$$

where T_s is the surface (skin) temperature, T_a the air temperature at reference height z_r and z_{0m} and z_{0h} are the roughness lengths for momentum and heat respectively. Given the other structural differences between JULES and CABLE, Equation (B2) is equivalent to Equation (B1) except that the sensible heat flux is now set by differences in potential temperature (not temperature). The JULES representation is more theoretically defensible and the difference possibly quantitatively importance over tall canopies. However, other components of CABLE (in particular the vapour pressure deficit and radiative exchange calculations) require to be determined by temperature.

ACCESS 1.3 attempted to resolve this issue by forcing the radiation and turbulent parts of CABLE with different (but related) air temperatures (met%tk and met%tvrad). This implementation was unfortunate (Ticket #197) in two ways

1. The usage of %Tk and %Tvrad was incomplete leading to a lack of energy closure within CABLE-in-ACCESS.
2. The incorrect, now potential, temperature %Tk propagated into parts of the energy balance where the temperature should have be used.

In effect CABLE-in-ACCESS operated with an undiagnosed energy source/sink of approximate magnitude 2Wm^{-2} and as if the atmosphere was 0.2K warmer than it actually was.

Within ACCESS-CM2 has this implementation has been resolved (i.e. energy closure is restored – Ticket #197) but also removed (%Tk = %Tvrad). CABLE-within-ACCESS thus mirrors as closely as possible CABLE in stand alone configuration. The underlying scientific error however remains unresolved.

Ticket #206 investigates the unresolved science in more detail and proposes a three-step methodology to recognise the role of potential temperature in driving the sensible heat flux, while retaining the general structure of CABLE. This would apply to CABLE in all configurations – stand alone and coupled. The steps involved in the implementation are

a. to adjust the equation for the soil sensible heat flux due to the lapse-rate (g/c_p) wherever this occurs (2 instances but complicated by litter and pore-scale resistances if those science options are active).
b. to adjust the C_H term (i.e. 1 equation) in the within_canopy algorithm.
c. to remove met%Tvrad variable entirely from CABLE.

The sensitivity terms in the soil energy balance and the associated correction terms to the energy balance are not impacted by this change. Further details and a full derivation are given in the documentation of Ticket #206.

In the absence of trial simulations it is difficult to assess the magnitude and character of any impact. In all cases the immediate, direct impact will be to require the land surface to be warmer (by approximately $(g/c_p)z_r$ i.e. 0.2K given a 20m reference level height) to provide the same potential temperature difference for the same sensible heat flux and atmospheric temperature. Indirect effects will also emerge. Firstly via the repartitioning of energy into (more) latent and (more outgoing) longwave radiation (alongside less sensible heat), as is necessary given a warmer surface, with subtle changes in the diurnal cycle. Secondly, feedbacks with the atmosphere (in coupled simulations) and through the evolution of the soil temperature and moisture will be triggered, leading to differences in the surface state over time.

Appendix C

There range of science options available within CABLE and ACCESS-CM2 do not exactly overlap. The following outlines options available as at 1st October 2018. Ongoing development of CABLE-within-ACCESS will endeavour to reduce the differences:

'Conservative' configuration of CABLE within ACCESS-CM2

l_rev_coupling, l_revcorr	TRUE	ACCESS specific coupling changes since ACCESS1.4
access13roots	FALSE	ACCESS now uses PFT dependent rooting distributions
fwsoil_switch	Haverd2013	
gs_switch	Medlyn	
Or_evap	FALSE	
litter	FALSE	
soil_thermal_fix	TRUE	

alongside changes to some parameter values (e.g. roughness and albedos over permanent ice as discussed in Section 2.4, 'convex', 'umin')

This is the likely configuration for ACCESS-CM2 within the CMIP6 activities.

configurations successfully tested in ACCESS-CM2

l_rev_coupling, l_revcorr	FALSE	ACCESS specific coupling changes since ACCESS1.4
access13roots	TRUE	revert to PFT independent rooting distributions
fwsoil_switch	standard, nonlinear extrapolation, lai and Ktaul 2013	
gs_switch	leuning	
Or_evap	TRUE	
litter[5]	TRUE	
soil_thermal_fix	FALSE	

[5] Additional analysis is required to determine whether the Or Evaporation parameterization and the litter parameterization can be run in combination or whether they are scientifically mutually exclusive.

Science options partially implemented in ACCESS-CM2

GW_model[6] implemented but requires further testing

Physical science options available in CABLE not tested in ACCES-CM2

l_new_roughness, l_new_runoff_speed, l_new_reduce_soilevap[7]

hydraulic redistribution

SLI

Earth System Science options implemented in CABLE not in ACCESS-CM2

CASA-CNP, POP, SRF and the land-use changes modules.

[6] A version of the Ground Water module was implemented and successfully tested within AMIP simulations using ACCESS-CM2. Testing within fully coupled ACCESS-CM2 revealed issues with the module concerning the initial period after restarts and an interaction between the ground water water, rivers and the ocean circulation that is yet to be fully resolved.

[7] It is likely that these three science options are no longer relevant and can be removed.

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